Advanced Data Structures and Algorithm Analysis

Project 1: Roll Your Own Mini Search Engine

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Chapter 1: Introduction

1.1 Problem Description

The project requires us to implement a mini search engine based on *The Complete Works of William Shakespeare*, which can return the corresponding articles according to the words users desire to query.

In addition, this search engine has the features below:

- Word count for over the article set and attain the stop words(i.e. meaningless words while searching) from this set.
- Use the **inverted file index** to store and access all words with their frequency and location.
- The precision and recall can be adjusted by setting the threshold of queries.

1.2 Purpose of Report

- Show the details of the implementation of the mini search engine by showcasing essential data structures and algorithms.
- Demonstrate the correctness and efficiency of the program by analysis based on testing data and diagrams.
- Summarize the whole project, analyze the pros and cons of the mini search engine, and put forward the prospect of further improvement.

1.3 Backgound of Data Structures and Algorithms

1. **B+ Trees**: It's an improved version of search trees, widely used in the relational database and file management in operating systems. We will use this data structure to store and access to the inverted index.
2. **Hashing**: Hash tables have an excellent performance in searching data(only cost O(1) time), hence we take advantage of this data structure for finding stopwords when building an inverted index.
3. **Queue**: The Queue ADT is one of the most basic data structrues used in printing the B+ tree, storing the positions for terms, etc.
4. **TF-IDF Algorithm**:

tf–idf (also **TF*IDF**, **TFIDF**, **TF–IDF**, or **Tf–idf**), short for **term frequency–inverse document frequency**, is a measure of importance of a word to a document in a collection or corpus, adjusted for the fact that some words appear more frequently in general.

It was often used as a weighting factor in searches of information retrieval, text mining, and user modeling.

One of the simplest ranking functions is computed by summing the tf–idf for each query term; many more sophisticated ranking functions are variants of this simple model.

There are many variations of how tf-idf is calculated. In our project, we use the following formula to calculate tf , idf and tf-idf.

$$\mathrm{tf}(\mathrm{word}, \mathrm{doc}) = \frac{\text{num of word in the doc}}{\text{total word count of the doc}}$$

$$\mathrm{idf}(\mathrm{word}, \mathrm{doc}) = \log \frac{\text{total num of documents}}{1 + |\text{num of documents that include the word}|}$$

$$\text{ti-idf}(\mathrm{word}, \mathrm{doc}) = \mathrm{tf} \times \mathrm{idf}$$

Chapter 2: Data Structure / Algorithm Specification

2.1 Algorithm Architecture

The overall algorithm architecture in the program is shown below:

```
the main program
├── word count
├── stop words
├── inverted index
│   ├── askforFilePos
│   └── fileTraversaler
│       ├── generate B+ tree
│       │   ├── CreateBP
│       │   ├── FindBP
│       │   │   └──isSameTerm
│       │   │
```

```
│         │     ├── InsertBP
│         │     ├── SplitBP
│         │     └── PrintBPTree
│         └── generate hash table
│               ├── InitHashTb
│               ├── FindHashSW
│               ├── InsertHashSW
│               ├── HashFunc
│               └── PrintHashTb
└── search
      ├── loadWordIdf
      ├── loadFileWordsNum
      └── loadStopWords
```

2.2 The Main Program

Inputs:

- All files of *The Complete Works of Shakespeare*
- User's queries

Outputs:

- The results of queries

Procedure: main()

Begin
  load necessary resources and establish inverted index
  set values for pageSize and threshold from user input
  while search_allow **do**
    get query from user input
    Calling the search function
    ask user if they want to continue searching or not and set search_allow accordingly
  end
End

The main idea of the code is to serve as the entry point for a search application named "ShakespeareFinder." It involves loading required resources, setting up an inverted index, and managing user queries.

2.3 Word Count & Stop Words

> Note
>
> Because the original open resources of *The Works* are written in HTML format with too many markups, we have converted them into TXT format, which is more readable and convenient for us to handle. And all titles of these articles are extracted to a TXT file at the same time.

The word count and stop words detection are relatively simple, we combined their functions into one program to cope with problems together.

Inputs: No obvious input parameters, but the program will read in:

- A file(`code/data/txt_title.txt`) contains all titles of articles in *The Works*
- A directory(`code/data/shakespeare_work`) includes *The Works* in TXT format

Outputs: 3 files

- `code/data/stop_words.txt`: Record all selected stopwords
- `code/data/word_count.txt`: Count for each word in all files
- `code/data/word_docs.txt`: Count the words for each file

Procedure: getStopWord()

```
Begin
    Read in the file txt_title.txt as infile
    Prepare the output file (outfile) named file_word_count.txt
    while reading in the content of infile do
        // file: one line content in infile, i.e. the title of each file
        Read in the file "shakespeare_works/" + file + ".txt" as in
        while reading each line(line) in file in do
            if find an English word (called word) then
                Do word stemming
                wordList[word] ← wordList[word] + 1
                wordNumOfDoc[file] ← wordNumOfDoc[file] + 1
                wordDocs[word] ← file
```

```
            endif
        end
        Output the wordNumOfDoc to outfile
        closefile(in)
    end
    closefile(infile)
    Sort(wordDocs) Prepare the output file (out) named word_count.txt
    Prepare the output file (out2) named stop_words.txt
    Prepare the output file (out3) named word_docs.txt
    for each item(word) in wordDocs do
        Output the word→content and word→frequency to out3
        if word→frequency > THRESHOLD then
            Output the word→content to out2
        endif
        Output the word→content and wordList[word→content] to out
    end
    closefile(out)
    closefile(out2)
    closefile(out3)
End
```

2.4 Word Stemming

We tap into the codes from a GitHub repository called "OleanderStemmingLibrary" by the author Blake-Madden. The codes are stored in the directory `code/scripts/wordStem`, and the link of repository is listed in the **References** section below.

> **Warning**
>
> We have to admitted that this word stemming program is kind of clumsy, especially for nouns, because the program will continue doing word stemming even though the word is in the simplest and the most common form. For example, for a simple English word "orange", it will convert it to another word "orang", which means "gorilla".
>
> Owing to the time and capability limitation, we couldn't find a better word stemming programs in C/C++ version or convert other languages version to C/C++ version. We hope that we will use a smarter word stemming program in the foreseeable future.

2.5 Inverted Index

Maybe this is the most complicated part of the whole program, because in this part we have a relatively complex algorithm architecture, and we use a couple of data structrues and algorithms, such as B+ trees, implicit queue ADT and linked list ADT. Here is the diagram of the functions used in the inverted index:

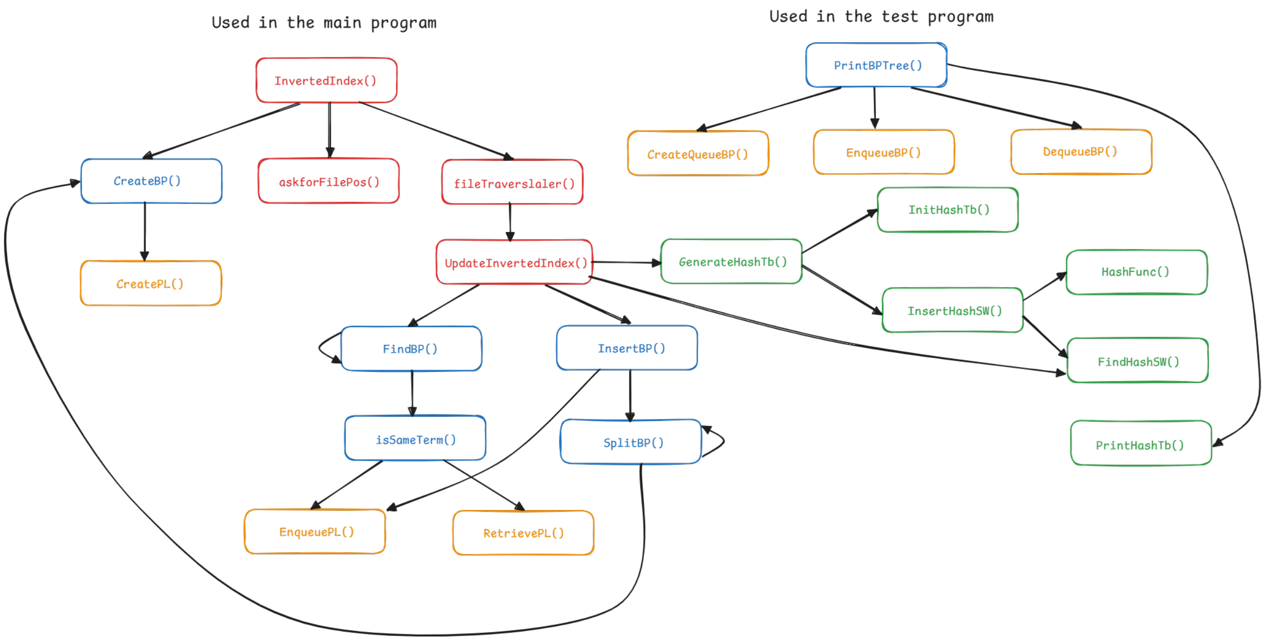


Figure 1: Relation diagram of all functions for inverted index

- Red: Overall Functions
- Blue: B+ Tree Operations

- Green: Hashing Functions
- Yellow: Other Functions

We'll introduce these functions in detail below.

2.5.1 Overall Functions

(1) InvertedIndex

Function: The highest-level function, which users can call it directly.

Inputs:

- *isTest*: `-t` or `--test` mode, just use one particular file
- *containStopWords*: `-s` or `--stopwords` mode, contain stop words when building inverted index

Outputs:

- *InvIndex*: A B+ tree containing the inverted index

Procedure: InvertedIndex(*isTest*: **bool**, *containStopWords*: **bool**)

```
Begin
    InvIndex ← CreateBP()
    askforFilePos(dir, fname, isTest)
    // dir: directory name, fname: filename
    InvIndex ← fileTraversaler(InvIndex, dir, fname, isTest,
    containStopWords)
    if InvIndex→size > 0 then
        print("Build successfully!")
    else
        print("Fail to build an inverted index!")
    endif
    return InvIndex
End
```

(2) askforFilePos

Function: Ask for the position of the directory or file.

Inputs:

- *dir*: directory name

- *fname*: file name
- *isTest*: `-t` or `--test` mode, just use one particular file

Outputs: None, but will update either *dir* or *fname*

Procedure: askforFilePos(dir: **string**, fname: **string**, isTest: **boolean**)

```
Begin
    if isTest is true then
        print("Now testing the correctness of inverted Index:")
        print("Please input the name of the input sample file:")
        input("Name:", fname)
    else
        dir ← SHAKESPEAREDIR
        print("Now building an inverted Index:")
        print("Do you want to search something in the default path({dir})?")
        print("Please input yes or no: ")
        input(choice)
        switch choice
            case 'y': case 'Y':
                break
            case 'n': case 'N':
                print("Please input the directory of the documents:")
                print("Path: ")
                input(dir)
                break
            default:
                print("Choice Error!")
                exit(1)
                break
        end
    endif
End
```

(3) fileTraversaler

Function: Make a traversal of all files(or a single file) and build the inverted index from them(or it).

Inputs:

- *T*: A B+ tree containing the inverted index
- *dir*: directory name
- *fname*: file name
- *isTest*: `-t` or `--test` mode, just use one particular file
- *containStopWords*: `-s` or `--stopwords` mode, contain stop words when building inverted index

Outputs: An updated B+ tree *T*

Procedure: fileTraversaler(T: **BplusTree**, *dir*: **string**, *fname*: **string**, *isTest*: **boolean**, *containStopWords*: **boolean**)

```
Begin
    docCnt = 0 // Count the number of documents and act as the index of the documents at the same time
    if isTest is false then
        if dir exists then
            for file in the dir directory do
                filename ← the name of file // string
                docNames[docCnt] ← filename
                // docNames: an array containing names of documents(global variable)
                wholePath ← dir + "/" + filename
            // wholePath: the complete path of the file to be read
            end
            closefile(fp)
        else
            Error("Could not open directory!")
        endif
    else
        docNames[docCnt] ← fname
        dir ← DEFAULTFILEPOS // Constant: "tests"(string)
        wholePath ← dir + "/" + fname
```

```
        endif
        fp ← openfile(wholePath, "r") // read mode
        // fp: the pointer to the file
        T ← UpdateInvertedIndex(T, docCnt, fp, containStopWords)
        return T
    End
```

(4) UpdateInvertedIndex

Function: Update the Inverted Index while reading a new document.

Inputs:

- *T*: A B+ tree containing the inverted index
- *docCnt*: the index of the document
- *fp*: pointer to the file
- *containStopWords*: `-s` or `--stopwords` mode, contain stop words when building inverted index

Outputs: An updated B+ tree *T*

Procedure: UpdateInvertedIndex(T: **BplusTree**, *docCnt*: **integer**, *fp*: **filePointer**, *containStopWords*: **boolean**)

```
Begin
    H ← GenerateHashTb()
    while reading texts in the file pointed by fp do
        if find an English word then do
            term ← the English word
            if containStopWords is false and FindHashSW(term, H, true) >= 0 then
                continue
            endif
            term ← WordStemming(term)
            isDuplicated ← false
            nodebp ← FindBP(term, docCnt, T, isDuplicated)
            if isDuplicated is false then
                T = InsertBP(term, docCnt, nodebp, T)
            endif
```

```
        else
            continue searching for next English word.
        endif
    end
    return T
End
```

2.5.2 B+ Tree Operations

Note

- The order of our B+ tree is 4.

(1) CreateBP

Function: Create a B+ tree.

Inputs: None

Outputs: A new and initialized B+ Tree

Procedure: CreateBP()

```
Begin
    Allocate a memory block for new B+ tree T
    for all data and children in T do
        Allocate memory blocks for term and poslist of the data, and
        children
        // Use CreatePL() to intialize the poslist
    end
    T→size ← 0
    T→childrenSize ← 0
    T→parent ← NULL
    return T
End
```

(2) FindBP

Function: Find a term in B+ tree.

Inputs:

- *term*: term
- *docCnt*: the index of the document
- *T*: inverted index
- *flag*: true if the term is found, false otherwise
- *isSearch*: mark the find mode(-f or –find)

Outputs: the (possibly updated) B+ tree *T* or recursively call itself again

Procedure: FindBP(*term*: **string**, *docCnt*: **integer**, *T*: **BplusTree**, *flag*: **booleanPointer**, *isSearch*: **boolean**)

```
Begin
    if T→childrenSize = 0 then
        isSameTerm(term, docCnt, T, flag, isSearch)
        return T
    endif
    pos ← −1
    for i in range(0, T→size) do // not contains T→size
        if term has less lexicographical order than T→data[i]→term
        then
            pos ← i
            break
        endif
    end
    if pos = −1 then
        pos ← i
    endif return FindBP(term, docCnt, T→children[pos], isSearch)
End
```

(3) isSameTerm

Function: Check if the term exists in the B+ tree.

Inputs:

- *term*: term
- *docCnt*: the index of the document

- *nodebp*: the appropriate node where the term may exists or will exists after insertion
- *flag*: true if the term is found, false otherwise
- *isSearch*: mark the find mode(-f or –find)

Outputs: None, but may update the flag and print some information regarding *term*

Procedure: isSameTerm(*term*: **string**, *docCnt*: **integer**, *nodebp*: **NodeBP**, *flag*: **booleanPointer**, *isSearch*: **boolean**)

```
Begin
    if nodebp→size > 0 then
        for i in range(0, T→size) do // not contains T→size
            if term = nodebp→data[i]→term then
                if isSearch is false then
                    EnqueuePL(docCnt, nodebp→data[i]→poslist)
                else
                    poslist ← nodebp→data[i]→poslist
                    size ← poslist→size
                    cnt ← 0
                    print("Successfully find the word!")
                    print("The word was found in files below:")
                    posArr ← RetrievePL(poslist)
                    for j in range(0, size) do // not contains size
                        if posArr[j][1] <= 1 then
                            print("{docNames[posArr[j][0]]}: {posArr[j][1]} time")
                        else
                            print("{docNames[posArr[j][0]]}: {posArr[j][1]} times")
                        endif
                        cnt ← cnt + posArr[j][1]
                    end
                    print("Frequency: {cnt}")
                    print("——————————————————————")
                endif
```

```
                flag ← true
                break
            endif
        end
    endif
End
```

(4) InsertBP

Function: Insert a term into the B+ tree.

Inputs:

- *term*: term
- *docCnt*: the index of the document
- *nodebp*: the appropriate node where the term will be inserted
- *Tree*: B+ tree containing the inverted index

Outputs: the updated B+ tree *Tree*

Procedure: InsertBP(*term*: **string**, *docCnt*: **integer**, *nodebp*: **NodeBP**, *Tree*: **BplusTree**)

```
Begin
    nodebp→data[nodebp→size]→term ← term
    EnqueuePL(docCnt, nodebp→data[nodebp→size]→poslist)
    nodebp→size ← nodebp→size + 1
    Sort(nodebp→data)
    Tree ← SplitBP(nodebp, Tree)
    return Tree
End
```

(5) SplitBP

Function: Split the node when the node is full.

