Implementation Of A Multithreaded Word Counter

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5 directories, 18 files
```

- **`README.pdf`** contains the explaination
- **`outputs/`** contains the `result.txt` generated by the program, along with screenshots
- **`assets/`** contains the provided input `WordOccurrenceDataset.txt`, and a `toVerify.txt` exists with the correct count of each of the words which was used to verify the program's result
- **`src/`** contains the actual source code
- **`perf_test/`** contains the results of the `perf record` command, along with the `perf.data` piped to a text file

1 · Data Structures

The program's foundation rests on two primary data structures: the trie tree for managing word storage and counts, and the thread data structure for coordinating parallel execution across multiple workers.

1.1 · Trie Tree

The trie, commonly referred to as a prefix tree, serves as the core mechanism for storing words and tracking their occurrence frequencies. Unlike alternative approaches like hash tables or simple arrays, the trie provides automatic alphabetical ordering and memory-efficient storage for words that share common prefixes. Each node represents a character, paths from the root spell out complete words, and a special flag marks word boundaries.

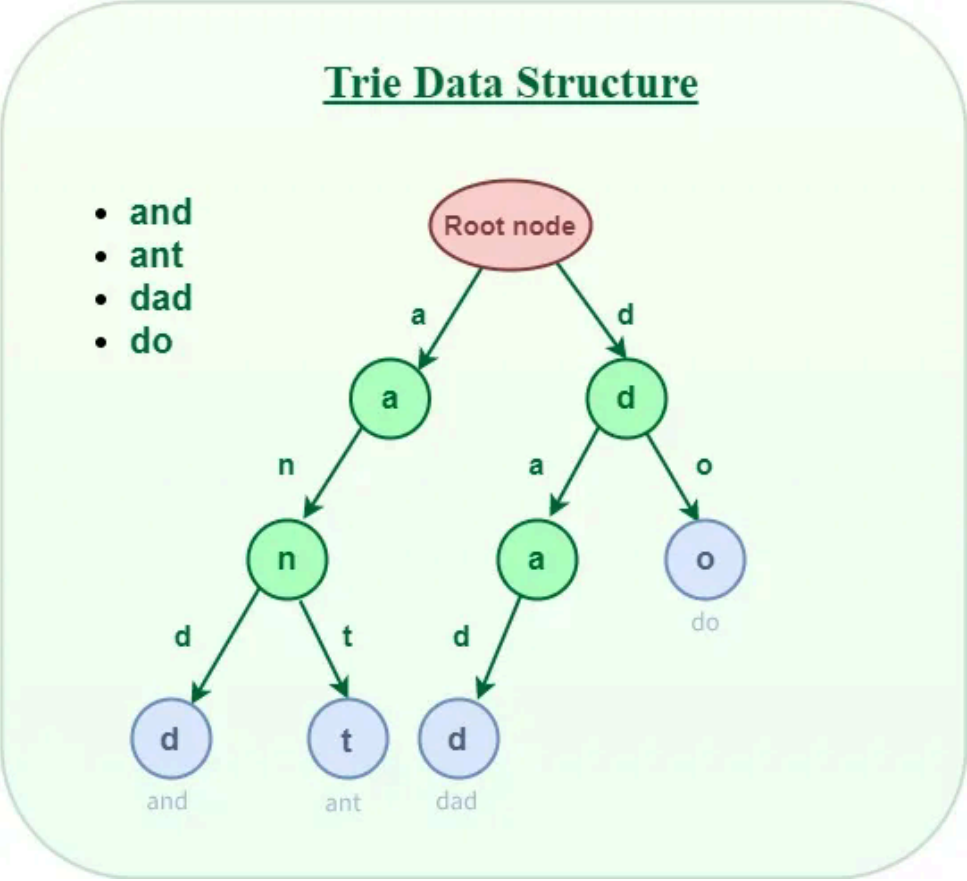


Figure 1: Trie Tree Example

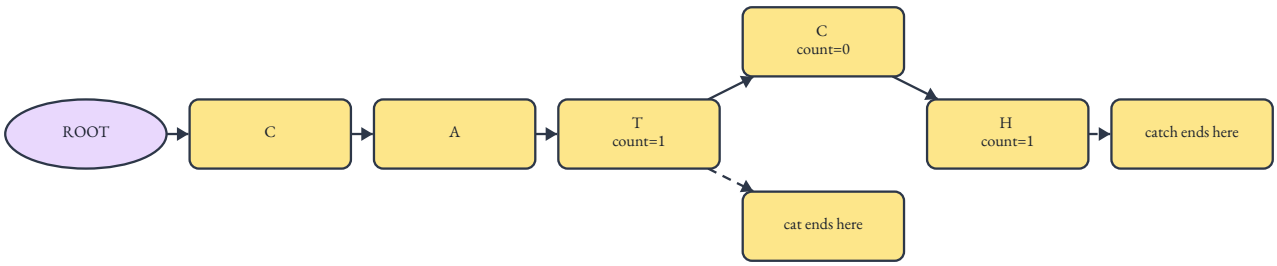
1.1.1 · Structure & Components

Each node in the trie represents a single character position within a word and contains three essential components that work together to enable efficient concurrent access:

```
typedef struct TrieNode {
  struct TrieNode* children[ALPHABET_SIZE];  // 26 pointers (a-z)
  int count;                                  // Word frequency
  pthread_mutex_t lock;                       // Thread safety
} TrieNode;
```

The `children` array maintains 26 elements, one for each lowercase letter from 'a' to 'z'. This design enables constant-time `O(1)` lookup for the next character in a word by calculating the array index as `character - 'a'`. The mapping is straightforward: 'a' corresponds to index 0, 'b' to index 1, and 'z' to index 25. This direct indexing eliminates the need for comparisons or hash computations, making character-by-character traversal extremely fast.

The `count` field tracks how many times a complete word ending at this particular node has been encountered during insertion. A count of zero indicates this node exists as part of a word's path but does not itself mark the end of a valid word. Consider inserting "cat" and "catch" into the trie: the node after 't' in "cat" would have a non-zero count marking it as a complete word, while the intermediate nodes in "catch" would maintain zero counts until reaching the final 'h'.



The `lock` mutex provides thread-safe access to each individual node. Rather than using a single global lock for the entire trie, which would create a bottleneck forcing threads to wait for each other unnecessarily, each node maintains its own lock. This fine-grained locking approach enables multiple threads to work on different parts of the trie simultaneously, which helps for achieving meaningful parallelization benefits.

1.1.2 · Why Trie (automatic sorting, memory efficiency)

The decision to use a trie over alternative data structures like hash tables or arrays comes from several important advantages that align well with this application's requirements:

- **Automatic Alphabetical Sorting**: Since we are tasked to sort the final result either alphabetically or by count, the trie tree makes sense because it's inherent structure maintains alphabetical order without any additional effort. When traversing children from index `[0-25]`, we naturally visit nodes in alphabetical sequence. This eliminates the need for a separate sorting phase that would be required with a hash table or unsorted array, making the output writing phase a simple `O(n)` traversal. The sorted output comes for free as a consequence of the data structure's design.

- **Thread-Safe Expansion:** The trie naturally accommodates concurrent insertions through fine-grained locking. Each path through the trie can be locked independently, allowing multiple threads to insert different words simultaneously without interfering with each other. This property makes the trie particularly well-suited for multithreaded word counting, as threads rarely contend for the same nodes unless processing very similar words.
- **Memory Efficiency for Shared Prefixes:** Words sharing common prefixes share the same nodes in memory. In a hash table, each word would require separate storage even for these shared prefixes. For large dictionaries containing many similar words, trie trees can result in significant memory savings. Given that our input dataset is substantially sized, this efficiency matters:

```
[wizard@archlinux ~/Projects/School/HPC/Assessment/t1/assets] -> wc -w
WordOccurrenceDataset.txt
120000 WordOccurrenceDataset.txt
[wizard@archlinux ~/Projects/School/HPC/Assessment/t1/assets] ->
```

With 120,000 words, the memory savings from shared prefixes become meaningful, particularly for common prefixes that appear across thousands of words.

1.1.3 · Operations (Insert, Write)

Word Insertion:
The insertion process walks through the trie character by character, creating nodes as needed along the path. Consider inserting the word “apple” into an empty trie:

1. Start at root, look for child ‘a’ (index 0)
2. Move to ‘a’ node, look for child ‘p’ (index 15)
3. Move to ‘p’ node, look for child ‘p’ (index 15)
4. Move to second ‘p’ node, look for child ‘l’ (index 11)
5. Move to ‘l’ node, look for child ‘e’ (index 4)
6. At final ‘e’ node, increment count

If any child doesn’t exist during this traversal, it must be created immediately. This is where we encounter our critical section, the point where multiple threads might attempt to create the same child node simultaneously, potentially causing a race condition.

```
void insert_word_into_trie(TrieNode* root, const char* word) {
  TrieNode* current = root;

  for (int i = 0; word[i] != '\0'; i++) {
    char c = tolower(word[i]);

    // Skip non-alphabetic ( if any )
    if (c < 'a' || c > 'z') continue;

    int index = c - 'a';

    if (current->children[index] == `NULL`) {
      pthread_mutex_lock(&current->lock);
```

```
      if (current->children[index] == `NULL`) {
        current->children[index] = create_trie_node();
      }
      pthread_mutex_unlock(&current->lock);
    }

    current = current->children[index];
  }

  pthread_mutex_lock(&current->lock);
  current->count++;
  pthread_mutex_unlock(&current->lock);
}
```

The Double-Check Locking Pattern

Notice the code checks if `children[index] == NULL` twice. This might appear redundant at first glance, but it's actually an optimization pattern called double-check locking for both correctness and speed.

The first check, performed without acquiring the lock, allows threads to quickly skip the locking mechanism when a child already exists. Acquiring and releasing locks is computationally expensive, so avoiding locks when possible provides significant performance benefits.

However, if the first check finds the child is NULL, we need to create it. But here's where the problem emerges: between the first check and acquiring the lock, another thread might have already created that same child node. This creates a classic race condition.

Consider this scenario with two threads inserting "apple" and "apply" simultaneously:

- Thread 1 checks: `children[p]` is NULL
- Thread 2 checks: `children[p]` is NULL
- Thread 1 acquires lock, creates the `p` node, releases lock
- Thread 2 acquires lock, but without the second check, it would create another `p` node, overwriting Thread 1's node and losing all the data stored in it

The second check, performed inside the lock after acquisition, prevents this race condition. After acquiring the lock, we verify that no other thread has created the child while we were waiting. If another thread beat us to it, we simply skip the creation and proceed. If the child is still NULL, we're guaranteed to be the only thread that can create it at this moment, ensuring no data loss or corruption.

Output Writing

The output writing process performs a simple depth-first traversal of the trie, building words character by character and writing them to the file when complete words are encountered:

```
void write_trie_to_file(TrieNode* node, char* prefix, int depth, FILE* fp)
{
  if (node->count > 0) {
    prefix[depth] = '\0';
    fprintf(fp, "%s: %d\n", prefix, node->count);
  }
```

```
  for (int i = 0; i < ALPHABET_SIZE; i++) {
    if (node->children[i] != `NULL`) {
      prefix[depth] = 'a' + i;
      write_trie_to_file(node->children[i], prefix, depth + 1, fp);
    }
  }
}
```

The function maintains a prefix string that represents the current path from the root. At each node with a non-zero count, it writes the complete word formed by the prefix along with its frequency. Because the children array is iterated from index 0 to 25 (corresponding to 'a' through 'z'), the output is automatically alphabetically sorted. This eliminates any need for a post-processing sort step, which would be computationally expensive for large dataset.

While recursion can sometimes lead to stack overflow issues with deeply nested structures, the depth of a trie is bounded by the length of the longest word, which is typically under 30 characters even for complex vocabularies. This makes the recursive approach safe for this application.

1.1.4 · Memory Management

Node Allocation

Each trie node is allocated using `calloc` rather than `malloc`,

