C++ Exercise 8: Balanced Trees

Deadline: Monday, November 30, 2020 by 23:59:59 EET Timezone.
How to submit: Check your code into your GitHub repository, the default `master` branch, tag it as `ex08submit` (all lowercase, no dashes).
Grading: This exercise is worth 100‰(or 10%) of the total grade.
Objectives: Using pointers, arrays, user-defined classes (but no external libraries like STL or Boost) implement an AVL tree to store string keys and integer values.
Important Guideline: The only predefined C++ libraries that can be used during this exercise are `iostream`, `sstream`, `string` (i.e. the "string" class to store keys and also the libraries related to input and output).
Another Important Guideline: There are many AVL tree implementations in the public Web. You are encouraged to look at this code, but you should avoid any copying of large chunks of such code. It is not just a matter of academic honesty, but writing your own balancing code with rotations is emotionally rewarding; and there may be subtle issues that you cannot properly address and fix unless you wrote it yourself.

Description

In the past there have been serious concerns with hostile user behavior in social networks (e.g. the suicide of a user of *Ask.fm*, a company founded in Latvia; see `https://bit.ly/3lCCmZ0`). For this reason a highly responsible social media startup *InstaDraugs* wants to monitor all verbal abuse or extremist speech in user comments and posts. They maintain a *lexicon of trigger words* – collection of words indicating threats of violence, ethnic or racial slurs, sexually explicit content, swearing, verbal abuse, cyberbullying as well as graphic descriptions of self-destructive or extremist behavior. If some user comment contains these words and the total badness score exceeds some threshold, it is removed immediately or a human moderator is alerted.
InstaDraugs stores their lexicon in an AVL tree (an ordered Binary Search Tree satisfying the AVL condition) containing all sorts of bad words. Every word w_i is associated with its badness – a positive integer b_i (badness indicates how many instances of that word appeared in the training datasets so far). All the entries in the lexicon look like this:

$$(w_1, b_1),\ (w_2, b_2),\ \ldots, (w_k, b_k),$$

where the keys are pairwise different. Sometimes the company finds that their lexicon is too large; in this case they erase one or more words w_i together with their associated values b_i.
In addition to the **insert** and **erase** of words, the lexicon also serves to **find** words (i.e. to add up the total badness for some text chunk to be verified). The QA department of *InstaDraugs* also wants the ability to **locate** any given key in the lexicon (how to navigate to it from the root of the AVL tree) to ensure that the lexicon always operates efficiently. They also need the ability to **dump** the entire lexicon (or some alphabetically sorted portion of it) for further review with their Linguistics department.
The program starts with an empty lexicon: the underlying AVL tree contains no entries. Every word contains one or more letters; *Instadraugs* allows 52 letters (26 upper-case letters and 26 lower-case letters in English alphabet). They do not analyze punctuation, digits or special characters to find offensive content. The keys in the AVL tree will never contain any hyphens, apostrophes or other special symbols (as well as non-English letters). All words are case sensitive (upper-case and lower case letters differ; for example, `ES`, `es`, `Es`, and `eS` are four different words.
There are five commands that can be executed on this lexicon. Two of them update the map, the other three just read the current state of the lexicon and produce some output.

- **Command "insert"**, preceded by a capital letter `I`. It is followed by one or more words that are inserted into a map. When some word (say, `abc`) is inserted for the first time, the map is initialized with a new entry ("`abc`", 1). When the same word is inserted again, the badness counter (its value in the map) is incremented: the entry becomes ("`abc`", 2), ("`abc`", 3) and so on. If there are multiple words on the same line, they are all inserted. The badness value for a word that repeats on the same line can be incremented multiple times.
  This command always succeeds and does not produce any output.

- **Command "erase"**, preceded by a capital letter `E`. It is followed by one or more words that are erased from the map. Such words are deleted along with their associated badness values. If the line with this command contains multiple words (separated by single spaces), they are all erased. Erasing words that are not present in the current lexicon is ignored.
  This command always succeeds and does not produce any output.

- **Command "get"**, preceded by a capital letter `G`. It is followed by a **single** word.
  This command outputs the line number (where it is in the input file) followed by a space and followed by the entry (word and the integer value associated with it). If the key does not exist, the key with value 0 should be returned

- **Command "locate"**, preceded by a capital letter `L`. Such commands are followed by a **single** word.
  This command outputs the line number (where the line it is in the input file) followed by a space and the letter `N` (if the word was not found) or the *location* of the key. The location can be either an asterisk `*` (if the word is the root) or an asterisk followed by some letters `L`, `R` indicating the location of the node in the tree (for example, `*LRR` means that the key can be found going to the root, moving one step to the left and then two steps to the right.)