Inputs:

- *nodebp*: the appropriate node where the term will be inserted
- *Tree*: B+ tree containing the inverted index

Outputs: The updated B+ tree *Tree*, or recursively call itself to split *nodebp*'s parent node

Procedure: SplitBP(*nodebp*: **NodeBP**, *Tree*: **BplusTree**)

```
Begin
    // ORDER: (constant)the order of B+ trees
    if (nodebp→childrenSize = 0 and nodebp→size <= ORDER) or (nodebp→childrenSize > 0 and nodebp→size < ORDER) then
        return Tree
    endif

    // lnodebp, rnodebp: the left and right part of the split node
    // tmpNodebp: store the node temporarily
    // parent: the parent node of nodebp
    // cut: the position of the middle data

    parent ← nodebp→parent
    if parent = NULL then
        tmpNodebp ← CreateBP()
        Allocate memory for parent
        Tree ← parent ← tmpNodebp
    endif
    lnodebp ← CreateBP()
    rnodebp ← CreateBP()
    lnodebp→parent ← rnodebp→parent ← parent
    if nodebp→childrenSize = 0 then
        cut ← LEAFCUT // constant: (ORDER / 2 + 1)
        for i in range(0, cut) do // not contains cut
            lnodebp→data[i] ← nodebp→data[i]
        end
        lnodebp→size ← cut
        for j in range(cut, nodebp→size) do // not contains nodebp→size
            rnodebp→data[j - cut] ← nodebp→data[j]
        end
```

```
        rnodebp→size ← nodebp→size - cut
    else
        cut ← NONLEAFCUT // constant: (ORDER / 2)
        for i in range(0, cut + 1) do // not contains cut + 1
            if i ≠ cut then
                lnodebp→data[i] ← nodebp→data[i]
            endif
            lnodebp→children[i] ← nodebp→children[i]
            lnodebp→children→parent ← lnodebp
        end
        lnodebp→size ← cut
        lnodebp→childrenSize ← cut + 1
        for j in range(cut + 1, nodebp→size) do // not contains
        nodebp→size
            rnodebp→data[j - cut - 1] ← nodebp→data[j]
        end
        for j in range(cut + 1, nodebp→childrenSize) do // not
        contains nodebp→childrenSize
            rnodebp→children[j - cut - 1] ← nodebp→children[j]
            rnodebp→children[j - cut - 1]→parent ← rnodebp
        end
        rnodebp→size ← nodebp→size - cut - 1 rnodebp→childrenSize
        ← nodebp→childrenSize - cut - 1
    end
    parent→data[parent→size] ← nodebp→data[cut]
    parent→size ← parent→size + 1
    if parent→childrenSize > 0 then
        for i in range(0, parent→childrenSize) do // not contains
        parent→childrenSize
            if parent→children[i] = nodebp then
                parent→children[i] ← lnodebp
                break
            endif
        end
    else
```

```
        parent→children[parent→childrenSize] ← lnodebp
        parent→childrenSize ← parent→childrenSize + 1
    endif
    parent→children[parent→childrenSize] ← rnodebp
    parent→childrenSize ← parent→childrenSize + 1
    Sort(parent→data)
    Sort(parent→children)
    Tree ← SplitBP(parent, Tree)
    return Tree
End
```

(6) PrintBPTree

Function: Print the B+ tree(level-order traversal).

Inputs:

- T: B+ tree containing the inverted index

Outputs: None, but will print the whole B+ tree

Procedure: PrintBPTree(T: **BplusTree**)

```
Begin
    print("B+ Tree of Inverted Index:")
    q ← CreateQueueBP()
    EnqueueBP(T, q)
    EnqueueBP(NULL, q)
    while q→size > 0 do
        nodebp ← DequeueBP(q)
        if nodebp is NULL then
            change to a newline
            if q→size > 0 then
                EnqueueBP(NULL, q)
            endif
        else
            print("[")
            for i in range(0, nodebp→size) do // not contains nodebp→size
```

```
                if i = 0 then
                    print(nodebp→data[i]→term)
                else
                    print(", {nodebp→data[i]→term}")
                endif
            end
            print("]")
        endif
        if nodebp is not NULL then
            for i in range (0, nodebp→childrenSize) do // not contains nodebp→childrenSize
                EnqueueBP(nodebp→children[i], q)
            end
        endif
    end
End
```

2.5.3 Hashing Operations

(1) GenerateHashTb

Function: Build a hash table.

Inputs: None

Outputs: A new hash table H, containing stopwords from the file

Procedure: GenerateHashTb()

```
Begin
    H ← InitHashTb()
    fname ← STOPWORDPATH // constant: "stop_words.txt"
    fp ← openfile(fname, "r") // read mode
    if fp is NULL then
        Error("Fail to open the file of stopwords!")
    endif
    while reading texts in the file pointed by fp do
        if find an English word then do
```

```
            term ← the English word
            InsertHashSW(term, H)
        endif
    end
    closefile(fp)
    return H
End
```

(2) InitHashTb

Function: Initialization of the hash table.

Inputs: None

Outputs: A new initialized hash table

Procedure: InitHashTb()

```
Begin
    Allocate memory block for H // HashTb
    if H is NULL then
        Error("Fail to create a hash table for stopwords!")
    end
    H→size ← STOPWORDSUM // maximum size
    for i in range(0, H→size) do // not contains H→size
        Allocate memory block for H→data[i]
        if H→data[i] is NULL then
            Error("Fail to create a hash table for stopwords!")
        end
        H→data[i]→stopword
        H→data[i]→info ← Empty // constant: 0
    end
    return H
End
```

(3) FindHashSW

Function: Find the stopwords or other words in the hash table.

Inputs:

- *stopword*: stop word
- *H*: hash table containing the stop words
- *justSearch*: find the term without subsequent insertion

Outputs: A appropriate position *pos* in hash table for stopword, or just search the term in the hash table

Procedure: FindHashSW(stopword: **string**, H: **HashTb**, justSearch: **boolean**)

```
Begin
    collisionNum ← 0
    pos ← HashFunc(stopword, H→size)
    if justSearch is true and (H→data[pos]→info = Empty or H→data[pos]→stopword = stopword) then
        return −1
    endif
    while H→data[pos]→info ≠ Empty and H→data[pos]→stopword = stopword do
        collisionNum ← collisionNum + 1 pos ← pos + 2 * collisionNum - 1
        if pos >= H→size then
            pos ← pos - H→size
        endif
    end
    return pos
End
```

(4) InsertHashSW

Function: Insert a new stopword in hash table.

Inputs:

- *stopword*: stop word
- *H*: hash table containing the stop words

Outputs: None, but will update the hash table *H*

Procedure: InsertHashSW(*stopword*: **string**, *H*: **HashTb**)

```
Begin
    pos ← FindHashSW(stopword, H, false)
    // Legitimate: (constant) 1
    if (H→data[pos]→info ≠ Legitimate) then
        H→data[pos]→info ← Legitimate
        H→data[pos]→stopword ← stopword
    endif
End
```

(5) HashFunc

Function: Hashing function.

Inputs:

- *stopword*: stop word
- *size*: the maximum size of the hash table

Outputs: A hash value to *stopword*

Procedure: HashFunc(*stopword*: **string**, *size*: **integer**)

```
Begin
    val ← 0
    for each character ch in stopword do
        val = (val << 5) + integer(ch)
    end
    return val % size
End
```

2.5.4 Other Functions

(1) CreateQueueBP

Function: Create the queue

Inputs: None

Outputs: A new queue Q

Procedure: CreateQueueBP()

Begin
    Allocate memory block **for** the queue Q
    $Q \rightarrow size \leftarrow 0$
    $Q \rightarrow front \leftarrow Q \rightarrow rear \leftarrow 0$
    return Q
End

(2) EnqueueBP

Function: Put the node of B+ tree into the queue.

Inputs:

- *nodebp*: the newly added node
- Q: the queue

Outputs: None, but will update Q

Procedure: EnqueueBP(*nodebp*: **NodeBP**, Q: **QueueBP**)

Begin
    if $Q \rightarrow size >= SIZE$ **then**
        Error("Full B+-tree-item queue!")
    endif
    $Q \rightarrow data[Q \rightarrow rear] \leftarrow nodebp$
    $Q \rightarrow rear \leftarrow Q \rightarrow rear + 1$
    $Q \rightarrow size \leftarrow Q \rightarrow size + 1$
End

(3) DequeueBP

Function: Get the front node and delete it from the queue.

Inputs:

- Q: the queue

Outputs: the front node *returnNodeBP*

Procedure: DequeueBP(Q: **QueueBP**)

Begin

if $Q \rightarrow size = 0$ **then**
  Error("Empty B+-tree-item queue!")
endif
$returnNodeBP \leftarrow Q \rightarrow data[Q \rightarrow front]$
$Q \rightarrow front \leftarrow Q \rightarrow front + 1$
$Q \rightarrow size \leftarrow Q \rightarrow size$ - 1
return *returnNodeBP*
End

(4) CreatePL

Function: Create the poslist

Inputs: None

Outputs: A new PosList L

Procedure: CreatePL()

Begin
  Allocate memory blocks **for** L(**PosList**), $L \rightarrow front$(**PosData**), $L \rightarrow rear$(**PosData**)
  $L \rightarrow size \leftarrow 0$
  $L \rightarrow front \leftarrow L \rightarrow rear$
  $L \rightarrow rear \rightarrow pos \leftarrow -1$
  return L
  End

(5) EnqueuePL

Function: Add new position.

Inputs:

- *pos*: the position
- L: the position list

Outputs: None, but will update L

Procedure: EnqueuePL(*pos*: **integer**, L: **PosList**)

Begin

```
    if L→rear→pos ≠ pos then
        Allocate memory block for tmp(PosData)
        if tmp is NULL then
            Error("Fail to create a new position data!")
        endif
        tmp→pos ← pos
        tmp→time ← 1
        tmp→next ← L→rear→next
        L→rear→next ← tmp
        L→rear ← tmp
        L→size ← L→size + 1
    else
        L→rear→time ← L→rear→time + 1
    endif
End
```

(6) RetrievePL

Function: Retrieve all position in the list.

Inputs:

- L: the position list

Outputs: An 2D array *posArr* containing the all position in L, and each data contains two attributes: document index and the frequency in that document

Procedure: RetrievePL(L: **PosList**)

```
Begin
    if L→size = 0 then
        Error("Empty position-data queue!")
    endif
    Allocate memory block for posArr cur ← L←front←next
    i ← 0
    while cur ≠ NULL do
        posArr[i][0] ← cur→pos
        posArr[i][1] ← cur→time
```

```
        cur ← cur→next
        i ← i + 1
    end
    return posArr
End
```

2.6 Query

2.6.1 Search Function

Inputs:

- *query*: User's query in string form
- *T*: Inverted index
- *pageSize*: Number of documents to be displayed per query
- *threshold*: The proportion of search terms to the total number of terms

Outputs: The query result

Procedure: search(*query*: **string**, *T*: **BplusTree**, *pageSize*: **integer**, *threshold*: **double**)

```
Begin
    for read every character in query do
        remove the Punctuation and Whitespace
        if get the word then
            store the word itself and the idf of word in a vector
        endif
    end
    sort the vector in descending order
    if no word then
        return
    else if one word then
        search the word in T
        sort the file name by tf
        print(file, tf)
    else
        according to the threshold get the word needed to searched
```

```
            for every word do
                search the word in T
                store the result in a hash table
                (the hash table store the file name and their tf-idf)
            end
            print(file, td-idf)
        endif
    End
```

The main idea of the function is to implement a search functionality that retrieves documents related to a given query from a B+ tree. Here is a more detailed summary of the function logic:

1. **Query parsing**: The code starts by loading and analyzing the query string, breaking it down into words while converting each to lowercase and stemming. It checks if each word exists in a stop words list or if it is present in the inverted index.

2. **Valid word collection**: Valid words are added to a vector, while warnings are displayed for invalid words (such as stop words or words not found in the inverted index).

3. **Search condition assessment**: Depending on the number of valid words, the processing is divided into two modes. If there is only one valid word, it searches directly in the inverted index and returns the matching documents with their TF values. For multiple valid words, the code calculates their TF-IDF values.

4. **Inverted index lookup**: For multi-word queries, the code traverses the inverted index for each valid word, using a hash table to store document IDs and their corresponding TF-IDF scores while ensuring it only retains documents that contain all the query words.

5. **Result sorting and output**: Finally, the results are sorted based on the TF-IDF values, and the document names along with their TF-IDF scores are printed, adhering to a specified limit on the number of results (page size).

Overall, this function provides an efficient document retrieval mechanism through valid word filtering and TF-IDF score calculation, suitable for the context of search engines or information retrieval systems.

2.6.2 Search Test

Inputs: Files of *The Works*

Outputs: The results of queries

Procedure: SearchTest()

```
Begin
    load necessary resources and establish inverted index
    while test_allow do
        get serial number of the test input form user
        get the query from the input file
        get important parameters from user's input
        call the search function with the query and parameters
        ask user if they want to continue testing or not and set
        test_allow accordingly
    end
End
```

The main idea of the code is to set up a testing framework for the "ShakespeareFinder" search application. This includes loading necessary resources, allowing users to input parameters from a test file, executing search queries multiple times to evaluate performance, and managing repeated tests.

2.6.3 Some helper functions

(1) Load function: loadWordIdf & loadFileWordsNum & loadStopWords

These functions have a similar structure. The main idea is to load resources from existing files. See the pseudocode for details.

Inputs: Files of *The Works*

Outputs: The results of queries

Procedure: SearchTest()

```
Begin
    load the input FILE
    read resource from the file
    load the resource into a hash table
End
```

(2) Search helper: FindBP2 & isSameTerm2 & RetrievePL2

These functions are very similar to their versions without the “2”, but in order to better cooperate with the search function, the type of data they return is changed to `vector<pair<docId, tf>>`, and the logic of getting data is changed accordingly.

Chapter 3: Testing Results

3.1 Inverted Index Tests

To verify the correctness of our inverted index, we have devised several tests from different aspects. Here is the **purpose** of each test:

- Check if every word in document(s) is inserted into the inverted index correctly.
- Build an inverted index from a single file, or a directory with a bunch of files.
- Check if the inverted index can eliminate all stopwords.

> Warning
>
> In the following tests, we will use the test programs to verify the correctness of our sub-programs seperately, and we **won’t tell you the usage of these intructions** we use below. If you are curious about it, please read the `README.md` file in the directory `code`, which will guide you how to run these instructions.

3.1.1 Word Insertion Test

We have two method to accomplish the first purpose: printing the whole inverted index(when the size is small), and finding the words existing in the inverted index(if words were correctly inserted).

(1) Printing the inverted index

Case 1: very simple example

`$ ./invIndexTest -t -p`
`Now testing the correctness of inverted Index:`
`Please input the name of the input sample file:`
`Name: input1.txt`
`Build successfully!`
`B+ Tree of Inverted Index:`
`[beauti, ice, peach]`
`[appl, are, banana][beauti, cherri][ice, icecream, orang][peach, pear, strawberri, watermelon]`

input1.txt
ice strawberry orange banana peach apple pear watermelon cherry icecream you are beautiful

Case 2: simple example

`$ ./invIndexTest -t -p`
`Now testing the correctness of inverted Index:`
`Please input the name of the input sample file:`
`Name: input2.txt`
`Build successfully!`

```
B+ Tree of Inverted Index:
[et, lorem, nullam]
[consectetur, dolor, elit][id, ipsum][nec][pretium, sed, ut]
[adipisc, amet, at, congu][consectetur, consequat, dapibus, diam]
[dolor, e, eget][elit, erat][et, etiam, facilisi, fringilla][id,
interdum][ipsum, lacus, lectus][lorem, metus, mi][nec, nulla]
[nullam, orci, pellentesqu][pretium, purus, rhoncus][sed, sit,
sollicitudin, tincidunt][ut, vita]
```

input2.txt
Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nullam nec erat sed nulla rhoncus dapibus et at lectus. Etiam in congue diam, ut interdum metus. Nullam pretium orci id mi pellentesque, vitae consequat lacus tincidunt. Pellentesque fringilla purus eget nulla facilisis sollicitudin.

(2) Finding words in the inverted index

> Note
>
> - This test is just used in checking the correctness of word insertion, which is similar to a simple query function, but the implementation is totally different from our formal query program, so you shouldn't mix them together.
> - The texts in the following tests are too long, therefore we won't show these text in our report, but you can see them in the files positioned in the directory called `code/data/tests`.

