

Analysis of Parallel Incremental/Decremental Graph Colouring on GPU

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **Analysis of Parallel Incremental/Decremental Graph Colouring on GPU**, submitted by **Mohammed Shamil**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Colour Quality; Compressed Sparse Row Representation; Incremental Graph Colouring; GPGPU; Graph Colouring; Incremental Graph Colouring; NP-hard; NVIDIA CUDA; One Time Propagation; Parallel Computing; Parallel Graph Algorithms; Vertex Colouring; Wave Propagation.

This work revolves around parallel graph colouring. We try to run parallel colouring algorithms on GPUs. Our work explores different parallel graph colouring algorithms. We implement some of these algorithms on NVIDIA CUDA platform to work with NVIDIA GPUs. We offer two GPU based approaches for parallel incremental graph colouring, namely, 2-Thread Incremental Colouring and Many Thread Incremental Colouring. We also suggest two approaches for parallel decremental graph colouring, namely, 2-Thread Decremental Colouring and Many Thread Decremental Colouring. We then try to improve the colour quality using two types of propagation techniques, One Time Propagation and Wave Propagation. Some of our approaches work really well in terms of both runtime and colour quality produced/maintained.

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ABBREVIATIONS

IITM	Indian Institute of Technology, Madras
GPU	Graphics Processing Unit
GPGPU	General-Purpose computing on Graphics Processing Units
CSR	Compressed Sparse Row
VIS	Vertex Independent Set

NOTATION

V	Set of vertices
E	Set of edges
n	No. of vertices
m	No. of edges

CHAPTER 1

INTRODUCTION

Graphs are a well studied and widely used data structure in the field of algorithms, programming and computing. There are a lot of interesting applications of graphs and various algorithms are built on top of the graph data structure. One of the most famous and well studied graph problems is that of graph colouring. There are a lot of different versions of graph colouring problem of which the most common ones are that of vertex colouring and edge colouring. The problem is seemingly simple, to allocate a colour to every vertex/edge of a graph so that adjacent vertices/edges don't share the same colour minimizing the number of colours used. Graph colouring is a very important and yet very challenging graph problem with ongoing active research. Graph colouring finds application in a varied range of problems including various scheduling problems like job scheduling on distributed computing systems, register allocation in compilers, pattern matching problems and solving Sudoku boards.

Though the problem is seemingly simple, it is computationally hard. The graph colouring problem we are exploring in this work, that of vertex colouring, is an NP-hard problem. The sequential approaches like greedy colouring are simply not fast enough whereas advanced approximate/randomized solutions either produce colourings of bad colour quality or aren't fast enough. Thus came the parallel approaches to Graph Colouring. Most of the parallel versions of Graph Colouring algorithms were designed with either multi-core CPUs or heavy duty supercomputers in mind. With the advent of General-Purpose computing on GPUs (GPGPU), we have access to cheap heavy multi-threaded parallel computing power. Our work is based on parallel computing on NVIDIA GPUs using CUDA programming language.

We explore different parallel graph colouring algorithms on NVIDIA GPUs in this work and try to adapt them to support addition of edges, called incremental graph colouring, and deletion of edges, called decremental graph colouring. In the first section, we explore different parallel graph algorithms and adapt a couple of them, one

based on *speculation* and *conflict resolution* and the other on *Vertex Independent Sets*, to work on NVIDIA GPUs. In the following sections, we adapt the GPU parallel colouring algorithm to support additions and deletions of edges. In the incremental part, we explore different methods to maximize parallelization while colouring newly added edges and use propagation to improve overall colour quality. In the decremental part, we explore different options to either process the vertices, on which the deleted edges were incident, on the go or to process them together and use propagation to propagate the information across the graph improving the colour quality.

1.1 Outline and Contributions

A background of the problem in hand, graph colouring, is discussed in Chapter 2. It also discusses the need for parallelization, incremental and decremental approach and why we want to parallelize the solution for GPUs. In Chapter 3, we discuss work already done related to parallel graph colouring on multi-core CPUs as well as GPUs. We classify the algorithms broadly into two categories and discuss many algorithms. We also present our approach for parallel graph colouring. In Chapter 4, we discuss the need for incremental graph colouring and how we deal with a growing graph. We then present two algorithms to deal with incremental graph colouring. We also introduce the idea of propagation in this chapter. In Chapter 5, we discuss the need for decremental graph colouring and how we deal with a shrinking graph. We then present two algorithms to deal with decremental graph colouring. We present two approaches for propagation of colouring information across the graph. In Chapter 6, we evaluate our implementations using a set of test graphs. In Chapter 7, we conclude and give pointers for future work in the area.

This work's biggest contribution is in introducing parallel incremental and decremental graph colouring. There are no other works done regarding the same as far the author understands even on multi-core CPUs, let alone on GPUs. Some of our approaches for parallel incremental and decremental colouring works well in terms of runtime and colour quality.

CHAPTER 2

Background

2.1 Graphs and Graph Algorithms

Graphs are really important mathematical concepts and in the area of computing, their various forms are widely used as data structures to aid various algorithms. Graphs are commonly used to denote relations between different entities and hence is a very important and integral part of many algorithms. On a practical level, we deal with graphs in the order of billions of nodes and edges on a daily basis. Especially with the advent of social networks and big data, a lot of active research is ongoing in the analysis and understanding of large graphs.

Many problems in the area of Computer Science, Biology etc. are solved with the help of algorithms which are based on graphs. Shortest path problem, Travelling Salesman Problem (TSP), network flow problems, vertex cover problem, graph colouring etc. are important graph-based problems with many practical applications in the real world. Our work is on Graph Colouring which is one of the most famous and well studied graph problems.

2.2 Vertex Colouring

Graph Colouring problem entails *colouring/labeling* of the vertices/edges of a graph based on some set of conditions which are to be satisfied (Jensen and Toft, 2011). In other words, it's a problem in which you allocate a colour/number to every vertex/edge of a graph such that a set of constraints are satisfied. There are different versions of Graph Colouring and the one which is of interest to us is that of Vertex Colouring.

2.2.1 Classical Vertex Colouring Problem

Vertex Colouring is the most basic version of Graph Colouring and other Graph Colouring problems can be presented as a Vertex Colouring problem. In its classical form, Vertex Colouring is:

Vertex Colouring: Colouring all the vertices of a graph such that adjacent vertices have different colours. That is, there shouldn't be an edge where the incident vertices share the same colour.

There are other forms of vertex colouring where additional conditions than the one given above need to be considered while colouring. In our work, we are concerned only with the classical form of vertex colouring which hereinafter interchangeably referred to simply as Graph Colouring. An example of Vertex Colouring is given in Figure 2.1. Vertex v_4 is coloured initially with blue (b) colour. Then, its neighbours, vertices v_3 , v_5 , v_6 and v_2 are coloured with red (r) colour. As v_1 has v_2 and v_3 also as its edges, it can't take colour red (r). So, it's coloured with a new colour, green (g).

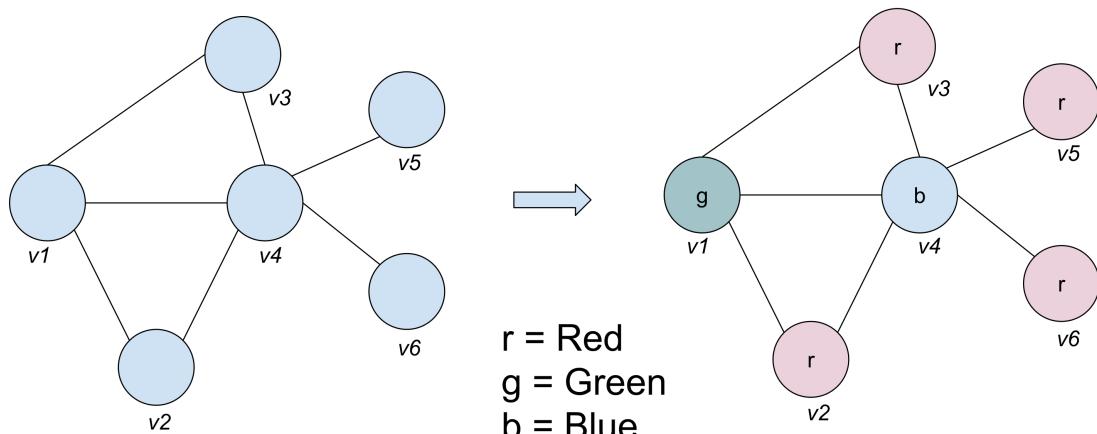


Figure 2.1: Vertex Colouring of a given graph using 3 colours.

2.2.2 Chromatic Number $\chi(G)$

A graph G is said to k -colourable, if G can be coloured using k colours. For example, from the *Four Colour Theorem* (Appel and Haken, 1977; Thomas, 1998; Wilson, 2014), we have that all planar graphs are 4-colourable. Also, all bipartite graphs are 2-colourable.

The *Chromatic Number* of a graph G , denoted by $\chi(G)$, is the minimum number of colours required to colour a graph. That is, $\chi(G)$, is the minimum value of all k for which the graph G is k -colourable.

For example, $\chi(G)$ of the graph given in Figure 2.1 is 3. Also, it follows that if a graph is k -colourable, we have:

$$\chi(G) \leq k$$

2.2.3 Colour Quality

Colour Quality is a term used to denote how good the colouring done by a particular algorithm is. Colour Quality is said to be better for an algorithm if the number of colours used by the algorithm to colour a graph G is closer to its Chromatic Number, $\chi(G)$.

Mathematically, Colour Quality of a colouring is said to be better as the fraction,

$$\frac{\text{No. of colours used by the algorithm}}{\chi(G)}$$

is closer to 1.

2.2.4 Complexity

Graph Colouring is a computationally complex problem. To decide if a Graph can be coloured using k colours, is an NP-complete problem. Whereas, finding the Chromatic Number of a graph ($\chi(G)$) is proved to be an NP-hard problem.

There exist many algorithms like Greedy Colouring, approximation algorithms and randomized algorithms. There also exist polynomial time algorithms for some specific family of graphs. For example, it can be decided if a graph can be coloured using 2 colours by checking if it is a bipartite graph. This can be done in polynomial time using Breadth First Search (BFS).

2.2.5 Applications

Graph Colouring problem, which started as a map colouring problem (four colour theorem), finds many important real applications including but not limited to:

- Scheduling problems like job scheduling across multiple nodes in a distributed computing environment (Leighton, 1979)
- Register allocation problem during compilation (Briggs *et al.*, 2004)
- Solving Sudoku (Herzberg and Murty, 2007)
- Applications on biological networks like Protein-Protein Interaction (PPI) Networks (Khor, 2009)
- Scheduling cell-transmissions in an ATM switch (Lakshman *et al.*, 1994)

2.3 Parallelization

2.3.1 Frequency Scaling

Moore's law, which observes that the number of transistors present in an integrated circuit approximately doubles every two years, still stands valid. Figure 2.2 shows Moore's Law in action. Processors, and hence computers, have grown faster and faster over years. More and more transistors meant the processors could run faster, at a faster frequency. Processors with better and better clock speeds were introduced every year since the 1980s until around 2004 when instead of single core processors running at faster clocks or higher clock speeds, multi-core processors started rolling out.

Microprocessor Transistor Counts 1971-2011 & Moore's Law

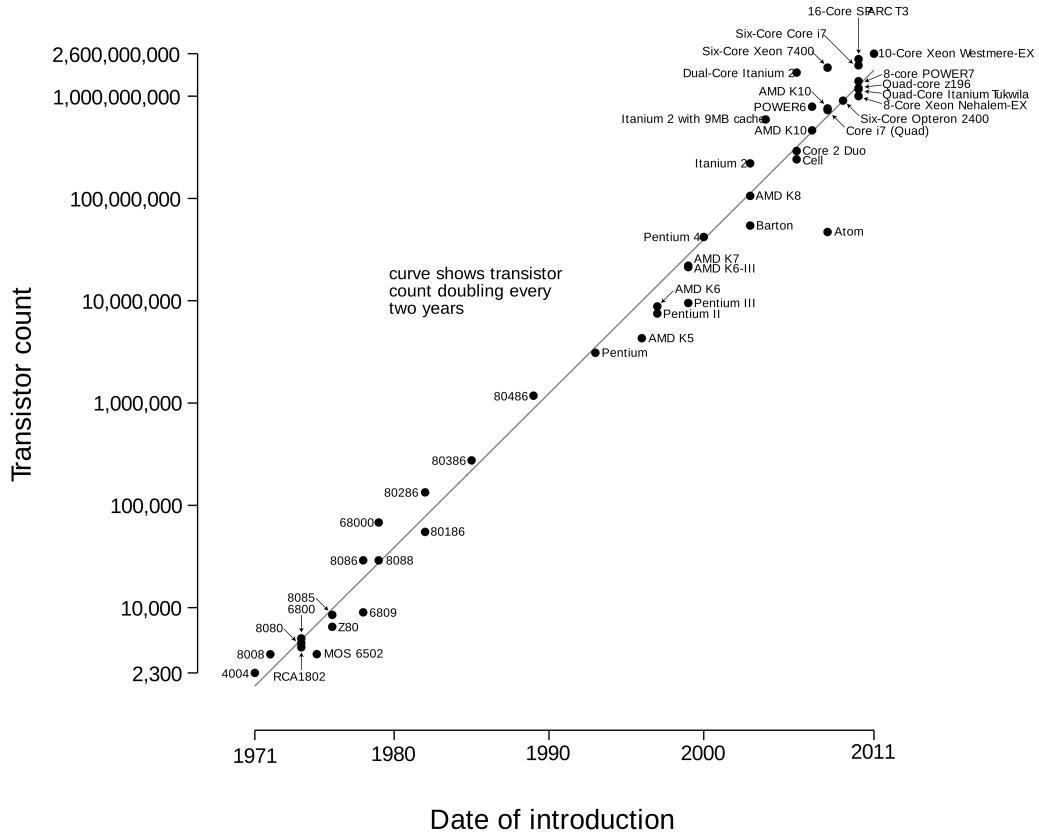


Figure 2.2: Graph showing Moore's Law in action, from Wikipedia, the free encyclopedia (2016). Each data point is a processor.

