**Comparing Parallel and Distributed Programming Models:**

**Coursework Stage 2**

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**Section 1 Comparative Sequential Performance**

|  |  |  |  |
| --- | --- | --- | --- |
| Data Set | Go Runtimes (s) | C Runtimes (s) | Erlang Runtimes (s) |
| DS1 | 15.91639141 | 15.21514 | 27.560312 |
| DS2 | 67.95405428 | 65.28168 | 118.87842 |

Figure 1.1: Comparing C, Go and Erlang Sequential Runtimes

The difference in sequential runtimes are almost negligible, however C does consistently achieve a runtime of 500-2500ms faster than Go. This is likely because of Go’s garbage collector (explained in further detail in section 2.4). Erlang on the other hand is much slower than Go or C, which suggests this problem cannot be done efficiently by a functional language. CPU bound problems are also likely slower in Erlang, and the typical solution is to push the problem to another language. Erlang is also designed for reliability and communications, and not tuned for performance (it prioritises low latency over high throughput, which is the opposite for Go and C).

**Section 2 Two Worker Totient Range Erlang Problem: totientrange2Workers**

|  |  |
| --- | --- |
| Ranges | Runtime (s) |
| (1, 4000) | 1.386345 |
| (1, 15000) | 21.413966 |

Figure 1.2: Erlang runtime

**Input: {1, 4000}**

1> c(totientrange2Workers).

{ok,totientrange2Workers}

2> totientrange2Workers:startServer().

true

3> server ! {range, 1, 4000}.

Worker: computing range 1 to 2000

Worker: computing range 2001 to 4000

{range,1,4000}

Server: Received Sum: 1216588

Server: Received Sum: 3647014

Server: Sum of totients: 4863602

Time taken in Secs, MicroSecs 1 386345

Worker: finished

Worker: finished

4>

**Input: {1, 15000}**

1> c(totientrange2Workers).

{ok,totientrange2Workers}

2> totientrange2Workers:startServer().

true

3> server ! {range, 1, 15000}.

Worker: computing range 1 to 7500

Worker: computing range 7501 to 15000

{range,1,15000}

Server: Received Sum: 17099412

Server: Received Sum: 51294904

Server: Sum of totients: 68394316

Time taken in Secs, MicroSecs 21 413966

Worker: finished

Worker: finished

4>

**Section 3 Multi Worker Erlang Totient Range Problem: totientrangeNWorkers**

|  |  |
| --- | --- |
| Ranges + Number of Workers | Runtime (s) |
| (1, 4000, 4) | 0. 864819 |
| (1, 15000, 6) | 9.259248 |

**Input: {1, 4000, 4}**

1> c(totientrangeNWorkers).

{ok,totientrangeNWorkers}

2> totientrangeNWorkers:startServer().

true

3> server ! {range, 1, 4000, 4}.

Worker: started

Worker: started

Worker: started

Worker: started

{range,1,4000,4}

Worker: computing range 1 to 1000

Worker: computing range 1001 to 2000

Worker: computing range 2001 to 3000

Worker: computing range 3001 to 4000

Server: Received Sum: 304192

Worker: finished

Server: Received Sum: 912396

Worker: finished

Server: Received Sum: 1519600

Worker: finished

Server: Received Sum: 2127414

Server: Sum of totients: 4863602

Time taken in Secs, MicroSecs 0 864819

Worker: finished

4>

**Input: {1, 15000, 6}**

1> c(totientrangeNWorkers).

{ok,totientrangeNWorkers}

2> totientrangeNWorkers:startServer().

true

3> server ! {range, 1, 15000, 6}.

Worker: started

Worker: started

Worker: started

Worker: started

Worker: started

Worker: started

{range,1,15000,6}

Worker: computing range 1 to 2500

Worker: computing range 2501 to 5000

Worker: computing range 5001 to 7500

Worker: computing range 7501 to 10000

Worker: computing range 10001 to 12500

Worker: computing range 12501 to 15000

Server: Received Sum: 1899878

Worker: finished

Server: Received Sum: 5700580

Worker: finished

Server: Received Sum: 9498954

Worker: finished

Server: Received Sum: 13298074

Worker: finished

Server: Received Sum: 17100872

Worker: finished

Server: Received Sum: 20895958

Server: Sum of totients: 68394316

Worker: finished

Time taken in Secs, MicroSecs 9 259248

4>

**Section 4 Reliable Multi Worker Erlang Totient Range Erlang Problem: totientrangeNWorkersReliable**

|  |  |
| --- | --- |
| Number of Workers + Number of Victims | Runtime (s) |
| (4, 3) | 14.367165 |
| (8, 6) | 9.82087 |
| (12, 10) | 6.610769 |

**Input: {4, 3}**

1> c(totientrangeNWorkersReliable).

{ok,totientrangeNWorkersReliable}

2> totientrangeNWorkersReliable:testRobust(4,3).

Watcher: Watching Worker worker1

Watcher: Watching Worker worker2

Watcher: Watching Worker worker3

Watcher: Watching Worker worker4

Worker: computing range 1 to 3750

Worker: computing range 3751 to 7500

Worker: computing range 7501 to 11250

Worker: computing range 11251 to 15000

workerChaos killing worker3

Watcher: Watching Worker worker3

Worker: computing range 7501 to 11250

workerChaos killing worker3

Watcher: Watching Worker worker3

Worker: computing range 7501 to 11250

workerChaos killing worker4

Watcher: Watching Worker worker4

Worker: computing range 11251 to 15000

[true,true,true]

Server: Received Sum: 4275174

Server: Received Sum: 12824238

Server: Received Sum: 21371600

Server: Received Sum: 29923304

Server: Sum of totients: 68394316

Time taken in Secs, MicroSecs 14 367165

3>

**Input: {8, 6}**

1> c(totientrangeNWorkersReliable).