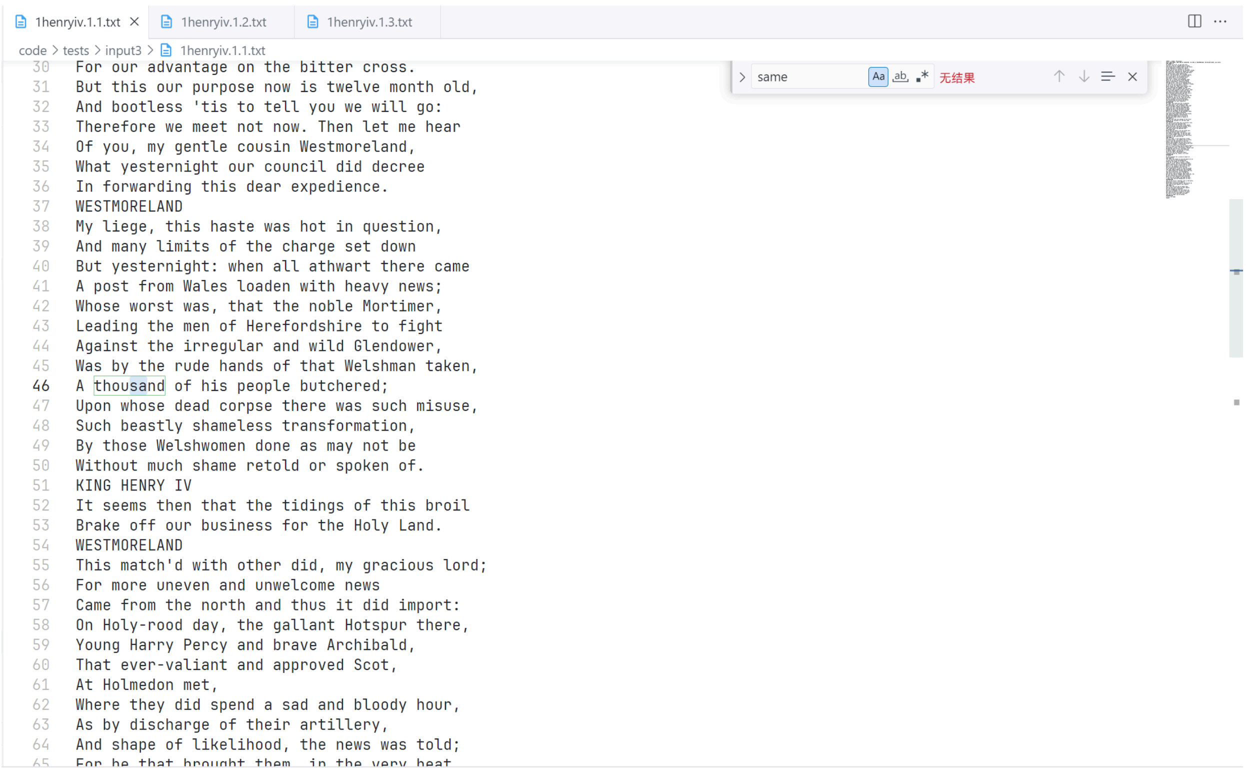
Case 3: intermediate-level example

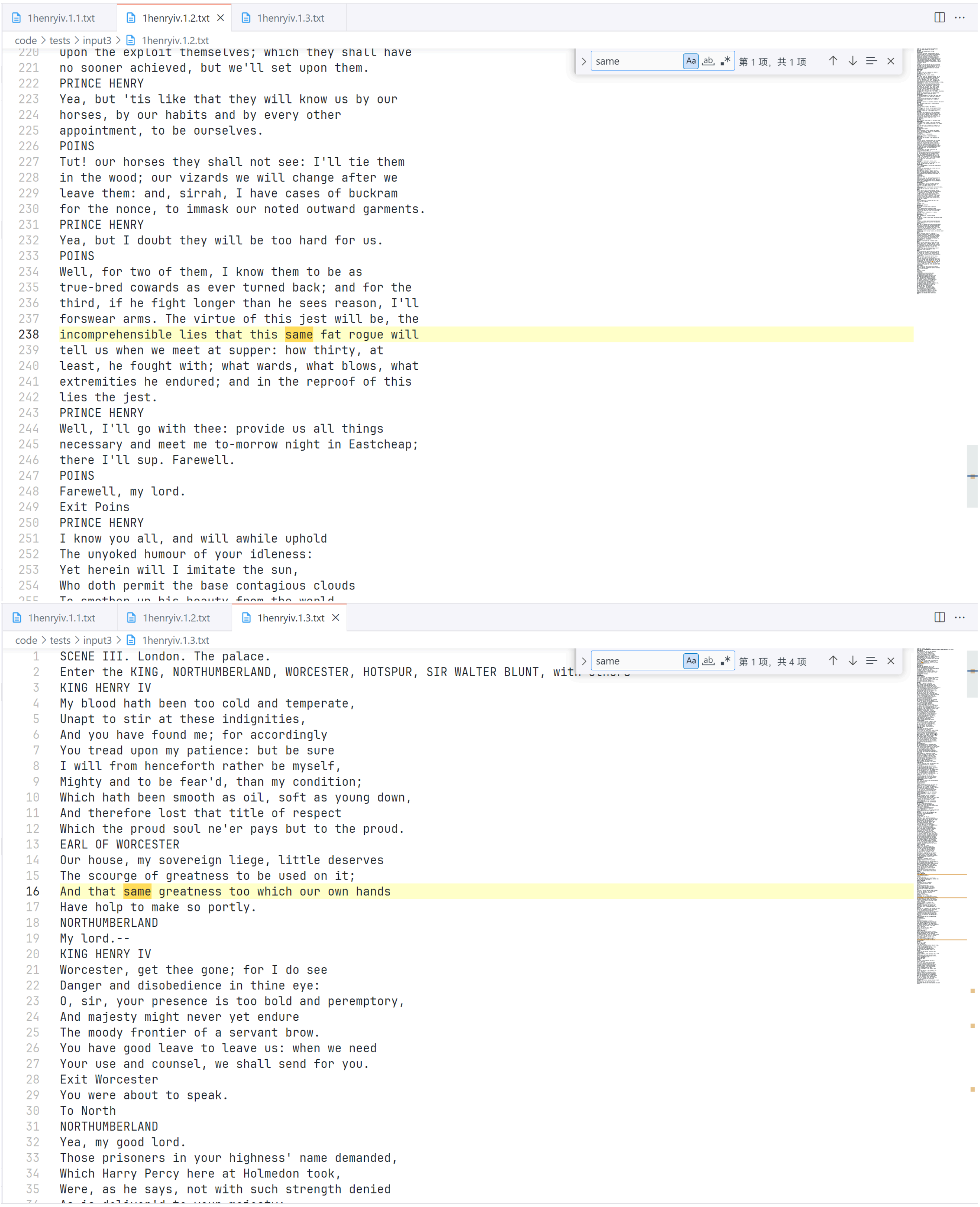
```
./invIndexTest -f=3
Now building an inverted Index:
Please input the directory of the documents:
Path: tests/input3
Build successfully!

Finding Words Mode(only supports single word finding):
Find 1: same
Successfully find the word!
```

```
The word was found in files below:
1henryiv.1.2.txt: 1 time
1henryiv.1.3.txt: 4 times
Frequency: 5
-----------------------------------
Find 2: star
Successfully find the word!
The word was found in files below:
1henryiv.1.2.txt: 1 time
Frequency: 1
-----------------------------------
Find 3: fantastic
Sorry, no such word in the inverted index!
-----------------------------------
```

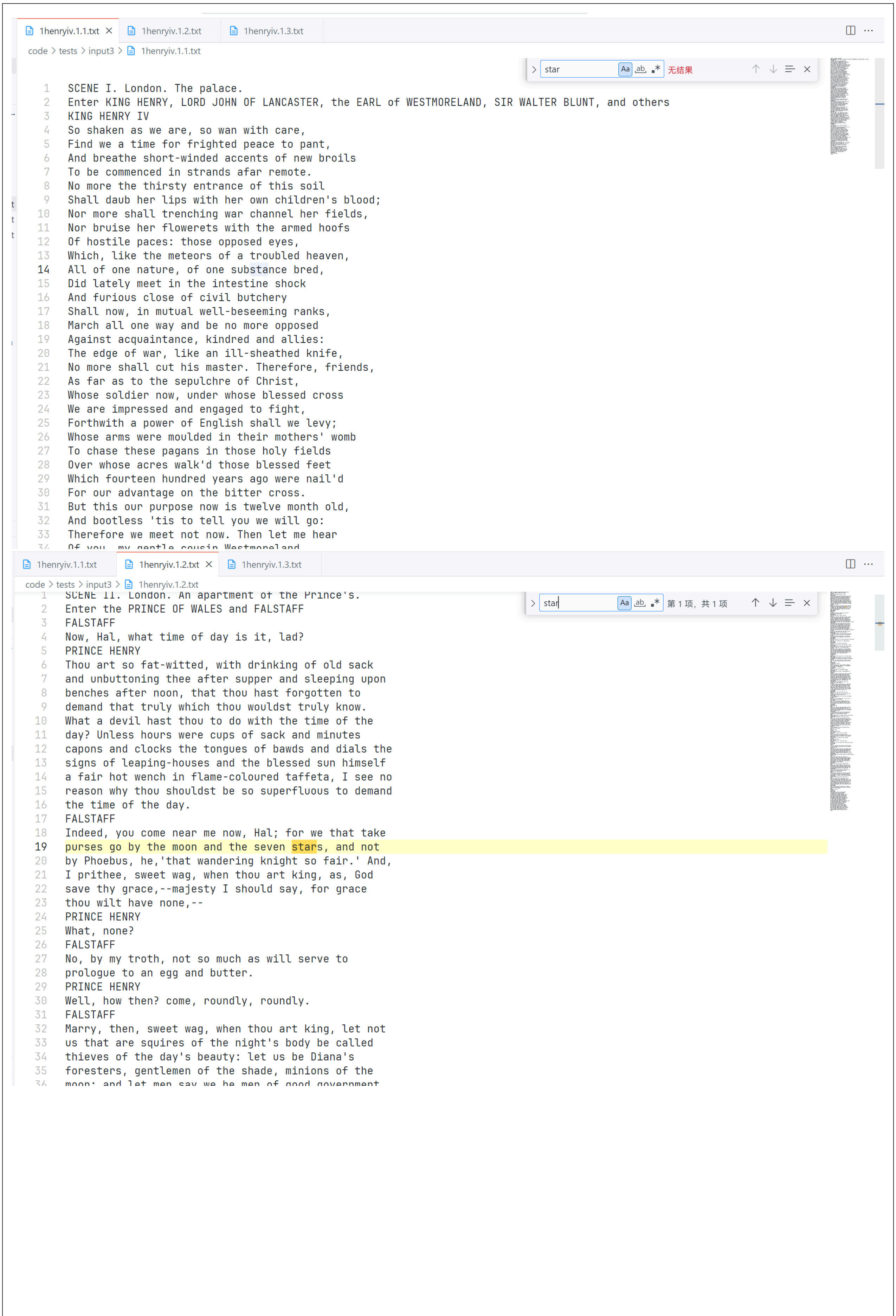
Verification by using finding function in Visual Studio Code

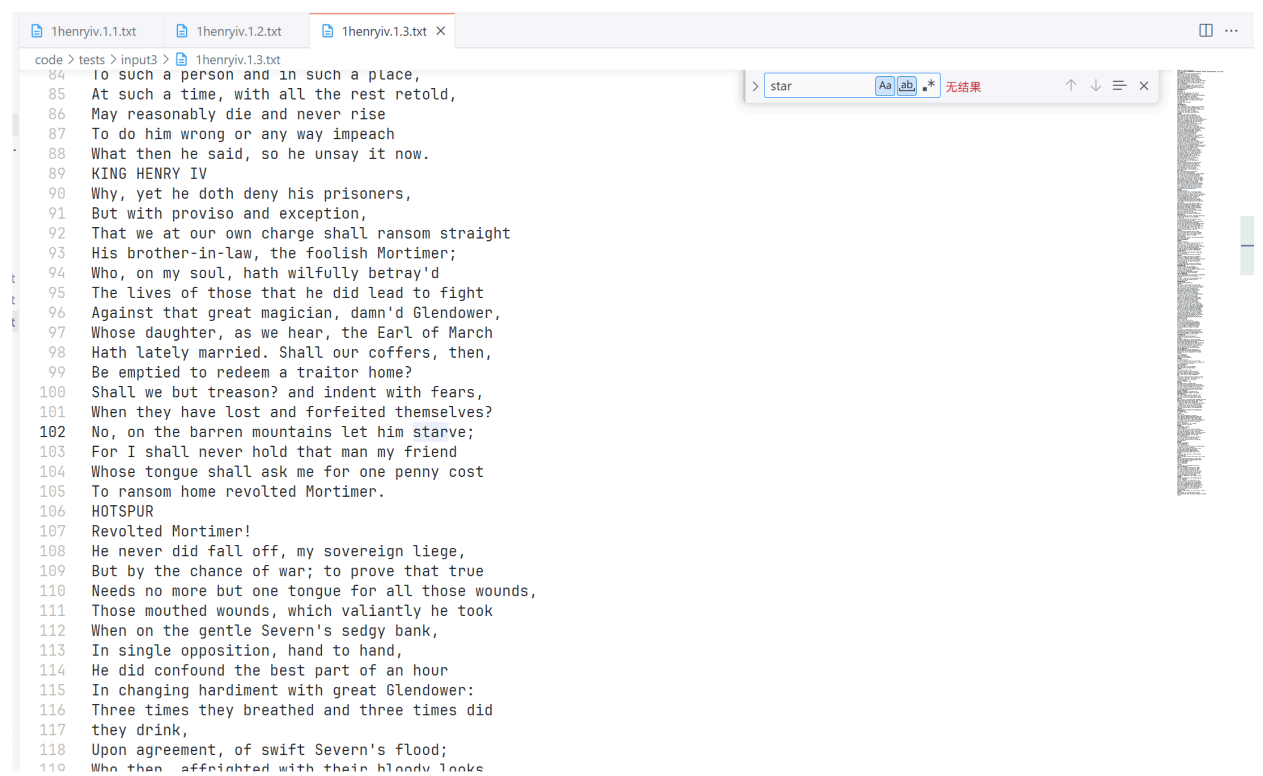
Find 1: same



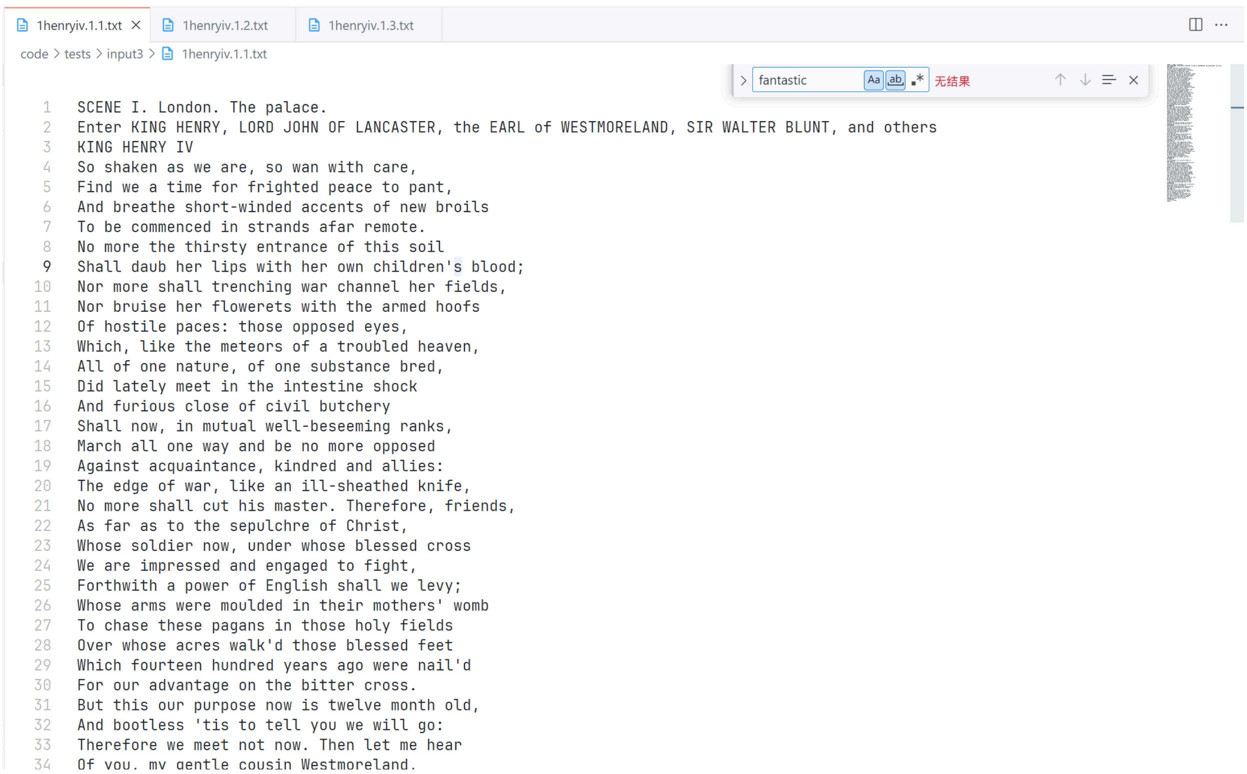

1henryiv.1.1.txt
1henryiv.1.2.txt
1henryiv.1.3.txt
code > tests > input3 > 1henryiv.1.2.txt
same
第 1 项，共 1 项
upon the exploit themselves; which they shall have
no sooner achieved, but we'll set upon them.
PRINCE HENRY
Yea, but 'tis like that they will know us by our
horses, by our habits and by every other
appointment, to be ourselves.
POINS
Tut! our horses they shall not see: I'll tie them
in the wood; our vizards we will change after we
leave them: and, sirrah, I have cases of buckram
for the nonce, to immask our noted outward garments.
PRINCE HENRY
Yea, but I doubt they will be too hard for us.
POINS
Well, for two of them, I know them to be as
true-bred cowards as ever turned back; and for the
third, if he fight longer than he sees reason, I'll
forswear arms. The virtue of this jest will be, the
incomprehensible lies that this same fat rogue will
tell us when we meet at supper: how thirty, at
least, he fought with; what wards, what blows, what
extremities he endured; and in the reproof of this
lies the jest.
PRINCE HENRY
Well, I'll go with thee: provide us all things
necessary and meet me to-morrow night in Eastcheap;
there I'll sup. Farewell.
POINS
Farewell, my lord.
Exit Poins
PRINCE HENRY
I know you all, and will awhile uphold
The unyoked humour of your idleness:
Yet herein will I imitate the sun,
Who doth permit the base contagious clouds
1henryiv.1.1.txt
1henryiv.1.2.txt
1henryiv.1.3.txt
code > tests > input3 > 1henryiv.1.3.txt
same
第 1 项，共 4 项
SCENE III. London. The palace.
Enter the KING, NORTHUMBERLAND, WORCESTER, HOTSPUR, SIR WALTER BLUNT, wit
KING HENRY IV
My blood hath been too cold and temperate,
Unapt to stir at these indignities,
And you have found me; for accordingly
You tread upon my patience: but be sure
I will from henceforth rather be myself,
Mighty and to be fear'd, than my condition;
Which hath been smooth as oil, soft as young down,
And therefore lost that title of respect
Which the proud soul ne'er pays but to the proud.
EARL OF WORCESTER
Our house, my sovereign liege, little deserves
The scourge of greatness to be used on it;
And that same greatness too which our own hands
Have holp to make so portly.
NORTHUMBERLAND
My lord.--
KING HENRY IV
Worcester, get thee gone; for I do see
Danger and disobedience in thine eye:
O, sir, your presence is too bold and peremptory,
And majesty might never yet endure
The moody frontier of a servant brow.
You have good leave to leave us: when we need
Your use and counsel, we shall send for you.
Exit Worcester
You were about to speak.
To North
NORTHUMBERLAND
Yea, my good lord.
Those prisoners in your highness' name demanded,
Which Harry Percy here at Holmedon took,
Were, as he says, not with such strength denied

