数据压缩

# 实验内容

将一段英文文献用最佳不等长编码进行压缩。即利用霍夫曼编码（Huffman Code）、算术编码（Arithmetic Code）和LZ编码（Lempel-Ziv Code）算法对英文文献实现无损压缩。

原本的英文文献中存在一个中文全角字符的单引号，为方便处理，手动将其修改为了英文的单引号。

# 霍夫曼编码

### 大体思路

将单个ASCII字符看作信源消息，统计英文文献中ASCII字符的频率分布，有了频率分布就可以构造霍夫曼树，有了霍夫曼树就可以得到霍夫曼编码，有了霍夫曼编码就可以将原本的英文文献压缩。

### 程序实现

读取存放在.txt文件中的英文文献，将其存放在string类型变量text中。注意标点符号和控制符号也需要考虑。另外，将换行符与回车符看成一个字符。

扫描变量text，统计ASCII字符的频率，具体可以使用unordered\_map数据结构存储ASCII字符和其对应的频率。

每次选取频率最低的两个ASCII字符组合形成1个子树，子树的频率是二者之和，直到最后所有ASCII字符都已经放入一棵树中，霍夫曼树就构造好了。为了方便选取频率最低的两个节点，可以使用优先队列。树的节点应该包含ASCII字符、频率、左孩子结点指针、右孩子节点指针。

我们假设树中向左走，编码为“0”，向右走，编码为“1”。通过递归，我们可以得到所有ASCII字符对应的编码。ASCII字符只存在于叶子节点。最终编码结果见附录C。

将英文文献的每一个ASCII字符直接转换为相应的二进制编码，即可完成压缩。压缩结果见附录B。

顺序读入二进制编码，从树根开始，读取到“0”，树中向左走，读取到“1”，树中向右走，直到走到叶子节点，则完成一个ASCII字符的译码，之后再次回到树根，反复操作，直到全部解码完成。就此，解码结束。

# 算术编码

## 大体思路

为了避免浮点数在计算过程中的精度损失，我们需要使用整数算数编码。

由于论文的字符数太多，如果参照课本上的思路，即使使用大数库仍然无法满足所需要的精度，因此我们需要使用重新归一化技术。

统计文献的ASCII字符频率分布，构建概率模型，为每个字符分配一个在总频率计数中的相对区间。编码时，对于输入文本中的每一个字符，编码器根据其在概率模型中的频率范围，按比例缩小当前的 [low, high] 区间。当 low 和 high 的最高有效位变得相同，或者区间变得过窄有下溢风险时，需要进行重新归一化以恢复精度。解码时，从输入比特流中读取的当前编码值，根据当前编码值在当前区间内的相对位置以及概率模型，确定下一个被编码的字符。

## 程序实现

获取输入：

读取存放在.txt文件中的英文文献，做法与霍夫曼编码相同，但是额外增加EOF字符用来在解码时标记结束。

构建概率模型：

扫描英文文献，提取出所有的ASCII字符，统计所有字符的频率，每个字符分配一个在总频率计数中的相对区间。

编码：

遍历 original\_text 中的每一个字符 c，根据 SymbolInfo 中的 cumulative\_low 和 cumulative\_high 以及 total\_frequency\_count\_global，更新 enc\_low 和 enc\_high，将当前区间缩小到代表该字符的部分。

进行重新归一化，

如果当前的区间落在低半区间，则下1个比特一定是0，输出0并将区间放大两倍；

如果当前的区间落在高半区间，则下1个比特一定是1，输出1，将区间放大两倍后再“平移”回下半部分；

如果区间变得很小且没有落在任何半区间内，无法确定是0还是1，需要记录一个“待输出的相反比特”的计数，并将区间围绕 M/4 和 3M/4 进行扩展。待后续比特可以确定后，先输出确定的比特，再输出相应数量的待定相反比特。直到所有字符完成编码。

解码：

从比特流中读取设定的精度位数（程序中是32位，这个可以自己决定），因此初始的编码值dec\_current\_code\_value 就确定了。

计算 dec\_current\_code\_value 在当前 [dec\_low, dec\_high] 区间内按比例映射到总频率 total\_frequency\_count\_global 上的对应值search\_target\_freq 。

通过搜索确定search\_target\_freq 落在哪个符号的范围内，即可确定解码出的符号。

更新解码区间，解码区间被更新到刚解码出的符号所对应的子区间，计算方式与编码器完全对应。

重新归一化与编码时完全对应，关键区别在于，解码器不输出比特，而是通过读入新的比特来调整 dec\_current\_code\_value，以保持其与不断调整的编码区间的相对位置。当解码出EOF（手动添加在最后，用来标志结束）就完成了解码。

# LZ78编码

## 大体思路

统计所有的ASCII字符，使用等长编码，得到字符编码表。扫描英文文献，将英文文献分段并形成段的编码字典，在构建编码字典的同时，将英文文献先进行预编码，因为此时不知道最终的段数，不知道要使用多少位比特来表示。在扫描完成后，整个编码字典的段数得知后，可以在预编码的基础上完成编码操作，具体是段编码+字符编码来编码每一个段。解码时，由于LZ78编码算法的编码结果是固定长度对应于一个字符串，我们每次取出固定长度的二进制串，分别解码段编码和字符编码，直到完成解码。