```
TrieNode* create_trie_node() {
    TrieNode* node = calloc(1, sizeof(TrieNode));
    if (!node) {
        fprintf(stderr, "Error: Memory allocation failed\n");
        exit(1);
    }
    pthread_mutex_init(&node->lock, `NULL`);
    return node;
}
```

Using `calloc` instead of `malloc` initializes all memory to zero, which automatically sets all 26 child pointers to `NULL` and the count to 0. This initialization is crucial because the insertion logic depends explicitly on `NULL` pointers to identify missing children. Using `malloc` would leave the memory uninitialized, containing whatever garbage values happened to be there previously, which would break the insertion algorithm completely.

The mutex is initialized immediately after allocation to ensure it's ready before any thread can possibly access the node.

Recursive Destruction:

The trie is destroyed using post-order traversal, where children are freed before their parent node:

```
void destroy_trie(TrieNode* node) {
    if (node == `NULL`) return;

    for (int i = 0; i < ALPHABET_SIZE; i++) {
```

```
        if (node->children[i] != `NULL`) {
            destroy_trie(node->children[i]);
        }
    }

    pthread_mutex_destroy(&node->lock);
    free(node);
}
```

This traversal order ensures that no node is freed while still referenced by a parent's children array. The mutex is destroyed before freeing the node to properly release system resources associated with the lock. If we freed nodes in pre-order (parent before children), we would lose the pointers to children, causing a memory leak as those child nodes would become unreachable but remain allocated.

1.2 · Thread Data Structure

Each worker thread receives its own `ThreadData` structure containing all information needed to process its assigned portion of the workload independently:

```
typedef struct {
    TrieNode* root;         // Shared trie root
    char** words;           // All words from file
    int total_words;        // Total word count
    int thread_id;          // This thread's ID
    int num_threads;        // Total number of threads
} ThreadData;
```

- The `root` pointer gives each thread access to the shared trie where all words are inserted. While the trie itself is shared among all threads, each thread maintains its own copy of this pointer in its ThreadData structure.
- The `words` array contains all words read from the input file. This array is shared among all threads in a read-only fashion. No thread modifies the array itself; they only read words from it to insert into the trie. This read-only sharing eliminates the need for synchronization when accessing the words array, as reads are inherently thread-safe.
- The `total_words` field specifies the length of the words array, allowing each thread to know when to stop processing without needing to search for a sentinel value or null terminator.
- Each thread possesses a unique `thread_id` ranging from `0` to `num_threads - 1`. This identifier determines which words the thread will process according to the round-robin distribution algorithm, creating a natural and balanced work distribution scheme.
- The `num_threads` field tells each thread the total number of threads in the pool, which is necessary for calculating the stride in the round-robin algorithm. Together with the thread_id, this enables each thread to independently determine its workload without any coordination.

1.2.1 · Memory Management

The ThreadData structures are allocated on the heap in a single contiguous block:

```
ThreadData* thread_data = malloc(num_threads * sizeof(ThreadData));
```

This allocates an array of `ThreadData` structures on the heap using `malloc`. Each structure is then initialized with pointers to shared resources (root and words) and unique values (thread_id and num_threads).

Importantly, the ThreadData structures do not own the memory they point to. The root and words pointers reference memory allocated elsewhere and managed separately. The main thread owns the trie and words array, while the `ThreadData` array is just a temporary structure for passing information to worker threads. This means when we free the thread_data array, we only free the array of structures themselves, not the trie or words array:

```
free(thread_data);  // Only frees the ThreadData array
// root and words are freed separately
```

The main thread is responsible for allocating the trie and words array before creating worker threads, and for freeing them after all threads have completed.

2 · Program Flow & File Parsing

2.1 · Execution Pipeline

The program executes through seven sequential phases, each building upon the previous to transform input text into frequency-counted output:

1. Parse command-line arguments (thread count, filename)
2. Read all words into memory
3. Create shared trie root
4. Allocate and initialize ThreadData structures
5. Launch worker threads
6. Wait for completion (`pthread_join`)
7. Write results and cleanup