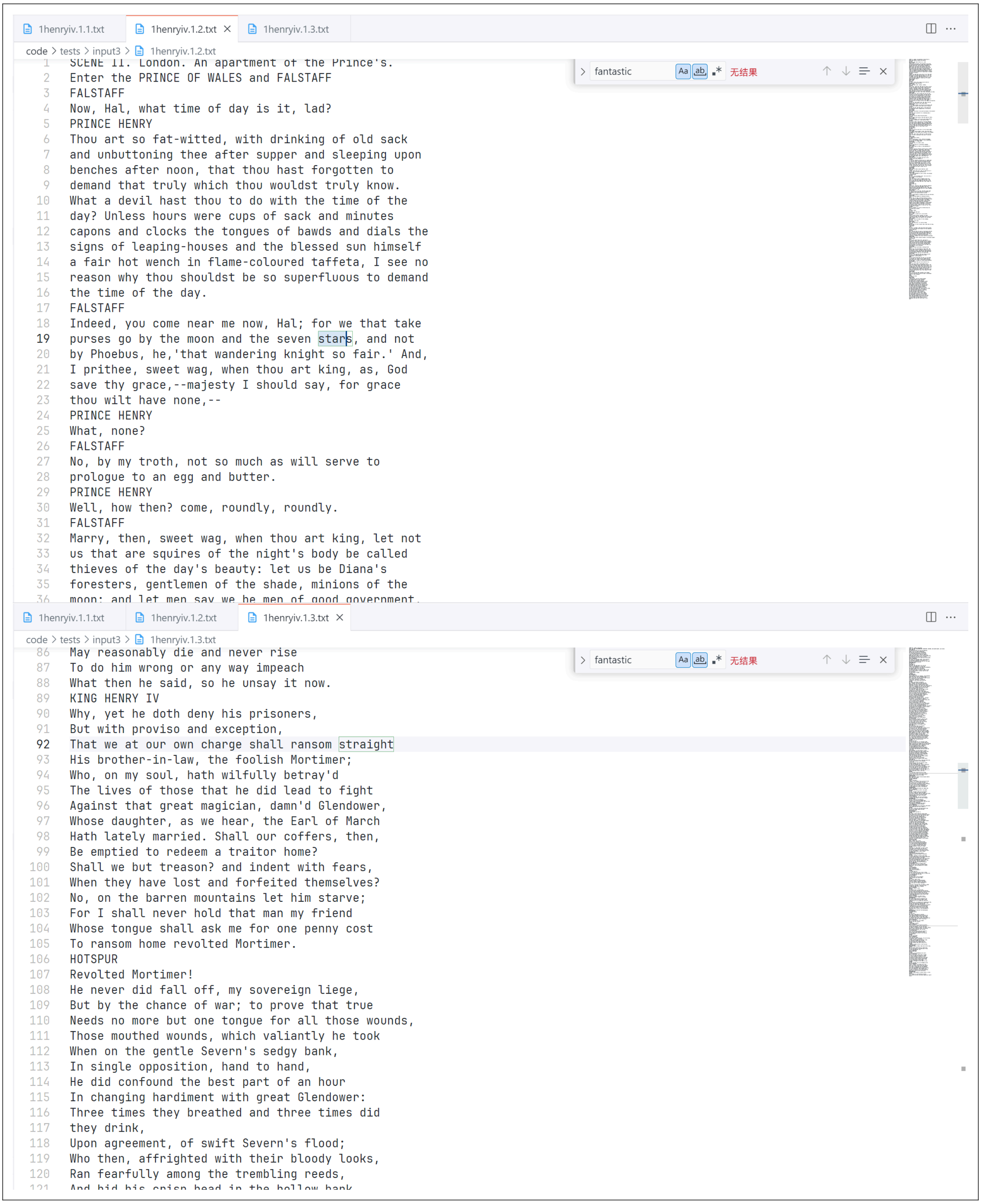
Find 2: star


1henryiv.1.1.txt
1henryiv.1.2.txt
1henryiv.1.3.txt
code > tests > input3 > 1henryiv.1.1.txt
star
无结果
SCENE I. London. The palace.
Enter KING HENRY, LORD JOHN OF LANCASTER, the EARL of WESTMORELAND, SIR WALTER BLUNT, and others
KING HENRY IV
So shaken as we are, so wan with care,
Find we a time for frighted peace to pant,
And breathe short-winded accents of new broils
To be commenced in strands afar remote.
No more the thirsty entrance of this soil
Shall daub her lips with her own children's blood;
Nor more shall trenching war channel her fields,
Nor bruise her flowerets with the armed hoofs
Of hostile paces: those opposed eyes,
Which, like the meteors of a troubled heaven,
All of one nature, of one substance bred,
Did lately meet in the intestine shock
And furious close of civil butchery
Shall now, in mutual well-beseeming ranks,
March all one way and be no more opposed
Against acquaintance, kindred and allies:
The edge of war, like an ill-sheathed knife,
No more shall cut his master. Therefore, friends,
As far as to the sepulchre of Christ,
Whose soldier now, under whose blessed cross
We are impressed and engaged to fight,
Forthwith a power of English shall we levy;
Whose arms were moulded in their mothers' womb
To chase these pagans in those holy fields
Over whose acres walk'd those blessed feet
Which fourteen hundred years ago were nail'd
For our advantage on the bitter cross.
But this our purpose now is twelve month old,
And bootless 'tis to tell you we will go:
Therefore we meet not now. Then let me hear
1henryiv.1.1.txt
1henryiv.1.2.txt
1henryiv.1.3.txt
code > tests > input3 > 1henryiv.1.2.txt
star
第 1 项，共 1 项
SCENE II. London. An apartment of the Prince's.
Enter the PRINCE OF WALES and FALSTAFF
FALSTAFF
Now, Hal, what time of day is it, lad?
PRINCE HENRY
Thou art so fat-witted, with drinking of old sack
and unbuttoning thee after supper and sleeping upon
benches after noon, that thou hast forgotten to
demand that truly which thou wouldst truly know.
What a devil hast thou to do with the time of the
day? Unless hours were cups of sack and minutes
capons and clocks the tongues of bawds and dials the
signs of leaping-houses and the blessed sun himself
a fair hot wench in flame-coloured taffeta, I see no
reason why thou shouldst be so superfluous to demand
the time of the day.
FALSTAFF
Indeed, you come near me now, Hal; for we that take
purses go by the moon and the seven stars, and not
by Phoebus, he,'that wandering knight so fair.' And,
I prithee, sweet wag, when thou art king, as, God
save thy grace,--majesty I should say, for grace
thou wilt have none,--
PRINCE HENRY
What, none?
FALSTAFF
No, by my troth, not so much as will serve to
prologue to an egg and butter.
PRINCE HENRY
Well, how then? come, roundly, roundly.
FALSTAFF
Marry, then, sweet wag, when thou art king, let not
us that are squires of the night's body be called
thieves of the day's beauty: let us be Diana's
foresters, gentlemen of the shade, minions of the



Find 3: fantastic





In a nutshell, our inverted index program successfully passes the first test.

3.1.2 Single File to Multiple Files Test

We executed our first test based on a single file and several files, but our ultimate goal is to let our mini search engine to search something from a dozens of files(i.e. *the Complete Works of Shakespeare*). So it's necessary for us to test whether the inverted index can be built from tons of files. Note that `the Works` is in the directory called `code/data/shakespeare_works`.

Case 1: Search some dedicated words from piles of files

```
./invIndexTest -f=3
Now building an inverted Index:
Please input the directory of the documents:
Path: ../data/shakespeare_works
Build successfully!

Finding Words Mode(only supports single word finding):
Find 1: hamlet
Successfully find the word!
The word was found in files below:
hamlet.1.1.txt: 3 times
hamlet.1.2.txt: 42 times
# Deleberate omisssion
hamlet.5.1.txt: 45 times
hamlet.5.2.txt: 83 times
Frequency: 470
-----------------------------------
Find 2: juliet
Successfully find the word!
The word was found in files below:
measure.1.2.txt: 3 times
measure.1.4.txt: 1 time
# Deleberate omisssion
romeo_juliet.5.2.txt: 1 time
romeo_juliet.5.3.txt: 19 times
Frequency: 199
-----------------------------------
Find 3: macbeth
Successfully find the word!
The word was found in files below:
```

```
macbeth.1.1.txt: 1 time
macbeth.1.2.txt: 4 times
# Deleberate omisssion
macbeth.5.7.txt: 8 times
macbeth.5.8.txt: 7 times
Frequency: 285
-----------------------------------
```

Case 2: Search some universal words from piles of files

```
./invIndexTest -f=3
Now building an inverted Index:
Please input the directory of the documents:
Path: ../data/shakespeare_works
Build successfully!

Finding Words Mode(only supports single word finding):
Find 1: moon
Successfully find the word!
The word was found in files below:
1henryiv.1.2.txt: 5 times
1henryiv.1.3.txt: 1 time
# Deleberate omisssion
winters_tale.4.3.txt: 1 time
winters_tale.4.4.txt: 1 time
Frequency: 152
-----------------------------------
Find 2: happy
Successfully find the word!
The word was found in files below:
1henryiv.2.2.txt: 1 time
1henryiv.4.3.txt: 1 time
# Deleberate omisssion
winters_tale.1.2.txt: 2 times
winters_tale.4.4.txt: 3 times
```

```
Frequency: 278
-----------------------------------
Find 3: hit
Successfully find the word!
The word was found in files below:
1henryiv.2.4.txt: 1 time
2henryiv.1.1.txt: 1 time
# Deleberate omisssion
VenusAndAdonis.txt: 2 times
winters_tale.5.1.txt: 1 time
Frequency: 74
-----------------------------------
```

In a nutshell, our inverted index program successfully passes the second test.

3.1.3 Stopwords Test

Finally, we should confirm whether our program can eliminate the stopwords we have selected in advance. So we can make a comparison with two test program: one includes the stopwords, while the other doesn't include them.

Case 1: stopwords **not included**(defualt situation)

```
./invIndexTest -f=3
Now building an inverted Index:
Please input the directory of the documents:
Path: ../data/shakespeare_works
Build successfully!

Finding Words Mode(only supports single word finding):
Find 1: much
Sorry, no such word in the inverted index!
-----------------------------------
Find 2: you
Sorry, no such word in the inverted index!
-----------------------------------
Find 3: great
```

```
Sorry, no such word in the inverted index!
-----------------------------------
```

Case 2: stopwords **included**

```
./invIndexTest -f=3 -s
Now building an inverted Index:
Please input the directory of the documents:
Path: ../data/shakespeare_works
# Delebrate omission for the display of all stopwords
Build successfully!

Finding Words Mode(only supports single word finding):
Find 1: much
# Delebrate omission for the very long position list
winters_tale.5.1.txt: 4 times
winters_tale.5.2.txt: 2 times
winters_tale.5.3.txt: 7 times
Frequency: 1070
-----------------------------------
Find 2: you
# Delebrate omission for the very long position list
winters_tale.5.1.txt: 40 times
winters_tale.5.2.txt: 19 times
winters_tale.5.3.txt: 29 times
Frequency: 14249
-----------------------------------
Find 3: great
# Delebrate omission for the very long position list
winters_tale.5.1.txt: 3 times
winters_tale.5.2.txt: 1 time
winters_tale.5.3.txt: 1 time
Frequency: 1032
-----------------------------------
```

Actually, the inverted index can eliminate all stopwords, but due to space limitation, we won't list all tests about them.

In a nutshell, our inverted index program successfully passes the third test.

Although we can't make a thorough test for the inverted index, but from the above tests, we can assure that our inverted index have no obvious error(maybe there're several small bugs existing).

3.1.4 Speed Test

> Note
>
> The specific analysis and comments about speed tests are written in **Chapter 4**.

To analyze the time complexity of the inverted index, especially the algorithms regarding the **finding** and **insertion** operations of B+ tree, we devise some timing tests for **diffrent numbers of words** in *The Works*. The results are shown below:

Number of Words(roughly)	100,000	200,000	400,000	600,000	800,000	880,000
Iterations	10	10	10	10	5	5
Ticks	1988219	3704927	7317245	11594770	7985568	8438331
Total Time(s)	1.99	3.70	7.32	11.59	7.99	8.44
Duration(s)	0.199	0.370	0.732	1.159	1.598	1.688

Table 1: Speed Tests for Inverted Index

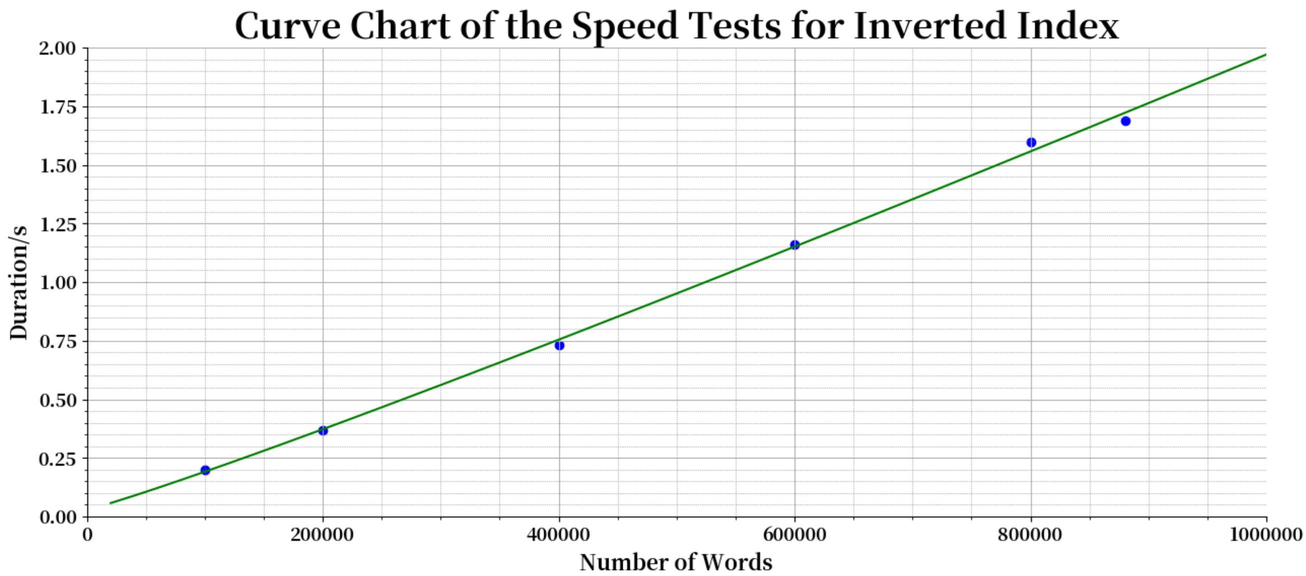


Figure 2: Curve Chart of the Speed Tests for Inverted Index

As you can see, these data points can be fitted with the product of linear function and **logarithmic function** (although the curve looks like a straight line due to the limitation of aspect ratio). So the result indicates that the time complexity of building inverted index approaches $O(\log N)$, and you will see the detailed explanation in Chapter 4.

3.2 Query Tests

Different from the oriented-procedure inverted index tests, the query tests are based on distinct and typical **input data**, which consider the performance, speed and threshold analysis simultaneously.