- **Command "dump"**, preceded by a capital letter `D`. Such commands are followed by two arguments `start` and `end`. Either of them or both can be underscores.
  Dump command outputs its corresponding line number (from the input file) followed by an ordered list of entries in your map (all pairs (w_i, b_i) where w_i is between the start and the end (may be also equal to them). If the start or the end are underscores, we should dump the lexicon from the very beginning (or until the very end respectively). If the `end` precedes the `start` (or nothing is found), this command returns an empty list.

AVL Tree

Every insert and erase should keep the underlying tree as an AVL tree. The concrete AVL tree implementation (what types of pointers, classes, private/public members) is up to you, but it should output the expected results for all the debug commands: If the lexicon is initialized in a certain way with insert/erase commands, then the location of each key has certain value (it is `*`, `*L`, `*R`, `*LL`, `*LR`, or similar).
See (Goodrich2011, p.438–449) Chapter 10.2; all AVL concepts and algorithms are explained there. See also AVL Tree Rotations reference, `https://bit.ly/2UEEbc8` (University of Florida) and other good tutorials explaining how to manipulate AVL trees.

BST Ordering

Binary Search Trees (BSTs) rely on a certain ordering of its keys (in our situation – case-sensitive words using the 52-symbol English alphabet).
The algorithm should support the following three orderings (the specific order to use is input at the very beginning of the algorithm).

(1) Lexicographic order. Define that word w_1 *lexicographically precedes* w_2 (write $w_1 \prec_{\text{lex}} w_2$), if w_1 is a prefix of w_2. For example `AB` $\prec_{\text{lex}}$ `ABA`. Also define that $w_1 \prec_{\text{lex}} w_2$, if neither is a prefix of another, but in the first position where they differ, the symbol in w_1 precedes the symbol in w_2. For example, `ABBD` $\prec$ `ABC` (the 3rd letter from the start differs: `ABBD` and `ABC`).

(2) Shortlex order. Shorter words precede longer words in the shortlex order; words of the same length are compared lexicographically. Namely, $w_1 \prec_{\text{shortlex}} w_2$ is true if and only if either $|w_1| < |w_2|$ (the length of w_1 is smaller; it contains fewer letters than w_2) or $|w_1| = |w_2|$ and at the same time $w_1 \prec_{\text{lex}} w_2$.

(3) Colexicographic order. Define that word w_1 colexicographically precedes w_2 ($w_1 \prec_{\text{colex}} w_2$), if w_1 is a suffix of w_2. For example `CDE` $\prec_{\text{colex}}$ `BCDE`. Also define that $w_1 \prec_{\text{colex}} w_2$, if neither is a suffix of another, but in the first position (counting from the end) where they differ, letter in w_1 precedes the letter in w_2. For example, `ZVYZ` $\prec_{\text{colex}}$ `XYZ` (the 3rd letter from the end differs: `ZVYZ` and `XYZ`).

All the English letters are arranged alphabetically where different letters have *primary differences*. If two words differ only by their capitalization, then we compare their *tertiarry differences* (a capital letter precedes the lower-case letter of the same type). Some examples:

1. `abc` $\prec_{\text{lex}}$ `ABD`, having letter `c` instead of `D` is a primary difference. If there is any primary difference between the words, the letter capitalizations (tertiary differences) are ignored.

2. `abc` $\prec_{\text{lex}}$ `ABCA`; being a prefix of another word is also a primary difference, so the capitalization is ignored.

3. `AB` $\prec_{\text{lex}}$ `Ab` $\prec_{\text{lex}}$ `aB` $\prec_{\text{lex}}$ `ab`, just because of the tertiary differences – there are no primary differences between these words. (BTW, the same lexicographic order is also used in real dictionaries, see Figure 1.)

4. `AbC` $\prec_{\text{shortlex}}$ `aBC`: both words have length 3, and there are no primary differences. But there is a tertiary difference: `A` "slightly precedes" the lower-case letter `a`, so `AbC` $\prec_{\text{lex}}$ `aBC` (and for the words of the same length lexicographic order is same as shortlex order).

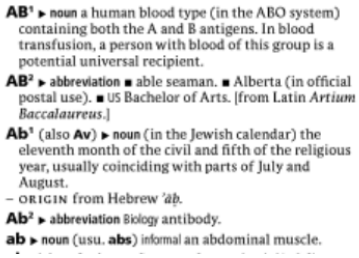
5. `aBC` $\prec_{\text{colex}}$ `AbC` in the colexicographic order (the tertiary difference is in the 2nd position from the end: `aBC` $<$ `AbC`).

6. `zzz` $\prec_{\text{shortlex}}$ `AAAA`, just because $|\texttt{zzz}| = 3$ is smaller than $|\texttt{AAAA}| = 4$, so the shortest word precedes any longer word.