{ok,totientrangeNWorkersReliable}

2> totientrangeNWorkersReliable:testRobust(8,6).

Watcher: Watching Worker worker1

Watcher: Watching Worker worker2

Watcher: Watching Worker worker3

Watcher: Watching Worker worker4

Watcher: Watching Worker worker5

Watcher: Watching Worker worker6

Watcher: Watching Worker worker7

Watcher: Watching Worker worker8

Worker: computing range 1 to 1875

Worker: computing range 1876 to 3750

Worker: computing range 3751 to 5625

Worker: computing range 5626 to 7500

Worker: computing range 7501 to 9375

Worker: computing range 9376 to 11250

Worker: computing range 11251 to 13125

Worker: computing range 13126 to 15000

Server: Received Sum: 1069230

workerChaos killing worker4

Watcher: Watching Worker worker4

Worker: computing range 5626 to 7500

workerChaos killing worker5

Watcher: Watching Worker worker5

Worker: computing range 7501 to 9375

Server: Received Sum: 3205944

workerChaos killing worker4

Watcher: Watching Worker worker4

Worker: computing range 5626 to 7500

workerChaos killing worker5

Watcher: Watching Worker worker5

Worker: computing range 7501 to 9375

Server: Received Sum: 5343712

workerChaos killing worker3

workerChaos already dead: worker3

workerChaos killing worker7

Watcher: Watching Worker worker7

Worker: computing range 11251 to 13125

[true,true,true,true,ok,true]

Server: Received Sum: 7480526

Server: Received Sum: 11754000

Server: Received Sum: 9617600

Server: Received Sum: 16029232

Server: Received Sum: 13894072

Server: Sum of totients: 68394316

Time taken in Secs, MicroSecs 9 82087

3>

**Input: {12, 10}**

1> c(totientrangeNWorkersReliable).

{ok,totientrangeNWorkersReliable}

2> totientrangeNWorkersReliable:testRobust(12,10).

Watcher: Watching Worker worker1

Watcher: Watching Worker worker2

Watcher: Watching Worker worker3

Watcher: Watching Worker worker4

Watcher: Watching Worker worker5

Watcher: Watching Worker worker6

Watcher: Watching Worker worker7

Watcher: Watching Worker worker8

Watcher: Watching Worker worker9

Watcher: Watching Worker worker10

Watcher: Watching Worker worker11

Watcher: Watching Worker worker12

Worker: computing range 1 to 1250

Worker: computing range 1251 to 2500

Worker: computing range 2501 to 3750

Worker: computing range 3751 to 5000

Worker: computing range 5001 to 6250

Worker: computing range 6251 to 7500

Worker: computing range 7501 to 8750

Worker: computing range 8751 to 10000

Worker: computing range 10001 to 11250

Worker: computing range 11251 to 12500

Worker: computing range 12501 to 13750

Worker: computing range 13751 to 15000

Server: Received Sum: 475306

workerChaos killing worker12

Watcher: Watching Worker worker12

Worker: computing range 13751 to 15000

Server: Received Sum: 1424572

workerChaos killing worker5

Watcher: Watching Worker worker5

Worker: computing range 5001 to 6250

Server: Received Sum: 2375296

workerChaos killing worker2

workerChaos already dead: worker2

Server: Received Sum: 3325284

workerChaos killing worker7

Watcher: Watching Worker worker7

Worker: computing range 7501 to 8750

Server: Received Sum: 5224570

workerChaos killing worker7

Watcher: Watching Worker worker7

Worker: computing range 7501 to 8750

Server: Received Sum: 4274384

workerChaos killing worker6

workerChaos already dead: worker6

Server: Received Sum: 7122972

workerChaos killing worker8

workerChaos already dead: worker8

Server: Received Sum: 8073526

workerChaos killing worker7

Watcher: Watching Worker worker7

Worker: computing range 7501 to 8750

Server: Received Sum: 9027346

workerChaos killing worker9

workerChaos already dead: worker9

Server: Received Sum: 9970596

workerChaos killing worker9

workerChaos already dead: worker9

[true,true,ok,true,true,ok,ok,true,ok,ok]

Server: Received Sum: 10925362

Server: Received Sum: 6175102

Server: Sum of totients: 68394316

Time taken in Secs, MicroSecs 6 610769

2>

**Section 5 Comparative Parallel Performance Measurements**

**Section 5.1 Runtimes**

|  |  |  |  |
| --- | --- | --- | --- |
| Threads | Go | OpenMP | Erlang |
| Sequential | 15.91639141 | 15.21514 | 27.560312 |
| 1 | 16.35538 | 15.171 | 27.64324 |
| 2 | 9.066147 | 7.592 | 21.84232 |
| 4 | 4.740579 | 3.973 | 12.90331 |
| 8 | 2.461242 | 2.06 | 7.674511 |
| 12 | 1.647562 | 1.376 | 5.155668 |
| 16 | 1.264213 | 1.041 | 3.84141 |
| 24 | 0.972845 | 0.795 | 2.711483 |
| 32 | 0.80053 | 0.649 | 2.310508 |
| 48 | 0.801696 | 0.651 | 2.15471 |
| 64 | 0.8027 | 0.653 | 1.877161 |