3.2.1 input0

- **content** : 1000*'a'
- **purpose**: Test for illegal words of extreme length
- **expected results**:

```
Warning: "a...a" is not in the inverted index and will be ignored.
Ops, your query is in StopList or empty, so there are no documents retrieved.
```

- **test results**:

output	ticks(ticks/search)	time(s/search)
correct	155.835	1.6e-4

The time is averaged from 1000 runs. Since irrelevant words will not enter the search phase, the threshold is irrelevant to this test.

3.2.2 input1

- **content** : peas and beans
- **purpose**: One stop word, two rare words (each appearing in only two documents), but all appearing in one document. This tests the retrieval correctness of the program and its handling of stop words.
- **expected results**:

```
Warning: "and" is in the stop list and will be ignored.
Your query has multiple valid words, so we will search for them
in the inverted index.
The words were found in files below:
File name                        Tf-Idf
1henryiv.2.1.txt                 0.014780
```

- **test result**:

output	ticks(ticks/search)	time(s/search)
correct	79.439	8e-5

The time is averaged from 1000 runs. Since the test purpose does not include the threshold, the threshold is set to 1 here.

3.2.3 input2

- **content** : blank input
- **purpose**: Testing for blank input
- **expected results**:

```
Ops, your query is in StopList or empty, so there are no documents
retrieved.
```

- **Test result**

output	ticks(ticks/search)	time(s/search)
correct	15.246	2e-5

The time is averaged from 1000 runs.Since irrelevant words will not enter the search phase, the threshold is irrelevant to this test.

3.2.4 input3

- **content** : three stop words
- **purpose**: Testing for stop words
- **expected results**:

```
Warning: "call" is in the stop list and will be ignored.
Warning: "other" is in the stop list and will be ignored.
Warning: "man" is in the stop list and will be ignored.
Ops, your query is in StopList or empty, so there are no documents
retrieved.
```

- **test result**:

output	ticks(ticks/search)	time(s/search)
correct	51.027	5e-5

The time is averaged from 1000 runs.Since irrelevant words will not enter the search phase, the threshold is irrelevant to this test.

3.2.5 input4

- **content** : Complete 1henryiv.1.2
- **purpose**: Test detection of extreme length correct text. Test the performance of searches at different thresholds
- **expected results**(threshold=1.0):

```
Warning:...
...(omit numorous warning about stop words)
Your query has multiple valid words, so we will search for them
in the inverted index.
The words were found in files below:
```

```
File name                         Tf-Idf
1henryiv.1.2.txt                  5.785513
```

- **test result**:

output	ticks(ticks/search)	time(s/search)
correct	129114.1	0.13

The time is averaged from 10 runs, and `threshold=1`

threshold	rank	tf-idf	search time
0.01	1/1	0.024940	0.02

No more thresholds were tested here because the situation was too extreme and the correct documents were already filtered out at a threshold of 0.01.Increasing the threshold will only increase the running time, so it is not tested here..

3.2.6 input5

- **content** : All sects, all ages smack of this vice; and he To die for't!
- **purpose**: This sentence is choose from measure.2.2. Select this to test the effect of the threshold on search results.
- **expected results**(threshold=1.0):

```
Warning: "all" is in the stop list and will be ignored.
Warning: "all" is in the stop list and will be ignored.
Warning: "of" is in the stop list and will be ignored.
Warning: "this" is in the stop list and will be ignored.
Warning: "and" is in the stop list and will be ignored.
Warning: "he" is in the stop list and will be ignored.
Warning: "to" is in the stop list and will be ignored.
Warning: "for" is in the stop list and will be ignored.
Warning: "t" is in the stop list and will be ignored.
Your query has multiple valid words, so we will search for them
in the inverted index.
The words were found in files below:
File name                         Tf-Idf
measure.2.2.txt                   0.017464   0.015054
```

- **test result**:

output	ticks(ticks/search)	time(s/search)
correct	992.903	9.9e-4

The time is averaged from 1000 runs, and `threshold=1`.

threshold	rank	tf-idf	search time
0.2	3/7	0.003003	2e-4
0.4	1/1	0.005808	2e-4
0.6	1/1	0.011469	3e-4
0.8	1/1	0.012638	5e-4
1.0	1/1	0.015054	9.9e-4

From the test results, we can see that the works can be correctly screened out with a threshold of about 0.4.

I also tested some sentences with similar results, which I will not list here.

Chapter 4: Analysis and Comments

> Note
>
> - We only care the memory space of **major** data structures
> - It's undeniable that every word has different length, but we set the smallest unit to "word", not "character" for our convenience of analysis

4.1 Space Complexity

Conclusion: $O(W + D + H + I + M + K)$

- W: Word count all articles in *The Works*
- D: The number of documents(files, or articles in *The Works*)
- H: The size of the hash table which contains all stopwords
- I: The size of the inverted index(notice: we have removed the duplicated words, so every two nodes contain distinct words)
- M: The number of valid words
- K: The number of found documents for a single word

Analysis:

We should analyze the space complexity step by step:

- **Word count**: We use C++ STL containers(`pair`, `map` and `set`) to store the essential information about words and files. Specifically, `wordList` records the word count in all files for every word; `wordNumOfDoc` involves the word count for every file; `wordDocs` contains the number of articles where words apppear for every word. Consequently, the memory space in this step depends on both word count in all files (W) and the number of files(D).
- **Stop words**: Actually, in the word count program, we also extracted the stop words from the variables mentioned above, then these words will be stored in a hash table for fast finding when building the inverted index. Therefore, the size of hash table(H) represents the space that stopwords use.
- **Inverted index**: The bulk of inverted index is stored in a B+ tree. It's universally acknowledged that the space complexity of B+ tree is $O(N)$, when N is the number of data. However, our program has some uncertain factors, for instance, we can't control the size of the position list for each word, because the specific frequency of words are different. But what we can assure is that the total size of all position list is proportional to unduplicated word count, which is less than W. As a consequence, we only care $I = N \times$ `ORDER`, where `ORDER` means the order of the B+ tree, and we allocate `ORDER + 1` bytes for data and children in each node.
- **Query**: There are four data structures used in this part: `queryWord` stores up to `m` words, yielding $O(M)$; `posVec` holds document positions, with a maximum size of `k`, contributing $O(K)$; `freqMap` may contain up to `d` documents, leading to $O(D)$.; Temporary hash table `currentDocIdMap` also contributes $O(D)$. Consequently, the overall space complexity is $O(M + K + D)$.

Although our main program calls other functions which are not listed above, but their space complexity overlaps with the above operations or they are too trivial to be considered, so we don't care much about these function.

To sum up, the space complexity of our program is $O(W + D + H + I + M + K)$.

4.2 Time Complexity

Conclusion: $O(W + I \log I + n + m + m \log m + X)$

- W: Word count all articles in *The Works*
- I: The size of the inverted index
- n: The query string of length
- m: The number of valid words
- X: Vary in different situation
  - **single** valid word: $k \log k$, where k is the number of documents
  - **multiple** valid words: $m \times (p \log p)$, where p is the total document results inworst-case scenario

Analysis:

- **Word count and stop words**: Apparently, we count and handle every word in all files to implement the functions of word count and stop words detection. Therefore, the time complexity of this part is proportional to W, which is mentioned above.

- **Inverted Index**: The most frequent operations we have run in the inverted index are insertion and finding, so we consider these operations mainly. It's proved that the efficiency is $O(\log N)$ for both insertion and finding, and for every node we should execute these operations at least once. Consequently, the whole time complexity of building inverted index is $O(I \log I)$. Additionally, in our speed test above, we have drawn the curve chart of it, which can be fitted with $a + b \cdot N \log N$ function, which proves the correctness of our analysis further.

- **Query**: We will analyze this part step by step:
  - **character iteration**: The function iterates through each character in the query string of length n, resulting in $O(n)$.
  - **word processing**: Each word is checked against the stop words list and the inverted index. If m is the number of valid words, this step is $O(m)$ since both checks have an average time complexity of $O(1)$.
  - **sorting**: The `queryWord` vector containing valid words is sorted, taking $O(m \log m)$.
  - **ocument Search**: If there is one valid word, it retrieves the positions from the B+ tree (let's assume k documents) and sorts them: $O(k \log k)$. If there are multiple valid words, for a worst-case scenario of p total document results, it processes each word, resulting in $O(m \times (p \log p))$.

As a consequence:

- For a **single** valid word: $O(n + m + m \log m + k \log k)$
- For **multiple** valid words: $O(n + m + m \log m + m \times (p \log p))$

For the same reason above, we also ignore the time complexity of some functions which have slight impact on the whole time complexity of our main program.

In a nutshell, the time complexity of our program is $O(W + I \log I + n + m + m \log m + X)$.

4.3 Further Improvement

1. **Algorithm refinement**: So far, we have learned few of the efficient algorithms and data structures, which means that our implementation of the mini search engine might not be the best practice. However, it's possible for us to devised more ingenious and efficient procedure to cope with this problem after we systematically learned more excellent algorithms and data structrues.
2. **Testing construction**: Although we come up with some testing cases, probably some crucial tests are still lost, and potential bugs may exists in our programs owing to our incomplete consideration. From our standpoint, it's difficult to find all typical cases for a program, but we're fully convinced that by delicate techniques and tricks for testing results, we can come up with tests as complete as possible.
3. **Complexity analysis**: As you can see, it's awkward to analyze the complexity of some programs such as the space complexity of position list in nodes of inverted index. As a consequence, our analysis on complexity isn't very accurate. We will study the systematic method of analyzing the complexity and improve the precision of our analysis in the foreseeable future.

Appendix: Source code

5.1 File Structure

```
.
├── README.md
├── code
```

```
│   ├── Makefile
│   ├── README.pdf
│   ├── build
│   ├── scripts
│   │   ├── getStopWord
│   │   ├── getStopWord.cpp
│   │   ├── html2txt.py
│   │   ├── iist_diagram.py
│   │   ├── invIndexFunc.cpp
│   │   ├── invIndexHeader.h
│   │   ├── invIndexSearch.cpp
│   │   ├── invIndexTest.cpp
│   │   ├── search_main.cpp
│   │   ├── search_test.cpp
│   │   └── wordStem
│   └── data
│       ├── file_word_count.txt
│       ├── search_test
│       ├── shakespeare-master
│       ├── shakespeare_works
│       ├── stop_words.txt
│       ├── inverted_index_tests
│       ├── txt_title.txt
│       ├── word_count.txt
│       └── word_docs.txt
└── documents
    └── report-p1.pdf
```

5.2 getStopWord.cpp

```
/*****************************************
 * This program is used to get stop words from the Shakespeare works.
 * At the same time, it also counts the number of occurrences of
 * each word in each document and then gets the stop words.
 * The output files are word_count.txt, stop_words.txt, and word_docs.txt.
 * All of them are stored in the code/data directory.
```

```
****************************************/
#include <iostream>
#include <fstream>      // for file input/output
#include <string>
#include <map>
#include <vector>
#include <set>
#include <algorithm>    // for sort()
#include <cctype>
#include "wordStem/english_stem.h"

using namespace std;

typedef pair<wstring, set<string>> Pair;
map<wstring, int> wordList;            // word → count(The total
number of times a word appears in the corpus)
map<string, int> wordNumOfDoc;         // file → word_count(Total
word count of the file)
stemming::english_stem<> StemEnglish;
map<wstring, set<string>> wordDocs;        // word → count(The
number of articles containing the word)

int main()
{
    string file;         // file name
    ifstream infile;     // input file
    ofstream outfile;    // output file

      infile.open("data/txt_title.txt");      // open the file
containing the file names
    outfile.open("data/file_word_count.txt",ios::out);
    while(infile >> file)
    {
        string line;
        ifstream in;

        // Read in the file and stem each word
        in.open("data/shakespeare_works/"+file+".txt", ios::in);
        while(getline(in, line))
```

```
        {
            wstring word = L"";
            for(char &c : line)
            {
                // if the character is alpha or number, add it to
the word. It solve the problem of the Punctuation and Whitespace
                if(isalnum(c))
                    word += tolower(c);
                else if(word.length() > 0)
                {
                     StemEnglish(word);                //stem the
word
                    wordList[word]++;
                    wordNumOfDoc[file]++;
                      wordDocs[word].insert(file);     //get the
number of files by the size of the file name vector
                    word = L"";
                }
            }
        }
        outfile << file << " " << wordNumOfDoc[file] << endl;
        in.close();
    }
    infile.close();

    // Sort the words by their frequency
    // PS : Map does not have a built-in sorting algorithm, so I
need to convert the map into a vector and then use sort().
    vector<Pair> vec(wordDocs.begin(), wordDocs.end());
    sort(vec.begin(), vec.end(), [](const Pair& a, const Pair& b)
{ return a.second.size() > b.second.size(); });

    wofstream out,out2,out3;     // output files
    out.open("data/word_count.txt", ios::out);
    out2.open("data/stop_words.txt", ios::out);
    out3.open("data/word_docs.txt", ios::out);
    for(Pair &word : vec)
    {
        out3 << word.first << " " << word.second.size() << endl;
```

```
            // To be honest, the threshold of stop words has no
scientific basis.
        if(word.second.size() ⩾ 334)
            out2 << word.first << endl; // stop words
            out << word.first << " " << wordList[word.first] <<
endl;   // word count
    }
    out.close();
    out2.close();
    out3.close();
}

// To compile the program, run the following command in the
terminal:
// Depends on where you are, maybe you need to change the path
accordingly.
// (I assume you are in the main dictionary of the project)
// g++ -o code/scripts/getstopwords/getStopWord code/scripts/
getstopwords/getStopWord.cpp -Werror -Wall -Wextra
```

5.3 invIndexHeader.h

```
// Use B+ tree to store and access to the inverted index
// Declaration of properties, methods and some constants related
to B+ tree
#include <stdbool.h>
#include <stdio.h>
#include <string>
#include <time.h>
#include <vector>

#ifndef INVINDEX_H
#define INVINDEX_H    // In case of re-inclusion of this header
file

#define ORDER 4                          // The order of B+ Tree
#define LEAFCUT (ORDER / 2 + 1)          // The position of the
middle data in the leaf node of B+ Tree
#define NONLEAFCUT (ORDER / 2)           // The position of the
```

```
middle data in the non-leaf node of B+ Tree
#define SIZE 1000000                    // The maximum size of the
queue used in printing the B+ Tree
#define MAXWORDLEN 31                   // The maximum length of a
single word(the longest word is about 27 or 28 in Shakespeare's
works)
#define MAXDOCSUM 500000                 // The maximum number of
documents(files)
#define MAXREADSTRLEN 101                // The maximum lenght of
string for one read
#define STOPWORDSUM 300                  // The maximum number of
stop words
#define STOPWORDPATH "data/stop_words.txt"         // The path of
the file storing stop words
#define DEFAULTFILEPOS "data/tests"                // The default
position of the file(for test mode)
#define SHAKESPEAREDIR "data/shakespeare_works"    // The path of
Shakespeare's Works
#define          IISPEEDTESTDIR          "data/tests/invIndex-
speedTest/880000"        // Speed test files for inverted index
#define                FILEWORDCOUNTPATH                "data/
file_word_count.txt"                   // The path of word count
file
#define WORDDOCSPATH "data/word_docs.txt"                         //
The path of word→doc file
#define ITERATIONS 5                                               //
Iteration time used in speed test for inverted index

// alias
typedef char * string;
typedef struct data * Data;
typedef struct nodebp * NodeBP;
typedef struct nodebp * BplusTree;
typedef struct poslist * PosList;
typedef struct posdata * PosData;
typedef struct queuebp * QueueBP;
typedef struct hashtb * HashTb;
typedef struct hashsw * HashSW;
```

```
enum Kind {Legitimate, Empty};          // The state of the cells
in hash table
extern string docNames[MAXDOCSUM];      // Array containing names
of documents(global variable)

// Nodes in B+ Trees
struct nodebp {
    int size;                          // The size of the data in
the node
    int childrenSize;                  // The size of the children
nodes of the node

    Data data[ORDER + 1];              // The data of the node
    NodeBP children[ORDER + 1];        // The children nodes
    NodeBP parent;                     // The parent node(for split
operation)
};

// Data of the node in B+ Trees
struct data {
    string term;                       // The term
    PosList poslist;                   // All position where the
term appears
};

// List of the position of terms(similar to the queue, but not
same)
struct poslist {
    int size;                          // The size of list
     PosData front;                         // The front node of
list(dummy node)
    PosData rear;                      // The rear node of list
};

// The specific position info
struct posdata {
    int pos;                           // Position, i.e. the index
of the document
    int time;                          // the frequency in a single
```

```
document
    PosData next;                          // the next pointer
};

// The queue of nodes in B+ tree(array implementation)
struct queuebp {
    int size;                              // The current size of queue
    int front;                              // The index of the front
node
    int rear;                                // The index of the rear
node
    NodeBP data[SIZE];                     // Data
};

// The hash table for stop words
struct hashtb {
    int size;                              // The maximum size of the
hash table
    HashSW data[STOPWORDSUM];              // Data
};

// The cells in hash table
struct hashsw {
    string stopword;                       // Stop word
    enum Kind info;                       // State. either legitimate
or empty
};

// All methods are listed here. The explanation of parameters are
in the file "invIndexFunc.cpp"
// Methods for building inverted index
// The highest-level function, which users can call it directly
BplusTree    InvertedIndex(bool    isTest    =    false,    bool
containStopWords = false);
// Ask for the position of the directory or file
void askforFilePos(char * dir, char * fname, bool isTest);
// Make a traversal of all files(or a single file) and build the
inverted index from them(or it)
BplusTree fileTraversaler(BplusTree T, char * dir, char * fname,
```

```
bool isTest, bool containStopWords);
// Update the Inverted Index while reading a new document
BplusTree UpdateInvertedIndex(BplusTree T, int docCnt, FILE * fp,
bool containStopWords);

// Methods about B+ tree
// Create a B+ tree
BplusTree CreateBP();
// Find a term in B+ tree
NodeBP FindBP(string term, int docCnt, BplusTree T, bool * flag,
bool isSearch = false);
// Check if the term is in the B+ tree
void isSameTerm(string term, int docCnt, NodeBP nodebp, bool *
flag, bool isSearch = false);
// Insert a term into the B+ tree
BplusTree InsertBP(string term, int docCnt, NodeBP nodebp,
BplusTree Tree);
// Split the node when the node is full
BplusTree SplitBP(NodeBP nodebp, BplusTree Tree);
// Print the B+ tree(level-order traversal)
void PrintBPTree(BplusTree T);

// Methods about the queue
// Create the queue
QueueBP CreateQueueBP();
// Put the node of B+ tree into the queue
void EnqueueBP(NodeBP nodebp, QueueBP Q);
// Get the front node and delete it from the queue
NodeBP DequeueBP(QueueBP Q);

// Methods about poslist
// Create the poslist
PosList CreatePL();
// Add new position
void EnqueuePL(int pos, PosList L);
// Retrieve all position in the list
int ** RetrievePL(PosList L);

// Methods about hash table
```

```
// Build a hash table
HashTb GenerateHashTb();
// Initialization of the hash table
HashTb InitHashTb();
// Find the stopwords or other words in the hash table
int FindHashSW(string stopword, HashTb H, bool justSearch);
// Insert a new stopword in hash table
void InsertHashSW(string stopword, HashTb H);
// Hashing function
int HashFunc(string stopword, int size);
// Print hash table
void PrintHashTb(HashTb H);

// Comparison functions used in qsort()
int cmpData(const void * a, const void * b);      // Compare data
of the node in B+ tree
int cmpNodeBP(const void * a, const void * b);    // Compare the
node by their data

// wstring <-> char *, for word stemming
std::wstring chararrToWstring(char * st);
char * wstringToChararr(std::wstring wst);

// Word Stmming wrapper
string WordStem(string term);

// Print the ticks and duration, for -tr or --time function
void PrintTime(clock_t start, clock_t end);

void loadWordIdf(std::string filePath);
void loadFileWordsNum(std::string filePath);
void loadStopWords(std::string filePath);
void search(std::string query, BplusTree T, int pageSize, double
threshold);
std::vector<std::pair<int,double>>  FindBP2(string  term,  int
docCnt, BplusTree T) ;
std::vector<std::pair<int,double>> isSameTerm2(string term, int
docCnt, NodeBP nodebp) ;
std::vector<std::pair<int,double>> RetrievePL2(PosList L) ;
```

```
#endif
```