In the notation of `RuleBasedCollator` (see `https://bit.ly/3nr0oH0`) this alphabetical order can be formally described like this:

$$< \texttt{A}, \texttt{a} < \texttt{B}, \texttt{b} < \texttt{C}, \texttt{c} < \texttt{D}, \texttt{d} < \ldots < \texttt{W}, \texttt{w} < \texttt{X}, \texttt{x} < \texttt{Y}, \texttt{y} < \texttt{Z}, \texttt{z}$$

Namely, the non-existent letter alphabetically precedes any other letter (the sequence starts with symbol $<$; shorter words always precede any other longer words containing that shorter



AB[1] ▸ **noun** a human blood type (in the ABO system) containing both the A and B antigens. In blood transfusion, a person with blood of this group is a potential universal recipient.

AB[2] ▸ **abbreviation** ■ able seaman. ■ Alberta (in official postal use). ■ US Bachelor of Arts. [from Latin *Artium Baccalaureus*.]

Ab[1] (also **Av**) ▸ **noun** (in the Jewish calendar) the eleventh month of the civil and fifth of the religious year, usually coinciding with parts of July and August.

– ORIGIN from Hebrew *'āḇ*.

Ab[2] ▸ **abbreviation** Biology antibody.

ab ▸ **noun** (usu. **abs**) informal an abdominal muscle.

Figure 1: A screenshot of the 1st page of an Oxford English dictionary.

word). A pair of two letters of the same type (say, `A`, `a`) can alphabetically precede another pair of letters (say, `B`, `b`), but the difference between upper-case `A` and lower-case `a` is tertiary, so they are separated by a comma (not the < sign).
Note. Since we are not using any accents as in French or `Ä`, `Ö`, `Ü` as in German or long vowels, we do not care about *secondary differences* between letters.
Some languages, including Latvian, need three levels of differences in their alphabets – primary, secondary and tertiary. For example, `A` and `Ā` have a secondary difference in most real-world dictionaries.

Limitations

- No word is longer than 30 characters.
- Input file can contain up to 10000 lines
- Input and erase commands contain up to 100 words each.
- The program should compile and run on a Linux OS (Xubuntu or similar) with 2GiB runtime memory; any input file should be processed into an output file under 10 seconds and the program should exit normally (not produce a segmentation fault or infinite loop).

Note. Pay some attention to your coding style, writing efficient code (in terms of memory use and time); and also deleting unused memory objects and avoiding *memory leaks*. These items will be discussed in our code review sessions (and leaving them unresolved may impact the operation of *InstaDraugs* business, if they run your lexicon code for a long time and the memory leaks accumulate; in severe cases of memory leeks they need to reboot their servers and initialize their lexicon from the scratch).
For this exercise all the credit is given just for successful testcases (but the performance and memory leak questions may arise during the code reviews that we will schedule separately).

Input

The syntax for any input file has the first line

```
OrderingMode
...
I wordToInsert1 wordToInsert2 ...
...
E wordToErase1 wordToErase2 ...
```

```
...
G wordToGet
...
L keyToLocate
...
D _ _
D wordBegin _
D _ wordEnd
D wordBegin wordEnd
...
F
```

All input files will be valid - regarding the format and the limitations defined above. Explanations of the notation used in the input files:

- "OrderingMode" takes one of the following values: `LEX`, `SHORTLEX`, `COLEX` (this determines the key ordering in your AVL tree – it is lexicographic, shortlex or colexicographic respectively). If two words are equal (w.r.t. their primary differences, i.e. with ignore-case), then upper-case letters always precede the lower-case letters (see the *tertiary difference* defined above).
- "wordToInsert1" etc. are the words that should be inserted in the lexicon with values 1 (or their badness should be incremented by 1, if they already exist).
- "wordToErase1" etc. are the words that should be erased from the lexicon.
- "wordToGet" is the key for which we want to know its value (the current badness).
- "keyToLocate" is the key for which we want to know its location in the AVL tree.
- "wordBegin" and "wordEnd" are two endpoints of the interval for which we dump the entries in our lexicon. (either of them or both can be underscore; then the respective endpoint is not checked).
- `F` is the marker of the end of the input; it always appears on the last line of the input.

Output

Commands "insert" and "erase" produce no output, but commands "get", "locate" and "dump" print the corresponding line number (where it appears in the input file) and the result of the query. For "get" it is either the entry `(key,value)` or `(key,0)` – if the word `key` was not found (and its badness is consequently 0).
For "locate" command it is the location starting with an asterisk and letters "L" and "R". For "dump" it is an ordered list of entries.