2.3.2 Why Parallelization?

Around 2004, Intel and other processor manufacturing companies came to realize that frequency scaling was not practical any more. The increase in frequency meant an increase in power consumption which in turn meant an increase in heat generation. Thus it was no longer practical to increase the clock speeds of processors. Rather, they started making processors with the same clock speeds, but with multiple cores. Since then the computer architecture industry held fast to the paradigm of multi-core processors. This, in the case of *Intel*, is indicated in the Figure 2.3.

Parallelization enables us to run programs faster by splitting the work across different cores of a processor which are ideally run in parallel. In an ideal setup, with n cores, we should see a speed up of n , which means the running time will become $1/n^{th}$

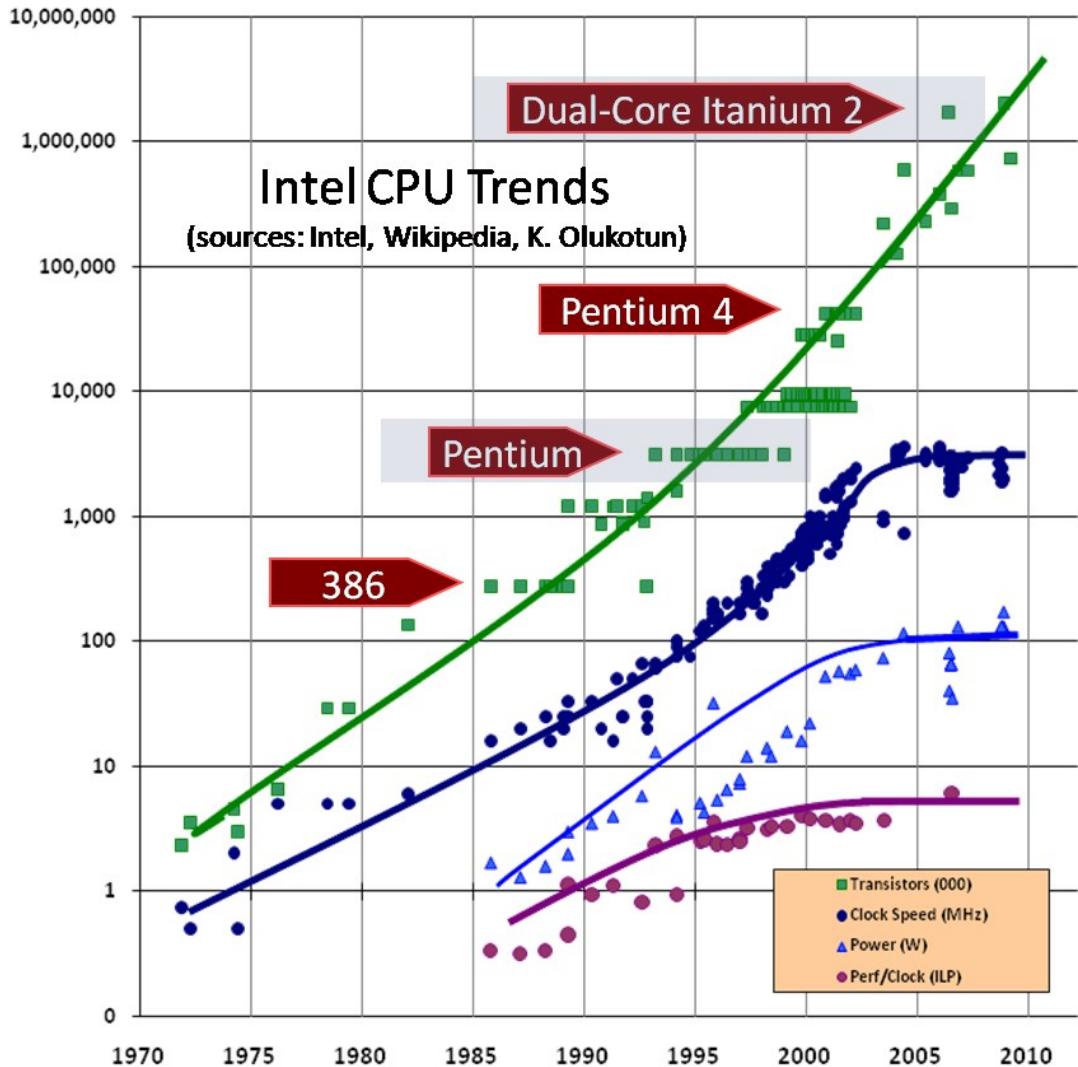


Figure 2.3: Intel's transition from single core processors to multi-core processors around 2004-2005, from Sutter (2005).

compared to the running time when run on a single core processor. Though we rarely really reach this ideal speedup, as stated by Amdahl's law (Amdahl, 1967) etc., we still achieve significant speed ups.

2.3.3 Parallelization of Graph Colouring

Since the computer architecture industry made a shift to the multi-core paradigm, there had to be a shift in programming paradigm to support the newly available parallelism. Almost all the algorithms, programs etc. were designed and developed to run sequentially on a single core processor. Things have changed recently as more and more algo-

rithms and programs are redesigned and redeveloped to make use of the newly available parallel hardware.

As discussed earlier, Graph Colouring is a computationally complex problem. It is NP-hard to solve. Also, the approximation algorithms for colouring a graph with n vertices are also NP-hard within $n^{1-\epsilon}$ for all $\epsilon > 0$ (Zuckerman, 2006). The existing solutions are either slow or are fast but produce bad colour quality. Also, practical graphs these days are very large with billions of vertices and edges. So, since the advent of parallel programming paradigms, there have been efforts to parallelize this well-celebrated graph problem though most of them were meant specifically for distributed computing setups (Bozdag *et al.*, 2008, 2005) and supercomputers (ÇAtalyüRek *et al.*, 2012). In our work, we focus on parallel graph colouring which can be run on parallel hardware available locally. Especially with the advent of GPGPUs, cheap massive parallelism is at a hand's reach.

2.4 GPGPU

In the domain of parallel programs and applications, one big deterrent was that the number of processor cores available for parallelism was small. Most of the multi-core processors have 32 cores at the maximum. Only supercomputers had a very high number of cores and they came at a price.

2.4.1 Why GPUs?

Graphics Processing Units, GPUs, have been using parallelism since their birth. They have almost always been very accessible to the normal public as they are much cheaper than supercomputers. They also came with thousands of cores. But they were specialized for graphics related operations. Then came the paradigm of GPGPU, General Purpose computing on Graphics Processing Units. With that, it was now possible to run regular operations and not just graphics related operations on the GPU. GPGPU brought with it easy, cheap access to massive parallelism.

2.4.2 NVIDIA CUDA

NVIDIA, one of the biggest players in the GPUs market, introduced its famous parallel computing platform, CUDA, in 2006, thus enabling easy GPU based parallel acceleration. In our work, we use CUDA C to parallelize graph colouring. CUDA lets us harness the power of thousands of cores in the CUDA enabled NVIDIA GPUs.

Architecture

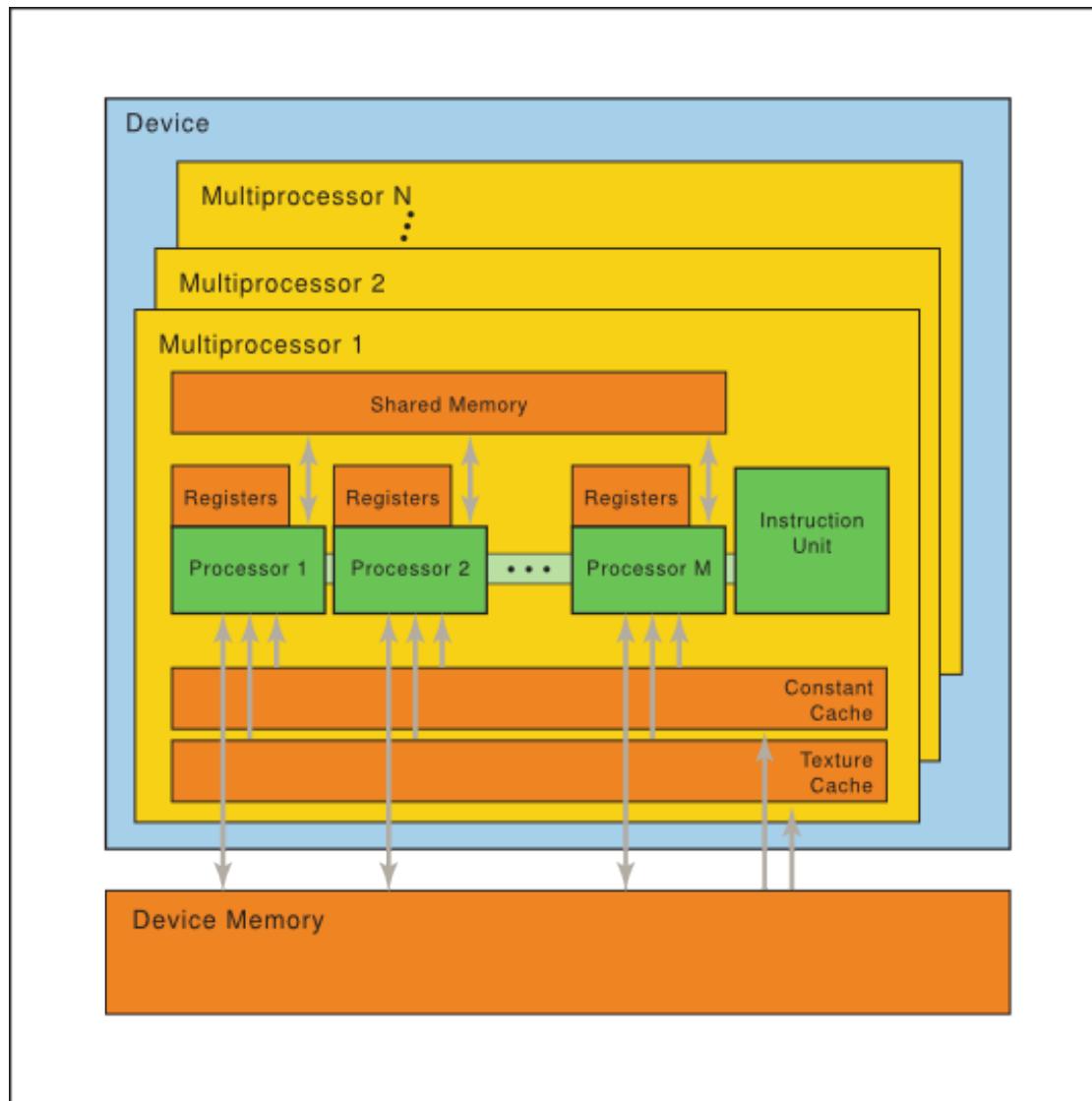


Figure 2.4: NVIDIA GPU hardware model, from NVIDIA Corporation (2016a).

In an NVIDIA GPU, as shown in the Figure 2.4, there are multiple streaming multi-processors, SMs, and each of these multi processors have thousands of cores/processors in it. Functions to be executed on the GPU are called Kernels and Kernels, once invoked,

spawn the required number of threads as blocks of threads which are then executed across SMs. All threads in a block have access to the shared memory inside the SM in which that block is executed.