Figure 2.1: Comparing C+OpenMP, Go and Erlang Parallel Runtimes for DS1

Figure 2.2: Comparing C+OpenMP, Go and Erlang Parallel Runtimes for DS1, plotted

|  |  |  |  |
| --- | --- | --- | --- |
| Threads | Go | OpenMP | Erlang |
| Sequential | 67.95405428 | 65.28168 | 118.87842 |
| 1 | 69.91227 | 65.085 | 117.7675 |
| 2 | 38.36811 | 32.562 | 89.97294 |
| 4 | 20.0648 | 17.042 | 56.27548 |
| 8 | 10.40659 | 8.839 | 31.34113 |
| 12 | 6.941679 | 5.894 | 21.14163 |
| 16 | 5.227036 | 4.43 | 16.74621 |
| 24 | 4.097904 | 3.399 | 12.12922 |
| 32 | 3.376901 | 2.76 | 9.570727 |
| 48 | 3.374534 | 2.761 | 7.924492 |
| 64 | 3.377058 | 2.76 | 7.197233 |

Figure 2.3: Comparing C+OpenMP and Go Parallel Runtimes for DS2

Figure 2.4: Comparing C+OpenMP, Go and Erlang Parallel Runtimes for DS2, plotted

|  |  |  |  |
| --- | --- | --- | --- |
| Threads | Go | OpenMP | Erlang |
| 8 | 43.90842 | 37.725 | 129.5024 |
| 16 | 22.00349 | 18.89 | 69.37089 |
| 32 | 14.206 | 11.741 | 42.37109 |
| 64 | 14.20571 | 11.741 | 32.1379 |

Figure 2.5: Comparing C+OpenMP and Go Parallel Runtimes for DS3

Figure 2.6: Comparing C+OpenMP, Go and Erlang Parallel Runtimes for DS3, plotted

**Section 5.2 Speedups**

Figure 2.7: Comparing C+OpenMP, Go and Erlang Absolute Speedups for DS1

Figure 2.8: Comparing C+OpenMP, Go and Erlang Absolute Speedups for DS2

Figure 2.9: Comparing C+OpenMP, Go and Erlang Absolute Speedups for DS3

**Section 5.3**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Language | Sequential Runtime (s) | Best Parallel Runtime (s) | Best Speedup | No. Threads |
| **DS1** |  |  |  |  |
| Go | 15.91639 | 0.878035 | 19.93095 | 32 |
| C+OpenMP | 15.22271 | 0.822 | 23.44398 | 32 |
| Erlang | 27.56031 | 1.877161 | 14.68191 | 64 |
| **DS2** |  |  |  |  |
| Go | 67.95405428 | 3.376901 | 20.1232 | 32 |
| C+OpenMP | 65.28168 | 2.76 | 23.65278 | 32 |
| Erlang | 118.8784 | 7.197233 | 16.51724 | 64 |
| **DS3** |  |  |  |  |
| Go | 294.5406 | 14.206 | 20.73353 | 32 |
| C+OpenMP | 278.581 | 11.741 | 23.7272 | 32 |
| Erlang | 495.9446 | 32.1379 | 15.43177 | 64 |

Figure 2.10: Comparing C+OpenMP, Go and Erlang Parallel Runtimes and Speedups for all data sets

**Section 5.4**

Looking at the graphs, the runtimes for both Go and C+OpenMP seem very similar, with C+OpenMP being slightly faster on average in all cases. Looking at figure 2.10 however, we can see that C+OpenMP clearly outperforms Go for best parallel runtimes, which is more apparent in DS2 and DS3. This is even true for sequential runtimes.

Looking at the numbers for speedups, the results for DS1, DS2 and DS3 are very similar, with 32 threads providing ~20 times speedup on average for Go and ~24 times speedup on average for C+OpenMP. C+OpenMP consistently shows a significantly higher speedup than Go, which is immediately obvious starting threads>1. The graphs are mostly linear and inversely proportional (runtime is almost exactly half when number of threads are doubled), which suggests the parallelism is ideal, until it plateaus at 32 threads. By running omp\_get\_max\_threads I found that 32 was the maximum number of cores in the gpg-nodes cluster (There are 32 CPUs) so this makes sense, as increasing the number of threads at this point would result in CPUs needing to context switch to give time to multiple threads.

It makes sense that C+OpenMP would be faster than Go because Go includes a garbage collector that will increase runtime, especially when handling a lot of data in a loop.

Erlang is noticeably slower than both C+OpenMP and Go. This is likely because those languages are designed to increase throughput, and hence perform better on CPU bound tasks (such as summing totients). Erlang on the other hand priorities low latency over high throughput, and hence is understandably slower.

The Erlang code could be tweaked to improve its speedup (just like how C+OpenMP and Go have been tuned). This would mean it’s runtime would converge at 32 threads just like the other two languages. But since the code is currently not tuned, using more workers will decrease the runtime, as more workers equals smaller chunks, and the program execution time is capped by the final worker (since it has the largest numbers to sum).