5.4 invIndexFunc.cpp

```
// Implementation of methods related to B+ tree in invIndex.h
#include "invIndexHeader.h"
#include "wordStem/english_stem.h"
#include <algorithm>
#include <codecvt>
#include <filesystem>
#include <locale>
#include <string>
// To avoid unexpected import problems
extern "C" {
    #include <ctype.h>
    #include <stdbool.h>
    #include <stdio.h>
    #include <stdlib.h>
    #include <string.h>
}
// file system namespace
namespace fs = std::filesystem;

string docNames[MAXDOCSUM];        // Array containing names of
documents(global variable)
HashTb H;                          // Hash table storing the stop
words

// The highest-level function, which users can call it directly
// isTest: -t or --test mode, just use one particular file
// containStopWords: -s or --stopwords mode, contain stop words
when building inverted index
BplusTree InvertedIndex(bool isTest, bool containStopWords) {
    char dir[MAXREADSTRLEN];             // Directory name
    char fname[MAXREADSTRLEN];           // File name
    BplusTree InvIndex = CreateBP();     // Inverted index, stored
in B+ tree
```

```
    // askforFilePos(dir, fname, isTest);   // Ask for the position
of file or directory
     // Make a traversal in the directory(or a single file) and
build the inverted index from it
    strcpy(dir, SHAKESPEAREDIR);
    isTest = false;
      InvIndex = fileTraversaler(InvIndex, dir, fname, isTest,
containStopWords);
    if (InvIndex->size) {                   // If the inverted index
contains the data, it indicates the success of building
        printf("Build successfully!\n");
    } else {                                // Otherwise, it fails
        printf("Fail to build an inverted index!\n");
    }

     return InvIndex;                           // Return the final
inverted index
}

// Ask for the position of the directory or file
// dir: directory name
// fname: file name
// isTest: -t or --test mode, just use one particular file
void askforFilePos(char * dir, char * fname, bool isTest) {
     if (isTest) {     // If we choose the test mode in the test
file,
         printf("Now testing the correctness of inverted Index:
\n");
        printf("Please input the name of the input sample file:
\nName: ");
        scanf("%s", fname);    // we should input the filename
     } else {          // Otherwise(in the main program or other
default situations),
        char choice[MAXWORDLEN];
        strcpy(dir, SHAKESPEAREDIR);        // Default path
        printf("Now building an inverted Index:\n");
         printf("Do you want to search something in the default
path(%s)?\n", dir);
        printf("Please input yes or no: ");
```

```
        scanf("%s", choice);          // Input your choice
        switch (choice[0]) {
            case 'y': case 'Y':       // Yes
                break;
            case 'n': case 'N':       // No
                printf("\nPlease input the directory of the
documents:\nPath: ");
                scanf("%s", dir);    // We should input the name
of the directory
                break;
            default:                  // Choice error
                printf("Choice Error!\n");
                exit(1);
                break;
        }
    }
}

// Make a traversal of all files(or a single file) and build the
inverted index from them(or it)
// T: B+ tree containing the inverted index
// dir: directory name
// fname: file name
// isTest: -t or --test mode, just use one particular file
// containStopWords: -s or --stopwords mode, contain stop words
when building inverted index
BplusTree fileTraversaler(BplusTree T, char * dir, char * fname,
bool isTest, bool containStopWords) {
    int docCnt = 0;       // Count the number of documents and act
as the index of the documents at the same time
    char * wholePath;     // The whole path name
    FILE * fp = NULL;     // File pointer

    H = GenerateHashTb();                    // Build a hash table
for stop words
     if (containStopWords) {                   // If in stopwords
mode, print the hash table
        PrintHashTb(H);
    }
```

```
    wholePath = new char[MAXREADSTRLEN];
    if (!isTest) {          // If we choose the test mode in the
test file,
        fs::path dirPath(dir);
          if (fs::exists(dirPath) && fs::is_directory(dirPath))
{   // Make a traversal in the directory
            for (const auto& entry : fs::directory_iterator(dirPath))
{
                if (fs::is_regular_file(entry)) {    // entry: a
single file
                                        std::string  filename  =
entry.path().filename().string();  // Get the file name
                    docNames[docCnt] = new char[filename.length()
+ 1];
                  strcpy(docNames[docCnt], filename.c_str());   //
Store the filename
                     strcpy(wholePath, (dirPath.string() + "/" +
filename).c_str());  // Get the whole path name
                    // Open the file
                    fp = fopen(wholePath, "r");
                    if (!fp) {  // Error handler
                        printf("Couldn't open the file!\n");
                        exit(1);
                    }
                    // Update the inverted index
                        T  = UpdateInvertedIndex(T, docCnt++, fp,
containStopWords);
                }
            }
            if (fp)  // Don't forget close the file pointer
                fclose(fp);
        } else {  // Input wrong directory
            perror("Could not open directory");

        }
    } else {
        strcpy(dir, DEFAULTFILEPOS);       // The file is in the
default position
```

```
        std::string sdir(dir);
        std::string sfname(fname);
        strcpy(wholePath, (sdir + "/" + sfname).c_str());  // Get
the whole path name

              docNames[docCnt]  =  (string)malloc(sizeof(char)  *
(strlen(fname) + 1));
         strcpy(docNames[docCnt], fname);                      //
Store the filename
        // Open the file
        fp = fopen(wholePath, "r");
        if (!fp) {  // Error handler
            printf("Couldn't open the file!\n");
            exit(1);
        }
        // Update the inverted index
                   T   =   UpdateInvertedIndex(T,   docCnt++,   fp,
containStopWords);
        fclose(fp);    // Don't forget close the file pointer
    }

    return T;
}

// Update the Inverted Index while reading a new document
// T: B+ tree containing the inverted index
// docCnt: the index of the document
// fp: file pointer
// containStopWords: -s or --stopwords mode, contain stop words
when building inverted index
BplusTree UpdateInvertedIndex(BplusTree T, int docCnt, FILE * fp,
bool containStopWords) {
    int i;
    int pre, cur;                              // Mark the start and
the end of one word
    char tmp[MAXREADSTRLEN];                  // Memory space storing
the reading data temporarily
    string term;                               // Term(or word)
     bool isDuplicated;                           // A flag, record
```

```
whether the term exists in the B+ tree
    NodeBP nodebp;                              // Node in B+ tree


      while (fgets(tmp, MAXREADSTRLEN - 1, fp) != NULL) {   //
Continue reading the file, until arrive at the end of file
        pre = cur = 0;                            // Initialization
         for (i = 0; i < strlen(tmp); i++) {    // Retrieve all
characters in the tmp string
            if (!isalpha(tmp[i])) {             // Maybe it's time
to record a word
                cur = i;
                  if (cur > pre) {                    // Legitimate
situation
                    term = (char *)malloc(sizeof(char) * (cur -
pre + 1));
                    strncpy(term, tmp + pre, cur - pre);
                     term[cur - pre] = '\0';    // Don't forget
this step

                    // Word stemming
                    term = WordStem(term);

                   // If we consider the stop words(default) and
assure the term is a stop word,
                    if (!containStopWords && FindHashSW(term, H,
true) >= 0) {
                        pre = cur + 1;
                        continue;   // then we should ignore it
                    }

                    isDuplicated = false;
                nodebp = FindBP(term, docCnt, T, &isDuplicated);  //
Find the appropriate position for the term
                    // If isDuplicated is true, then the time of
the term will +1 in function isSameTerm()
                    if (!isDuplicated) {  // If it's a new term,
insert it!
                        T = InsertBP(term, docCnt, nodebp, T);
```

```
                    }
                }

                pre = cur + 1;      // Move the start position for possible new word
            }
        }

        // Handle the last possible word in the tmp string
        if (!cur || pre > cur && pre != i) {
            cur = i;
              term = (char *)malloc(sizeof(char) * (cur - pre + 1));
            strncpy(term, tmp + pre, cur - pre);
            term[cur - pre] = '\0';

            // Word stemming
            term = WordStem(term);

            // If we consider the stop words(default) and assure the term is a stop word,
           if (!containStopWords && FindHashSW(term, H, true) >= 0) {
                pre = cur + 1;
                continue;  // then we should ignore it
            }

            isDuplicated = false;
             nodebp = FindBP(term, docCnt, T, &isDuplicated); // Find the appropriate position for the term
            // If isDuplicated is true, then the time of the term will +1 in function isSameTerm()
             if (!isDuplicated) {  // If it's a new term, insert it!
                T = InsertBP(term, docCnt, nodebp, T);
            }
        }
    }
```

```
    return T;
}

// Create a B+ tree
BplusTree CreateBP() {
    BplusTree T = (BplusTree)malloc(sizeof(struct nodebp));  //
Allocate the memory space for new B+ tree
    if (T == NULL) {    // Allocation failure
        printf("Failed to create a B+ Tree!\n");
        return T;
    }

    int i;

    // Memory allocation and initialization of data and children
    for (i = 0; i <= ORDER; i++) {
        T->data[i] = (Data)malloc(sizeof(struct data));
              T->data[i]->term  =  (string)malloc(sizeof(char)  *
MAXWORDLEN);
        T->data[i]->poslist = CreatePL();
        T->children[i] = (NodeBP)malloc(sizeof(struct nodebp));
    }
    // Initialization of other fields
    T->size = 0;
    T->childrenSize = 0;
    T->parent = NULL;

    return T;
}

// Find a term in B+ tree
// term: term
// docCnt: the index of the document
// T: inverted index
// flag: true if the term is found, false otherwise
// isSearch: mark the find mode(-f or --find)
NodeBP FindBP(string term, int docCnt, BplusTree T, bool * flag,
bool isSearch) {
    int i;
```

```
    if (!T) {    // If the tree is empty, return the tree(actually, it's impossible in our program)
        return T;
    } else if (!T->childrenSize) {  // If we arrive at the leaf node, search its data
        isSameTerm(term, docCnt, T, flag, isSearch);
        return T;
    }

    int pos = -1;  // The index of the appopriate non-leaf node
    for (i = 0; i < T->size; i++) {
        if (strcmp(term, T->data[i]->term) < 0) { // Find the first node which have term with higher lexicographic number
            pos = i;
            break;
        }
    }
    if (pos == -1) {  // If no position found in above loop, choose the last node
        pos = i;
    }

    return FindBP(term, docCnt, T->children[pos], flag, isSearch);  // Continue finding in the children node
}

// Check if the term exists in the B+ tree
// term: term
// docCnt: the index of the document
// nodebp: the appropriate node where the term may exists or will exists after insertion
// flag: true if the term is found, false otherwise
// isSearch: mark the find mode(-f or --find)
void isSameTerm(string term, int docCnt, NodeBP nodebp, bool *flag, bool isSearch) {
    int i;

    if (nodebp->size) {     // If it's not an empty node, start
```

```
searching
        for (i = 0; i < nodebp->size; i++) {
            if (!strcmp(term, nodebp->data[i]->term)) {     // If
the term exists in the inverted index
                if (!isSearch) {     // If it's not in the find
mode
                 EnqueuePL(docCnt, nodebp->data[i]->poslist);  //
Update the poslist of the term
                } else {     // Otherwise, print all info of the
term
                 PosList poslist = nodebp->data[i]->poslist;     //
Position list
                  int size = poslist->size;                      //
The number of all documents where the term appears
                  int cnt = 0;                                   //
Record the total frequency of the term

                 printf("Successfully find the word!\n");        //
Some banners
                     printf("The word was found in files below:
\n");

                     int j;
                     int ** posArr = (int **)malloc(sizeof(int *)
* size);  // Allocation of a 2D array
                     for (j = 0; j < size; j++) {
                          posArr[i] = (int *)malloc(sizeof(int) *
2);
                     }

                  posArr = RetrievePL(poslist);                  //
Put the poslist in a 2D array

                      for (j = 0; j < size; j++) {  // Print the
name of documents and their frequency respectively
                          if (posArr[j][1] <= 1)  // Singular
                          printf("%s: %d time\n", docNames[posArr[j]
[0]], posArr[j][1]);
                          else   // Plural
```

```
                        printf("%s: %d times\n", docNames[posArr[j]
[0]], posArr[j][1]);
                         cnt += posArr[j][1];
                     }
                 printf("Frequency: %d\n", cnt);          //
The total frequency
                    printf("-----------------------------------
\n");
                }

                *flag = true;       // mark the flag, indicating
we find the term
                break;
            }
        }
    }
}

// Insert a term into the B+ tree
// term: term
// docCnt: the index of the document
// nodebp: the appropriate node where the term will be inserted
// Tree: B+ tree containing the inverted index
BplusTree InsertBP(string term, int docCnt, NodeBP nodebp,
BplusTree Tree) {
    int i;

    strcpy(nodebp->data[nodebp->size]->term, term);
   EnqueuePL(docCnt, nodebp->data[nodebp->size++]->poslist);   //
Add the data info
     qsort(nodebp->data, nodebp->size, sizeof(nodebp->data[0]),
cmpData);    // Sort the data in time

    Tree = SplitBP(nodebp, Tree);     // Split the node
    return Tree;
}

// Split the node when the node is full
// nodebp: the appropriate node where the term will be inserted
```

```
// Tree: B+ tree containing the inverted index
BplusTree SplitBP(NodeBP nodebp, BplusTree Tree) {
    if (!nodebp->childrenSize && nodebp->size <= ORDER     // If
the node is not full
        || nodebp->childrenSize && nodebp->size < ORDER) {    //
(consider both leaf node and non-leaf node),
        return Tree;                                          // do
nothing!
    }

     // lnodebp, rnodebp: the left and right part of the split
node
    // tmpNodebp: store the node temporarily
    // parent: the parent node of nodebp
    NodeBP lnodebp, rnodebp, tmpNodebp, parent;
    int cut;    // The position of the middle data
    int i, j;

    parent = nodebp->parent;

    if (!parent) {  // If the node has no parent(i.e. this node
is the root),
         tmpNodebp = CreateBP();   // create a new node as the
parent(and also the root of the tree)
        parent = (NodeBP)malloc(sizeof(struct nodebp));
        Tree = parent = tmpNodebp;
    }

    lnodebp = CreateBP();
    rnodebp = CreateBP();
    lnodebp->parent = rnodebp->parent = parent;   // Connect the
two parts with the parent node

     if (!nodebp->childrenSize) {    // If the node is the leaf
node
        cut = LEAFCUT;

        for (i = 0; i < cut; i++) {     // Assign the data in the
left part of original node to lnodebp
```

```c
            lnodebp->data[i] = nodebp->data[i];
        }
        lnodebp->size = cut;

        for (j = cut; j < nodebp->size; j++) {    // Assign the data in the right part of original node to rnodebp
            rnodebp->data[j - cut] = nodebp->data[j];
        }
        rnodebp->size = nodebp->size - cut;

    } else {                             // If the node is the non-leaf node
        cut = NONLEAFCUT;

        for (i = 0; i <= cut; i++) {     // Assign the data and children in the left part of original node to lnodebp
            if (i != cut)
                lnodebp->data[i] = nodebp->data[i];
            lnodebp->children[i] = nodebp->children[i];
            lnodebp->children[i]->parent = lnodebp;
        }
        lnodebp->size = cut;
        lnodebp->childrenSize = cut + 1;

        // Assign the data and children in the right part of original node to rnodebp
        for (j = cut + 1; j < nodebp->size; j++) {
            rnodebp->data[j - cut - 1] = nodebp->data[j];
        }
        for (j = cut + 1; j < nodebp->childrenSize; j++) {
            rnodebp->children[j - cut - 1] = nodebp->children[j];
            rnodebp->children[j - cut - 1]->parent = rnodebp;
        }
        rnodebp->size = nodebp->size - cut - 1;
        rnodebp->childrenSize = nodebp->childrenSize - cut - 1;
    }

    // Assign the middle data in the original node to its parent
    parent->data[parent->size++] = nodebp->data[cut];
```

```
    if (parent->childrenSize) {    // If the parent has children(not
be created newly)
        for (i = 0; i < parent->childrenSize; i++) {
            if (parent->children[i] == nodebp) {     // Replace
the original node with lnodebp
                parent->children[i] = lnodebp;
                break;
            }
        }
    } else {     // newly created parent
        parent->children[parent->childrenSize++] = lnodebp;   //
Insert the lnodebp
    }
    parent->children[parent->childrenSize++] = rnodebp;       //
Insert the rnodebp

    // Sort the data and children of the parent
     qsort(parent->data, parent->size, sizeof(parent->data[0]),
cmpData);
    qsort(parent->children, parent->childrenSize, sizeof(parent-
>children[0]), cmpNodeBP);

    free(nodebp); // Free the memory of the original node

    Tree = SplitBP(parent, Tree);  // Continue spliting the upper
node

    return Tree;
}

// Print the B+ tree(level-order traversal)
// T: B+ tree containing the inverted index
void PrintBPTree(BplusTree T) {
    int i;
    NodeBP nodebp;        // The node obtained from the queue
    QueueBP q;            // The queue containing the nodes from
B+ tree

    printf("B+ Tree of Inverted Index:\n");
```

```
    q = CreateQueueBP();  // Create an empty queue
    EnqueueBP(T, q);       // Put the root of the tree into the
queue first
    EnqueueBP(NULL, q);    // Put the NULL pointer, for creation
of newline

    while (q->size) {     // If the queue isn't empty, repeat the
following steps
        nodebp = DequeueBP(q);  // Get the front node
        if (!nodebp) {          // If it's an NULL pointer, it's
time to add a newline
            printf("\n");
              if (q->size) {       // If the queue isn't empty,
continue add a new NULL pointer
                EnqueueBP(NULL, q);
            }
        } else {
            printf("[");        // Print the node's data(just the
term)
            for (i = 0; i < nodebp->size; i++) {
                if (!i) {
                    printf("%s", nodebp->data[i]->term);
                } else {
                    printf(", %s", nodebp->data[i]->term);
                }
            }
            printf("]");
        }

        if (nodebp) {           // If nodebp isn't a NULL pointer,
then put its children into the queue
            for (i = 0; i < nodebp->childrenSize; i++) {
                EnqueueBP(nodebp->children[i], q);
            }
        }
    }
}
```

```c
// Create the queue
QueueBP CreateQueueBP() {
    QueueBP Q = (QueueBP)malloc(sizeof(struct queuebp));
    Q->size = 0;
    Q->front = Q->rear = 0;

    return Q;
}

// Put the node of B+ tree into the queue
// nodebp: the newly added node
// Q: the queue
void EnqueueBP(NodeBP nodebp, QueueBP Q) {
     if (Q->size >= SIZE) {  // If the queue is full, enqueue
operation fails
        printf("Full B+-tree-item queue!\n");
        exit(1);
    }
    Q->data[Q->rear++] = nodebp;  // Add new node
    Q->size++;
}

// Get the front node and delete it from the queue
// Q: the queue
NodeBP DequeueBP(QueueBP Q) {
     if (!Q->size) {          // If the queue is empty, dequeue
operation fails
        printf("Empty B+-tree-item queue!\n");
        exit(1);
    }
    NodeBP returnNodeBP = Q->data[Q->front++];  // Get the front
node
    Q->size--;     // Delete the node from queue
    return returnNodeBP;
}

// Create the poslist
PosList CreatePL() {
    PosList L;
```

```
    L = (PosList)malloc(sizeof(struct poslist));
    L->size = 0;
    L->front = (PosData)malloc(sizeof(struct posdata));
    L->rear = (PosData)malloc(sizeof(struct posdata));
    L->front = L->rear;
    L->rear->pos = -1;   // Distinguish from other nodes

    return L;
}

// Add new position
// pos: the position
// L: the position list
void EnqueuePL(int pos, PosList L) {
    if (L->rear->pos != pos) {  // If it's a new position
        PosData tmp = (PosData)malloc(sizeof(struct posdata));
        if (!tmp) {
            printf("Fail to create a new position data!\n");
            exit(1);
        }  // Insert the new one in the position list
        tmp->pos = pos;
        tmp->time = 1;
        tmp->next = L->rear->next;
        L->rear->next = tmp;
        L->rear = tmp;
        L->size++;
    } else {    // Otherwise, just increment the frequency
        L->rear->time++;
    }

}

// Retrieve all position in the list
// L: the position list
int ** RetrievePL(PosList L) {
     if (!L->size) {        // If the list is empty, retrieve
operation fails
        printf("Empty position-data queue!\n");
```

```c
        exit(1);
    }

    int i = 0, j;
    int ** posArr = (int **)malloc(sizeof(int *) * L->size);
    for (j = 0; j < L->size; j++) {  // Memory Allocation for 2D array
        posArr[j] = (int *)malloc(sizeof(int) * 2);
    }

    PosData cur = L->front->next;

     while (cur != NULL) {  // Make a traversal in the position list
        posArr[i][0] = cur->pos;  // Get the specific info of the position
        posArr[i][1] = cur->time;
        cur = cur->next;
        i++;
    }

    return posArr;
}

// Build a hash table
HashTb GenerateHashTb() {
    int i;
    int pre, cur;                  // Mark the start and the end of one word
    HashTb H;                      // The hash table containing the stop words
    FILE * fp;                     // File pointer
    char fname[MAXWORDLEN];        // File name
    char tmp[MAXREADSTRLEN];       // Memory space storing the reading data temporarily
    char * term;                   // Term(or word)

    H = InitHashTb();              // Initialization
```

```
            strcpy(fname,   STOPWORDPATH);      //   Use   default
path(stop_words.txt)
    fp = fopen(fname, "r");        // Open the file
    if (!fp) {
        printf("Fail to open the file of stopwords!\n");
        exit(1);
    }

     while (fgets(tmp, MAXREADSTRLEN - 1, fp) != NULL) {   //
Continue reading the file, until arrive at the end of file
        pre = cur = 0;                              // Initialization
         for (i = 0; i < strlen(tmp); i++) {          // Retrieve
all characters in the tmp string
            if (!isalpha(tmp[i])) {                  // Maybe it's
time to record a word
                cur = i;
                if (cur > pre) {                     // Legitimate
situation
                     term = (char *)malloc(sizeof(char) * (cur -
pre + 1));
                    strncpy(term, tmp + pre, cur - pre);
                    term[cur - pre] = '\0';
                    InsertHashSW(term, H);           // Insert the
new term
                }

                pre = cur + 1;
            }
        }

        // Handle the last possible word in the tmp string
        if (!cur || pre > cur && pre != i) {
            cur = i;
              term = (char *)malloc(sizeof(char) * (cur - pre +
1));
            strncpy(term, tmp + pre, cur - pre);
            term[cur - pre] = '\0';
            InsertHashSW(term, H);                   // Insert the
new term
```

```
        }
    }
    fclose(fp);
    return H;
}

// Initialization of the hash table
HashTb InitHashTb() {
    HashTb H;             // Hash table
    int i;

       H  =  (HashTb)malloc(sizeof(struct  hashtb));    //  Memory
allocation for the whole table
    if (H == NULL) {
        printf("Fail to create a hash table for stopwords!\n");
        exit(1);
    }

    H->size = STOPWORDSUM;    // maxixum size

    for (i = 0; i < H->size; i++) {
        H->data[i] = (HashSW)malloc(sizeof(hashsw));
         if (H->data[i] == NULL) {     // Memory allocation for
cells
             printf("Fail to create a hash table for stopwords!
\n");
            exit(1);
        }
           H->data[i]->stopword = (string)malloc(sizeof(char) *
MAXWORDLEN);
        H->data[i]->info = Empty;
    }

    return H;
}

// Find the stopwords or other words in the hash table
// stopword: stop word
// H: hash table containing the stop words
```

```
// justSearch: find the term without subsequent insertion
int FindHashSW(string stopword, HashTb H, bool justSearch) {
    int pos;                             // Appropraite position
     int collisionNum = 0;                 // collision number,
for quadratic probe
    pos = HashFunc(stopword, H->size);    // Use hashing function
first

    // Collision occurs!
     while (H->data[pos]->info != Empty && strcmp(H->data[pos]-
>stopword, stopword)) {
        pos += 2 * ++collisionNum - 1;  // Quadratic probe
        if (pos >= H->size)
            pos -= H->size;
        if (justSearch && H->data[pos]->info == Empty) {
            return -1;
        }
    }
    return pos;
}

// Insert a new stopword in hash table
// stopword: stop word
// H: hash table containing the stop words
void InsertHashSW(string stopword, HashTb H) {
    int pos;
    pos = FindHashSW(stopword, H, false);   // Find the correct
position
     if (H->data[pos]->info != Legitimate)    // Insert the stop
word
    {
        H->data[pos]->info = Legitimate;
        strcpy(H->data[pos]->stopword, stopword);
    }
}

// Hashing function
// stopword: stop word
// size: the maximum size of the hash table
```

```
int HashFunc(string stopword, int size) {
    unsigned int val = 0;
    while (*stopword != '\0')
        val = (val << 5) + *stopword++;     // Generate the hash
value from every character in the string
    return val % size;
}

// Print hash table
void PrintHashTb(HashTb H) {
    int i;

    printf("Stopwords in hash table:\n");
    for (i = 0; i < H->size; i++) {
        if (H->data[i]->info != Empty) {
            printf("%d: %s\n", i, H->data[i]->stopword);
        }
    }
    printf("\n");
}

// Comparison functions used in qsort()
int cmpData(const void * a, const void * b) {
    const Data dataA = *(const Data*)a;
    const Data dataB = *(const Data*)b;

    return strcmp(dataA->term, dataB->term);
}

int cmpNodeBP(const void * a, const void * b) {
    const NodeBP nodebpA = *(const NodeBP*)a;
    const NodeBP nodebpB = *(const NodeBP*)b;

        return  strcmp(nodebpA->data[0]->term,  nodebpB->data[0]-
>term);
}

// wstring <--> char *, for word stemming
std::wstring chararrToWstring(char * st) {
```

```
    std::string tmp(st);
    std::wstring_convert<std::codecvt_utf8<wchar_t>> converter;
    std::wstring wstr = converter.from_bytes(tmp);

    return wstr;
}

char * wstringToChararr(std::wstring wst) {
    std::wstring_convert<std::codecvt_utf8<wchar_t>> converter;
    std::string tmp = converter.to_bytes(wst);
    char * st = new char[tmp.size() + 1];
    strcpy(st, tmp.c_str());

    return st;
}

// Word Stmming wrapper
string WordStem(string term) {
    std::wstring term_wstr;                // the wstring form of
the term
      stemming::english_stem<>  StemEnglish;    //  Word  stemming
function(a little clumsy)

    term_wstr = chararrToWstring(term);
                transform(term_wstr.begin(),    term_wstr.end(),
term_wstr.begin(), ::tolower);
    StemEnglish(term_wstr);
    term = wstringToChararr(term_wstr);

    return term;
}

// Print the ticks and duration, for -tr or --time function
void PrintTime(clock_t start, clock_t end) {
    clock_t tick;       // ticks
    double duration;    // duration(unit: seconds)
    int iterations;

    iterations = ITERATIONS;
```

```
    tick = end - start;
    duration = ((double)(tick)) / CLOCKS_PER_SEC;
    printf("Iterations: %d\n", iterations);
    printf("Ticks: %lu\n", (long)tick);     // Print the info
    printf("Duration: %.2fs\n", duration);
}
```