Sample Input and Output

Sample input **test01in.txt**:

```
COLEX
I abate abatija abats abats abi abinieki abonements
G abats
G abi
E abinieki abpus abra
G abinieki
L abi
L abats
L abi
D _ _
D ATE zzzzzats
D zz aa
F
```

Expected output **test01expected.txt**:

```
3 (abats,2)
4 (abi,1)
6 (abinieki,0)
7 *LR
8 *
9 N
10 (abatija,1) (abate,1) (abi,1) (abats,2) (abonements,1)
11 (abate,1) (abi,1) (abats,2)
12
```

Due to the colexicographic ordering, the keys in the AVL tree should be ordered like this:

$$\texttt{abatija} \prec_{\text{colex}} \texttt{abate} \prec_{\text{colex}} \texttt{abi} \prec_{\text{colex}} \texttt{abinieki} \prec_{\text{colex}} \texttt{abats} \prec_{\text{colex}} \texttt{abonements}.$$

Looking at 3-letter suffixes makes it obvious: ija, ate, abi, eki, ats, nts (the word ending with "a" comes first, etc.).
This order of the keys (colexicographic in this case) should be always respected as we build the BST. Furthermore, there are some rotation steps (named "treenode restructurings" in the textbook) and other manipulations related to the BST insert and erase commands.

- Right after `abinieki` is inserted, the AVL balancing property is violated in the right child of the root (node `abats`). We denote it with its child and grandchild (in the direction where the height is excessive). After the rotation we rearrange nodes as shown in Figure 2.
- Right after `abonements` is inserted, the AVL balancing property is violated in the root itself. The rotation is shown in Figure 3.
- When `abi` is deleted, it is replaced by its in-order successor `abats`. See Figure 4. No restructuring is needed in this case (but in other situations the AVL balance condition might be violated after restructuring and in these cases you should rotate).

Note. When deleting any internal node from a BST, there is a choice (and both options are technically possible as they both preserve the BST ordering invariant): we could take either the in-order predecessor or the in-order successor of the node you are deleting. In this exercise you should avoid ambiguity and always delete the in-order **successor**, if there is one. (Otherwise the testcases will not match.)

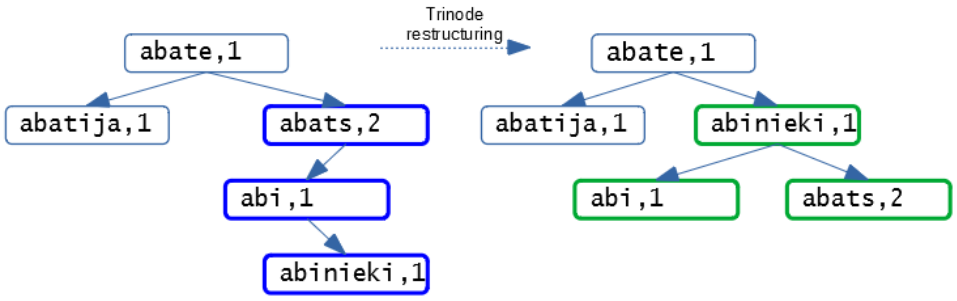


Figure 2: Restructuring right after inserting `abinieki`.

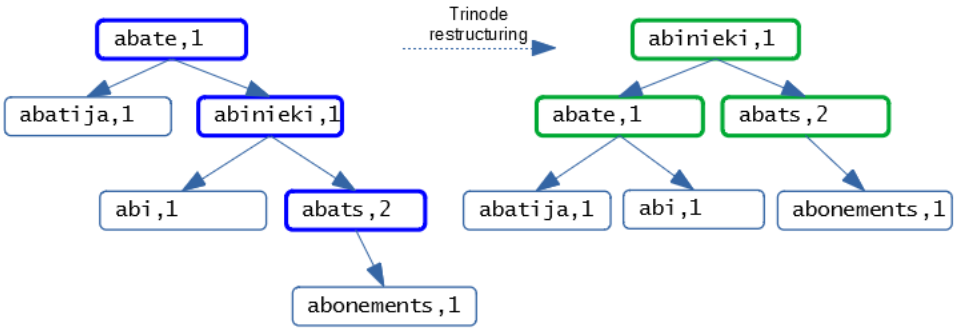


Figure 3: Restructuring right after inserting `abonements`.

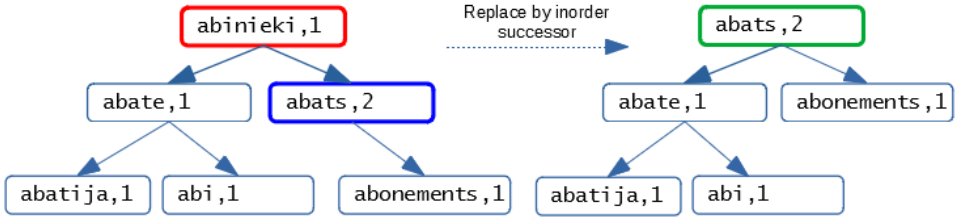


Figure 4: Erasing `abinieki`.