**Section 6 Programming Model Comparison**

The Go and OpenMP models each have their advantages. Goroutines have very little overhead (minimum size 8kb) and fast startup times, and hence you can run many more of them (millions, if desired) than traditional threads. Goroutines are also simpler to manage, as mutexes are avoided and they will scale according to the complexity of the work. Goroutines are best used if development time and memory usage is a concern. I also found goroutines easier to grasp than OpenMP, as it is written in a traditional coding style. OpenMP with its one-line pragma comments was a little more unusual, so for programmers unfamiliar with parallelism I would recommend goroutines.

However, if peak performance is desired, then C+OpenMP should be used. It can be seen from my previous results in the totientRange application that C+OpenMP outperforms Go. The pragma paradigm in OpenMP is much simpler and easier to setup than pthreads and provides powerful tools for reductions. There are also scheduling styles (e.g. guided) that can adapt to the work being done and improve the efficiency of the runtimes.

The biggest challenge I had was deciding how to split the dataset into correctly sized chunks for the Go program. This was especially difficult as the count of goroutines would often not be a factor of the dataset (e.g. 60000 / 64) and due to Go’s integer division always rounding down this could cause some numbers to be skipped/processed twice. I first experimented with converting the integers to floats and rounding explicitly, but this was messy and didn’t guarantee the final upper number would be correct (e.g. could be rounded up to 60001). I then decided to use integer division to divide the dataset into a variable named chunk\_size (threads\*chunk\_size < dataset because integer division rounds down). Each goroutine would process work of chunk\_size, and the last goroutine would handle whatever was remaining. This guarantees that every number is processed and splits the data into almost even chunks.

However, I ultimately changed this to a round-robin style where goroutines are spawned and only deal with one number from a channel containing all numbers to be processed. This proved to be significantly faster than the original method (as seen in Appendix B).

My biggest challenge with OpenMP was figuring out how to tune it to run faster (I gathered that my runtimes weren’t ideal from the original speedup graphs, as the results were not inversely proportional). This is discussed further in Appendix A.

**Appendix A C+OpenMP TotientRange Program**

**Code:**

// TotientRangePar.c - Parallel Euler Totient Function (C Version)

// compile: gcc -Wall -O2 -o TotientRangePar TotientRangePar.c

// run:     ./TotientRangePar lower\_num upper\_num num\_threads(optional)

// Author: Max Kirker Burton 2260452b     13/11/19

// This program calculates the sum of the totients between a lower and an

// upper limit using C longs, and can be run with several Goroutines either set as an argument or

// as an environment variable

// It is based on earlier work by:

// Phil Trinder, Nathan Charles, Hans-Wolfgang Loidl and Colin Runciman

// The comments provide (executable) Haskell specifications of the functions

#include <stdio.h>

#include <omp.h>

#include <sys/time.h>

// hcf x 0 = x

// hcf x y = hcf y (rem x y)

long hcf(long x, long y)

{

  long t;

  while (y != 0) {

    t = x % y;

    x = y;

    y = t;

  }

  return x;

}

// relprime x y = hcf x y == 1

int relprime(long x, long y)

{

  return hcf(x, y) == 1;

}

// euler n = length (filter (relprime n) [1 .. n-1])

long euler(long n)

{

  long length, i;

  length = 0;

  for (i = 1; i < n; i++)

    if (relprime(n, i))

      length += 1;

  return length;

}

// sumTotient lower upper = sum (map euler [lower, lower+1 .. upper])

long sumTotient(long lower, long upper, int n\_threads)

{

  long sum, i;

  sum = 0;

  #pragma omp parallel for schedule(guided) reduction(+: sum) num\_threads(n\_threads)

    for (i = lower; i <= upper; i++)

      sum += euler(i);

  return sum;

}

int main(int argc, char \*\* argv)

{

  long lower, upper;

  int num\_threads = omp\_get\_num\_threads();

  float msec;

  struct timeval start, stop;

  if (argc < 3) {

    printf("fewer than 2 arguments\n");

    return 1;

  }

  sscanf(argv[1], "%ld", &lower);

  sscanf(argv[2], "%ld", &upper);

  if (argc == 4){

    sscanf(argv[3], "%d", &num\_threads);

  }

  gettimeofday(&start, NULL);

  printf("C: Sum of Totients  between [%ld..%ld] is %ld\n",

         lower, upper, sumTotient(lower, upper, num\_threads));

  gettimeofday(&stop, NULL);

  if (stop.tv\_usec < start.tv\_usec) {

    stop.tv\_usec += 1000000;

    stop.tv\_sec--;

  }

  msec = 1000 \* (stop.tv\_sec - start.tv\_sec) +

                (stop.tv\_usec - start.tv\_usec) / 1000;

  printf("%f\n", msec);  // Rename to elapsed time:

  return 0;

}

Uses a Pragma-based Shared Memory paradigm (e.g. using shared variables and reduction for loops).

I used only one pragma in the final code, but I experimented with using nested pragmas, with another pragma inside of the euler function. I thought that I could parallelise the calculations of relprimes and tried assigning threads in different ways (e.g. 2 threads for the euler function, and all other threads for the sumTotient function) but all these methods resulted in similar or slower runtimes than simply using one pragma.

What did improve runtimes noticeably was changing the schedule parameter of the pragma. By default, it takes the “static” argument, which splits chunks into even sizes. Because my original Go program did something similar, I tried to find a way to improve the runtimes in OpenMP. I found that setting schedule to “guided” which starts chunk\_size high then decreases it for later threads. This reduces runtime since higher numbers take longer to compute (explained in Appendix B).