5.5 invIndexTest.cpp

```
#include "invIndexHeader.h"
#include "wordStem/english_stem.h"
#include <stdbool.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <string>
#include <time.h>

int main(int argc, char * argv[]) {         // Use command line
parameters
    int i;
    bool isTest = false;                       // Whether open test
mode(-t or --test)
    bool Print = false;                        // Whether open print
mode(-p or --print)
    bool isFound;                              // Whether the term is
found in the inverted index
    bool containStopWords = false;          // Whether open stopword
mode(-s or --stopwords)
    bool timeRecord = false;                   // Whether open time
record mode(-tr or --time)
    int findCnt = 0;                           // The time of finding
a single word for find mode(-f=n or --find=n)
    char * pos;                                // Get the number after
`=` in parameters
     char tmp[MAXWORDLEN];                        // Store the input
string temporarily
     char * word;                                  // The word to be
searched
```

```
    double duration;                            // Duration of running
a function
     std::wstring word_wstr;                     // wstring form of
word
      stemming::english_stem<>  StemEnglish;    //  Word  stemming
function
    BplusTree InvIndex;                         // Inverted Index
    clock_t start, end, tick;                    // Record the start
and the end of the clock

    for (i = 1; i < argc; i++) {                // Read the parameters
        if (!strcmp(argv[i], "--test") || !strcmp(argv[i], "-t"))
{  // Test mode
            isTest = true;
        } else if (strstr(argv[i], "--find") || strstr(argv[i],
"-f")) {  // Find mode
            if ((pos = strchr(argv[i], '='))) {
                findCnt = atoi(pos + 1);    // Get the number
behind `=`
                if (!findCnt) {
                    printf("Wrong Number!\n");
                    exit(1);
                }
            } else {
                findCnt = 1;    // Use default number
            }
        } else if (!strcmp(argv[i], "--print") || !strcmp(argv[i],
"-p")) {  // Print mode
            Print = true;
            }  else  if  (!strcmp(argv[i],  "--stopwords")  ||  !
strcmp(argv[i], "-s")) {  // Stopword mode
            containStopWords = true;
        } else if (!strcmp(argv[i], "--time") || !strcmp(argv[i],
"-tr")) {  // Time record mode
            timeRecord = true;
        } else {    // Error
            printf("Wrong Parameter!\n");
            exit(1);
        }
```

```
    }

    if (!timeRecord) {   // No time record
        InvIndex = InvertedIndex(isTest, containStopWords);
    } else {  // Time record
        char dir[MAXREADSTRLEN];
        strcpy(dir, IISPEEDTESTDIR);
        start = clock();
        for (i = 0; i < ITERATIONS; i++) {
            InvIndex = CreateBP();
          InvIndex = fileTraversaler(InvIndex, dir, NULL, isTest,
containStopWords);
        }
        end = clock();
        PrintTime(start, end);
    }

    if (Print) {  // Print the B+ tree
        PrintBPTree(InvIndex);
    }

    if (InvIndex->size && findCnt) {  // Search the single word
        word = (char *)malloc(sizeof(char) * MAXWORDLEN);
         printf("\nFinding Words Mode(only supports single word
finding):\n");
        for (i = 0; i < findCnt; i++) {  // For every search
            isFound = false;
            printf("Find %d: ", i + 1);
            scanf("%s", tmp);
            strcpy(word, tmp);

            // Word stemming
            word = WordStem(word);

            // Find the word
            if (!timeRecord) {  // No time record
                FindBP(word, -1, InvIndex, &isFound, findCnt);
            } else {  // Time record
                start = clock();
```

```
                FindBP(word, -1, InvIndex, &isFound, findCnt);
                end = clock();
                PrintTime(start, end);
            }

            // If not found, then give relevant information
            if (!isFound) {
               printf("Sorry, no such word in the inverted index!
\n");
                printf("-----------------------------------\n");
            }
        }
    }

    return 0;
}
```