## 程序实现

获取输入：读取存放在.txt文件中的英文文献，做法与霍夫曼编码相同。

构建字符编码表：扫描英文文献，提取出所有的ASCII字符，使用unordered\_map数据结构存储ASCII字符和其对应的二进制编码。

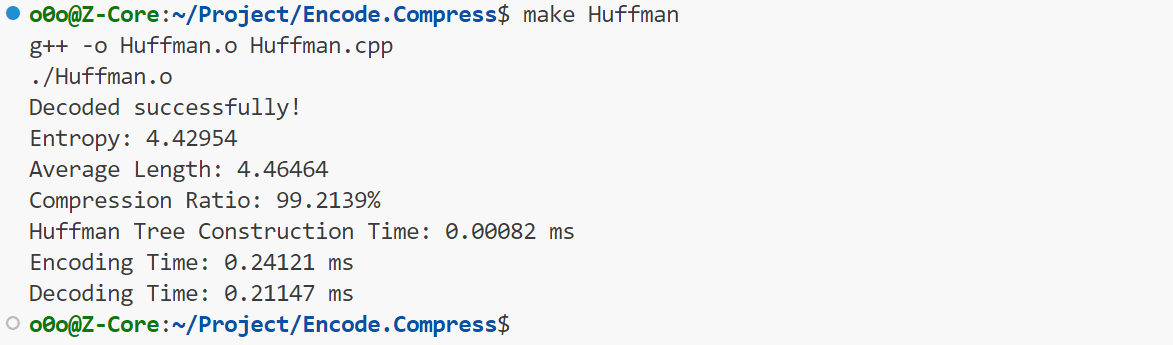
构建逆字符编码表：方便后面解码时，将二进制编码转换成单个ASCII字符。

编码：首先对英文文献进行分段，从前至后扫描，将扫到的字符拼接成字符串，如果新加入的字符构成的新的字符串不在编码字典中，则把该字符串加入编码字典，加入编码字典的次序就是该字符串对应的编码，同时将该字符串删去最后1个字符形成的字符串对应的次序和最后一个字符对应的编码放入预编码序列。接着从空字符串开始重新拼接字符串，直到下一个不在编码字典中的字符串出现，将其再加入，循环直到完成扫描。加入编码字典的次序就是该字符串对应的编码。完成扫描后，我们才能得知总共有多少段，才能直到需要使用多少位二进制来编码，之后将预编码序列中的次序转换为二进制编码，则完成编码。

解码：先提取出段号对应的二进制串，通过构建的编码字典还原回字符串，再提取出字符对应的二进制串，通过逆字符编码表，将二进制编码转换成单个ASCII字符。解码时使用的编码字典是在解码的同时构建出来的，因为编码的时候是从前至后依次编码，解码的时候，将还原出来的字符串直接加入编码字典，就可以完美的还原出编码时使用的编码字典。

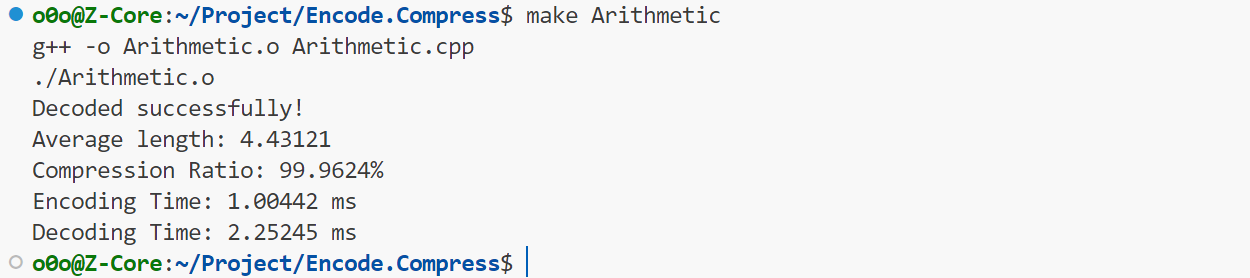
# 编码效率与时间开销分析

## 霍夫曼编码

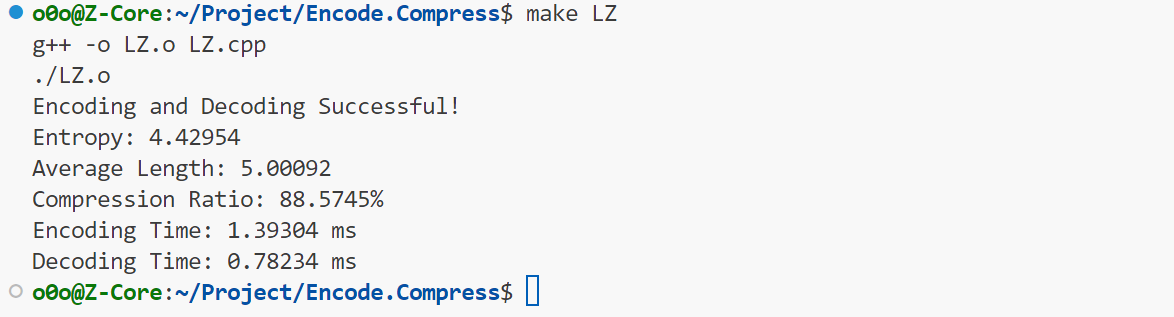


运行100次编码解码，得到平均编码时间，我们忽略统计字符频率的时间，而建树得到霍夫曼编码的时间为0ms，因此也可以忽略。

## 算术编码



## LZ78编码



## 对比

|  |  |  |  |
| --- | --- | --- | --- |
|  | 哈夫曼编码 | 算数编码 | LZ78编码 |
| 信源熵 | 4.42954 | 4.42954 | 4.42954 |
| 平均编码长度 | 4.46464 | 4.43121 | 5.00092 |
| 编码效率 | 99.2139% | 99.9624% | 88.5745% |
| 平均编码时间 | 0.24121ms | 1.00442ms | 1.39304ms |
| 平均解码时间 | 0.21147ms | 2.25245ms | 0.78234ms |

通过对比可以发现，在可以获得准确的符号概率分布的情况下，哈夫曼编码和算数编码可以取得极高的编码效率，LZ78编码则相对不足。

而在编码和解码时间上，哈夫曼编码消耗的时间最低，算数编码消耗的时间最多。

# 附录

## 源代码

### Huffman

#include <fstream>

#include <iostream>

#include <math.h>

#include <queue>

#include <unordered\_map>

#include <vector>

using namespace std;