The runtimes stop increasing after 32 threads, because the gpgnode cluster “only” has 32 CPUs. I tried adding multiple parallel sections to see if that could increase performance with threads > CPUs but all methods resulted in the same runtimes.

Figure 3.1: Comparing C+OpenMP runtime performance before and after tuning with DS2

**Appendix B Go TotientRange Program**

**Code:**

// totientRangePar.go - Parallel Euler Totient Function (Go Version)

// compile: go build

// run:     totientRangePar lower\_num upper\_num num\_threads

// Author: Max Kirker Burton 2260452b   07/11/2019

// This program calculates the sum of the totients between a lower and an

// upper limit, and can be run with several Goroutines

//

// Each function has an executable Haskell specification

//

// It is based on earlier work by: Greg Michaelson, Patrick Maier, Phil Trinder,

// Nathan Charles, Hans-Wolfgang Loidl and Colin Runciman

package main

import (

    "fmt"

    "os"

    "runtime"

    "strconv"

    "sync"

    "time"

)

// Compute the Highest Common Factor, hcf of two numbers x and y

//

// hcf x 0 = x

// hcf x y = hcf y (rem x y)

func hcf(x, y int64) int64 {

    var t int64

    for y != 0 {

        t = x % y

        x = y

        y = t

    }

    return x

}

// relprime determines whether two numbers x and y are relatively prime

//

// relprime x y = hcf x y == 1

func relprime(x, y int64) bool {

    return hcf(x, y) == 1

}

// sequential euler function

func euler\_seq(n int64) int64 {

    var length, i int64

    length = 0

    for i = 1; i < n; i++ {

        if relprime(n, i) {

            length++

        }

    }

    return length

}

// euler(n) computes the Euler totient function, i.e. counts the number of

// positive integers up to n that are relatively prime to n

//

// euler n = length (filter (relprime n) [1 .. n-1])

func euler(value int64, ch chan int64, wg \*sync.WaitGroup) {

    var length, i int64

    length = 0

    for i = 1; i < value; i++ {

        if relprime(i, value) {

            length++

        }

    }

    ch <- length

    wg.Done()

}

// sumTotient lower upper sums the Euler totient values for all numbers

// between "lower" and "upper".

//

// sumTotient lower upper = sum (map euler [lower, lower+1 .. upper])

func sumTotient(lower, upper, cores int64) int64 {

    var sum, i int64

    sum = 0

    // If more than 1 core is being used, utilise parallelism, otherwise run sequentially (with 1 core in this program, sequential is faster)

    if cores > 1 {

        chIn := make(chan int64, 100000)

        chSum := make(chan int64, 100000)

        var goroutines int64 = cores

        runtime.GOMAXPROCS(int(goroutines))

        var wg sync.WaitGroup // using a waitgroup to close the channel after all threads are completed

        // add all numbers in range of lower and upper to a channel

        for i = lower; i <= upper; i++ {

            chIn <- i

        }

        close(chIn)

        // repeatedly spawn goroutines to take 1 entry in chIn and calculate its totient, which is then sent onto channel chSum

        for value := range chIn {

            wg.Add(1)

            go euler(value, chSum, &wg)

        }

        wg.Wait()

        close(chSum)

        // sum all values in channel chSum

        for value := range chSum {

            sum += value

        }

    } else {

        for i = lower; i <= upper; i++ {

            sum = sum + euler\_seq(i)

        }

    }

    return sum

}

func main() {

    var lower, upper, cores int64

    var err error

    // Read and validate lower and upper arguments

    if len(os.Args) < 3 {

        panic(fmt.Sprintf("Usage: must provide lower and upper range limits and number of cores as arguments"))

    }

    if lower, err = strconv.ParseInt(os.Args[1], 10, 64); err != nil {

        panic(fmt.Sprintf("Can't parse first argument"))

    }

    if upper, err = strconv.ParseInt(os.Args[2], 10, 64); err != nil {

        panic(fmt.Sprintf("Can't parse second argument"))

    }

    if cores, err = strconv.ParseInt(os.Args[3], 10, 64); err != nil {

        panic(fmt.Sprintf("Can't parse third argument"))

    }

    // Record start time

    start := time.Now()

    // Compute and output sum of totients

    fmt.Println("Sum of Totients between", lower, "and", upper, "is", sumTotient(lower, upper, cores))

    // Record the elapsed time

    t := time.Now()

    elapsed := t.Sub(start)

    fmt.Println("Elapsed time", elapsed)

}

Uses a Message Passing paradigm (e.g. creating a channel with send and receives).

Originally my program didn’t provide a large reduction in runtime because of how it separated work into chunks. My program split work into even chunks and calculating the sum of totients in a range 1-1000 would take much less time than 1000-2000, as more relative primes need to be calculated. Since I used a waitgroup to ensure all goroutines are completed before the sum of the channel is calculated, the program runtime will be the runtime of the slowest goroutine. This becomes less of a problem at higher counts of goroutines as the chunks are smaller. I thought of ways to have different sized chunks, with larger sized chunks for the earlier numbers (e.g. for a range of 2000 and 2 threads, split into chunks of 1-1500 and 1500-2000), but this proved difficult to implement, and would require heavy tuning to be optimal.

