Performance analysis & optimization

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# Environment description

**Workstation:**

MacBook Pro 16-inch, 2019

RAM: 16 GB 2667 MHz DDR4

CPU: 2,6 GHz 6-Core Intel Core i7

**Note**:

\* since for numbers close to INT\_MAX output to the console can take significant time (proof in profiling), we will initially eliminate this factor by printing only a maximum prime number found by the algorithm

A screen shot of a computer

Description automatically generated

**Profiler setup**:

A screenshot of a black screen

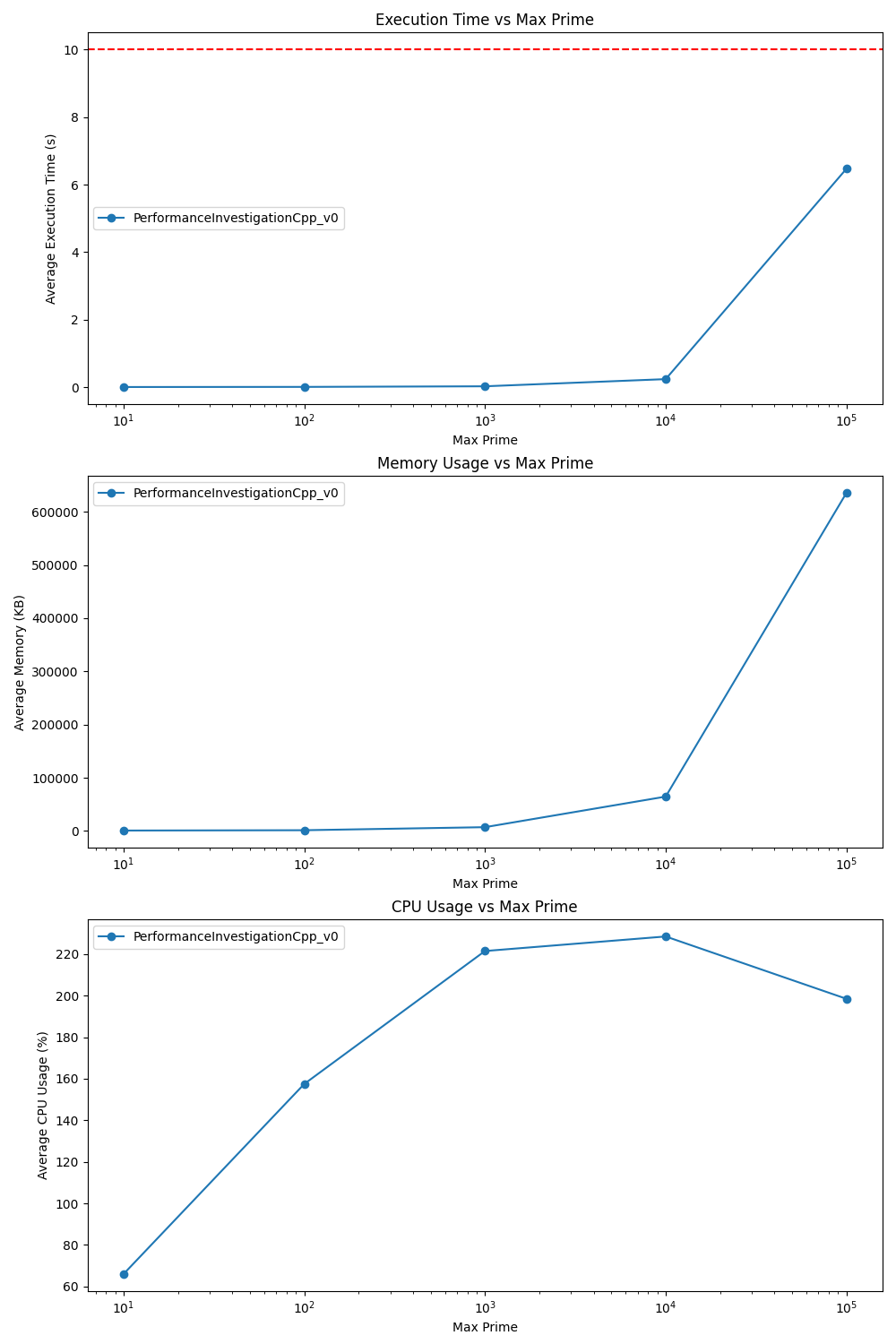
Description automatically generatedDefault CLion profiler (based on Dtrace) is used:

# Original solution

## Original solution (v0)

Original implementation is labeled as **PerformanceInvestigationCpp\_v0**.

Visible signs of performance problems: both execution time and memory consumption (6s+ and 600Mb+ with maxPrime=100k)



Apparently, ‘myFiller’ vector is not needed as it’s playing a temporary role to store int numbers that are pushed into ‘primeNumbers’ vector later:

std::vector<BigIntegerIterator> myFiller;

for (auto integer: myFiller) {  
 primeNumbers.push\_back(integer.getContain());  
}

The problem is that it not only store them in additional vector, but uses two additional vectors of ‘int’ and ‘string’ types reserved for 500 elements to store a single value:

private:  
 std::vector<std::string> contain;  
 std::vector<int> reference;  
};

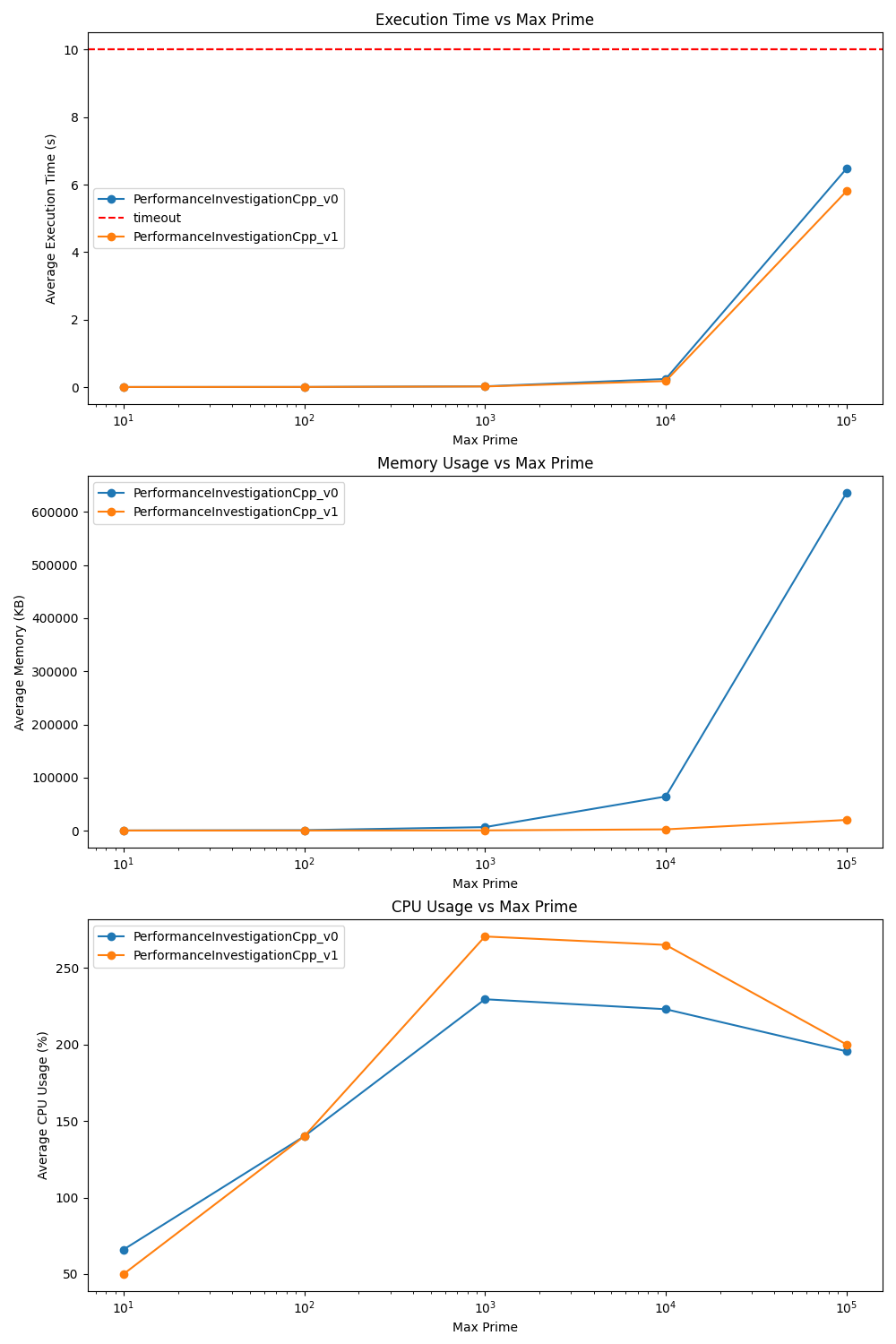
contain.reserve(500);  
reference.reserve(500);