// 定义霍夫曼树节点结构体

struct Node {

  char ch;            // 字符

  int freq;           // 频率

  Node \*left, \*right; // 左右子节点指针

};

// 比较函数，用于优先队列，按频率降序排列

struct compare {

  bool operator()(Node \*l, Node \*r) { return l->freq > r->freq; }

};

double culculateTime(clock\_t start, clock\_t end) {

  // 返回以ms计算的时间

  return (double)((end - start) \* 1000) / CLOCKS\_PER\_SEC;

}

// 递归打印霍夫曼编码

void printCodes(Node \*root, string str,

                unordered\_map<char, string> &huffmanCode) {

  if (!root)

    return; // 如果节点为空，返回

  if (!root->left && !root->right) {

    huffmanCode[root->ch] = str; // 如果是叶子节点，存储字符对应的霍夫曼编码

  }

  printCodes(root->left, str + "0", huffmanCode);  // 递归遍历左子树，编码加'0'

  printCodes(root->right, str + "1", huffmanCode); // 递归遍历右子树，编码加'1'

}

string encode(string text, unordered\_map<char, string> &huffmanCode) {

  string encodedText = ""; // 初始化编码后的字符串

  for (char ch : text) {

    encodedText += huffmanCode[ch]; // 将每个字符替换为其霍夫曼编码

  }

  return encodedText;

}

string decode(Node \*root, string encodedText) {

  string decodedText = ""; // 初始化解码后的字符串

  Node \*curr = root;       // 当前节点指向根节点

  for (int i = 0; i < encodedText.size(); ++i) {

    if (encodedText[i] == '0')

      curr = curr->left; // 如果当前位为'0'，移动到左子节点

    else

      curr = curr->right; // 如果当前位为'1'，移动到右子节点

    if (curr->left == nullptr && curr->right == nullptr) {

      decodedText += curr->ch; // 如果到达叶子节点，添加字符到解码字符串

      curr = root;             // 重置当前节点为根节点

    }

  }

  return decodedText;

}

int main() {

  // 读取整个文件内容

  ifstream file("input.txt");

  if (!file.is\_open()) {

    cerr << "Failed to open file." << endl;

    return 1;

  }

  string text((istreambuf\_iterator<char>(file)), istreambuf\_iterator<char>());

  file.close();

  unordered\_map<char, int> frequency; // 存储字符频率的哈希表

  // 计算每个字符的频率

  for (char ch : text) {

    frequency[ch]++;

  }

  // 创建优先队列，按频率升序排列

  priority\_queue<Node \*, vector<Node \*>, compare> heap;

  // 将所有字符作为单独节点插入优先队列

  for (auto pair : frequency) {

    heap.push(new Node({pair.first, pair.second, nullptr, nullptr}));

  }

  clock\_t start = clock();

  // 构建霍夫曼树

  while (heap.size() != 1) {

    Node \*left = heap.top();

    heap.pop();

    Node \*right = heap.top();

    heap.pop();

    int sum = left->freq + right->freq;

    heap.push(new Node({'\0', sum, left, right})); // 合并两个频率最小的节点

  }

  // 获取每个字符的霍夫曼编码

  Node \*root = heap.top(); // 根节点指向霍夫曼树的根

  unordered\_map<char, string> huffmanCode;

  printCodes(root, "", huffmanCode);

  clock\_t end = clock();

  // 编码

  string encodedText = encode(text, huffmanCode);

  // 解码

  string decodedText = decode(root, encodedText);

  // 检查解码是否正确

  if (text == decodedText) {

    cout << "Decoded successfully!" << endl;

  } else {

    cout << "Decoding failed!" << endl;

  }

  // 计算信源的熵

  double entropy = 0.0;

  int totalChars = text.size();

  for (auto pair : frequency) {

    double prob = (double)pair.second / totalChars; // 计算概率

    entropy -= prob \* log2(prob);                   // 计算熵

  }

  // 计算平均长度

  double avgLength = encodedText.size() / (double)totalChars;

  cout << "Entropy: " << entropy << endl;          // 输出信源熵

  cout << "Average Length: " << avgLength << endl; // 输出平均长度

  cout << "Compression Ratio: " << (entropy / avgLength) \* 100 << "%"

       << endl; // 输出编码效率

  // 统计构建霍夫曼树的时间开销

  cout << "Huffman Tree Construction Time: "

       << culculateTime(start, end) / 100.0 << " ms" << endl;

  // 统计编码时间开销

  start = clock();

  for (int i = 0; i < 100; i++) {

    string encodedText = encode(text, huffmanCode);

  }

  end = clock();

  cout << "Encoding Time: " << culculateTime(start, end) / 100.0 << " ms"

       << endl;

  // 统计解码时间开销

  start = clock();

  for (int i = 0; i < 100; i++) {

    string decodedText = decode(root, encodedText);

  }

  end = clock();

  cout << "Decoding Time: " << culculateTime(start, end) / 100.0 << " ms"

       << endl;

  return 0;

}

### Arithmetic

#include <algorithm>

#include <fstream>

#include <iomanip>

#include <iostream>

#include <map>

#include <stdexcept>

#include <string>

#include <vector>

// --- 共享配置和数据 ---

const int PRECISION\_BITS = 32; // 使用32位精度进行计算

const uint64\_t TOP\_VALUE = (1ULL << PRECISION\_BITS) - 1;

const uint64\_t FIRST\_QUARTER = (TOP\_VALUE / 4) + 1;

const uint64\_t HALF = (TOP\_VALUE / 2) + 1;

const uint64\_t THIRD\_QUARTER = FIRST\_QUARTER \* 3;

struct SymbolInfo {

  char symbol;

  uint64\_t frequency;

  uint64\_t cumulative\_low;

  uint64\_t cumulative\_high;