Instead, I changed my program to disregard chunk\_size and instead spawn an arbitrary number of goroutines that only compute 1 number each, until all numbers are processed. This works as at the start of the program, all numbers are sent to a separate channel, and the goroutines receive one number from the channel to compute. This significantly improved runtimes compared to my original method, and reaches ideal parallelism based on absolute speedups (double the threads = half the runtime)

Figure 3.2: Comparing Go runtime performance before and after tuning with DS2

However, as you can see from the graph above, this method also increased the runtime for 1 thread. To improve that, I added an if statement that would run the program sequentially if only 1 core was set by runtime.GOMAXPROCS. The result is my final Go program.

**Appendix C Erlang totientrange2Workers Program**

-module(totientrange2Workers).

-export([hcf/2,

   relprime/2,

   euler/1,

     startServer/0,

     server/4,

     totientWorker/0

  ]).

%% totientrange2Workers.erl - Parellel Euler Totient Function (Erlang Version)

%% compile from the shell: >c(totientrange2Workers).

%% run from the shell:     >totientrange2Workers:startServer().

%%                         >server ! {range, x, y}.

%% Max Kirker Burton 2260452b

%% This program calculates the sum of the totients between a lower and an

%% upper limit. It is based on earlier work by: Nathan Charles,

%% Hans-Wolfgang Loidl and Colin Runciman

%% The comments provide (executable) Haskell specifications of the functions

%% hcf x 0 = x

%% hcf x y = hcf y (rem x y)

hcf(X,0) -> X;

hcf(X,Y) -> hcf(Y,X rem Y).

%% relprime x y = hcf x y == 1

relprime(X,Y) ->

  V = hcf(X,Y),

  if

    V == 1

      -> true;

    true

      -> false

  end.

%%euler n = length (filter (relprime n) (mkList n))

euler(N) ->

  RelprimeN = fun(Y) -> relprime(N,Y) end,

  length (lists:filter(RelprimeN,(lists:seq(1,N)))).

%% Take completion timestamp, and print elapsed time

printElapsed(S,US) ->

  {\_, S2, US2} = os:timestamp(),

                       %% Adjust Seconds if completion Microsecs > start Microsecs

  if

    US2-US < 0 ->

      S3 = S2-1,

      US3 = US2+1000000;

    true ->

      S3 = S2,

      US3 = US2

  end,

  io:format("Time taken in Secs, MicroSecs ~p ~p~n",[S3-S,US3-US]).

%% We pass in these variables to keep their value over successive receive calls

server(Total, Count, S, US) ->

    receive

        %% Check if all workers have finished, otherwise continue

        {finished, Sum} when Count < 1 ->

            io:format("Server: Received Sum: ~p~n", [Sum]),

            server(Total+Sum, Count+1, S, US);

        {finished, Sum} ->

            io:format("Server: Received Sum: ~p~n", [Sum]),

            io:format("Server: Sum of totients: ~p~n", [Total+Sum]),

            worker1 ! finished,

            worker2 ! finished,

            printElapsed(S,US);

        {range, Lower, Upper} ->

            {\_, Sec, USec} = os:timestamp(),

            register(worker1, spawn(totientrange2Workers, totientWorker, [])),

            worker1 ! {range, Lower, trunc(Upper/2)},

            register(worker2, spawn(totientrange2Workers, totientWorker, [])),

            worker2 ! {range, trunc(Upper/2 + 1), Upper},

            server(Total, Count, Sec, USec)

    end.

%% calculate sumTotient on a subset of the dataset

totientWorker() ->

    receive

        finished ->

            io:format("Worker: finished~n", []);

        {range, Lower, Upper} ->

            io:format("Worker: computing range ~p to ~p~n", [Lower, Upper]),

            Sum = lists:sum(lists:map(fun euler/1,lists:seq(Lower, Upper))),

            server ! {finished, Sum},

            totientWorker()

    end.

%%start the server process

startServer() ->

    register(server, spawn(totientrange2Workers, server, [0, 0, 0, 0])).

**Appendix D Erlang totientrangeNWorkers Program**

-module(totientrangeNWorkers).

-export([hcf/2,

     relprime/2,

     euler/1,

     startServer/0,

     workerName/1,

     registerWorker/3,

     server/7,

     totientWorker/0

    ]).

%% totientrangeNWorkers.erl - Parallel Euler Totient Function (Erlang Version)

%% compile from the shell: >c(totientrangeNWorkers).

%% run from the shell:     >totientrangeNWorkers:startServer().

%%                         >server ! {range, x, y, N}.

%% Max Kirker Burton 2260452b

%% This program calculates the sum of the totients between a lower and an

%% upper limit. It is based on earlier work by: Nathan Charles,

%% Hans-Wolfgang Loidl and Colin Runciman

%% The comments provide (executable) Haskell specifications of the functions

%% hcf x 0 = x

%% hcf x y = hcf y (rem x y)

hcf(X,0) -> X;

hcf(X,Y) -> hcf(Y,X rem Y).

%% relprime x y = hcf x y == 1

relprime(X,Y) ->

  V = hcf(X,Y),

  if

    V == 1

      -> true;

    true

      -> false

  end.

%%euler n = length (filter (relprime n) (mkList n))

euler(N) ->

  RelprimeN = fun(Y) -> relprime(N,Y) end,

  length (lists:filter(RelprimeN,(lists:seq(1,N)))).