## No BigIntegerIterator (v1)

In order to fix **Memory Inefficiencies**, we can completely **get rid of ‘BigIntegerIterator’ class and ‘myFiller’ vector** by pushing numbers directly to ‘primeNumbers’ vector:

std::vector<int> primeNumbers;  
  
for (int j = 2; j <= maxPrime; ++j) {  
 primeNumbers.push\_back(j);  
}

That version is marked as **PerformanceInvestigationCpp\_v1**.

Benchmark comparison (**v0 vs v1**):

Memory consumption has dropped from **~650Mb to ~20Mb** for maxPrime = 100k.

A screenshot of a computer

Description automatically generatedHowever, we haven’t dealt with slow execution time yet. Let’s analyze performance profile:

**Throwing an exception appears to be inefficient way** to indicate that a number is not prime:

if (candidate % primeNumbers[j] == 0) {  
 throw std::exception();  
}

## No exception thrown (v2)

**Boolean value should be returned** instead:

if (candidate % prime == 0) {  
 return false;  
}

‘isPrime’ also can iterate over numbers up to a candidate’s square root to check for a divisibility:

int sqrtCandidate = static\_cast<int>(std::sqrt(candidate));  
 for (int prime : primeNumbers) {  
 if (prime > sqrtCandidate) {  
 break;  
 }  
 if (candidate % prime == 0) {  
 return false;  
 }  
 }  
 return true;  
}

Solution is marked as **PerformanceInvestigationCpp\_v2**.

Benchmark comparison (**v1 vs v2**):

Surprisingly, there’s no significant benefit compared to a version with exceptions thrown.

A graph of a number of data

Description automatically generated with medium confidence

Let’s profile our new version to see a bottleneck:

maxPrime = 1000

A screen shot of a computer

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Seems like **threads creation overhead** is significant on lower maxPrime numbers.

**Inefficient algorithms** (need to do `.find()` and `.erase()` to remove non-primes instead of identifying primes and adding them to a vector) is taking over on higher numbers (maxPrime = 100000):

A screenshot of a computer

Description automatically generated

Interestingly, **lock (mutex) impact is not visible yet** as the entire process takes much more time on iterating rather than injecting found numbers:

A screenshot of a computer

Description automatically generated

To summarize, seems like these are the main inefficiencies that are impacting overall performance at that point:

1. **Spawning too many threads / lack of work division**: a new thread is created to check multiples of a single numbers instead of dividing work more efficiently (for vector segments);
2. **Iterating over non-primes**: the code checked each candidate number against all numbers less than itself, rather than only known primes;

Instead of trying to optimize algorithms and threading approach at once, let’s first try to implement more efficient single-threaded solution.