2.4.3 Challenges

Though, GPUs let us access thousands of threads easily, it comes with a cost (Lee *et al.*, 2010). In discrete GPUs like the NVIDIA GPUs used in our work, GPU memory and CPU memory are mutually exclusive. So, we have to first copy all the data which are to be processed by the GPU threads to the GPU before invoking the kernels. As the communication between the CPU and the GPU is enabled through the PCI-Express Bus, which is not super fast with bit rates at around 5 Gbits/sec, and the fact that while transferring data, we force the CPU to wait for the GPU, there is a cost for transferring data between the CPU and the GPU, the so called *memory latency*. This data transferring cost is one of the biggest overheads in GPU computing (Hovland, 2008). So, as a GPU programmer, one must try to reduce data transfer between the CPU and the GPU. Also, GPUs are not yet ready to do everything that a normal CPU does.

2.5 Incremental/Decremental

As we discussed already, Graph Colouring is a very important problem on graphs. We have so many practical applications for the same. But most of the practical graphs are dynamic in nature. Vertices and edges are added and deleted often. But the number of these changes is very small compared to the size of the full graph. So, it follows that it is not wise to rerun the graph colouring algorithm on the entire graph every time some vertices/edges are added or deleted. Our work on Incremental/Decremental graph colouring tries to take care of precisely the same.

In our work, we try to re-colour only the relevant parts of the graphs on addition/deletion of edges instead of re-colouring the entire graph. We consider only addition/deletion of edges as deletion of a vertex is considered as the deletion of all edges incident on that vertex. We consider different implications of Incremental/Decremental

colouring such as the amount of time we save versus maintaining/improving the colour quality.

CHAPTER 3

PARALLEL GRAPH COLOURING

We have established why we are interested in the paradigm of parallel programming and why we want to parallelize graph colouring.

3.1 Graph Colouring Problem

The problem we are concerned with is that of *1-distance Vertex Colouring* or simply, *Vertex Colouring*.

Parallel 1-distance Vertex Colouring: Colouring all V vertices of a graph $G(V,E)$ in parallel, such that vertices at a distance of 1 edge, adjacent vertices, don't share the same colour.

3.2 Related Work

Graph Colouring is a well studied problem and there have been so many works on the same over years. But most of them were regarding sequentially solving the problem using various paradigms, like that of semi-definite programming, integer programming etc.

Recently there have been some parallel approaches to the same, but most of them like the works by Bozdag *et al.* (2008, 2005) and ÇAtalyüRek *et al.* (2012) are based on distributed computing setups, supercomputers or other expensive hardware. There have been only a few work done regarding parallel graph colouring on GPUs like Grosset *et al.* (2011), Naumov *et al.* (2015) and Sengupta (2014) and none regarding Incremental/Decremental versions as far as the author understands.

3.3 Broad Classification of Parallel Graph Colouring Algorithms

As we are dealing with NVIDIA GPUs, we are concerning ourselves with algorithms pertaining to shared memory architectures only. Most of the parallel colouring algorithms based on shared memory architecture can be broadly classified into two of the following categories:

3.3.1 Vertex Independent Sets and Colouring

Algorithms falling under this category work in two phases:

1. Vertex Independent Sets: Find VIS
2. Colouring: Colour the VIS found without conflicts

This set of algorithms relies upon finding Vertex Independent Sets of vertices and colouring them in parallel. Most of the earlier parallel algorithms developed for graph colouring were based on this idea.

Vertex Independent Set (VIS): A vertex independent set of a graph G is a set of vertices who don't have any edges amongst each other.

Mathematically, γ is a valid Vertex Independent Set of a graph $G(V, E)$ if

$$\gamma \subseteq V$$

and

$$\forall v_i, v_j \in \gamma, e \in E, \text{ if } v_i \text{ is incident on } e, \text{ then } \forall j \neq i, v_j \text{ is not incident on } e.$$

The idea is pretty straightforward. These are iterative algorithms where, in each iteration, you find a Vertex Independent Set of the given graph and colour all of the vertices in that VIS with a single colour. The process is continued with different colours until there are no more vertices to be coloured. Both the steps, finding VIS and colouring the

vertices in that VIS, can be done in parallel. This category of algorithms roughly works as explained in Algorithm 1.

Phase 1 of the Algorithm 1 is done in Line 5 where we find a VIS of the graph. This step can be parallelized as discussed later in Algorithm 4 and Algorithm 9. Phase 2 of the algorithm, colouring the newly found VIS of the graph, is done in Lines 6 and 7. In Line 8, we remove the vertices which were coloured in the current iteration from the graph. We then choose a new colour for the next iteration as in Line 9 and return to Line 4. The algorithm iterates until there are no more vertices to be processed.

Algorithm 1 Vertex Independent Sets and Colouring

```

1: procedure VISPARALLELGRAPHCOLOURING( $G(V,E)$ )
2:   Initialization                                 $\triangleright$  Initialize all the variables and other data structures
3:    $currentColour \leftarrow 1$ 
4:   while  $V \neq \emptyset$  do                       $\triangleright$  Run until all the vertices are coloured
5:      $\gamma \leftarrow a\ VIS\ of\ G(V,E)$             $\triangleright$  VIS can be found in parallel
6:     for each  $v \in \gamma$  do                  $\triangleright$  This loop can be run in parallel
7:        $colour[v] \leftarrow currentColour$ 
8:      $V \leftarrow V \setminus \gamma$ 
9:      $currentColour \leftarrow currentColour + 1$ 
```

3.3.2 Speculation and Conflict Resolution

Algorithms falling under this category work in two phases:

1. Speculation: Colour the graph based on some pre-existing knowledge possibly generating conflicts
2. Conflict Resolution: Resolve the conflicts possibly generated in the first phase

The first category of algorithms relied upon finding Vertex Independent Sets iteratively so that we could colour the vertices in the VIS found in each step without any conflict. This second category of algorithms instead lets us commit some mistakes, or rather conflicts, in our colouring. That is, it saves us from finding a VIS in each step, instead we colour the graph using some pre-existing knowledge like existing colouring of the graph or some structural information regarding the graph.

So, in the first phase, instead of finding a VIS and colouring just the vertices in that VIS without any conflict in an iteration, we speculate the colours of the entire

graph with some pre-existing knowledge and possibly commit conflicts. The possible conflicts inflicted in this first phase are rectified in the second phase in which we find the conflicts and resolve them. For practical reasons, the first phase is done in parallel and the second phase is done sequentially or partially in parallel. This category of algorithms roughly works as explained in Algorithm 2.

Phase 1 of the Algorithm 2, *speculation*, is done in Lines 4 and 5. We are not explicitly mentioning how this speculation is done as there are many possible ways to speculate the colours. Some of the ways to speculate colours are discussed in Algorithms 6, 7 and 8. Conflicts are then resolved, mostly using some form of Greedy Colouring, in the phase 2 of the algorithm as in Lines 7, 8 and 9. Line 8 assumes conflicts are already detected. This *Conflicts Detection* part can be parallelized.

Algorithm 2 Speculation and Conflict Resolution

```

1: procedure SPECCRPARALLELGRAPHCOLOURING( $G(V, E)$ )
2:   Initialization
3:   speculation:
4:     for each  $v \in V$  do                                 $\triangleright$  Can be done in parallel
5:        $colour[v] \leftarrow \text{speculatedColour}$ 
6:   conflict resolution:                                 $\triangleright$  Done serially or partially in parallel
7:     for each  $v \in V$  do
8:       if  $colour[v]$  has a conflict then       $\triangleright$  Conflicts can be found in parallel
9:          $colour[v] \leftarrow$  a new colour which resolves the conflict       $\triangleright$  Greedy

```

3.4 Algorithms

In this section, we will discuss some of the existing graph colouring algorithms belonging to both categories, Vertex Independent Set and Colouring and Speculation and Conflict Resolution, as discussed in the previous section. We also concern ourselves with only those parallel algorithms which are scalable. Hence algorithms like Parallel First Fit graph colouring (Zaman, 2011), the parallel version of the First Fit colouring heuristic (GyÅarfÅs and Lehel, 1988), are not considered.

3.4.1 Sequential Greedy Graph Colouring

We start with discussing a sequential graph colouring algorithm, one of the easiest, the Greedy Colouring algorithm. Many other algorithms, including many parallel graph colouring algorithms, are based on greedy colouring.

In Greedy Colouring, you choose each vertex of the graph and assign it the smallest colour number available which is not currently in use by one of its adjacent vertices. This is described in Algorithm 3. As is evident, the colour quality produced by Greedy Colouring can be arbitrary. In other words, the colour quality produced will depend on the order in which vertices are processed by the algorithm.

Algorithm 3 proceeds by choosing each vertex in some order, Line 3, and colouring them in a greedy fashion. The order in which the vertices are chosen is very important in deciding the colour quality. There are many ways to decide the order in which the vertices are processed and we assume one of the ways is chosen. We then check the vertex's neighbourhood, Line 4, and if a neighbour is already coloured, Line 5, we mark its colour as unavailable as in Line 6. Now, for the vertex, we check which is the smallest colour less than or equal to $\Delta + 1$ (Greedy Colouring uses at most $\Delta + 1$ colours, where Δ is the maximum degree among all the vertices of the graph) that is available. This is done in Lines 7 and 8. Then finally we colour the vertex with this new colour as in Line 9. The `availableColours[]` array is reinitialized to all *TRUE* values in Line 11 before the algorithm goes back to Line 3.

Greedy Colouring can produce a colour quality of $\chi(G)$ for atleast one ordering of the vertices. But, on an average, this heuristic performs far from optimal. But the greedy colouring algorithm gives us an upper bound on the number of colours that it uses. The colouring produced uses at most $\Delta + 1$ colours, where Δ is the maximum degree among all the vertices of the graph. As the order in which the vertices are processed is very important, there have been many approaches suggested over the years which on an average produce a better colour quality. One of them is the so called Welsh-Powell Algorithm (Welsh and Powell, 1967), in which we process the vertices in the order of their degrees.

Algorithm 3 Sequential Greedy Graph Colouring

```
1: procedure GREEDYCOLOURING(G(V,E))
2:   Initialization
3:   for each  $v \in V$  do
4:     for each  $u \in V$  adjacent to  $v$  do
5:       if  $\text{colour}[u] \neq 0$  then
6:          $\text{availableColours}[\text{colour}[u]] \leftarrow \text{FALSE}$ 
7:       for  $i$  from 1 to  $\Delta + 1$  do
8:         if  $\text{availableColours}[i]$  is TRUE then
9:            $\text{colour}[v] \leftarrow i$ 
10:          break
11:   Re-initialize availableColours[] array to TRUE
```

3.4.2 Parallel VIS Based Colouring

Here, we consider an algorithm belonging to the category covered by Algorithm 1. As discussed earlier, this involves finding Vertex Independent Sets and colouring those VIS in parallel. Now, we will introduce two more terms:

Maximal Vertex Independent Set: A Vertex Independent Set, γ , is said to be a Maximal Vertex Independent Set of a graph $G(V, E)$ if,

$$\forall \eta, \gamma \not\subset \eta$$

where η is a valid Vertex Independent Set of $G(V, E)$. It follows that there can be multiple Maximal Vertex Independent Sets.

Maximum Vertex Independent Set: A Vertex Independent Set, γ , is said to be a Maximum Vertex Independent Set of a graph $G(V, E)$, if γ is a Maximal Independent Set and,

$$|\gamma| = \max_{\eta} |\eta|$$

where η is a Maximal Vertex Independent Set of $G(V, E)$. It follows that there can be multiple Maximum Vertex Independent Sets.

Ideally, we want to find a Maximum Vertex Independent Set of the graph in each iteration and colour those vertices in parallel. But finding Maximum Independent Sets

of a graph is an NP-Complete problem. So, we have to instead go for non-optimal solutions. We consider the parallel algorithm suggested by Luby (1985) which finds Maximal Vertex Independent Sets of a graph in parallel.

In Luby's algorithm, every node is first assigned with some random number. Now, in each iteration, the random number assigned to each node is compared to its neighbours, done in parallel, to see if it is the local maximum, in which case, that node is added to a set S . At the end of each iteration, S , is a Maximal Vertex Independent Set of the graph $G(V,E)$ and the vertices in S are removed from V . The set S is emptied before a new iteration. This is a very simple algorithm to generate Maximal Vertex Independent Sets of a graph as depicted in Algorithm 4.

We assume random numbers are generated and stored in `randomNumber[]` as in Line 2. We consider all the vertices of the graph in parallel as in Line 4. In Lines 6 to 9, we check if the current vertex is indeed a local maxima and if so, it is added to the Maximal Set S which is then returned after all threads are synchronized.