5.6 invIndexSearch.cpp

```
/*****************************************
 * The following code is the implementation of the inverted index
search algorithm.
 * The algorithm takes a query from the user and searches for the
documents that contain all the valid query words.
 * The algorithm uses the B+ tree to search for the documents and
the inverted index to get the word frequencies.
 * The algorithm also uses the stop list to ignore the common
words and the stemming algorithm to reduce the words to their
root form.
*****************************************/

#include <iostream>                  // for input/output
#include <fstream>                   // for file input/output
#include <string>
#include <string.h>
#include <map>                       // for map data structure
#include <unordered_map>               // for unordered_map data
structure (hash)
#include <algorithm>                 // for sorting
```

```
#include <cctype>
#include <cmath>                           // for log()
#include "wordStem/english_stem.h"    // for stemming
#include "invIndexHeader.h"

#define DOCTOTALNUM 992              // total number of documents

//hash table: {word:wordIdf}
std::unordered_map<std::wstring, double> wordIdf;
//hash table: {docId:fileWordCount}
std::unordered_map<std::wstring, int> fileWordsNum;
//hash table: {word:bool}  PS: Bool is just a placeholder and has
no actual function.
std::unordered_map<std::wstring, bool> stopWords;
stemming::english_stem<> StemEnglish;

/****************************************
 * This function is the main function for searching.
 * In this function, we analyzes the query
 *  and search for the documents that contain all the valid query
words.
 * Input: T: Inverted index (B+ tree)
 *        pageSize: number of documents to be displayed per query
 *        threshold: the proportion of search terms to the total
number of terms
*****************************************/
void search(std::string query, BplusTree T, int pageSize, double
threshold)
{
    /*load the query and analyze it*/
    //vector: Elements are {word:wordIdf}
    std::vector<std::pair<std::wstring,double>> queryWord;
    std::wstring word=L"";
     //Iterate through each character in the string and extract
the words
    for(char &c : query)
    {
         // if the character is alpha or number, add it to the
word. It solve the problem of the Punctuation and Whitespace
```

```
        if(isalnum(c))
            word += tolower(c);
        else if (word.length() > 0)
        {
            std::wstring tmp = word;    // save original word
            StemEnglish(word);
            // check if the word is in the stop list
            auto it = stopWords.find(word);
            if(it != stopWords.end())
               // if the word is in the stop list, print a warning
message and ignore it.
              std::wcout << L"\033[1;31mWarning: \033[0m\"" << tmp
<< L"\" is in the stop list and will be ignored." << std::endl;
            else
            {
                // if the word is not in the stop list, check if
it is in the inverted index.
                auto it2 = wordIdf.find(word);
                if(it2 == wordIdf.end())
                    // if the word is not in the inverted index,
print a warning message and ignore it.
                     std::wcout << L"\033[1;31mWarning: \033[0m\""
<< tmp << L"\" is not in the inverted index and will be ignored."
<< std::endl;
                else
                     // if the word is in the inverted index, add
it to the queryWord vector.
                    queryWord.push_back({word,wordIdf[word]});
            }
            word = L"";    // reset the word
        }
    }
    // Sort the queryWord vector by wordIdf in descending order
                                sort(queryWord.begin(),queryWord.end(),
[](const     std::pair<std::wstring,double>&     a,     const
std::pair<std::wstring,double>& b){return a.second > b.second;});

    /* Search for documents that contain all the query words */
    int cntForDoc = 0;                                           //
```

```
counter for pageSize
    int cntForWord = (int)(queryWord.size() * threshold);     //
counter for threshold
    //control the size of cntForWord, to avoid bugs
    if (cntForWord == 0)
        cntForWord = 1;
    else if (cntForWord > queryWord.size())
        cntForWord = queryWord.size();

    char * wordForSearch;                                      //
char array for search
    //if the query is empty or only has stop words, return
    if(queryWord.size() == 0)
    {
        std::cout << "\033[1;31mOps, your query is in StopList or
empty, so there are no documents retrieved. \033[0m" << std::endl;
        return;
    }
    //if the query has only one valid word, search for it in the
inverted index
    //here, we only use "Tf" to sort the documents in rusult
    else if(queryWord.size() == 1)
    {
        //vector: Elements are {docId:tf}
        std::vector<std::pair<int,double>> posVec;
        std::cout << "Your query has only one valid word, so we
will search for it in the inverted index." << std::endl;
            std::cout << "The word was found in files below:"<<
std::endl;
        printf("\033[1,32mFile name                \tTf\033[0m\n");
         //don't need to traverse here, but I wrote the case of
multiple words first, so I reused it directly
        for(auto &p : queryWord)
        {
            wordForSearch = wstringToChararr(p.first);
            //find all the positions of the word in the B+ tree
            posVec = FindBP2(wordForSearch, -1, T);
            //sort the positions by tf in descending order
                        sort(posVec.begin(),posVec.end(),[](const
```

```
std::pair<int,double>& a, const std::pair<int,double>& b){return
a.second > b.second;});
            //print the file name and tf of the word
            for(auto &pos : posVec)
            {
                if(cntForDoc == pageSize)
                    break;
                printf("\033[34m%-25s\t%lf\033[0m\n",docNames[pos.first],
                cntForDoc++;
            }
        }
    }
    // if the query has multiple valid words, search for them in
the inverted index
    // Here, we use "Tf-Idf" to sort the documents in result
    else
    {
        std::cout << "Your query has multiple valid words, so we
will search for them in the inverted index." << std::endl;
         std::cout << "The words were found in files below:"<<
std::endl;
        //hash table: {docId : sum of tf-idf}
        std::unordered_map<int, double> freqMap;
        //traverse the queryWord vector and search for each word
in the inverted index
        bool flag=false;
        for(auto &p : queryWord)
        {
            if(cntForWord == 0)
                break;

            wordForSearch = wstringToChararr(p.first);
            auto currentPosVec = FindBP2(wordForSearch, -1, T);

             //Transfer the values in the vector to a temporary
hash table, mainly for efficiency reasons.
            //The temporary hash table only contains the pair of
docId and idf.
            std::unordered_map<int, double> currentDocIdMap;
```

```
            if(flag == false)
            {
                for(auto &pos : currentPosVec)
                 freqMap[pos.first] += pos.second * p.second;    // tf-idf = tf * idf
                flag = true;
            }
            else
            {
                for(auto &pos : currentPosVec)
                      currentDocIdMap[pos.first] = pos.second * p.second;
                if(freqMap.size()>0)
                {
                        //remove "it++" in "for(;;)"" to remove duplicates
                         for (auto it = freqMap.begin(); it != freqMap.end(); )
                    {
                         if (currentDocIdMap.find(it->first) == currentDocIdMap.end())
                            it = freqMap.erase(it);//safe deletion
                        else
                        {
                              it->second += currentDocIdMap[it->first];
                            ++it;
                        }
                    }
                }
                else
                    break;
            }
            cntForWord--;
        }
         //if there is no document that contains all the query words, return
        if(freqMap.size() == 0)
        {
```

```
            std::cout << "Ops, your query is not in the inverted
index, so there are no documents retrieved. " << std::endl;
            std::cout << "Please try again with different query."
<< std::endl;
            return;
        }
        //if there is at least one document that contains all the
query words, sort them by tf-idf in descending order
        else
        {
             printf("\033[1;32mFile name                  \tTf-
Idf\033[0m\n");
            //convert the unordered_map to a vector and sort it
by tf-idf in descending order
                              std::vector<std::pair<int,double>>
sortedFreqVec(freqMap.begin(), freqMap.end());
           std::sort(sortedFreqVec.begin(), sortedFreqVec.end(),
[](const std::pair<int, double>& a, const std::pair<int, double>&
b) {return a.second > b.second; });
            //print the file name and tf-idf of the word
            for(auto &p : sortedFreqVec)
            {
                if(cntForDoc == pageSize)
                    break;
                printf("\033[34m%-25s\t%lf\033[0m\n",docNames[p.first],p.s
                cntForDoc++;
            }

        }
    }
}

// similar to FindBP() in invIndexFunc.cpp, but desgined just for
searching
// return <word, tf>
std::vector<std::pair<int,double>>  FindBP2(string  term,  int
docCnt, BplusTree T)
{
    int i;
```

```
    // if the tree is empty, return an empty vector
    if (!T)
        return std::vector<std::pair<int,double>>();
    else if (!T->childrenSize)
        return isSameTerm2(term, docCnt, T);

    int pos = -1;

    // find the position of the term in the current node
    for (i = 0; i < T->size; i++) {
        if (strcmp(term, T->data[i]->term) < 0) {
            pos = i;
            break;
        }
    }
    if (pos == -1) {
        pos = i;
    }

    return FindBP2(term, docCnt, T->children[pos]);
}

//similar to isSameTerm() in invIndexFunc.cpp, but designed just for searching
//return <docId, tf>
std::vector<std::pair<int,double>> isSameTerm2(string term, int docCnt, NodeBP nodebp)
{
    int i;
    // vector: Elements are {docId:idf}
    std::vector<std::pair<int,double>> posVec;

    if (nodebp->size)
    {
        for (i = 0; i < nodebp->size; i++) {
            if (!strcmp(term, nodebp->data[i]->term))
            {
                PosList poslist = nodebp->data[i]->poslist;
```

```
                posVec = RetrievePL2(poslist);
                break;
            }
        }
    }
    return posVec;
}

//similar to RetrievePL() in invIndexFunc.cpp, but designed just
for searching
//return <docId, tf>
std::vector<std::pair<int,double>> RetrievePL2(PosList L)
{
    // if the position-data queue is empty, return an empty vector
    if (!L->size) {
        printf("Empty position-data queue!\n");
        exit(1);
    }

    double tf;
    std::vector<std::pair<int,double>> posVec;
    PosData cur = L->front->next;

    while (cur != NULL) {
          std::wstring docName = chararrToWstring(docNames[cur-
>pos]);
        // calculate tf : tf = word freq/total words in file
        tf = (double)cur->time / (double)(fileWordsNum[docName]);
        posVec.push_back({cur->pos, tf});
        cur = cur->next;
    }

    return posVec;
}

/*The functions below load the wordIdf, fileWordsNum, and
stopWords from files*/

void loadWordIdf(std::string filePath)
```

```
{
    std::wifstream infile;
    std::wstring word;
    int freq;
    double idf;
    infile.open(filePath,std::ios::in);
    //if the file is empty, return
    if(!infile.is_open())
    {
        std::cout << "Error: unable to open file " << filePath <<
std::endl;
        return;
    }
    //read the word and its frequency from the file and calculate
its idf
    while(infile >> word >> freq)
    {
        //calculate idf : idf = log(total number of documents/(1
+ number of documents contain the word))
        idf = log((double)DOCTOTALNUM/(double)(1+freq));
        wordIdf[word] = idf;
    }
    infile.close();
    std::cout << "Word Idf loaded successfully." << std::endl;
}

void loadFileWordsNum(std::string filePath)
{
    std::wifstream infile;
    std::wstring filename;
    int num;
    infile.open(filePath,std::ios::in);
    //if the file is empty, return
    if(!infile.is_open())
    {
        std::cout << "Error: unable to open file " << filePath <<
std::endl;
        return;
    }
```

```
    //read the file name and its word count from the infile
    while(infile >> filename >> num)
    {
        filename += L".txt";
        fileWordsNum[filename] = num;
    }
    infile.close();
   std::cout << "The word count of every file loaded successfully."
<< std::endl;
}

void loadStopWords(std::string filePath)
{
    std::wifstream infile;
    std::wstring word;
    infile.open(filePath,std::ios::in);
    //if the file is empty, return
    if(!infile.is_open())
    {
        std::cout << "Error: unable to open file " << filePath <<
std::endl;
        return;
    }
    while(infile >> word)
        stopWords[word] = true;
    std::cout << "Stop words loaded successfully." << std::endl;
}
```

5.7 search_test.cpp

```
#include <iostream>
#include <fstream>          // for file input/output
#include <string>
#include <time.h>            // for clock()
#include "invIndexHeader.h"

const std::string root_path = "data/search_test/input";

int main()
```

```
{
    clock_t start, end;

    //load inverted index and other necessary resources
    std::cout << "Please wait for resources to load and inverted index to be established..."<<std::endl;
     loadWordIdf(WORDDOCSPATH);                    //load word-idf dictionary
   loadFileWordsNum(FILEWORDCOUNTPATH);    //load file-word count dictionary
     loadStopWords(STOPWORDPATH);                //load stop words list
    BplusTree InvIndex = CreateBP();           //create B+ tree for inverted index
    InvIndex = fileTraversaler(InvIndex, (char *)SHAKESPEAREDIR, (char *)"", false, true);
        std::cout << "Inverted Index has been established successfully!"<<std::endl;
                                                 std::cout << "--------------------------------------------------" << std::endl;

    std::cout << "Welcome to ShakespeareFinder's test program!" << std::endl;
    std::cout << "The program tests the performance of the search engine in different situations" << std::endl;

    //test loop begin
    testbegin:
    std::cout << "Please enter the serial number of the input you want to test: " << std::endl;
    int serial_num;          //serial number of input file
    std::cin >> serial_num;
             std::string input_file_path = root_path + std::to_string(serial_num);     //input file path
    std::ifstream input_file;                             //input file object
     input_file.open(input_file_path, std::ios::in);       //open input file
```

```
    // if input file is not found, return
    if (!input_file.is_open())
        std::cout << "Invalid input serial number!" << std::endl;
    // if input file is found, continue
    else
    {
        //read input parameters
        int pageSize, k;
        double threshold;
        std::cout << "Input file opened successfully!" << std::endl;
         std::cout << "Please enter the pageSize, threshold and
the times of cycles : " << std::endl;
        std::cin >> pageSize >> threshold >> k;
        std::string query;
        std::getline(input_file, query);
        query += " ";

        //test performance
        start = clock();
        for(int i=0; i<k; i++)
        {
               std::cout << "Cycle " << i+1 << " starts..." <<
std::endl;  //print cycle number
            search(query, InvIndex , pageSize, threshold);
        }
        end = clock();

        PrintTime(start,end);
    }

    //ask user if they want to test another input
     std::cout << "Do you want to test another input? (y/n)" <<
std::endl;
    char choice;
    std::cin >> choice;
    if(choice == 'y')
    {
        getchar();
        goto testbegin;         //jump to testbegin
```

```
    }
    else
        return 0;

}
```

5.8 search_main.cpp

```
/****************************************
 * This is the main function of the search engine.
 * It first loads the inverted index and the necessary resources.
 * Then it enters a loop to repeatedly search for a query until
the user chooses to exit.
****************************************/
#include <iostream>
#include "invIndexHeader.h"

int main()
{
    //load necessary resources and inverted index
    std::cout << "Please wait for resources to load and inverted
index to be established..."<<std::endl;
     loadWordIdf(WORDDOCSPATH);                  //load word-idf
dictionary
   loadFileWordsNum(FILEWORDCOUNTPATH);    //load file-word count
dictionary
     loadStopWords(STOPWORDPATH);              //load stop words
list
    BplusTree InvIndex = CreateBP();        //create B+ tree for
inverted index
   InvIndex = InvertedIndex(); // fileTraversaler(InvIndex, (char
*)SHAKESPEAREDIR, (char *)"", false, true);
        std::cout  <<  "Inverted  Index  has  been  established
successfully!"<<std::endl;
                                          std::cout          <<
"--------------------------------------------------"<<
std::endl;

    //set values for pageSize and threshold from user input
```

```
                    std::cout    <<    "\033[1;32mWelcome    to
***ShakespeareFinder***\033[0m" << std::endl;
    std::cout << "\033[34mPlease set the maximum number of records
to be displayed per query\033[0m" << std::endl;
    int pageSize = 10;          //default value
    std::cout << "Size(int): ";
    std::cin >> pageSize;
    std::cout << "\033[34mPlease set the threshold (0-1) of the
query:\033[0m" << std::endl;
    std::cout << "Threshold(double): ";
    double threshold = 0.8;     //default value
    std::cin >> threshold;
    getchar();                  //clear the buffer to avoid input
error

    //start the search loop
    Searchbegin:
    std::cout << "Please enter your query:" << std::endl;
    std::string query;
    /* Read query from user and analyse it*/
    std::getline(std::cin,query);
    query += " ";                   // add a space at the end of
the query to avoid errors

    search(query, InvIndex, pageSize, threshold);
    //ask user if they want to search again
      std::cout  <<  "Do  you  want  to  search  again?\033[1;31m(y/
n)\033[0m: ";
    char choice;
    std::cin >> choice;
    if(choice == 'y' || choice == 'Y')
    {
        getchar();
        goto Searchbegin;
    }
    //exit the program
    else
    {
                 std::cout  <<  "\033[1;32mThank  you  for  using
```

```
ShakespeareFinder!" << std::endl << "Have a nice day~\033[0m" <<
std::endl;
        return 0;
    }
}
```

References

- Blake-Madden, OleanderStemmingLibrary, https://github.com/Blake-Madden/OleanderStemmingLibrary
- William Shakespeare, "The Complete Works of William Shakespeare", http://shakespeare.mit.edu/

Author list

- **Huang Xingyao**: Extracted the txt files of *The Complete Work of Shakespeare*, implemented the functions of word count, obtaining stop words, coping with queries and the main program, devised the tests of the threshold of queries.
- **Qian Ziyang**: Accomplished the foundation of the inverted index by B+ trees, designed the tests of inverted index, and wrote the bulk of this report.

Declaration

We hereby declare that all the work done in this project titled "Roll Your Own Mini Search Engine" is of our independent effort as a group.

Signatures

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