# Single-threaded solution

## Naïve solution (v3)

Let’s start from implementing naive single-threaded solution without significant changes to the algorithm itself.

Identifying numbers that are non-primes is done withing single thread (implementation **PerformanceInvestigationCpp\_v3**):

for (int candidate: primeNumbers) {  
 if (!isPrime(primeNumbers, candidate)) {  
 primeNumbersToRemove.push\_back(candidate);  
 }  
}

Benchmark comparison (**v2 vs v3**):

Single threaded version appears to be **~20% faster** with maxPrime = 100k and consumes significantly less memory (**1.6Mb vs 20Mb**).

A graph of a number of data

Description automatically generated with medium confidence

Let’s now profile naïve single-threaded solution to identify next bottleneck (maxPrime = 100k):

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A screenshot of a computer

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Seems like **iterating over all numbers (not only already known primes) and making operations like ‘>’, ‘%’, ‘==’** is taking too much time.

## Basic Eratosthenes Sieve (v4)

To mitigate that problem let’s use a well-known algorithm called the Sieve of Eratosthenes.

It implies multiple optimizations in comparison to a naïve implementation.

Store numbers in bool vector instead of int, where index represents a number (memory efficiency):

std::vector<bool> isPrime(maxPrime + 1L, true);

It iterates over a bool vector and in case it finds a prime number, it eliminates its multiples so there’s no need to check divisibility of a number explicitly:

for (int candidate = 2; candidate <= sqrtMaxPrime; ++candidate) {  
 if (isPrime[candidate]) {  
 for (long primeMultiple = candidate \* candidate; primeMultiple <= maxPrime; primeMultiple += candidate) {  
 isPrime[primeMultiple] = false;  
 }  
 }  
}

Implementation labeled as **PerformanceInvestigationCpp\_v4.**

Benchmark comparison (**v3 vs v4**):

V4 started to take over from maxPrime = 100k and showed extreme advantage at maxPrime = 500k (**1Mb vs 6Mb** & **0.04s vs 96s**)

A graph of different types of data

Description automatically generated with medium confidence

## Eratosthenes Sieve odd numbers (v5)

However, there’s still a space for improvement. Let’s see a profiling result:

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Description automatically generated

A loop that eliminates multiples is taking major part of a processing time:

for (long primeMultiple = candidate \* candidate; primeMultiple <= maxPrime; primeMultiple += candidate) {  
 isPrime[primeMultiple] = false;  
}

We can iterate over odd numbers only (as all even number are divisible by 2):

// Starting from 3 and incrementing by 2 to check odd numbers only  
for (int candidate = 3; candidate <= sqrtMaxPrime; candidate += 2) {  
 if (isPrime[candidate]) {  
 for (long primeMultiple = candidate \* candidate; primeMultiple <= maxPrime; primeMultiple += candidate) {  
 isPrime[primeMultiple] = false;  
 }  
 }  
}

.push\_back() of identified prime numbers to a int vector doesn’t seem to take much time, but let’s also try to reserve a memory to prevent vector resizing:

// could be also maxPrime / log(maxPrime) as per the prime number theorem (PNT)  
primeNumbers.reserve(maxPrime / 2);

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Optimized solution is labeled as **PerformanceInvestigationCpp\_v5.**

Benchmark comparison (**v4 vs v5**):

Both execution time and memory consumption decreased: **4.5s vs 3.3s & 67Mb vs 35Mb** (for maxPrime = 100m)

A screenshot of a graph

Description automatically generated

# Multi-threaded solution

As we can see, **v5** utilizes only single core throughout entire processing (100% utilization is a max), which is not taking advantage of multi-core processor. Let’s try to introduce threads for parallel calculation. There’re multiple ways to divide their work with SoE algorithm (see [example](https://himsen.github.io/pdf/Project1_parallel_algorithms_Torben.pdf)), but we’ll stuck with a following one at first:

1. Calculate prime numbers up to square root of max prime -> store them in *vector<int>*
2. Create N threads, divide initial vector from square root of max prime to max prime into N chunks, for each thread then:  
   - apply same sieving algorithm using already identified prime numbers  
   - add them to its own *vector<int>* and return it
3. Within single thread concatenate all separate vectors created by all threads (to avoid locks and race conditions)

Numbers of threads N is calculated depending on available cores and utilizes 1 thread in case of a small number to avoid processing of single numbers:

static int calculateThreadsNumber(int maxPrime) {  
 const int maxThreads = static\_cast<int>(std::thread::hardware\_concurrency());  
 // For small maxPrime Numbers  
 int numThreads = maxPrime <= maxThreads ? 1 : std::min(static\_cast<int>(maxPrime/maxThreads), maxThreads);  
 //std::cout << "Threads number is " << numThreads << std::endl;  
 return numThreads;  
}

Implementation labeled as **PerformanceInvestigationCpp\_v6.**

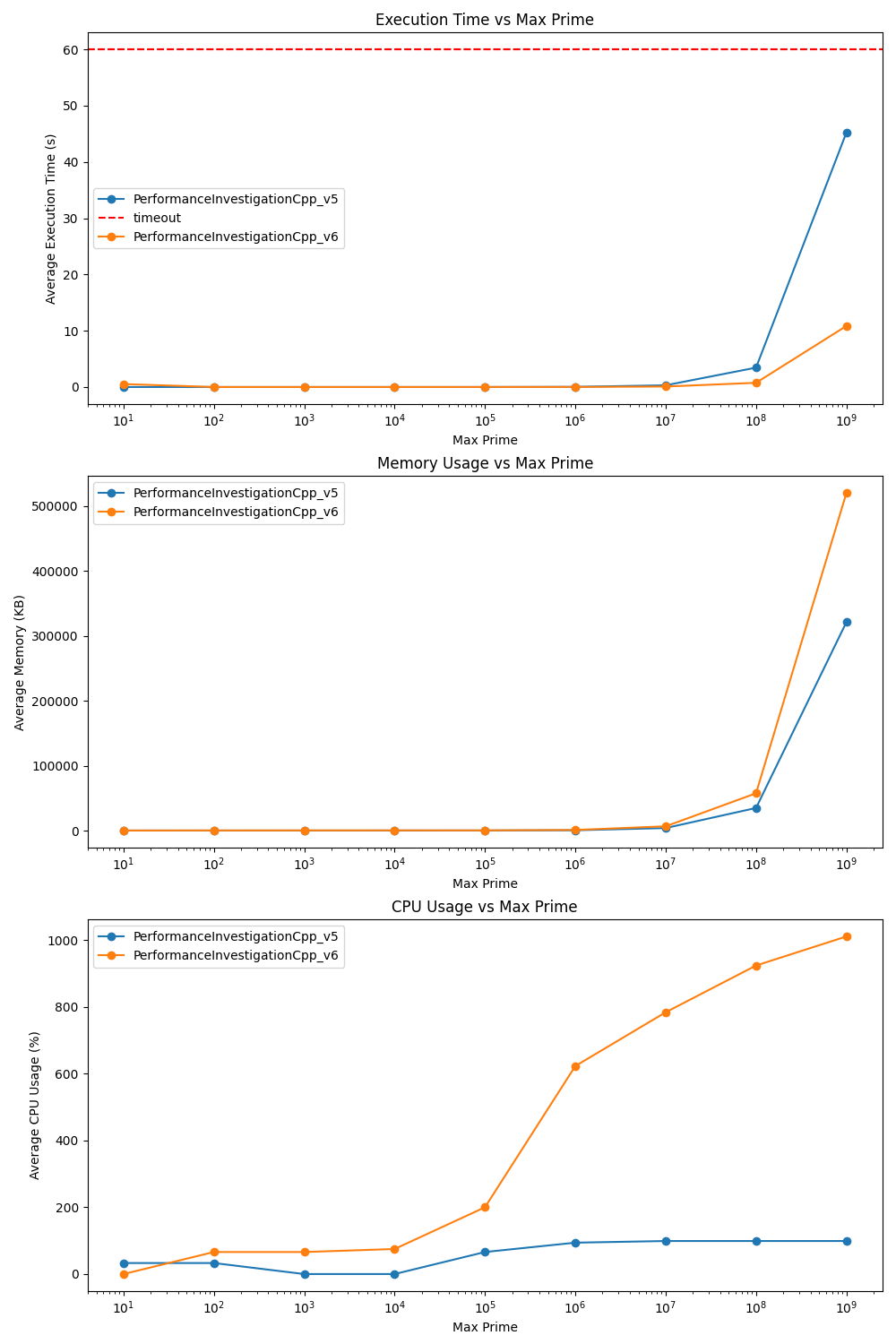
## Vectors of <int> concatenation (v6)