Algorithm 4 Maximal Vertex Independent Set

```

1: procedure MAXIMALSET( $G(V,E)$ )
2:   Initialization                                 $\triangleright$  randomNumber[] is initialized only once
3:    $S \leftarrow \emptyset$ 
4:   for each  $v \in V$  do                       $\triangleright$  Done in parallel
5:      $S \leftarrow S \cup \{v\}$ 
6:     for each  $u \in V$  such that  $u$  is adjacent to  $v$  do
7:       if  $randomNumber[u] \geq randomNumber[v]$  then
8:          $S \leftarrow S \setminus v$ 
9:         break
10:    Synchronize
11:    return  $S$ 

```

Jones and Plassmann (1993) introduced a parallel graph colouring algorithm based on Luby's Maximal Vertex Independent Set algorithm. By their algorithm, in each iteration, we find a Maximal Vertex Independent Set of the graph using Luby's algorithm and then colour all the vertices in the set found, in parallel, using a single colour. Each iteration uses a different colour. We do this iteratively until all the vertices of the graph are coloured. This is explained in Algorithm 5.

In each iteration until all the vertices are processed (Line 6), we find a Maximal VIS in Line 7 and colour them as in Lines 8 and 9. We then choose a new colour for the next

iteration as in Line 10, remove the vertices that were coloured in the current iteration as in Line 12 and return to Line 6. The algorithm iterates until there are no more vertices to be processed.

Algorithm 5 Jones-Plassmann-Luby Parallel Colouring Heuristic

```

1: procedure PARALLELCOLOURING( $G(V,E)$ )
2:   Initialization
3:    $n \leftarrow 0$ 
4:    $currentColour \leftarrow 1$ 
5:    $graphSize \leftarrow |V|$ 
6:   while  $n \neq graphSize$  do                                 $\triangleright$  Or  $V \neq \phi$ 
7:      $S \leftarrow \text{MaximalSet}(V, E)$ 
8:     for each  $v \in S$  do                                $\triangleright$  Done in parallel
9:        $colour[v] \leftarrow currentColour$ 
10:       $currentColour \leftarrow currentColour + 1$ 
11:       $n \leftarrow n + |S|$ 
12:       $V \leftarrow V \setminus S$ 

```

3.4.3 Parallel Conflict Resolution Based Colouring

Here, we consider two algorithms belonging to the category covered by Algorithm 2. It involves two phases, the first colouring phase with potential conflicts and the second phase where these conflicts are resolved either sequentially or partially in parallel.

3.4.3.1 Conflict Resolution: Sequential

Here, we discuss an algorithm presented by Gebremedhin and Manne (2000) which instead of finding Maximal Vertex Independent Sets in each iteration, relaxes the condition, so that we find and colour sets which are not really independent sets in each iteration possibly incurring conflicts. These conflicts are then identified in parallel in phase 2. In phase 3, we re-colour the vertices identified with conflicts sequentially.

This involves an initial graph partitioning phase, during which we partition the graph into n parts, where n is the number of processors/cores we have. Each processor/core takes up each partition and then colours them using some sequential colouring method. At the end of this phase 1, we thus have a colouring with possible conflicts at the partition boundaries. In phase 2, we identify these conflicts in parallel. In phase 3,

we re-colour these vertices with conflicts sequentially. The scheme is presented in Algorithm 6.

In Line 3, the graph $G(V, E)$ is partitioned into n partitions V_1 to V_n . In Lines 5 and 6, each thread colours its partition using some sequential colouring algorithm. In Lines 8 to 12, the set of vertices with colouring conflicts, `conflictSet`, is found. In Lines 14 and 15, the conflicts are resolved by recolouring the vertices in `conflictSet` using some sequential colouring algorithm.

Algorithm 6 Partitioning, Speculation and Conflict Resolution

```

1: procedure PARTITIONCOLOURING( $G(V,E)$ )
2:   Initialization
3:    $G(V,E)$  is partitioned into  $n$  partitions  $V_1$  to  $V_n$      $\triangleright$  Each of  $n$  threads gets one
4:   Phase 1 (Partition Colouring):
5:   for each  $v \in V_i$  do                                 $\triangleright$  Done in parallel by  $n$  threads
6:      $colour[v] \leftarrow$  A colour by some sequential colouring algorithm
7:   Phase 2 (Conflict Detection):
8:    $conflictSet \leftarrow \emptyset$ 
9:   for each  $v \in V$  do                                 $\triangleright$  Done in parallel
10:    for each  $u \in V$  such that  $u$  and  $v$  are adjacent do
11:      if  $colour[v] = colour[u]$  then
12:         $conflictSet \leftarrow conflictSet \cup \{min(v, u)\}$ 
13:   Phase 3 (Conflict Resolution):
14:   for each  $v \in conflictSet$  do
15:      $colour[v] \leftarrow$  A colour by some sequential colouring algorithm

```

3.4.3.2 Conflict Resolution: Partially in Parallel

We also have a GPU based graph partitioning, speculation and conflict resolution algorithm by Grosset *et al.* (2011). The graph is first partitioned in the CPU. The partitions are then coloured using some sequential colouring heuristics on the GPU. At the end of this phase, the potential conflicts are found in parallel at the boundary vertices. If the number of conflicts detected is above some threshold, in the next iteration, the graph partitions are recoloured in parallel and newly generated conflicts are detected. This process is continued until the total number of conflicts is below some threshold. Then the conflicts are resolved sequentially. This is depicted in Algorithm 7.

In Line 4, the graph $G(V, E)$ is partitioned into n partitions V_1 to V_n in the CPU. In Lines 6 and 7, each thread colours its partition using some sequential colouring

algorithm in the GPU. In Lines 9 to 13, the set of vertices with colouring conflicts, `conflictSet`, is found in the GPU. We then check if the number of conflicts is below some threshold in Line 14 in which case we proceed straight to the *Conflict Resolution* phase which happens in the CPU. If the number of conflicts is not below the threshold, we try to repeat the parallel colouring of the partitions and subsequent conflict resolution process on the GPU as in Line 16 by going back to the GPU *Partition Colouring* phase at Line 5. In Lines 18 and 19, the conflicts are resolved by recolouring the vertices in `conflictSet` using some sequential colouring algorithm in the CPU.

Algorithm 7 GPU: Partitioning, Speculation and Conflict Resolution

```

1: procedure PARTITIONCOLOURING( $G(V,E)$ )
2:   Initialization
3:   CPU:
4:      $G(V,E)$  is partitioned into  $n$  partitions  $V_1$  to  $V_n$      $\triangleright$  Each of  $n$  threads gets one
5:   GPU (Partition Colouring):
6:     for each  $v \in V_i$  do                                 $\triangleright$  Done in parallel by  $n$  threads
7:        $colour[v] \leftarrow$  A colour by some sequential colouring algorithm
8:   GPU (Conflict Detection):
9:      $conflictSet \leftarrow \emptyset$ 
10:    for each  $v \in V$  do                                $\triangleright$  Done in parallel
11:      for each  $u \in V$  such that  $u$  and  $v$  are adjacent do
12:        if  $colour[v] = colour[u]$  then
13:           $conflictSet \leftarrow conflictSet \cup \{min(v, u)\}$ 
14:        if  $|conflictSet| < threshold$  then
15:          goto CPU (Conflict Resolution)
16:        goto GPU (Partition Colouring)
17:   CPU (Conflict Resolution):
18:     for each  $v \in conflictSet$  do
19:        $colour[v] \leftarrow$  A colour by some sequential colouring algorithm
  
```

3.5 Our Approach

In our work, we try a number of options like `RANDCOLOURING` and `MINMAXCOLOURING` which uses some of the suggestions by Cohen and Castonguay (2012) on top of the algorithm put forward by Jones and Plassmann (1993). Like every other implementation, the data structures used are really important. Especially in our case, as we are using a GPU, the structure and size of data copied to and stored on the GPU are very important. From here on, n represents the number of vertices and m represents the number of

edges in the graph.

3.5.1 CSR: Compressed Sparse Row Representation

Graphs are usually stored in an adjacent matrix representation or an adjacency list representation. Both have their own pros and cons. Graphs in practical applications are usually huge. In our case, as we have to copy the entire graph to the GPU, we can't have the luxury of adjacent matrix representation as it requires $O(n^2)$ storage space. Also, we deal with a lot of sparse graphs and for sparse graphs, adjacent matrix representation is very wasteful in terms of space. For sparse graphs, adjacency list based representations are better. As we are dealing with GPUs, which don't really provide enough support for using connected lists, adjacency list representation ($O(m + n)$) in its classical form is also not practical. So, we use an array based adjacency list representation called Compressed Sparse Row Representation.

Compressed Sparse Row Representation of a graph involves the use of just three arrays (two in case the edges are of unit weight). The first array, called the Offset Array, has a size of $n + 1$, where n is the number of vertices. The second array, called the Edges Array, and the third array, called the Weights Array, have the size of the number of edges each.

With respect to our problem, the third array, Weights Array, is not used as all the edges are assumed to be of unit weight. So, CSR takes up $O(m + n)$ space, but uses only arrays which are easier to work with on GPUs.

Offsets Array

The offsets array (`offsetArray[]`) has $n + 1$ (n is the no. of vertices) elements. Each of these elements represents the offset in the Edges Array where the edges adjacent to the respective vertices are stored. So, `offsetArray[i]` represents the offset in the `edgesArray[]` where the edges adjacent to vertex $i + 1$ (assuming vertices are numbered 1 to n) are stored from. Therefore, it follows that the adjacent edges of the vertex $i + 1$ will be stored from index `offsetArray[i]` upto, but not including,

`offsetArray[i+1]` for all $i < n - 1$. To extend this to vertex n , that is, $i = n - 1$, we initialize `offsetArray[n]` with the value m . It also follows that if a vertex $i + 1$ is of degree 0, that is if a vertex doesn't have any adjacent vertices, then

```
offsetArray[i] = offsetArray[i+1]
```

Edges Array

The edges array (`edgesArray[]`) has m (no. of edges) elements. All these m elements represent one of the n vertices. For a vertex, $i + 1$, the `edgesArray[]` stores its adjacent vertices from index `offsetArray[i]` upto, but not including, `offsetArray[i+1]` for all $i < n$.

Undirected Graphs in CSR: UCSR

It is to be noted that CSR is predominantly used for directed graphs. It can be used as such for undirected graphs too, but that might cause some extra processing to be done to find the neighbourhood of a vertex in the graph and might lead to a data race in parallel computing. So, one way around this is to include all edges of a graph as directed edges in both directions. That is, given an undirected graph $G(V, E)$ with m edges, our `edgesArray[]` graph will have $2m$ elements instead of m elements. But the order of space remains the same. We call this *Undirected CSR* or *UCSR*.

Example

Here, we take an example to explain how CSR works. We take both a directed graph and an undirected graph to show how we use the CSR.

Consider the directed graph with $n = 4$ and $m = 4$ as given in the Table 3.1. Its corresponding CSR is given in the Figure 3.1.

Consider the undirected graph with $n = 4$ and $m = 3$ as given in the Table 3.2. Its corresponding CSR is given in the Figure 3.2 and its UCSR is given in the Figure 3.3. Note that the `edgesArray[]` has $2m = 6$ elements in the UCSR.

From Node	To Node
1	2
1	3
2	3
2	4

Table 3.1: A Directed Graph with $n = 4$ and $m = 4$

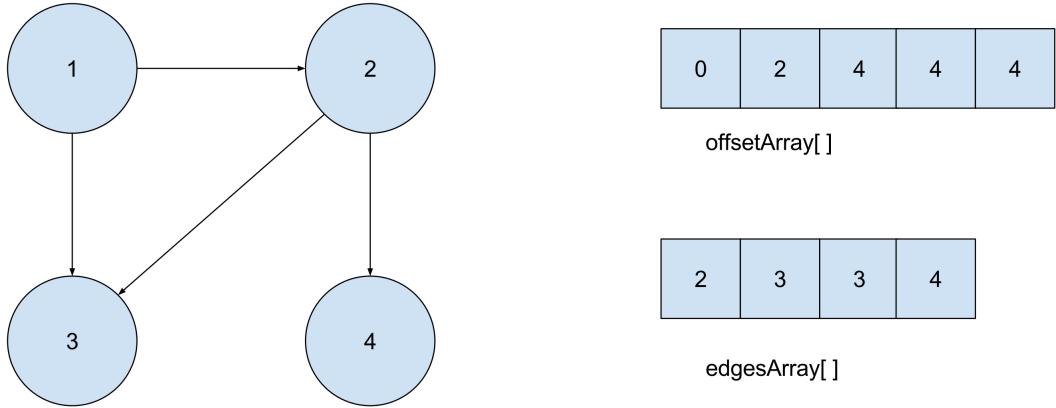


Figure 3.1: The Directed Graph from Table 3.1 and its CSR

Incident Node	Incident Node
1	2
1	4
2	3

Table 3.2: An Undirected Graph with $n = 4$ and $m = 3$

3.5.2 RANDCOLOUR: Random Colouring And Conflict Resolution

We started with a random colouring and conflict resolution based algorithm which we call RANDCOLOUR. This is an algorithm pertaining to the category covered by Algorithm 2. We first speculate the colours randomly and then find the conflicts on the GPU, both of which are done in parallel. Then we resolve the conflicts sequentially on the CPU. As we know, a graph $G(V, E)$ with maximum degree Δ can be coloured with atmost $\Delta + 1$ colours, RANDCOLOUR is an attempt at a fast $\Delta + 1$ colouring using GPU. RANDCOLOUR algorithm produces a worst colour quality of $\Delta + 1$ and was aimed at a fast colouring compromising colour quality in the process.