};

std::map<char, SymbolInfo> probability\_model\_global; // 共享模型

uint64\_t total\_frequency\_count\_global;               // 共享总频率

char EOF\_SYMBOL\_CONST; // 结束符号

// --- 通用函数 ---

double culculateTime(clock\_t start, clock\_t end) {

  // 返回以ms计算的时间

  return (double)((end - start) \* 1000) / CLOCKS\_PER\_SEC;

}

void build\_shared\_probability\_model(const std::string &text) {

  probability\_model\_global.clear();

  std::map<char, uint64\_t> freqs;

  for (char c : text) {

    freqs[c]++;

  }

  freqs[EOF\_SYMBOL\_CONST]++; // 添加EOF频率

  total\_frequency\_count\_global = 0;

  for (auto const &[symbol, count] : freqs) {

    total\_frequency\_count\_global += count;

  }

  uint64\_t current\_cumulative\_low = 0;

  for (auto const &pair : freqs) {

    char symbol = pair.first;

    uint64\_t freq = pair.second;

    if (freq == 0)

      continue;

    SymbolInfo info;

    info.symbol = symbol;

    info.frequency = freq;

    info.cumulative\_low = current\_cumulative\_low;

    info.cumulative\_high = current\_cumulative\_low + freq;

    probability\_model\_global[symbol] = info;

    current\_cumulative\_low += freq;

  }

}

// --- 编码器状态和函数 ---

uint64\_t enc\_low;

uint64\_t enc\_high;

uint64\_t enc\_pending\_underflow\_bits;

std::string enc\_output\_bits\_stream;

void enc\_output\_bit(int bit) { enc\_output\_bits\_stream += (bit ? '1' : '0'); }

void enc\_output\_bit\_plus\_pending(int bit) {

  enc\_output\_bit(bit);

  for (uint64\_t i = 0; i < enc\_pending\_underflow\_bits; i++) {

    enc\_output\_bit(!bit);

  }

  enc\_pending\_underflow\_bits = 0;

}

void enc\_renormalize() {

  while (true) {

    if (enc\_high < HALF) { // 如果编码器的上限小于一半，可以确定下一个比特为0

      enc\_output\_bit\_plus\_pending(0);

      enc\_low = enc\_low \* 2;

      enc\_high = enc\_high \* 2 + 1;

    } else if (enc\_low >=

               HALF) { // 如果编码器的下限大于等于一半，可以确定下一个比特为1

      enc\_output\_bit\_plus\_pending(1);

      enc\_low = (enc\_low - HALF) \* 2;

      enc\_high = (enc\_high - HALF) \* 2 + 1;

    } else if (

        enc\_low >= FIRST\_QUARTER &&

        enc\_high <

            THIRD\_QUARTER) { // 如果编码器的下限大于等于四分之一且上限小于四分之三，无法确定下一个比特，需要等待更多比特

      enc\_pending\_underflow\_bits++;

      enc\_low = (enc\_low - FIRST\_QUARTER) \* 2;

      enc\_high = (enc\_high - FIRST\_QUARTER) \* 2 + 1;

    } else {

      break;

    }

  }

}

void initialize\_encoder\_state() {

  enc\_low = 0;

  enc\_high = TOP\_VALUE;

  enc\_pending\_underflow\_bits = 0;

  enc\_output\_bits\_stream.clear();

}

void encode\_symbol(char symbol\_to\_encode) {

  const SymbolInfo &sym\_info = probability\_model\_global.at(symbol\_to\_encode);

  uint64\_t current\_range = enc\_high - enc\_low + 1;

  enc\_high = enc\_low +

             (current\_range \* sym\_info.cumulative\_high /

              total\_frequency\_count\_global) -

             1;

  enc\_low = enc\_low + (current\_range \* sym\_info.cumulative\_low /

                       total\_frequency\_count\_global);

  enc\_renormalize();

}

void flush\_encoder() {

  enc\_pending\_underflow\_bits++;

  if (enc\_low < FIRST\_QUARTER) {

    enc\_output\_bit\_plus\_pending(0);

  } else {

    enc\_output\_bit\_plus\_pending(1);

  }

}

std::string arithmetic\_encode(const std::string &input\_text) {

  initialize\_encoder\_state();

  for (char c : input\_text) {

    encode\_symbol(c);

  }

  encode\_symbol(EOF\_SYMBOL\_CONST);

  flush\_encoder();

  return enc\_output\_bits\_stream;

}

// --- 解码器状态和函数 ---

uint64\_t dec\_low;

uint64\_t dec\_high;

uint64\_t dec\_current\_code\_value; // 从输入比特流派生出的值

const std::string \*dec\_input\_bits\_stream\_ptr;

size\_t dec\_current\_bit\_idx;

int read\_next\_bit\_for\_decoder() {

  if (dec\_input\_bits\_stream\_ptr &&

      dec\_current\_bit\_idx < dec\_input\_bits\_stream\_ptr->length()) {

    return (\*dec\_input\_bits\_stream\_ptr)[dec\_current\_bit\_idx++] - '0';

  }

  return 0;

}

void dec\_renormalize() {

  while (true) {

    if (dec\_high < HALF) {

      dec\_low = dec\_low \* 2;

      dec\_high = dec\_high \* 2 + 1;

      dec\_current\_code\_value =

          dec\_current\_code\_value \* 2 + read\_next\_bit\_for\_decoder();

    } else if (dec\_low >= HALF) {

      dec\_low = (dec\_low - HALF) \* 2;

      dec\_high = (dec\_high - HALF) \* 2 + 1;

      dec\_current\_code\_value =

          (dec\_current\_code\_value - HALF) \* 2 + read\_next\_bit\_for\_decoder();