Let’s benchmark it against single-threaded (**v5 vs v6**)**:**

with maxPrime = 1000000000:

Average execution time: **~45s vs ~11s**

Average memory used: **321Mb vs 519Mb**



As we can see, multithreaded version efficiently utilizes all available cores on higher max prime numbers and provides significant speed improvement. However, it requires more memory to store temporary <int> vectors.

Let’s try to decrease its memory footprint.

## Synchronized vector<int> (v7)

Instead of manipulating with *vector<int>* structures, each thread now will utilize it’s own *vector<bool>* and will push prime numbers it has identified to a resulting *vector<int>* using mutex lock:

// Block sieving algorithm for numbers after sqrt(N)  
std::vector<bool> isPrime(endSegment - startSegment + 1, true);  
// Sieve within the segment  
for (int i = 0; i<= lastInitialPrimeIndex; i++) {  
 int prime = primeNumbers[i];  
 int startNumber = std::max(prime \* prime, (startSegment + prime - 1) / prime \* prime);  
 for (long j = startNumber; j <= endSegment; j += prime) {  
 isPrime[j - startSegment] = false;  
 }  
}  
  
// Add the primes in this segment to the shared vector  
for (long i = startSegment; i <= endSegment; ++i) {  
 if (isPrime[i - startSegment]) {  
 std::lock\_guard<std::mutex> lock(primeNumbersLock);  
 primeNumbers.push\_back(i);  
 }  
}

Implementation is labeled as **PerformanceInvestigationCpp\_v7**.

Let’s benchmark it against basic multithreaded version (**v6 vs v7**)

with maxPrime = 1000000000:

Average execution time: **~11s vs ~33s**

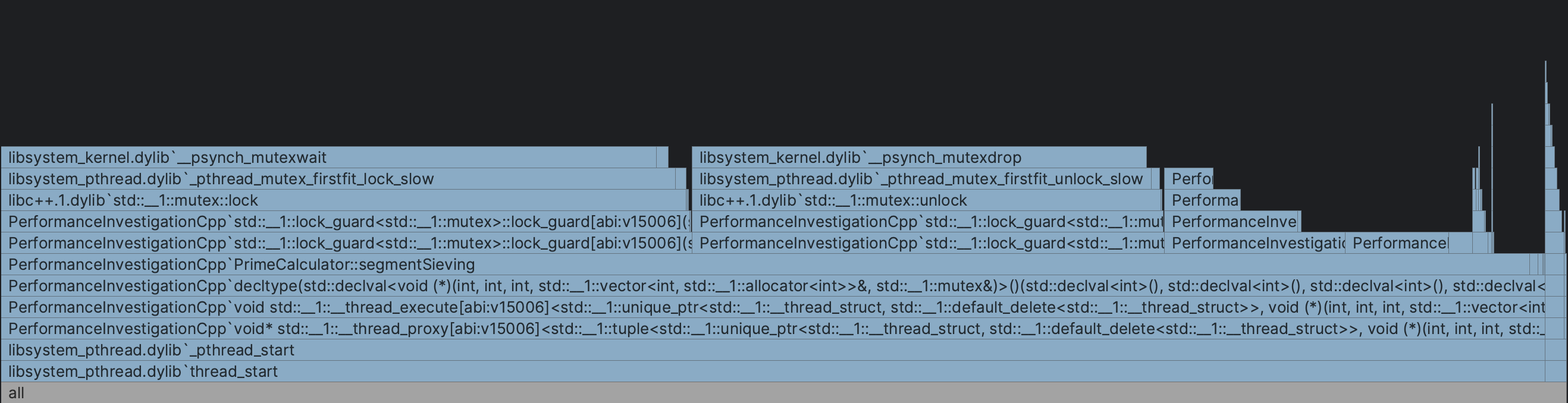
Average memory used: **519Mb vs 321Mb**

It utilizes same amount of memory as single-threaded and is faster than it (33s vs 45s), however it’s significantly slower than the previous multithreaded solution.

A screenshot of a graph

Description automatically generated

Let’s see profiling result to identify a bottleneck:



As expected, **locking introduces significant delay**. However, it can’t be avoided while using **concurrent modifications** on vector.

Sorting is also done at the very end as multiple threads are pushing numbers to the same vector concurrently, but it doesn’t bring any visible performance degradation:

A screenshot of a computer

Description automatically generated

## Bit array (v8)

As neither *vector<int>* nor *vector<bool>* aren’t suitable for concurrent modification without lock, we can’t rely on them and should introduce **custom structure to keep memory efficiency with processing performance** at the same time (without need to lock).

Custom structure will be a set (*vector<uint8\_t>*) of bytes where position of each individual bit represents a number:

private:  
 std::vector<uint8\_t> bits\_;  
};

Each element of a vector will contain 8 bits.

Whenever we need to mark a number as not prime (set bit to 0), it can be done fast by identifying bit position and using bit operators:

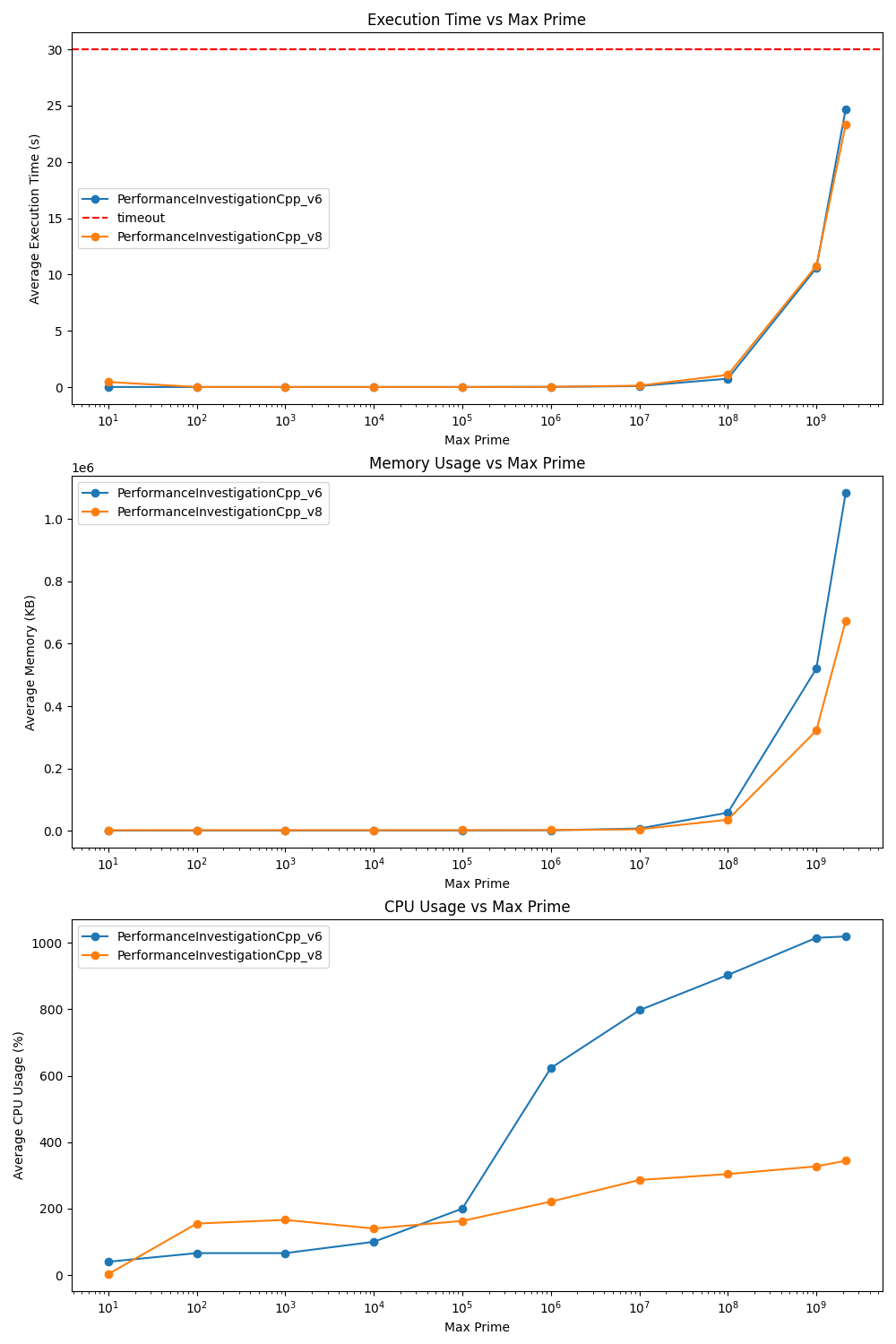
// Set a specific bit to 0  
void clearBit(size\_t index) {  
 size\_t byteIndex = index >> 3;  
 size\_t bitIndex = index & 0x07;  
  
 uint8\_t mask = ~(1 << bitIndex);  
  
 bits\_[byteIndex] &= mask;  
}

Same goes for an operation of getting a bit at position:

// Get the value of a specific bit (0 or 1)  
int getBit(size\_t index) const {  
 size\_t byteIndex = index >> 3;  
 size\_t bitIndex = index & 0x07;  
  
 return (bits\_[byteIndex] >> bitIndex) & 1;  
}

Implementation is labeled as **PerformanceInvestigationCpp\_v8.**

Let’s benchmark it against basic multithreaded solution (**v6 vs v8**):



with maxPrime = 2147483647:

Average execution time: **24.7s vs 23.3s**

Average memory used: **1GB vs 673Mb**

with maxPrime = 1000000000:

Average execution time: **10.6s vs 10.8s**

Average memory used: **519Mb vs 321Mb**

It doesn’t bring any performance improvement comparing to v6, however it consumes much less memory.

**Note:**

Algorithm ensures that each segment is aligned to byte boundaries (concurrent threads are not modifying same bits\_ structures) and that the size of each segment is equalized as much as possible.

For max prime < 100 single-threaded SoE is used.

Segmentation:

for (int i = 0; i < num\_threads; ++i) {  
 segmentStart = segmentEnd + 1;  
  
 // Calculate the end of the segment  
 // Align the end of the segment on a byte boundary, if it's not the last segment  
 segmentEnd += segmentSize;  
 if (i < num\_threads - 1) {  
 segmentEnd = ((segmentEnd + 7) / 8) \* 8 - 1; // Ensure the segment end is a multiple of 8  
 }  
  
 // Make sure we do not go beyond maxPrime in the last segment  
 if (segmentEnd > maxPrime || i == num\_threads - 1) {  
 segmentEnd = maxPrime;  
 }