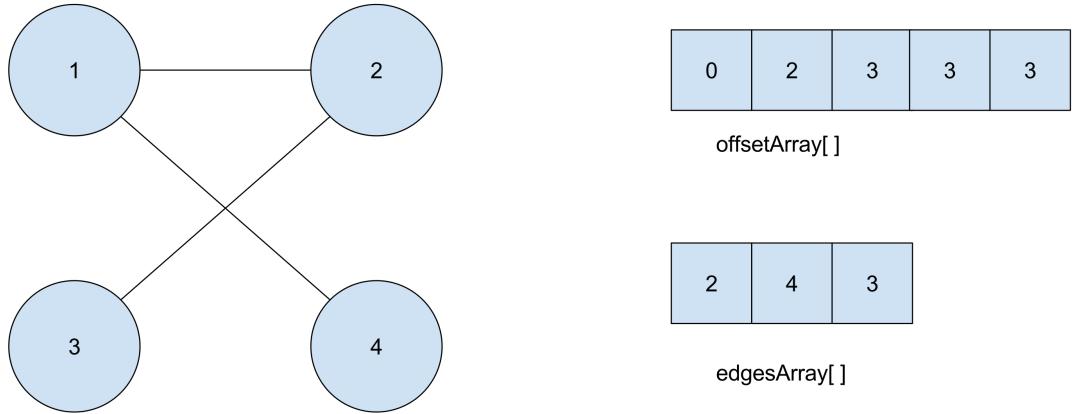


Figure 3.2: The Undirected Graph from Table 3.2 and its CSR

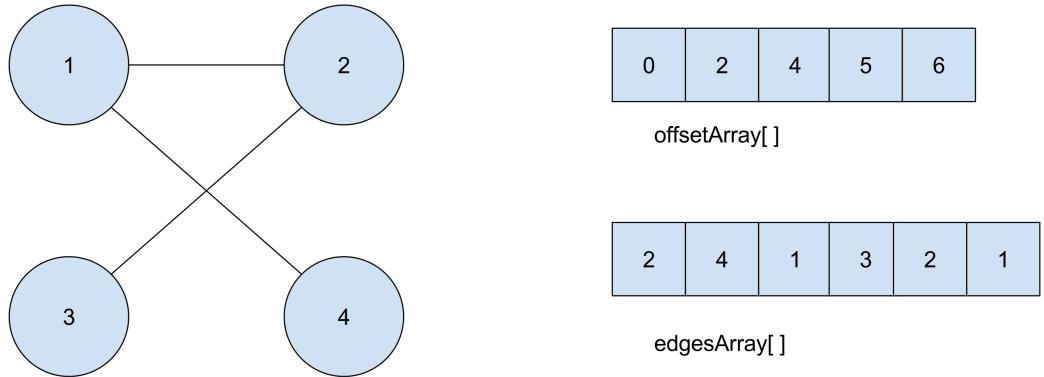


Figure 3.3: The Undirected Graph from Table 3.2 and its UCSR

The scheme is given in Algorithm 8. First we find Δ , the maximum degree of the graph (Line 4). This task can be done in parallel on the GPU. With UCSR of the graph, the degree of a vertex $i + 1$ is given by `offsetArray[i+1]`–`offsetArray[i]`. Once we have Δ , we use cuRAND library (NVIDIA Corporation, 2016b), which generates random numbers really fast using CUDA capable GPUs, to colour the graph with random integers ranging from 1 to $\Delta + 1$ (Lines 5 and 6). Once this colouring is over, we try to find out the conflicts that were inflicted. This can be done in parallel on the GPU too (Lines 8 to 12). We mark all the conflicts and then resolve them on the CPU using a greedy approach (Lines 14 and 15).

In RANDCOLOUR, we try to colour a graph with $\Delta + 1$ colours. Brook's theorem (Brooks, 1987) tells us that except for odd cycles, Δ colours suffice. So, we can possibly

Algorithm 8 RANDCOLOUR

```
1: procedure RANDOMCOLOURING( $G(V, E)$ )
2:   Initialization
3:   GPU (Speculation):
4:     Initialize MaxDegree                                 $\triangleright$  Found in parallel on GPU
5:     for each  $v \in V$  do                                $\triangleright$  Done in parallel by  $|V|$  threads
6:        $colour[v] \leftarrow CURAND(\text{MaxDegree} + 1) + 1$        $\triangleright$  RAND on GPU
7:   GPU (Conflict Detection):
8:      $conflictSet \leftarrow \emptyset$ 
9:     for each  $v \in V$  do                                $\triangleright$  Done in parallel
10:       for each  $u \in V$  such that  $u$  and  $v$  are adjacent do
11:         if  $colour[v] = colour[u]$  then
12:            $conflictSet \leftarrow conflictSet \cup \{min(v, u)\}$ 
13:   CPU (Conflict Resolution):
14:   for each  $v \in conflictSet$  do
15:      $colour[v] \leftarrow A \text{ colour by some greedy colouring algorithm}$ 
```

save on a colour that way by just using Δ colours during the initial speculation phase.

3.5.3 MINMAXCOLOUR: Maximal VIS And Colouring

We then tried a version of the algorithm put forward by Jones and Plassmann (1993) which uses some of the suggestions by Cohen and Castonguay (2012). As discussed earlier, the algorithm by Jones and Plassmann (1993) is based on the category covered by Algorithm 1. So, here, we try to find Maximal Vertex Independent Sets and then colour them in parallel.

Improvements

- The original version uses a Max approach for finding a Maximal Vertex Independent Set. A Min approach also gives us a Maximal Vertex Independent Set which is mutually exclusive with the Max based set (except when a vertex doesn't have any adjacent vertices; discussed in the next point). So, we find two Maximal Vertex Independent Sets in each iteration, one based on Max approach and the other on Min approach. Then, we colour both sets with two different colours in each iteration. This way we get to speed up the colouring by reducing the number of iterations required.
- Conflicts can arise when two neighbouring vertices have the same random number allotted to them. That same random number could be a neighbourhood minimum or maximum in which case we have multiple candidates for the Max set or Min set from the same neighbourhood. If a vertex doesn't have any neighbours,

it can possibly be added to the Max set as well as Min set. To avoid conflicts between the Max based set and Min based set in each iteration, we follow a set of conventions as follows:

- In each iteration, the Max based set takes the smaller of the two colour numbers allowed in that iteration.
- If two neighbours have the same random number allotted to them, the vertex with a smaller index has higher precedence for Max set.
- If two neighbours have the same random number allotted to them, the vertex with a higher index has higher precedence for Min set.
- If a vertex doesn't have any neighbours, it is considered a local maxima and is added to Max set. This is because Max sets get a lower colour number compared to Min sets in an iteration as discussed earlier.

The scheme for this is given in Algorithms 9 and 10. In Algorithm 9, we have the Min-Max Maximal Independent Set algorithm which is an improved version of Luby (1985). The two inner for loops in the algorithm at Line 7 and Line 17 can be merged together using some conditionals. We find two maximal sets in each iteration. If a vertex doesn't have any neighbours, it will be a part of both the Min set and the Max set. In Line 26, we make sure such vertices go to only the Max set. In the colouring part, in each iteration, we colour the Max set with a colour c (Lines 8 and 9) and the Min set with $c+1$ (Lines 10 and 11). The algorithm is iterated until there are no vertices left to colour (Line 6). The maximal sets are found in parallel and they can be coloured in the same kernel call.

The Maximal VIS based algorithm might be a little more time consuming as it employs an iterative approach, but should produce better colour quality. The main reason why this approach was our choice is because the entire process happens in parallel here, that is there is no sequential colouring component. As we use GPU, we try to maximize the use of the massive parallelism GPUs offer.

Algorithm 9 Min-Max Maximal Vertex Independent Sets

```
1: procedure MINMAXMAXIMALSET(G(V,E))
2:   Initialization                                 $\triangleright$  randomNumber[] is initialized only once
3:    $MinS \leftarrow \emptyset$ 
4:    $MaxS \leftarrow \emptyset$ 
5:   for each  $v \in V$  do                       $\triangleright$  Done in parallel
6:      $MaxS \leftarrow MaxS \cup \{v\}$ 
7:     for each  $u \in V$  such that  $u$  is adjacent to  $v$  do
8:       if  $randomNumber[u] > randomNumber[v]$  then
9:          $S \leftarrow S \setminus v$ 
10:        break
11:       else
12:         if  $randomNumber[u] = randomNumber[v]$  then
13:           if  $u > v$  then
14:              $S \leftarrow S \setminus v$ 
15:             break
16:          $MinS \leftarrow MinS \cup \{v\}$ 
17:         for each  $u \in V$  such that  $u$  is adjacent to  $v$  do
18:           if  $randomNumber[u] < randomNumber[v]$  then
19:              $S \leftarrow S \setminus v$ 
20:             break
21:           else
22:             if  $randomNumber[u] = randomNumber[v]$  then
23:               if  $u < v$  then
24:                  $S \leftarrow S \setminus v$ 
25:                 break
26:      $MinS \leftarrow MinS \setminus MaxS$ 
27:   return  $MaxS, MinS$ 
```

Algorithm 10 MINMAXCOLOUR

```
1: procedure MINMAXCOLOURING(G(V,E))
2:   Initialization
3:    $n \leftarrow 0$ 
4:    $currentColour \leftarrow 1$ 
5:    $graphSize \leftarrow |V|$ 
6:   while  $n \neq graphSize$  do                   $\triangleright$  Or  $V \neq \emptyset$ 
7:      $MaxS, MinS \leftarrow \text{MinMaxMaximalSet}(V, E)$ 
8:     for each  $v \in MaxS$  do                   $\triangleright$  Done in parallel
9:        $colour[v] \leftarrow currentColour$ 
10:      for each  $v \in MinS$  do                   $\triangleright$  Done in parallel
11:         $colour[v] \leftarrow currentColour + 1$ 
12:         $currentColour \leftarrow currentColour + 2$ 
13:         $n \leftarrow n + |MaxS| + |MinS|$ 
14:         $V \leftarrow V \setminus MaxS$ 
15:         $V \leftarrow V \setminus MinS$ 
```

CHAPTER 4

PARALLEL GRAPH COLOURING: INCREMENTAL

4.1 Why Incremental?

Graphs are being used in a varied lot of applications these days. Graphs are ever more important and ever growing. Practical graphs like social networks graphs, communication networks graphs are inherently dynamic. Most of them keep on changing. Edges and Vertices get added and deleted every now and then. It is not a great idea to run a computationally intensive algorithm again on a graph just because a few thousands (a small fraction compared to total graph size) of edges are added to it. Thus incremental approaches are very important so as to save on computation and time.

4.2 Handling a Growing Graph

So, with incremental graph colouring, we are accommodating additions of vertices and edges. We assume without any loss of functionality that no new vertices are added. Only edges are added. This is easy to see as adding a new vertex (with some edges incident on it) is equivalent to adding edges to a vertex with zero degree. As long as we have an idea about the upper bound on the number of vertices through the applications of the graph, we should be fine.

Through the additions of edges, the `offsetArray[]` of UCSR doesn't grow in size. But the size of `edgesArray[]` will grow. So, we should have a reasonable upper bound on the number of edges that can be incident on each vertex. We can set the extra `edgesArray[]` elements to zero initially. When an edge is added, the new edge's information can be added to the `edgesArray[]` at these elements which are set to zero.

4.3 The Two Thread Incremental Model

We assume we have a graph which is already coloured using one of the algorithms, in our case Algorithm 10 from last chapter, on the GPU. We also assume that we have the UCSR graph already residing on the GPU memory.

In the incremental model, when an edge is added, only two vertices are immediately affected. The vertices on which the added edge is incident. If those two vertices have different colours, already, we assume they were coloured optimally by the main algorithm already and leave those two vertices be with their existing colours. If those two vertices have the same colour, then we have a conflict on the addition of the new edge. We are concerned with only those two vertices for the immediate task of resolving the conflict.