%% Take completion timestamp, and print elapsed time

printElapsed(S,US) ->

  {\_, S2, US2} = os:timestamp(),

                       %% Adjust Seconds if completion Microsecs > start Microsecs

  if

    US2-US < 0 ->

      S3 = S2-1,

      US3 = US2+1000000;

    true ->

      S3 = S2,

      US3 = US2

  end,

  io:format("Time taken in Secs, MicroSecs ~p ~p~n",[S3-S,US3-US]).

workerName(Num) ->

    list\_to\_atom( "worker" ++ integer\_to\_list( Num )).

workerNames([]) ->

    0;

workerNames(Range) ->

    [Head | Rest] = Range,

    WorkerName = workerName(Head),

    server ! {names, WorkerName, Head},

    workerNames(Rest).

registerWorker(WorkerNum, Lower, Upper) ->

    register(WorkerNum, spawn(totientrangeNWorkers, totientWorker, [])),

    WorkerNum ! {range, Lower, Upper}.

%% We pass in these variables to keep their value over successive receive calls

server(Total, Count, Lower, Upper, N\_workers, S, US) ->

    receive

        %% Check if all workers have finished, otherwise continue

        {finished, Sum, Pid} when Count < (N\_workers-1) ->

            io:format("Server: Received Sum: ~p~n", [Sum]),

            Pid ! finished,

            server(Total+Sum, Count+1, Lower, Upper, N\_workers, S, US);

        {finished, Sum, Pid} ->

            io:format("Server: Received Sum: ~p~n", [Sum]),

            io:format("Server: Sum of totients: ~p~n", [Total+Sum]),

            Pid ! finished,

            printElapsed(S,US);

        %% if this is the first worker, start from Lower

        {names, WorkerNum, Num} when Num == 1 ->

            LocalLower = Lower,

            LocalUpper = Lower + trunc(((Upper - Lower)/N\_workers) \* (Num)),

            registerWorker(WorkerNum, LocalLower, LocalUpper),

            server(Total, Count, Lower, Upper, N\_workers, S, US);

        %% if this is the last worker, set the Upper limit

        {names, WorkerNum, Num} when Num == N\_workers ->

            LocalLower = 1 + Lower + trunc(((Upper - Lower)/N\_workers) \* (Num - 1)),

            LocalUpper = Upper,

            registerWorker(WorkerNum, LocalLower, LocalUpper),

            server(Total, Count, Lower, Upper, N\_workers, S, US);

        %% otherwise calculate an equal range

        {names, WorkerNum, Num} ->

            LocalLower = 1 + Lower + trunc(((Upper - Lower)/N\_workers) \* (Num - 1)),

            LocalUpper = Lower + trunc(((Upper - Lower)/N\_workers) \* (Num)),

            registerWorker(WorkerNum, LocalLower, LocalUpper),

            server(Total, Count, Lower, Upper, N\_workers, S, US);

        {range, L, U, N} ->

            {\_, Sec, USec} = os:timestamp(),

            Range = lists:seq(1, N),

            workerNames(Range),

            server(Total, Count, L, U, N, Sec, USec)

    end.

%% calculate sumTotient on a subset of the dataset

totientWorker() ->

    receive

        finished ->

            io:format("Worker: finished~n", []);

        {range, Lower, Upper} ->

            io:format("Worker: started~n", []),

            io:format("Worker: computing range ~p to ~p~n", [Lower, Upper]),

            Sum = lists:sum(lists:map(fun euler/1,lists:seq(Lower, Upper))),

            server ! {finished, Sum, self()},

            totientWorker()

    end.

%%start the server process

startServer() ->

    register(server, spawn(totientrangeNWorkers, server, [0, 0, 0, 0, 0, 0, 0])).

**Appendix E Erlang totientrangeNWorkersReliable Program**

-module(totientrangeNWorkersReliable).

-export([hcf/2,

     relprime/2,

     euler/1,

     startServer/0,

     workerNames/1,

     workerName/1,

     registerWorker/3,

     server/7,

     totientWorker/0,

     watcher/3,

     workerChaos/2,

     testRobust/2

    ]).

%% totientrangeNWorkersReliable.erl - Parallel & Reliable Euler Totient Function (Erlang Version)

%% compile from the shell: >c(totientrangeNWorkersReliable).

%% run from the shell:     >totientrangeNWorkersReliable:startServer().

%%                         >server ! {range, x, y, N}.

%% Max Kirker Burton 2260452b

%% This program calculates the sum of the totients between a lower and an

%% upper limit. It is based on earlier work by: Nathan Charles,

%% Hans-Wolfgang Loidl and Colin Runciman

%% The comments provide (executable) Haskell specifications of the functions

%% hcf x 0 = x

%% hcf x y = hcf y (rem x y)

hcf(X,0) -> X;

hcf(X,Y) -> hcf(Y,X rem Y).

%% relprime x y = hcf x y == 1

relprime(X,Y) ->

  V = hcf(X,Y),

  if

    V == 1

      -> true;

    true

      -> false

  end.

%%euler n = length (filter (relprime n) (mkList n))

euler(N) ->

  RelprimeN = fun(Y) -> relprime(N,Y) end,

  length (lists:filter(RelprimeN,(lists:seq(1,N)))).