    } else if (dec\_low >= FIRST\_QUARTER && dec\_high < THIRD\_QUARTER) {

      dec\_low = (dec\_low - FIRST\_QUARTER) \* 2;

      dec\_high = (dec\_high - FIRST\_QUARTER) \* 2 + 1;

      dec\_current\_code\_value = (dec\_current\_code\_value - FIRST\_QUARTER) \* 2 +

                               read\_next\_bit\_for\_decoder();

    } else {

      break;

    }

  }

}

void initialize\_decoder\_state(const std::string &input\_bits) {

  dec\_low = 0;

  dec\_high = TOP\_VALUE;

  dec\_current\_code\_value = 0;

  dec\_input\_bits\_stream\_ptr = &input\_bits;

  dec\_current\_bit\_idx = 0;

  for (int i = 0; i < PRECISION\_BITS; ++i) {

    dec\_current\_code\_value =

        (dec\_current\_code\_value << 1) | read\_next\_bit\_for\_decoder();

  }

}

std::string arithmetic\_decode(const std::string &encoded\_bits) {

  initialize\_decoder\_state(encoded\_bits);

  std::string decoded\_text;

  while (true) {

    uint64\_t current\_range = dec\_high - dec\_low + 1;

    uint64\_t search\_target\_freq =

        ((dec\_current\_code\_value - dec\_low) \* total\_frequency\_count\_global) /

        current\_range;

    char current\_decoded\_symbol = EOF\_SYMBOL\_CONST;

    bool found\_symbol = false;

    for (auto const &pair : probability\_model\_global) {

      const SymbolInfo &sym\_info = pair.second;

      // 检查search\_target\_freq是否落在该符号的累积范围内

      if (search\_target\_freq >= sym\_info.cumulative\_low &&

          search\_target\_freq < sym\_info.cumulative\_high) {

        current\_decoded\_symbol = sym\_info.symbol;

        // 更新解码器的下限和上限到该符号的子区间

        // 镜像编码器

        dec\_high = dec\_low +

                   (current\_range \* sym\_info.cumulative\_high /

                    total\_frequency\_count\_global) -

                   1;

        dec\_low = dec\_low + (current\_range \* sym\_info.cumulative\_low /

                             total\_frequency\_count\_global);

        found\_symbol = true;

        break;

      }

    }

    if (current\_decoded\_symbol == EOF\_SYMBOL\_CONST)

      break;

    decoded\_text += current\_decoded\_symbol;

    dec\_renormalize();

  }

  return decoded\_text;

}

int main() {

  // 读取文件内容

  std::ifstream file("input.txt");

  if (!file.is\_open()) {

    std::cerr << "无法打开文件" << std::endl;

    return 1;

  }

  std::string original\_text((std::istreambuf\_iterator<char>(file)),

                            std::istreambuf\_iterator<char>());

  file.close();

  EOF\_SYMBOL\_CONST = '\3'; // ETX (End of Text) as EOF symbol

  build\_shared\_probability\_model(original\_text);

  // 编码

  std::string compressed\_bits = arithmetic\_encode(original\_text);

  // 解码

  std::string decoded\_text = arithmetic\_decode(compressed\_bits);

  // 检查解码是否正确

  if (decoded\_text == original\_text) {

    std::cout << "Decoded successfully!" << std::endl;

  } else {

    std::cout << "Decoding failed!" << std::endl;

    return 0;

  }

  double entropy = 4.42954; // 信源熵

  // 计算平均编码长度

  double avg\_length =

      compressed\_bits.length() / (double)(original\_text.length() + 1);

  std::cout << "Average length: " << avg\_length << std::endl;

  std::cout << "Compression Ratio: " << (entropy / avg\_length) \* 100 << "%"

            << std::endl; // 输出编码效率

  // 统计编码时间消耗

  clock\_t start = clock();

  for (int i = 0; i < 100; i++) {

    arithmetic\_encode(original\_text);

  }

  clock\_t end = clock();

  std::cout << "Encoding Time: " << culculateTime(start, end) / 100.0 << " ms"

            << std::endl;

  // 统计解码时间消耗

  start = clock();

  for (int i = 0; i < 100; i++) {

    arithmetic\_decode(compressed\_bits);

  }

  end = clock();

  std::cout << "Decoding Time: " << culculateTime(start, end) / 100.0 << " ms"

            << std::endl;

  return 0;

}

### LZ78

#include <bitset>

#include <fstream>

#include <iostream>

#include <string>

#include <unordered\_map>

#include <vector>

using namespace std;

unordered\_map<char, string> symbolTable;

unordered\_map<string, char> reverseSymbolTable;

int symbolBits = 0;

int segBits = 0;

double culculateTime(clock\_t start, clock\_t end) {

  // 返回以ms计算的时间

  return (double)((end - start) \* 1000) / CLOCKS\_PER\_SEC;

}

void buildSymbolTable(const string &input) {

  int dictSize = 0;

  unordered\_map<char, int> tempSymbolTable;

  // 统计所有的字符，得到符号编码表

  for (char c : input) {

    if (tempSymbolTable.find(c) ==

        tempSymbolTable.end()) { // 如果字符不在符号表中

      tempSymbolTable[c] = dictSize++;

    }

  }

  // 计算编码所需的位数

  dictSize = tempSymbolTable.size();

  while ((1 << symbolBits) < dictSize) {

    symbolBits++;

  }

  // 将int值转换为二进制字符串，存入符号表

  for (const auto &pair : tempSymbolTable) {

    string binaryString =

        bitset<8>(pair.second).to\_string().substr(8 - symbolBits);

    symbolTable[pair.first] = binaryString;

  }

}

void buildReverseSymbolTable() {

  for (const auto &pair : symbolTable) {

    reverseSymbolTable[pair.second] = pair.first;

  }

}

string lz78Encode(const string &input) {

  unordered\_map<string, int> dictionary;

  vector<pair<int, string>> encodedData;

  string encodedBits;

  int dictSize = 1;

  string currentString = "";