We introduce an algorithm called The Two Thread Incremental Model to deal with recolouring the graph. This model makes use of only two threads, each thread for each of the two vertices in conflict, as our immediate objective is to remove the conflict. But, in our model, while removing the conflict, we try to optimize the colours of those two vertices and thus locally maximizing the colour quality. It follows that when the colours of the two vertices are changed in a locally optimized way, there could be positive changes in the other parts of the graph. We will deal with this later in the propagation part.

Our Two Thread Incremental Model is explained in Algorithm 11. From the structure of the problem and our algorithm, it is clear that we actually need only two threads to deal with locally maximizing the colour quality at the region of edge addition. As we have the graph already on the GPU memory, we don't have an issue with memory latency, the biggest hurdle with GPGPU.

This algorithm is meant for addition of a single edge. Two threads are spawned to run the algorithm. Each thread takes charge of one of the vertices on which the new edge is incident. In our algorithm, we assume uv is the added edge and *Thread 0* is in charge of u and *Thread 1* in charge of v . Initially, each thread modifies its portion of the UCSR to accommodate the newly added edge. Then they check if the current colouring of u and v are the same. If not, we are through.

Algorithm 11 The Two Thread Incremental Model

```

1: procedure TWOTHREADINCREMENTALCOLOURING(G(V,E), EDGE)
2:   Initialization
3:   Let  $uv$  be the newly added edge
4:   Thread 0 represents  $u$  and thread 1 represents  $v$ 
5:   Add the new edge information to the UCSR     $\triangleright$  Each thread add its neighbour
6:   synchronize
7:   if  $\text{colour}[u] \neq \text{colour}[v]$  then
8:     return
9:   for  $i \in \{u, v\}$  do                                 $\triangleright$  In parallel by two threads
10:     $\text{oldColour} \leftarrow \text{colour}[i]$ 
11:     $\text{possibleColour}[\text{threadId}] \leftarrow \text{Smallest possible colour for } i$ 
12:     $\text{possibleColour2}[\text{threadId}] \leftarrow \text{Second smallest possible colour for } i$ 
13:    synchronize
14:    if  $\text{possibleColour}[\text{threadId}] = \text{possibleColour}[1 - \text{threadId}]$  then
15:      if  $\text{possibleColour}[\text{threadId}] < \text{oldColour}$  then
16:        if  $\text{possibleColour2}[\text{threadId}] < \text{possibleColour2}[1 - \text{threadId}]$ 
17:          then
18:            Label 1:
19:              if  $\text{possibleColour2}[\text{threadId}] < \text{oldColour}$  then
20:                 $\text{colour}[i] \leftarrow \text{possibleColour2}[\text{threadId}]$ 
21:              else
22:                if  $\text{possibleColour2}[\text{threadId}] = \text{possibleColour2}[1 - \text{threadId}]$  then
23:                  if  $\text{threadId} = 0$  then
24:                     $\text{colour}[i] \leftarrow \text{possibleColour}[\text{threadId}]$ 
25:                  else
26:                    Label 3:
27:                      if  $\text{possibleColour2}[\text{threadId}] < \text{colour}[i]$  then
28:                         $\text{colour}[i] \leftarrow \text{possibleColour2}[\text{threadId}]$ 
29:                      else
30:                        Label 4:
31:                           $\text{colour}[i] \leftarrow \text{possibleColour}[\text{threadId}]$ 
32:                        else
33:                          Label 5:
34:                            if  $\text{threadId} = 1$  then
35:                               $\text{colour}[i] \leftarrow \text{possibleColour}[\text{threadId}]$ 
36:                            else
37:                              Label 6:
38:                                if  $\text{possibleColour}[\text{threadId}] < \text{oldColour}$  then
39:                                   $\text{colour}[i] \leftarrow \text{possibleColour}[\text{threadId}]$ 
40:                                else
41:                                  Label 7:
42:                                    if  $\text{possibleColour}[\text{threadId}] < \text{possibleColour}[1 - \text{threadId}]$ 
43:                                      then
44:                                         $\text{colour}[i] \leftarrow \text{possibleColour}[\text{threadId}]$ 

```

If the current colouring of u and v are the same, we first try to find out the least colour they can assume considering their neighbourhood in a greedy fashion. This new colouring cannot be their existing colour, as both of them have each other as a neighbour now. Let the current colouring be called p . Let the newly found least possible colour for each of them be x and y . Now, we have $x \neq p$ and $y \neq p$. In the case of $x = y$, let a and b be the least colour greater than x and y respectively that u and v can take respectively in a greedy fashion. We have many cases that can arise in most of which u, x, a and v, y, b are interchangeable with no side effects. These cases and the actions required are tabulated in Table 4.1.

No	Case	Action	Label No. in Algorithm
1	$x = y < p; a = b < p$	$\text{colour}[u] = x; \text{colour}[v] = b$	2, 3
2	$x = y < p; p < a = b$	$\text{colour}[u] = x$	2
3	$x = y < p; a < b; a < p$	$\text{colour}[u] = a; \text{colour}[v] = y$	1, 4
4	$x = y < p; a < b; p < a$	$\text{colour}[v] = y$	4
5	$p < x = y$	$\text{colour}[v] = y$	5
6	$x \neq y; x < y < p$	$\text{colour}[u] = x; \text{colour}[v] = y$	6
7	$x \neq y; x < p < y$	$\text{colour}[u] = x$	6
8	$x \neq y; p < x < y$	$\text{colour}[u] = x$	7

Table 4.1: Two Threads Model: Different Cases

Each of the cases given in the Table 4.1 are explained using examples in the figures 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7 and 4.8.

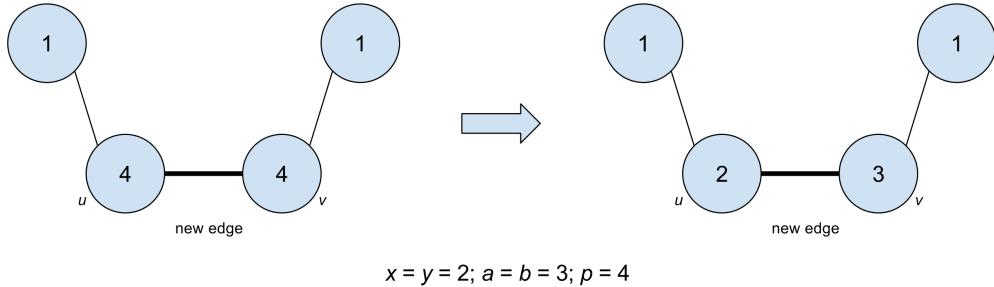


Figure 4.1: **Case 1:** $x = y < p; a = b < p$

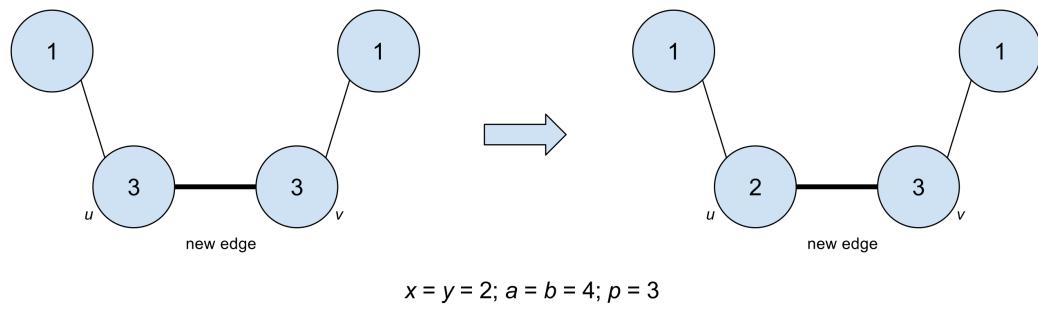


Figure 4.2: **Case 2:** $x = y < p$; $p < a = b$

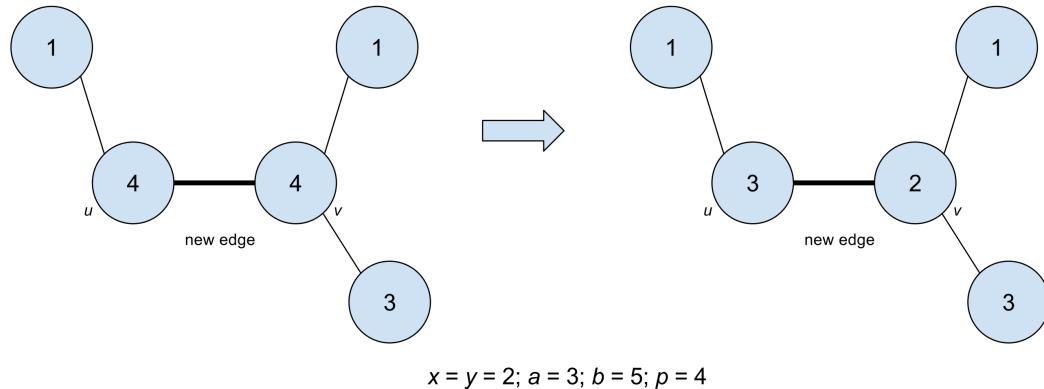


Figure 4.3: **Case 3:** $x = y < p$; $a < b$; $a < p$

4.4 The Many Thread Incremental Model

We have seen in The Two Thread Incremental Model in the last section and how it actually requires only two threads per addition of a new edge. As the graph is already on the GPU, we don't have much memory latency issues too. But then, GPUs are devices for massive parallelism. In this section, we will try to increase the parallelism involved in Incremental colouring.

As we have seen in the last session, we can handle a newly added edge with 2 threads. That is, if we colour on the go, we have to call a kernel with 2 threads each time we come across a new edge. To increase parallelism, we can try to club a bunch of new edges and process them together. But these edges shouldn't have any data races

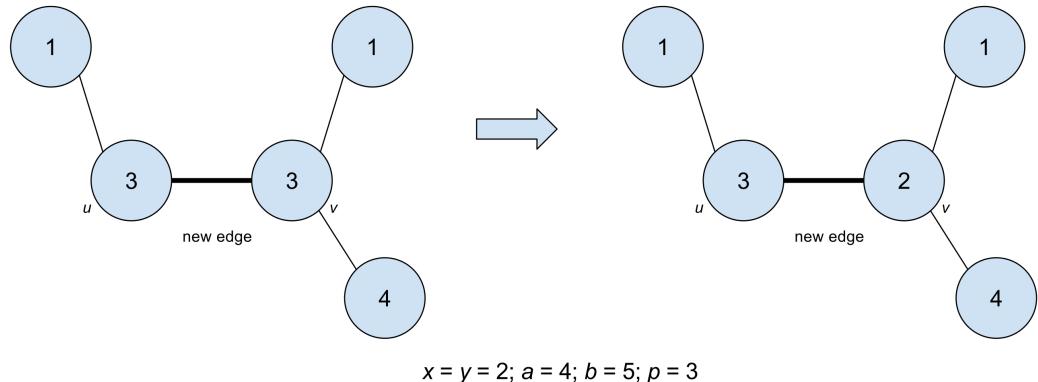


Figure 4.4: **Case 4:** $x = y < p; a < b; p < a$

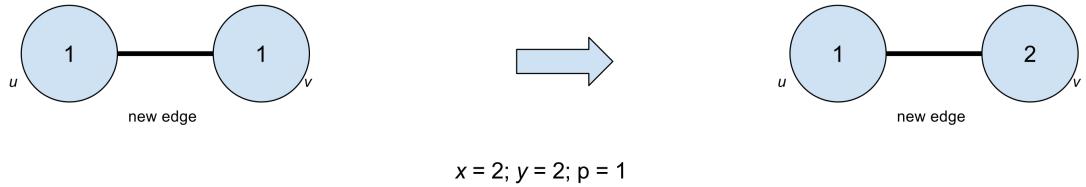


Figure 4.5: **Case 5:** $p < x = y$

among them. So, we try to club edges which won't have any data races amongst them and process them all together in parallel. We call our new approach **The Many Thread Incremental Model** and it is explained in Algorithm 12.

According to our algorithm, we keep on taking new edges as inputs and add them to `edgeSet`, as long as all the edges stored in our `edgeSet` are data race free. That is, there are no two edges which are incident on a common vertex. If a new edge added doesn't hold this true, we process the existing `edgeSet`, all the edges processed in parallel with each edge getting two threads each, using `TwoThreadIncrementalModel` as discussed in the previous section. Once all the edges from `edgeSet` are processed, it is cleared and the new edge is added to it. Then it goes back to accepting more edges.