```
int main(int argc, char* argv[]) {
    int num_threads = atoi(argv[1]);
    char* input_filename = argv[2];

    int total_words;
    char** words = read_words_from_file(input_filename, &total_words);

    TrieNode* root = create_trie_node();

    pthread_t* threads = malloc(num_threads * sizeof(pthread_t));
    ThreadData* thread_data = malloc(num_threads * sizeof(ThreadData));

    for (int i = 0; i < num_threads; i++) {
        pthread_create(&threads[i], `NULL`, count_words_in_thread,
                       &thread_data[i]);
```

```
    }

    for (int i = 0; i < num_threads; i++) {
        pthread_join(threads[i], `NULL`);
    }

    write_trie_to_file(root, prefix, 0, output);

    destroy_trie(root);
    free(words);
    free(threads);
    free(thread_data);
}
```

The main thread performs setup, spawns worker threads to do the computational work, waits for all workers to complete, then performs cleanup.

The separation between reading words and processing them was intentional. By reading all words upfront, we avoid file I/O contention during the parallel processing phase. File I/O is inherently sequential and would create a bottleneck if threads tried to read from the file simultaneously.

2.2 · Reading Words

The file reading process handles the input file line by line, building a dynamically growing array of strings:

```
char** read_words_from_file(const char* filename, int* word_count) {
    FILE* fp = fopen(filename, "r");

    int capacity = 1000;
    int count = 0;
    char** words = malloc(capacity * sizeof(char*));
    char buffer[MAX_WORD_LENGTH];

    while (fgets(buffer, sizeof(buffer), fp)) {
        buffer[strcspn(buffer, "\n\r")] = '\0';
        if (strlen(buffer) == 0) continue;

        if (count >= capacity) {
            capacity *= 2;
            words = realloc(words, capacity * sizeof(char*));
        }

        words[count] = strdup(buffer);
        count++;
    }

    *word_count = count;
    return words;
}
```

The function reads line by line using `fgets`. It strips newlines with `strcspn`, which finds the first occurrence of any newline character and replaces it with a null terminator. Empty lines are skipped to avoid inserting empty strings into the trie and each word is duplicated using `strdup`, which allocates new memory for the string.

2.3 · Memory Management

2.3.1 · Dynamic Array Growth

The array starts with a capacity of 1000 elements. When this capacity is reached, the array doubles in size using `realloc`. This doubling strategy provides amortized O(1) insertion time, meaning that over many insertions, the average cost per insertion remains constant despite occasional expensive resize operations.

For our dataset containing 120,000 words, this results in approximately 7-8 reallocations ($\log_2(120000/1000)$). Each reallocation copies the existing array to a new, larger location, but since these happen exponentially less frequently as the array grows, the total copying overhead remains reasonable.

```
if (count >= capacity) {
    capacity *= 2;
    words = realloc(words, capacity * sizeof(char*));
}
```

2.3.2 · Cleanup

Memory must be freed in the reverse order of allocation, which ensures we never attempt to free memory through a pointer that has already been freed:

```
for (int i = 0; i < total_words; i++) {
    free(words[i]);  // Free individual strings first
}
free(words);  // Then free array
```

We must free the individual strings before freeing the array because each string was allocated separately by `strdup`. The words array itself only contains pointers to these strings, not the string data itself. If we freed the array first, we would lose access to the string pointers, making it impossible to free the string data and causing a memory leak.

3 · Multithreading Implementation

3.1 · Work Distribution

The round-robin distribution scheme assigns work to threads in a cyclic pattern: thread `i` processes indices `i, i+n, i+2n, i+3n, ...` where `n = num_threads`. This creates a natural load balancing mechanism without requiring any coordination between threads.