  // 分段，得到字典，并进行初步编码

  for (char c : input) {

    currentString += c;

    if (dictionary.find(currentString) == dictionary.end()) {

      // 如果当前字符串不在字典中

      int index =

          currentString.length() > 1

              ? dictionary[currentString.substr(0, currentString.length() - 1)]

              : 0;

      char lastChar = currentString.back();

      string lastCharBits = symbolTable[lastChar];

      encodedData.push\_back(make\_pair(index, lastCharBits));

      dictionary[currentString] = dictSize++;

      currentString = "";

    }

  }

  // 处理最后一个字符

  if (!currentString.empty()) {

    int index =

        currentString.length() > 1

            ? dictionary[currentString.substr(0, currentString.length() - 1)]

            : 0;

    char lastChar = currentString.back();

    string lastCharBits = symbolTable[lastChar];

    encodedData.push\_back(make\_pair(index, lastCharBits));

  }

  // 计算段号所需的位数

  dictSize = dictionary.size();

  while ((1 << segBits) < dictSize) {

    segBits++;

  }

  // 在初步编码的基础上完成编码

  for (const auto &pair : encodedData) {

    // 将索引转换为二进制字符串

    int index = pair.first;

    string indexBits = bitset<16>(index).to\_string().substr(16 - segBits);

    // 拼接编码结果

    encodedBits += indexBits + pair.second;

  }

  return encodedBits;

}

string lz78Decode(const string &encodedBits) {

  string decodedText;

  unordered\_map<int, string> dictionary;

  int dictSize = 1;

  // 解码

  size\_t pos = 0;

  while (pos < encodedBits.length()) {

    // 提取出段号

    if (pos + segBits > encodedBits.length())

      break;

    string indexBitSequence = encodedBits.substr(pos, segBits);

    pos += segBits;

    // 提取出符号

    if (pos + symbolBits > encodedBits.length())

      break;

    string symbolBitSequence = encodedBits.substr(pos, symbolBits);

    pos += symbolBits;

    // 将索引转换为整数

    int index = bitset<64>(indexBitSequence).to\_ulong();

    // 解码

    char nextChar = reverseSymbolTable[symbolBitSequence];

    string decodedString =

        (index > 0) ? dictionary[index] + nextChar : string(1, nextChar);

    decodedText += decodedString;

    dictionary[dictSize++] = decodedString;

  }

  return decodedText;

}

int main() {

  // 读取整个文件内容

  ifstream file("input.txt");

  if (!file.is\_open()) {

    cerr << "Failed to open file." << endl;

    return 1;

  }

  string text((istreambuf\_iterator<char>(file)), istreambuf\_iterator<char>());

  file.close();

  buildSymbolTable(text);    // 构建符号表

  buildReverseSymbolTable(); // 构建化反向符号表

  // 编码

  string encodedText = lz78Encode(text);

  // 解码

  string decodedText = lz78Decode(encodedText);

  // 比较编码和解码结果

  if (text == decodedText) {

    cout << "Encoding and Decoding Successful!" << endl;

  } else {

    cout << "Encoding and Decoding Failed!" << endl;

  }

  // 计算编码效率

  double entropy = 4.42954;

  double avgLength = encodedText.size() / (double)text.size();

  cout << "Entropy: " << entropy << endl;          // 输出信源熵

  cout << "Average Length: " << avgLength << endl; // 输出平均长度

  cout << "Compression Ratio: " << (entropy / avgLength) \* 100 << "%"

       << endl; // 输出编码效率

  // 统计编码时间消耗

  clock\_t start = clock();

  for (int i = 0; i < 100; i++) {

    lz78Encode(text);

  }

  clock\_t end = clock();

  cout << "Encoding Time: " << culculateTime(start, end) / 100.0 << " ms"

       << endl;

  // 统计解码时间消耗

  start = clock();

  for (int i = 0; i < 100; i++) {

    lz78Decode(encodedText);

  }

  end = clock();

  cout << "Decoding Time: " << culculateTime(start, end) / 100.0 << " ms"

       << endl;

  return 0;