%% Take completion timestamp, and print elapsed time

printElapsed(S,US) ->

  {\_, S2, US2} = os:timestamp(),

                       %% Adjust Seconds if completion Microsecs > start Microsecs

  if

    US2-US < 0 ->

      S3 = S2-1,

      US3 = US2+1000000;

    true ->

      S3 = S2,

      US3 = US2

  end,

  io:format("Time taken in Secs, MicroSecs ~p ~p~n",[S3-S,US3-US]).

%% Generate a worker name with a given number

workerName(Num) ->

    list\_to\_atom( "worker" ++ integer\_to\_list( Num )).

%% Recursively generate worker names from a sequential list

workerNames([]) ->

    0;

workerNames(Range) ->

    [Head | Rest] = Range,

    WorkerName = workerName(Head),

    server ! {names, WorkerName, Head},

    workerNames(Rest).

%% register a worker, then pass a message to it

registerWorker(WorkerNum, Lower, Upper) ->

    register(WorkerNum, spawn\_link(totientrangeNWorkersReliable, totientWorker, [])),

    WorkerNum ! {range, Lower, Upper}.

%% We pass in these variables to keep their value over successive receive calls

server(Total, Count, Lower, Upper, N\_workers, S, US) ->

    receive

        %% Check if all workers have finished, otherwise continue

        {finished, Sum, Pid} when Count < (N\_workers-1) ->

            io:format("Server: Received Sum: ~p~n", [Sum]),

            Pid ! finished,

            server(Total+Sum, Count+1, Lower, Upper, N\_workers, S, US);

        {finished, Sum, Pid} ->

            io:format("Server: Received Sum: ~p~n", [Sum]),

            io:format("Server: Sum of totients: ~p~n", [Total+Sum]),

            Pid ! finished,

            printElapsed(S,US);

        %% if this is the first worker, start from Lower

        {names, WorkerNum, Num} when Num == 1 ->

            LocalLower = Lower,

            LocalUpper = Lower + trunc(((Upper - Lower)/N\_workers) \* (Num)),

            spawn(totientrangeNWorkersReliable, watcher, [WorkerNum, LocalLower, LocalUpper]),

            server(Total, Count, Lower, Upper, N\_workers, S, US);

        %% if this is the last worker, set the Upper limit

        {names, WorkerNum, Num} when Num == N\_workers ->

            LocalLower = 1 + Lower + trunc(((Upper - Lower)/N\_workers) \* (Num - 1)),

            LocalUpper = Upper,

            spawn(totientrangeNWorkersReliable, watcher, [WorkerNum, LocalLower, LocalUpper]),

            server(Total, Count, Lower, Upper, N\_workers, S, US);

        %% otherwise calculate an equal range

        {names, WorkerNum, Num} ->

            LocalLower = 1 + Lower + trunc(((Upper - Lower)/N\_workers) \* (Num - 1)),

            LocalUpper = Lower + trunc(((Upper - Lower)/N\_workers) \* (Num)),

            spawn(totientrangeNWorkersReliable, watcher, [WorkerNum, LocalLower, LocalUpper]),

            server(Total, Count, Lower, Upper, N\_workers, S, US);

        {range, L, U, N} ->

            {\_, Sec, USec} = os:timestamp(),

            Range = lists:seq(1, N),

            workerNames(Range),

            server(Total, Count, L, U, N, Sec, USec)

    end.

%% If an exit message is received and the worker had not completed, trap it and respawn the linked worker

watcher(WorkerNum, LocalLower, LocalUpper) ->

    process\_flag(trap\_exit, true),

    registerWorker(WorkerNum, LocalLower, LocalUpper),

    io:format("Watcher: Watching Worker ~p~n", [WorkerNum]),

    receive

        Msg ->

            {\_Message, \_Pid, Reason} = Msg,

            if

                Reason == chaos ->

                    watcher(WorkerNum, LocalLower, LocalUpper);

                true ->

                    0

            end

    end.

%% calculate sumTotient on a subset of the dataset

totientWorker() ->

    receive

        finished ->

            0;

        {range, Lower, Upper} ->

            io:format("Worker: computing range ~p to ~p~n", [Lower, Upper]),

            Sum = lists:sum(lists:map(fun euler/1,lists:seq(Lower, Upper))),

            server ! {finished, Sum, self()},

            totientWorker()

    end.

workerChaos(NVictims, NWorkers) ->

    lists:map(

        fun( \_ ) ->

            timer:sleep(500),   %% Sleep for .5s

                                %% Choose a random victim

            WorkerNum = rand:uniform(NWorkers),

            io:format("workerChaos killing ~p~n",

                      [workerName(WorkerNum)]),

            WorkerPid = whereis(workerName(WorkerNum)),

            if %% Check if victim is alive

                WorkerPid == undefined ->

                    io:format("workerChaos already dead: ~p~n",

                              [workerName(WorkerNum)]);

                true -> %% Kill Kill Kill

                    exit(whereis(workerName(WorkerNum)),chaos)

                end

            end,

            lists:seq( 1, NVictims ) ).

testRobust(NWorkers, NVictims) ->

    ServerPid = whereis(server),

    if %% Is server already running?

        ServerPid == undefined ->

            startServer();

        true ->

            ok

    end,

    server ! {range, 1, 15000, NWorkers},

    workerChaos(NVictims,NWorkers).

%%start the server process

startServer() ->

    register(server, spawn(totientrangeNWorkersReliable, server, [0, 0, 0, 0, 0, 0, 0])).