```
void* count_words_in_thread(void* arg) {
    ThreadData* data = (ThreadData*)arg;

    for (int i = data->thread_id; i < data->total_words; i += data-
>num_threads) {
        insert_word_into_trie(data->root, data->words[i]);
    }

    return `NULL`;
}
```

Each thread starts at its own unique offset (thread_id) and increments by the total number of threads (num_threads) on each iteration. This ensures that no two threads ever attempt to process the same word, eliminating the need for any synchronization when accessing the words array.

3.1.1 · Load Balancing

The maximum difference between any two threads is exactly one word. This property holds regardless of the total word count or number of threads, making the distribution scheme very flexible.

Example with 13 words and 4 threads:

```
Thread 0: 0, 4, 8, 12     (4 words)
Thread 1: 1, 5, 9         (3 words)
Thread 2: 2, 6, 10        (3 words)
Thread 3: 3, 7, 11        (3 words)
```

The first thread gets one extra word because 13 doesn't divide evenly by 4, but this imbalance is minimal.

3.2 · Thread Synchronization

3.2.1 · Race Conditions

Without proper synchronization, two primary race conditions could corrupt the trie structure and produce incorrect results:

Node Creation Race: Two threads detect that a child node is missing and both attempt to create it. Without synchronization, both threads would allocate and initialize a new node, and one would overwrite the other's pointer in the children array. This overwrites the first node created, causing a memory leak (the overwritten node is never freed) and data loss (any words already inserted into that subtree are lost).

Count Increment Race: The operation `count++` appears atomic in the source code but actually consists of three separate machine instructions: read the current value, increment it, and write the new value back. If two threads execute this sequence simultaneously, they might both read the same initial value, both increment it to the same new value, and both write that same new value back. The result is that only one increment is recorded instead of two, producing an incorrect word count.

These race conditions would occur unpredictably, making the program's behavior non-deterministic. The same input might produce different outputs on different runs, depending on the exact timing of

thread execution. This non-determinism makes debugging extremely difficult, as the program might appear to work correctly most of the time but occasionally produce wrong results.

3.2.2 · Solution: Fine-Grained Locking

The solution employs fine-grained locking, where each node has its own mutex rather than using a single global lock for the entire trie:

```
typedef struct TrieNode {
    struct TrieNode* children[ALPHABET_SIZE];
    int count;
    pthread_mutex_t lock;  // One lock per node
} TrieNode;
```

This design enables multiple threads to work on different paths through the trie simultaneously without interfering with each other. Locks are acquired only in two specific cases:

1. Creating a child node (lock the parent)
2. Incrementing the count (lock the final node)

Imagine two threads inserting completely different words, like “apple” and “zebra”. These threads will follow completely different paths through the trie, touching different nodes. With fine-grained locking, they can proceed completely independently, never waiting for each other. The alternative, a single global lock for the entire trie, would serialize all insertions. Threads would have to wait for each other even when working on completely unrelated parts of the trie, effectively eliminating any benefit from parallelization.

3.2.3 · Memory Barriers

Mutex operations provide implicit memory barriers that ensure proper synchronization of memory accesses across threads. When thread A releases a lock and thread B subsequently acquires the same lock, B is guaranteed to see all memory modifications made by A before the release. So in our case, for the trie, this means:

- When a thread creates a child node and releases the lock, any other thread that later acquires that lock will see the newly created child
- When a thread increments a count and releases the lock, any other thread that later acquires that lock will see the updated count

Without these guarantees, provided automatically by the mutex implementation, the program would mysteriously produce incorrect results.

4 · Compilation Instructions

To Run The Code With A Default Of 4 Threads And Provided Input Dataset:

```
[wizard@archlinux ~/Projects/School/HPC/Assessment/t1/code] -> ls
file_utils.c  file_utils.h  main.c  Makefile  trie.c  trie.h
[wizard@archlinux ~/Projects/School/HPC/Assessment/t1/code] -> make run
```

To Run The Code With A Custom Number Of Threads And Custom Dataset:

```
// compile:
[wizard@archlinux ~/Projects/School/HPC/Assessment/t1/code] -> gcc *.c -
Wall -Wextra -O2

// alternatively to compile:
[wizard@archlinux ~/Projects/School/HPC/Assessment/t1/code] -> make

// run
[wizard@archlinux ~/Projects/School/HPC/Assessment/t1/code] -> ./
wordCounter -h
Usage: ./wordCounter <num_threads> <input_file>
Example: ./wordCounter 4 input.txt

[wizard@archlinux ~/Projects/School/HPC/Assessment/t1/code] ->
```

5 · Performance Analysis

5.1 · Profiling Results

The program was tested using a dataset containing 120,000 words from `WordOccurrenceDataset.txt`, running on an Arch Linux system with x86-64 architecture. The profiling results provide insight into where the program spends its time and how effectively it utilizes multiple cores.

5.1.1 · Execution Time

Running the program with 4 threads yields the following results using the `time` command:

```
$ time ./word_counter 4 WordOccurrenceDataset.txt
0.01s user 0.00s system 128% cpu 0.012 total
```

The execution completes in just 0.012 seconds of real time, with 0.01 seconds spent in user mode and essentially zero time in kernel mode. The CPU utilization of 128% indicates that the program is using more than one core, which is exactly what we expect from a multithreaded application. This value represents the sum of CPU time across all threads divided by the real time, so 128% means the program is utilizing the equivalent of about 1.3 cores actively working.

With 4 threads, the theoretical maximum CPU utilization would be 400% if all four threads were continuously busy. The lower actual utilization of 128% occurs because the program includes sequential phases, particularly file I/O and the final output writing, where only one thread is active. Additionally, synchronization overhead from acquiring and releasing locks, and time spent in memory allocation, contributes to threads occasionally waiting rather than computing.

5.1.2 · CPU Profile (`perf report`)

Top functions by CPU time:

```
  16.32%  wordCounter    wordCounter               [.]
insert_word_into_trie
  13.08%  wordCounter    libc.so.6             [.] 0x00000000000a4f15
  11.37%  wordCounter    libc.so.6             [.] 0x000000000009b9fc
   7.03%  wordCounter    wordCounter               [.]
read_words_from_file
   5.82%  wordCounter    libc.so.6             [.] malloc
   5.27%  wordCounter    libc.so.6             [.] _IO_fgets
   4.58%  wordCounter    libc.so.6             [.] pthread_mutex_lock
   4.13%  wordCounter    libc.so.6             [.] 0x000000000018d60c
   3.74%  wordCounter    libc.so.6             [.] _IO_getline_info
   3.29%  wordCounter    libc.so.6             [.] 0x000000000017d4ef
   2.61%  wordCounter    libc.so.6             [.] 0x000000000018d6d8
   2.47%  wordCounter    libc.so.6             [.] cfree
   2.20%  wordCounter    libc.so.6             [.] 0x00000000000a6431
   2.18%  wordCounter    libc.so.6             [.] 0x000000000017d4c4
   2.17%  wordCounter    wordCounter               [.] main
   2.09%  wordCounter    [unknown]             [k] 0xffffffff89401280
   2.00%  wordCounter    libc.so.6             [.] 0x00000000000a686c
   1.91%  wordCounter    libc.so.6             [.] 0x0000000000180da8
   1.21%  wordCounter    libc.so.6             [.] 0x0000000000186de8
   1.09%  wordCounter    libc.so.6             [.] 0x0000000000180da2
   1.00%  wordCounter    libc.so.6             [.] 0x000000000009b9f0
   0.93%  wordCounter    libc.so.6             [.] 0x00000000000a643d
   0.83%  wordCounter    wordCounter               [.]
count_words_in_thread
   0.83%  wordCounter    libc.so.6             [.] __strdup
   0.81%  wordCounter    libc.so.6             [.] 0x0000000000186e37
   0.69%  wordCounter    libc.so.6             [.] 0x000000000018d68f
   0.20%  wordCounter    ld-linux-x86-64.so.2  [.] 0x0000000000014dbd
   0.04%  wordCounter    libc.so.6             [.] 0x00000000000a418d
   0.03%  wordCounter    libc.so.6             [.] 0x00000000000a6441
   0.03%  wordCounter    libc.so.6             [.] 0x00000000000a6e82
   0.03%  wordCounter    ld-linux-x86-64.so.2  [.] 0x0000000000014787
   0.02%  wordCounter    libc.so.6             [.] 0x00000000000a6aed
   0.00%  wordCounter    libc.so.6             [.] 0x0000000000065404
   0.00%  wordCounter    ld-linux-x86-64.so.2  [.] 0x000000000001f70a
   0.00%  wordCounter    libc.so.6             [.] 0x0000000000186dd3
   0.00%  wordCounter    libc.so.6             [.] 0x000000000005b56d
   0.00%  wordCounter    libc.so.6             [.] 0x0000000000186d84
   0.00%  wordCounter    libc.so.6             [.] 0x00000000001803b0
   0.00%  wordCounter    libc.so.6             [.] __ctype_init
   0.00%  wordCounter    libc.so.6             [.] 0x0000000000180380
   0.00%  wordCounter    libc.so.6             [.] 0x000000000009676c
   0.00%  wordCounter    libc.so.6             [.] 0x00000000000966e0
   0.00%  wordCounter    libc.so.6             [.] 0x000000000011aa00
   0.00%  wordCounter    ld-linux-x86-64.so.2  [.] 0x000000000001eb43
   0.00%  wordCounter    ld-linux-x86-64.so.2  [.] 0x000000000001f6ab
   0.00%  wordCounter    libc.so.6             [.] 0x000000000011aa07
```

Expected Results

- **Insertion Dominates Execution:** The `insert_word_into_trie` function consuming 16.32% of total CPU time aligns perfectly with expectations. This is the computational core where actual work happens. With 120,000 words being processed, this function executes 120,000 times, making it the natural hotspot.
- **File I/O is Significant:** The combination of `read_words_from_file` (7.03%) and `_IO_fgets` (5.27%) totaling roughly 12.3% represents the sequential file reading phase. This is unavoidable overhead as in this case, every word must be read from disk into memory before processing. The fact that this represents only about 12% of total time validates the design decision to read all words upfront rather than having threads fight for file access during processing.
- **Low Lock Contention:** The `pthread_mutex_lock` consuming only 4.58% is what was expected. This low overhead comes from the fine grained locking strategy. If threads were frequently contending for the same locks, we'd see this percentage much higher. The relatively low value indicates that threads are mostly working on different parts of the trie, acquiring locks briefly and releasing them quickly.

Unexpected Findings

- **Memory Allocation Overhead is Substantial:** The combined memory management overhead of `malloc` (5.82%), various libc memory functions (24.45% total), and `cfree` (2.47%), consumes approximately 32.74% of total execution time. This is significantly higher than anticipated. Each trie node allocation requires interaction with the memory allocator's internal structures. With the trie potentially containing tens of thousands of nodes, the cumulative cost seems to have become substantial.
    - This suggests a potential optimization: implementing a custom memory pool for trie nodes. Instead of calling `malloc` for each node individually, we could pre-allocate large blocks and subdivide them ourselves. This would trade memory efficiency for speed gains, though it would complicate the code and might interfere with the fine-grained locking strategy.
- **Minimal Time in Thread Function:** The `count_words_in_thread` function itself appears at only 0.83% of total time. This makes sense upon reflection: this function is essentially just a loop that calls `insert_word_into_trie`. The actual work happens inside the insert function, so the thread function's overhead is minimal. This means thread management itself isn't adding significant overhead.
- **Kernel Time is Negligible:** The near-zero kernel time (0.00s) is somewhat surprising given the mutex operations and memory allocations. The lack of kernel time suggests that most locks are acquired without blocking. This is excellent for performance but does mean the program might behave differently with much larger datasets that don't fit in cache.