}

## 压缩结果

### Huffman

01010011100101010100111101110100010111010111010100111001100001110101100001110100110100101111111011001001101011111010010110001110100000011011100101101000111110010010000001011100111010010101010101010001011011110111110111101011001110100011011011111110110101111101110100111111011000100001010010110011000110000010001101011001111110110001000011010010000100011101000001001011010111110101011101011001111110110001000011000011110101100101010100111101110100010111010111010100111001100001011111001001011100110001110111010000101101100101010100111101110100010111010111010100111001100001110001000010101011010000101010111111011000100001010010110100100001000111000100001001111011101000001011111001000101100001010011110110000111001111000011110101101011100010010000111110111111101100101111101010000101111110101111001010101001111011101000101110101110101001110011000011101010100101101111101111101010111010110011111001011101010001100101001110111001011010001111100100110001000010011110111010000010111110010010111001011001111101001000010001110011110000101111111001111000101111101111000111001110011010101001011000101000100001110001101000101110101010111001000011100110011101000110011111100111000011000001001011011011110101100111010110000111100101100000001111111010010000100011101000001001011010111110101000011101111010110011100100000111100111011111110111110001100110101100001110000111101011010101001011011111011111010101110101100111110011000000000101100010100010001101100001110011110001000011111011111110110010111101001011001110100110101010111101001011111010100000011110111011100101101000001001011001111010010110000111110101100101101101001010011111010110010000111110111010110011111001100011100111001011010000010010110011111010010000100011101011000010001101110000011011100010100110010100001110101000110111000010101011001110111001011010001111100100110001000010011110111010000010111110010010111001011001111101111000111010010100111110101100100001111101110101100111110011101000110111110011101111111001010001101010100101101111101111101010111010110011111001110010110001010001000100101100111101001011010010111110101000000101000010001101001011111011110001110111000100110001101110011111001110111101011001110010101011000011010100101110111110000111101011010101001011011111011111010101110101100111110011100110001100000100011010110011111101100010000101001011001001011110110000111001111010101011010000101010111110001111001101101001010101010111011101011101001010001110011000101101011111101011111000101111101111000111001110011010101001011000111011110101100111001010101100001101010010111011101010001110110111101100111011011110110011100101101000111110010011010101001011011111011111010101110101100111110010111110101100001010101000010011000100111010011100101010100111101110100010111010111010100111001100001110010010111001100011101110100001011011000100001010101101000010101011111101100010000110100100001000111010101011010000101010111110001111001101101001010101010111011101011101001010011111010110010000111110111010110011111101100010000110000111101011010001100111111001110011100100001111110111100011100001011011011101001100001111000111011110101100111000100001111101111111000011101111010111001111111010100001001011111010110111011101001001100011101111010110011101010100101101111101111101010111010110011111001010100011010100110000111101011001011011010110000111010000101101110001100111111011000100001101011000010101010000100110001001100011101011000011010011101110010110100011111001001101010100101101111101111101010111010110011111001110101100001010101000010011000100101111101011100010010000111110111110101000011011000011100111101011000011101000010110111000110011111101100010000110100111101110001010011111110111101011001110101010010110111110111110101011101011001111100111001011000101000100010010110101001011010011110111000101001111111011110101100111011100101101000111110010011011110101110011111110101101110111010010011000111011110101100111010101001011011111011111010101110101100111110011010010110100100001000111000011111010110010110110100011001111110011101011000010101010000100110001101100001110011110111101011001110101010010110111110111110101011101011001111100110000000110111110101010110001100111111011000100001101000110011111001110100100001000111010000011001010001011100011011111110000111001010100101101011000110001010100011101101111011001110110111101100111000011011011111101011000101001111111011100101101000111110010010100101100111001000001111011111110111000001001110101100001110100001011011100011001111110110001000011010101100100001100111111110110100001000110111011100111000100001010101101000010101011111001100011010010110001000001110100101101011000011100111101010100010000111010101110001001000011111011100101000101111111000011010010110100100001000111000110100010111010101011100100001110011001100011101110111001111110100000010010000110111110100000001110001000011111011111110110010111101001011011101110100111111101111010110010110001110101000000010100101000100011101110111001110000000011101001011101110100101101001000010101001110000111101011011110101100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### Arithmetic

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01101001000000000000000000000000111010101001101100001101011110101110001001000101001110110110101001110010011110101010101010001111010001111000000001000110000110000011010000001000000101011000100100001111001100010010000100100111010110000001000000000110001101000100011110010000000001101000001001000001000000001100100000110010000000101010011110000100101001101110001001011000110000001011001101101110010000101010110010000010011101100000000110001110110100000110000000011010011010001010010000011010001001100110000110011001110000000001010000011010001110001001110110010000010011001110000101000111110110000001001000110100010000000101101110000011001110101100010110001000101100000110100010010110000101011010101100001100001001110000001111011010100000000101101001010100000011000110000110010111010100001000101010010100000000001111010011100000001001010010110110001001000000011100001001000000011110001101011011010000001110100110010010101111001111111100001111001110111100000001000001000010000110000000011110011000000010000110001110001101010010011001011110010110001111010011011000010000001100001000011110000100110000001111010010011000010000000101101110001111010111011110000011101001010110000001101011110110010110000011000010011000000011101110001111001111010100011010010000000010000110001010000110001111011101110100000001001001101000001101010111011110001001001000100110000001000000010110001001010000000010001111011110110110001110000001000000110000000000010100010110001101010000001101000110000100101100001010100010001101100110011000000110101100010100001001001100100110001101100100001010010100010011000010000001001100100010010111010110110010000001010000111110001011101000000110001001001000110010011000000000010100000010000010010010011000000000100010011101010101011010001100010011000010001001011010100010000001010110011010000111010001001110001101001000111010000110001000001000011001100010000000001001000111011100001101010011011010010110001101000010010111010001111010010000000000001110001101101110001000000001010110011010001110011000111110000110000000100010001000000101101010110110001110001010011111011001101000000010000101110110011001010010011000110111101000001100111011000000000000111011000101001000100110011110101010000100101100000010001101100010100110001011010110011100001101000110011100001101011101001110010110000000011110000111011011010000000100000000001100001110000000010000001000000010001010001111001000110010001110010000011000000111011110011110000110010101010010001001010100000110000001001110010010111100000001001100000111011011111010101010010010101000111100011010101000111101000101001010001110011000110000001100001101110110000001000100011100010110011001000100010000001111000000001011000000000100110011101010001100000001000000011100001110000010001110000001101011001010001001101111010110001001100001011010001111001100001000011010000001100100001001000010000000011101010111110000010100001011110000110111101111001000111000000101001000111110010010111000011011000101110110000001000010010010011011011000100100001001010001010010000110100010010000000110011101011110001101000001010110000100100110001000000001001100100010000110011011100000000111101111101000001111100010111000011000000111100000001101001010000110011011011011111010111111000000010110011110000010011100010000010111011110100101000001000000101010010010101000000100011100100100001011000111100110011001010111111100000111011011111010000101011011010000001111000010001000001111011001000000000011000010110000000001000110000100001111101101000010010000011011101110000101100101011000001001100100001110000001010011110010001001101111101100111111110001000000001110011101011010000111101010111000000110001000110110010000011110110010010111011001001110001110110000100010010110000001110000000110011100101000101010110001001000000011011011100110001001010010000100000001001000110100111100011010101000101010000100100100000001101111011110001111001000110010001010011011100100001101011010100000000001001100100010001001000000001010000001010000010000001101011110010010100010001111011000001011100001110010010000000001100100001011001001011110011010010010000010000010101101011110001110000100111100010000000011101010000011011011100110011011101100110010000000011101010110000011101011010110001110000110010010000010100001010100000111010111100010000001000010100110001100001010000000010000100001101100000110100110010010011000101101101110001011000001001000001110000010001010101100101110000000000011010110110110011110100101100000000101011000011000000101000101110110011000010100001000101111110010001110000100100110010110000011000011100100011001011110010110001110101001111110000111101110010110010000010000110100011000010010011000010010010111100000010000000010010000111110010010111000011000000011010000001101000101100010001110000000010000001010101000111010010010000000000000111110000000110000010101001100010010010110001101001110100100010100100000001011000000110000111110000000110000100000101101010010000010001001011110000100110000100010001111000000010110001111101010110110001111000101101010010100010010110000010000011011100100011000001111010100001101001101111110001010000111000100001111001010010000001001010011000100010110011101100100010111000010110100001101010000000010000111001110100110000001001101011100000111010110010010001110010100010000000110001100101000001111010001001100001001110001100010001110011001000100001111011101101010011000001100101100001010011111101010001001000101001110000011000011011100001111011001110110001001000001100000010110000110011000001001001010011000001110010010000100010110010100100010001110001011000100010110101110110000001110001000110010000010110010110000000001001110011100000001110000110010010000100011110100010111000111100010001001000110011000010110100010001010000001100001000110000001101111100010010000101100010010001011010101100100001001100010111110011101010111110000100100010110011110000010100110000110000101000011100110000001110101001010010111000111100000000110000001000000011110000100001000010111001011010110000001101110111000000001010011000000001101101101110110001111011001110110010000011111000010001110010000011000010000101010010010001001101101010110010111000000101100001000000011000000000111100111000000001011011001110110000100010111101010010110001101111000001111000000100100011001000000111000010110010010110010100101000110110010001100000100000100001011001110101000001111001000110010001111011001000010010000110001010010011110011000000010011001010000110100001101100100110100011110000100011100000011100101100100010000010001011010000001101001011110001101000011110010001110100100011000000101010111111010000001010000110000001001100100110000000010001011010100001111100011111100000011000100101110000001010011000000000001000111111110011100011110101010010110011110010000000011010110110110001100100101101110010111000110000000000111010110100100011011001010011000000110011011011100000001001101011100000110011100101000000110100100110000001011100001011110001110000011100000001101011000101010010000100100010010001111101010101110001011000010011110011000000001010100000110000110110000011101010101011010010000100100110100000011110110111010001110100000010010000001101011111000000001100111010000010000010010110100001011011010100010011001000111000010000110001100000110001111101010100110011100100111100000001111100111111110010111010001100111000000000001101000001101011111000110010110011111111010000001101001000000001001101000100010111111000101011010000110010000101010010000000011101010000110101111101010000001001000010110001101000110111100001000000001000100000110101100100110000001110000001100001111000111101000100011