New added edges can create conflicts. These conflicts will be resolved only after these edges are processed. So, it is not wise to wait for very long to club them with other edges for added parallelism. So, in our implementation, we have set a limit of

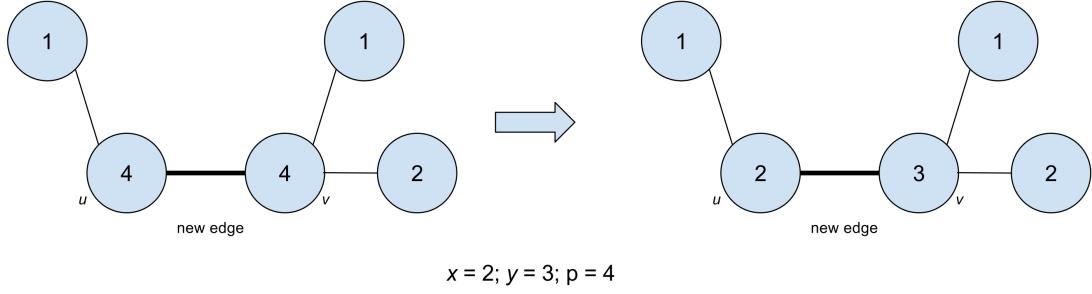


Figure 4.6: **Case 6:** $x \neq y$; $x < y < p$

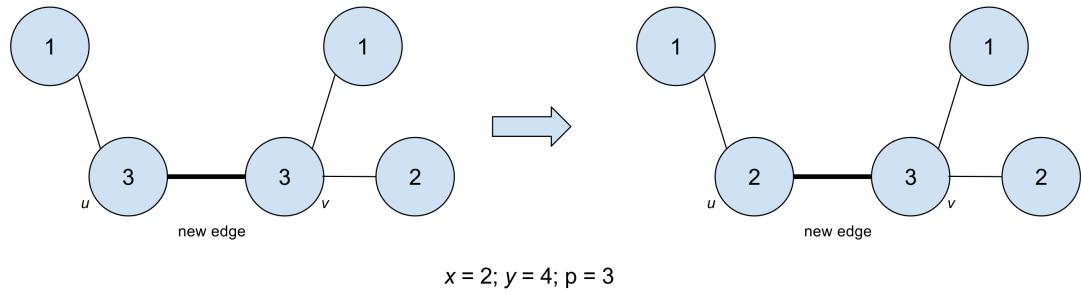


Figure 4.7: **Case 7:** $x \neq y$; $x < p < y$

1024 edges as the maximum `edgeSet` size before it is forcibly processed.

4.5 Propagation

As discussed earlier, our algorithm tries improves the colouring locally at the end points of the new edge added. But, we consider only those two vertices. If any of them changes its colouring, it could have an effect on its adjacent vertices who could now probably improve their own colouring as they themselves might not be locally optimized. When they indeed change their colours, there could be scope for improvement in their neighbourhood. So, this has a ripple effect. The need for propagation and propagation itself is portrayed with the help of an example in the Figure 4.9.

Though our locally optimizing algorithm works well without considering the ripple effect, it's always good to try for better colour quality. We introduce the idea of propagation to handle this ripple effect. Propagation is done only after a fixed number of edge

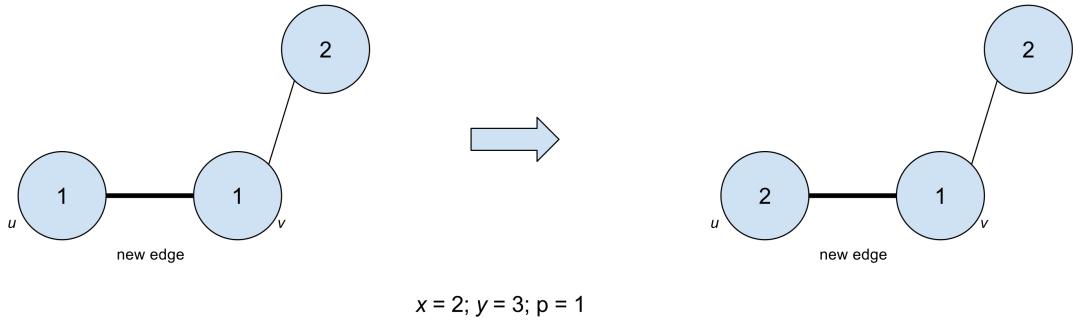


Figure 4.8: **Case 8:** $x \neq y$; $p < x < y$

Algorithm 12 The Many Thread Incremental Model

```

1: procedure MANYTHREADINCREMENTALCOLOURING( $G(V, E)$ ,  $\text{EDGE}$ )
2:   Initialization
3:    $\text{edgeSet} \leftarrow \emptyset$ 
4:   NewEdge:
5:     Take the new edge to be added,  $\bar{e}$ , as the input
6:      $\bar{u}, \bar{v} \leftarrow \text{endpoints of } \bar{e}$ 
7:     for each  $e \in \text{edgeSet}$  do
8:        $u, v \leftarrow \text{endpoints of } e$ 
9:        $\text{setU} \leftarrow V \setminus \text{adj}(u)$             $\triangleright \text{adj}(k)$  gives adjacent vertices of  $k$ 
10:       $\text{setV} \leftarrow V \setminus \text{adj}(v)$ 
11:       $\text{setPermissible} \leftarrow \text{setU} \cap \text{setV}$ 
12:      if  $\bar{u} \notin \text{setPermissible}$  OR  $\bar{v} \notin \text{setPermissible}$  then
13:        // Done in parallel for all edges in the edgeSet
14:        TwoThreadIncrementalColouring ( $G(V, E)$ ,  $\text{edgeSet}$ )
15:         $\text{edgeSet} \leftarrow \{\bar{e}\}$ 
16:        goto NewEdge
17:       $\text{edgeSet} \leftarrow \text{edgeSet} \cup \bar{e}$ 
18:      goto NewEdge

```

additions are done so as to save on computation. Our propagation procedure propagates the newly changed colouring info across the graph to the vertices who could possibly be affected.

We discuss our propagation algorithm in the next chapter when we discuss Decremental graph colouring as the propagation step is one and the same for both Incremental and Decremental graph colouring.

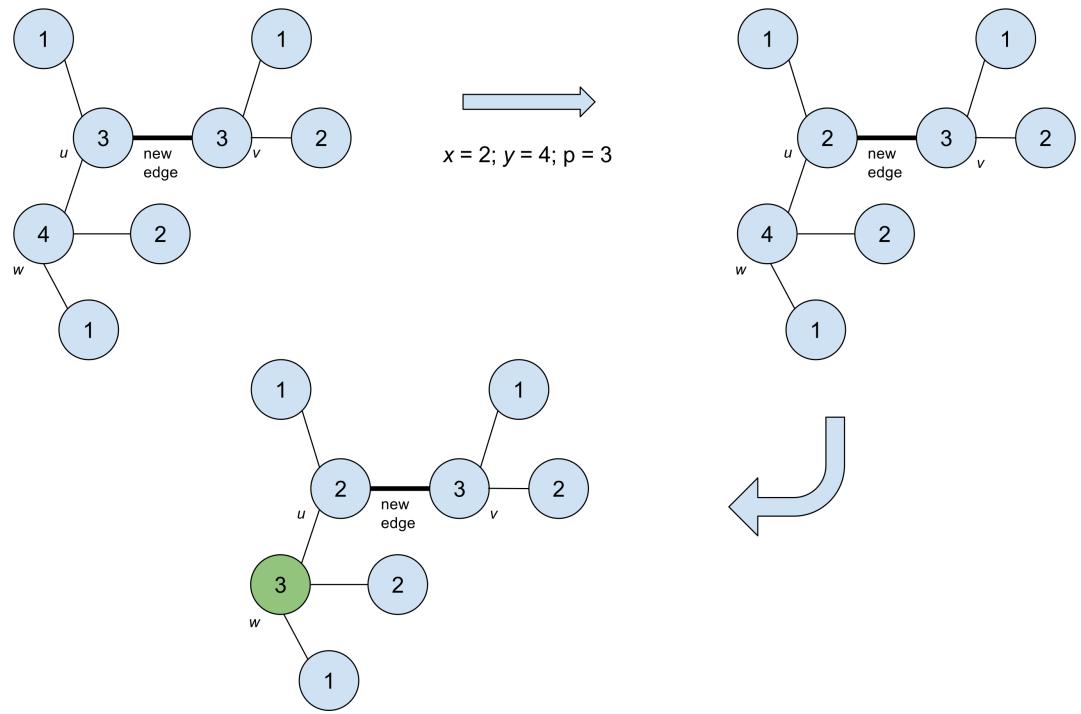


Figure 4.9: 1-step propagation after adding a new edge and processing it.

CHAPTER 5

PARALLEL GRAPH COLOURING: DECREMENTAL

5.1 Why Decremental?

As discussed in the last chapter, almost all practical graphs keep on changing. Edges and Vertices get added and deleted often. Deletion of a small fraction of edges compared to total graph size shouldn't call for running a computationally intensive algorithm all over again on the graph. Decremental approach helps save running time and avoids unnecessary computations.

5.2 Handling a Shrinking Graph

With decremental graph colouring, we are removing vertices and edges. Without any loss of functionality, we can choose not to remove vertices. Only edges are deleted. Removing a vertex (with some edges incident on it) is equivalent to removing all the edges incident on that vertex.

So, through the deletions of edges, the `offsetArray` [] of UCSR doesn't change in size as we don't really remove vertices. But the size of `edgesArray` [] can change. As we want the size of `edgesArray` [] to not change, when an edge is deleted, the new edge's information can be removed from the `edgesArray` [] by setting those elements to zero.

5.3 The Two Thread Decremental Model

We assume that we have the already coloured graph residing in the GPU memory. Now, we decrement an edge, that is, we remove an edge. When an edge is removed, there

is no necessity to change the colouring as it can't inflict any conflict. So, if an edge is removed, we can leave the colouring as it is. But when an edge is removed, there is a possibility that we can improve the existing colouring. And to deal with the same, we introduce our model which we call *The Two Thread Decremental Model*.

In *The Two Thread Decremental Model*, we try to optimize the existing colouring in a localized fashion. As in the case of Incremental colouring discussed in the last chapter, we need only two threads to achieve the same. The scheme for *The Two Thread Decremental Model* is given in Algorithm 13.

Algorithm 13 The Two Thread Decremental Model

```

1: procedure TWOTHREADDECREMENTALCOLOURING( $G(V, E)$ , EDGE)
2:   Initialization
3:   Let  $uv$  be the newly deleted edge
4:   Thread 0 represents  $u$  and thread 1 represents  $v$ 
5:   Remove the deleted edge from the UCSR     $\triangleright$  Each thread deletes its neighbour
6:   synchronize
7:   for  $i \in \{u, v\}$  do                                 $\triangleright$  In parallel by two threads
8:      $oldColour \leftarrow colour[i]$ 
9:      $possibleColour \leftarrow$  Smallest possible colour for  $i$ 
10:    if  $possibleColour < oldColour$  then
11:       $colour[i] \leftarrow possibleColour$ 

```

The model is pretty simple. Two threads are spawned to run the algorithm. Each thread takes charge of one of the vertices on which the deleted edge was incident. We assume uv is the newly deleted edge and *Thread 0* is in charge of u and *Thread 1* in charge of v (Line 4). Initially, each thread modifies its portion of the UCSR to reflect the deletion of edge uv (Line 5). Once the UCSR is updated and synchronized (Line 6), each thread tries to find the smallest colour its vertex can assume in the changed neighbourhood, $possibleColour$ (Line 7 to 9). If this smallest colour the vertex can assume, $possibleColour$, is smaller than its current colour, its colour is updated to $possibleColour$ (Line 10 to 11).

5.4 The Many Thread Decremental Model

In the previous section we discussed our *Two Thread Decremental Model*. As was discussed, we need only two threads to handle a deleted edge. The issue here is that,

for every edge deleted, we need to spawn a CUDA kernel with just two threads. There are two issues with this. The first issue is that we are not enough use of the massive parallelism that GPUs offer. The second issue is that each kernel call comes with some overhead. There is some cost involved while CPU invokes the GPU for computation. So, it is in our best interest to increase the number of threads used per kernel call and to reduce the number of times kernels are invoked. We present our model we call *The Many Thread Decremental Model* to handle the same.

Algorithm 14 The Many Thread Decremental Model

```

1: procedure MANYTHREADDECREMENTALCOLOURING( $G(V, E)$ ,  $\text{EDGE}$ )
2:   Initialization
3:    $\text{edgeSet} \leftarrow \emptyset$ 
4:   Edges To Be Deleted:
5:   Take the newly deleted edge,  $\bar{e}$ , as the input
6:    $\text{edgeSet} \leftarrow \text{edgeSet} \cup \bar{e}$ 
7:   if more edges to be deleted then
8:     goto Edges To Be Deleted
9:   // Two threads per edge are spawned
10:  for each  $e \in \text{edgeSet}$  do                                 $\triangleright$  Done in parallel
11:    Each thread modifies UCSR to remove its corresponding neighbour
```

The scheme for *The Many Thread Decremental Model* is given in Algorithm 14. As deletions of edges don't inflict in colouring conflicts, we can actually choose not to recolour the graph on edge deletions. But the edge deletions should be reflected in the UCSR of the graph residing on the GPU. This we can do in parallel for all the deleted edges together. We can't really locally recolour the vertices on which the deleted edges were incident in parallel, like in Algorithm 13, as this might lead to data races. The edges considered in parallel might not be independent of each other. So, our model chooses not to recolour the graph, atleast not right away, and just deletes the edges from the UCSR of the graph residing on the GPU in parallel (Lines 10 and 11).