## 编码对照表

### Huffman

* t -> 1111
* b -> 1110111
* -> 11101101 //控制字符之类的
* -> 11101100
* f -> 111010
* g -> 1110011
* z -> 10100010001
* / -> 101000100001
* j -> 10100010101
* N -> 101000100000
* w -> 1010000
* d -> 10001
* ) -> 1000000101
* y -> 100001
* v -> 1000001
* ; -> 10100010011
* B -> 10000001111
* ( -> 1000000110
* c -> 10101
* D -> 10100010010
* a -> 1001
* ' -> 1000000011
* n -> 0000
* - -> 100000000
* h -> 01011
* 5 -> 1000000100
* p -> 010101
* o -> 0001
* e -> 001
* r -> 0110
* 7 -> 111000010011
* u -> 01001
* : -> 1110000110011
* A -> 0101001
* . -> 0101000
* i -> 1011
* S -> 10000001110
* s -> 0111
* l -> 01000
* 1 -> 10100110001
* 2 -> 1000000010
* m -> 1110001
* R -> 10100010100
* x -> 1010001011
* K -> 10100011
* , -> 1010010
* O -> 10100110000
* " -> 1010011001
* F -> 1010011010
* X -> 101001101100
* H -> 1010011011010
* U -> 1010011011011
* q -> 10100110111
* k -> 10100111
* 0 -> 1110000111
* -> 110
* C -> 11100000
* G -> 11100001000
* E -> 111000010010
* T -> 1110000101
* 9 -> 111000011000
* M -> 1110000110010
* W -> 11100001101
* I -> 11100100
* P -> 11100101

### LZ78

* B -> 0111001
* F -> 0110110
* X -> 0110010
* / -> 0111010
* j -> 0110000
* " -> 0101111
* n -> 0001011
* -> 0000001
* w -> 0011100
* A -> 0000000
* 7 -> 0111000
* r -> 0001101
* s -> 0001111
* 9 -> 0110101
* t -> 0010000
* : -> 0101000
* u -> 0000011
* P -> 0010010
* K -> 0010011
* h -> 0010111
* - -> 0100000
* M -> 1000000
* g -> 0011011
* , -> 0011001
* S -> 0111111
* a -> 0001110
* D -> 0111100
* N -> 0111101
* 1 -> 0111011
* l -> 0000101
* v -> 0011010
* ; -> 0101110
* o -> 0010110
* G -> 0111110
* d -> 0011000
* ) -> 0010101
* p -> 0000010
* 5 -> 0110011
* c -> 0000111
* ( -> 0010001
* b -> 0000100
* ' -> 0100101
* y -> 0001010
* i -> 0000110
* . -> 0011101
* k -> 0001000
* 0 -> 0110100
* e -> 0001001
* I -> 0010100
* f -> 0001100
* m -> 0011110
* 2 -> 0110111
* x -> 0011111
* T -> 0100001
* -> 0100010
* H -> 0110001
* -> 0100011
* E -> 0100111
* O -> 0100100
* W -> 0100110
* U -> 0101001
* C -> 0101010
* R -> 0101011
* z -> 0101100
* q -> 0101101