But it is clear that all these edge deletion could lead to better colouring of the graph. And to accommodate the same, we introduce propagation to propagate the changed structure of the graph through the graph.

5.5 Propagation

The need for propagation should already be clear from last chapter as well as last section. In Figure 4.9, we showed how propagation could help improve the colouring after addition of edges. If we use Algorithm 13 for edge deletions, then we already should have locally improved colouring. In that case, we can use propagation to possibly improve colour quality. If we use Algorithm 14, we leave the colours as it is. We don't change them. In that case, propagation very likely will improve the colour quality.

In terms of likelihood for improvement in colour quality, we have three approaches to propagation namely the pessimistic approach, the semi-optimistic approach and the optimistic approach.

5.5.1 Pessimistic: No Propagation

In the pessimistic approach, or what we call No Propagation, we leave the colours untouched. That is, we don't do any propagation. After Algorithms 11, 12 and 13, which changes the colouring locally, if we feel that there is meagre chance for the colour quality to improve or if we feel the cost-benefit in terms of time/computation involved *vs* colour quality improved, we can choose not to do propagation in order to save on computation and time.

5.5.2 Semi-Optimistic: One Time Propagation

In the semi-optimistic approach, or what we call One Time Propagation, we propagate the information through the graph in one go. That is, the information is transferred only by one level. The possible ripple effect of propagation is downplayed in this approach. After Algorithms 11, 12 and 13, the immediate neighbours of the locally improved vertices could possibly get better colours. After Algorithm 14, the affected vertices themselves and their immediate neighbours could possibly get better colours.

This approach is a trade off between improvement in colour quality *vs* computation/time. We try to improve the colour quality by doing less computation and hence

Algorithm 15 One Time Propagation

```
1: procedure ONETIMEPROPAGATION(G(V,E))
2:   Initialization
3:    $processQueue \leftarrow V$ 
4:   while  $processQueue \neq \emptyset$  do
5:      $maxSet \leftarrow \text{MaximalSet}(processQueue)$ 
6:      $processQueue \leftarrow processQueue \setminus maxSet$ 
7:     for each  $v \in maxSet$  do
8:        $possibleColour \leftarrow \text{Smallest possible colour for } v$ 
9:       if  $colour[v] > possibleColour$  then
10:         $colour[v] \leftarrow possibleColour$ 
```

supposedly saving on time. We use Algorithm 4 to find Maximal VIS iteratively to propagate the information. Every node will see the colouring information and the graph structure up until the propagation step. That is, the colouring changes made during the propagation step don't percolate/ripple through the graph. The scheme is given in Algorithm 15.

5.5.3 Optimistic: Wave Propagation

In the optimistic approach, or what we call Wave Propagation, we consider the possible ripple effect of propagation. That is, if a vertex changes its colour, its new colouring could affect the colouring of all its neighbours. So, we process all its neighbours for possible colouring improvements. In case any of such neighbours improves its colouring, then its neighbours could also possibly improve their colouring. So, we add its neighbours too to our process queue. This then ripples through the graph until there are no more vertices with possible colouring improvements. This propagation happens in waves of possible colouring improvements and hence we call it Wave Propagation. In each wave, the algorithm adds the neighbours of those vertices who had a colouring improvement in the current wave to the process queue. The algorithm is terminated when there are no more vertices to be processed in the process queue.

This approach might be a little time consuming as we have to keep on adding and removing vertices to and from the process queue. But this approach is highly likely to improve colour quality as it propagates the latest information through the graph. All the colouring changes made during propagation ripple/percolate through the entire graph.

The biggest challenges here are the number of iterations, *waves*, before the algorithm terminates and the maintenance of a concurrent process queue. As we have to add all neighbours of each vertex who has had a colouring improvement, we could be looking at a fast growing process queue as large graphs possibly contain vertices with very high degrees. The scheme is given in Algorithm 16.

Algorithm 16 Wave Propagation

```

1: procedure WAVEPROPAGATION(G(V,E), PROPAGATIONSET)
2:   Initialization
3:    $processQueue \leftarrow propagationSet$ 
4:   while  $processQueue \neq \emptyset$  do
5:      $maxSet \leftarrow MaximalSet(processQueue)$ 
6:      $processQueue \leftarrow processQueue \setminus maxSet$ 
7:     for each  $v \in maxSet$  do
8:        $possibleColour \leftarrow Smallest\ possible\ colour\ for\ v$ 
9:       if  $colour[v] > possibleColour$  then
10:         $colour[v] \leftarrow possibleColour$ 
11:        for each  $u \in V$  such that  $u$  is adjacent to  $v$  do
12:           $processQueue \leftarrow processQueue \cup \{u\}$ 
```

Termination

This algorithm is guaranteed to terminate. In each wave, the processed vertices get removed from the process queue. Neighbours of vertices are added to the process queue only if they improve their own colouring. Colour can take only a minimum value of 1. So, a vertex can only improve its own colouring up until value 1. And if it doesn't improve its colouring in a wave, its neighbours are not added to the process queue. So, the process queue is guaranteed to get emptied after several waves of additions and deletions of vertices. But this wave propagation algorithm could be too slow for large graphs with vertices of very high degrees. In each wave, for every bunch of independent vertices who are processed, if some of them improves their colouring, then we will be adding all their neighbours to the process queue. This number of vertices added can easily be higher than the number of vertices processed. So, the process queue will become bigger and bigger until it reaches a point when most of the vertices in the list are already at their best colouring. And from that point, the process queue shrinks until becoming empty, at which point the algorithm terminates.

CHAPTER 6

EXPERIMENTAL EVALUATION

6.1 Experimental Setup

Our experiments were run on a computing setup based on a *Intel(R) Xeon(R) CPU E5-2650 v2* processor with 32 cores at a clock speed of 2.60 Ghz. The setup was equipped with 8 *NVIDIA TESLA K40c* graphics cards each with 12 GB of *GDDR5* memory. Each of these *K40c* graphics cards has 15 SMs (Streaming Multi-processors) with each SM having 192 *CUDA* cores taking the total count of *CUDA* cores to 2880. Each of these *K40c* devices has a peak single precision computing capacity of 4.29 Tflops.

All our experiments were run using NVIDIA CUDA runtime version 6.5. The version of GCC used was 4.4.7.

6.2 Test Data

We obtained most of our test datasets from Stanford Network Analysis Project (SNAP) (Leskovec and Krevl, 2014). We also use the 30 graph colouring datasets from Beasley (1990) which are very small graphs and also appear in Table 6 of the paper Fleurent and Ferland.

Pre-processing

Not all the graphs we chose are undirected graphs. So, we pre-processed the graphs thus rendering the directed graphs undirected. Also, we remove all self-loops in all the graphs as Vertex Colouring problem is based on undirected graphs with no self-loops.

Datasets

Details of our test datasets are tabulated in Table 6.1. n represents the number of vertices in the graph and m represents the number of edges in the graph. Δ represents the maximum degree of all the vertices of the graph. Source column cites the source from which that particular graph was obtained.

In most of our experiments, we consider only 14 large graphs with $m > 900000$.

6.3 Parallel Graph Colouring on GPU

6.3.1 RANDCOLOUR

We first evaluated the performance of our RANDCOLOUR approach as described in Algorithm 8. As discussed earlier, RANDCOLOUR involves a parallel phase where it randomly colours the graph and finds all the conflicts and a sequential phase where it resolves all the conflicts.

First of all, we found some correlation between the Max Degree of a graph and the number of conflicts that RANDCOLOUR endures while colouring. This is plotted in Figure 6.1. The two trend graphs, which are based on linear regression of the given data, show that, in general, graphs with higher Max Degrees endure a lesser number of conflicts.

We then tried to evaluate the parallel and sequential components of the runtime. This is plotted in Figure 6.2. Here we notice that, in general, the sequential component of runtime is larger than the parallel component. This trend is reversed for the graphs with high Max Degrees. From Figure 6.1, we have that the number of conflicts endured by such graphs with very high Max Degrees is very small. So, the sequential component of RANDCOLOUR’s runtime becomes smaller as the number of conflicts decrease, that is, as the Max Degree of the graph increases.

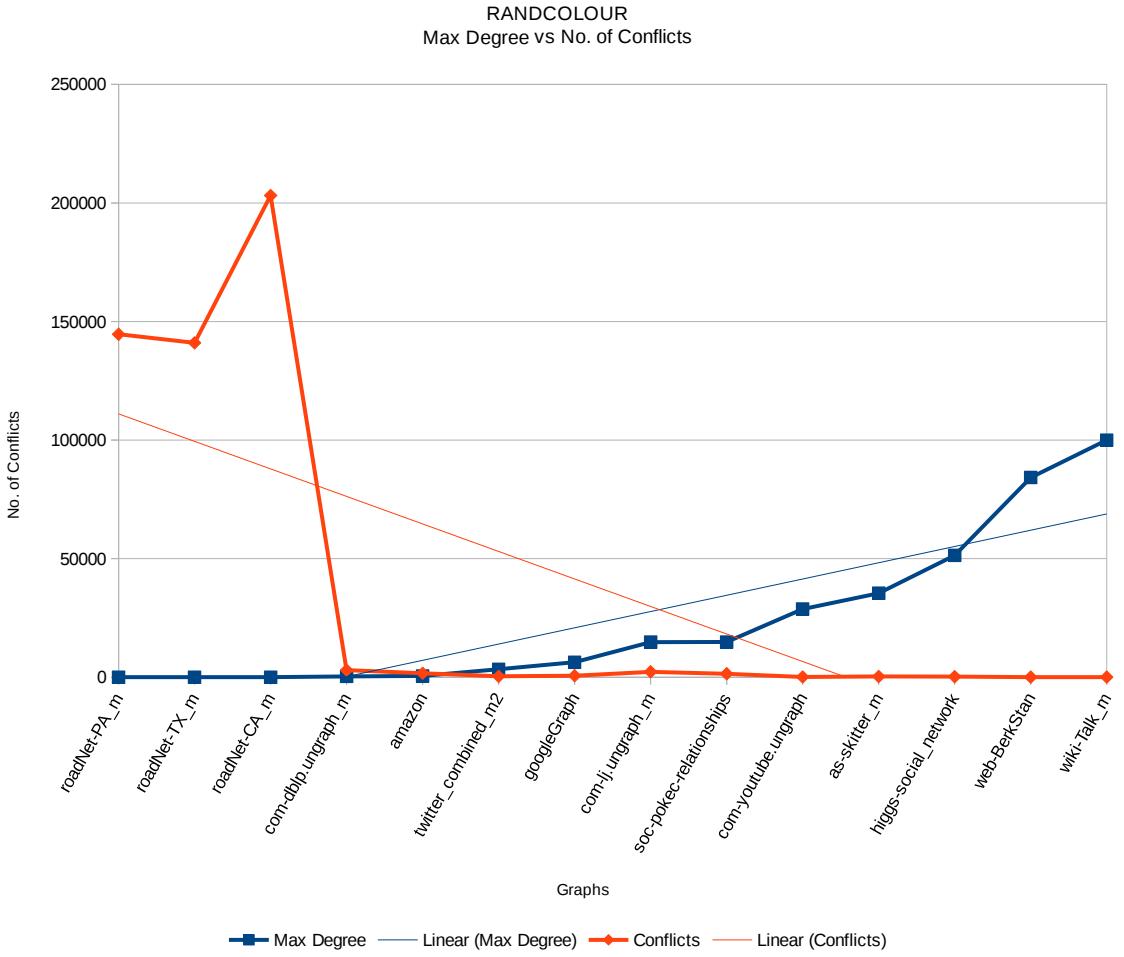


Figure 6.1: RANDCOLOUR: Max Degree vs No. of Conflicts

6.3.2 MAXCOLOUR

We tried to implement Algorithm 5, which, as we discussed earlier, finds a Maximal VIS (Algorithm 4) and colours that set in each iteration. We call this implementation MAXCOLOUR. The runtime and the number of colours used by MAXCOLOUR for our test graphs are tabulated in Table 6.2.

6.3.3 MINMAXCOLOUR

We then implemented Algorithm 10, which, as we discussed earlier, finds two Maximal VIS (Algorithm 9) and colours those sets with different colours in each iteration. The runtime and the number of colours used by MINMAXCOLOUR for our test graphs are tabulated in Table 6.3.

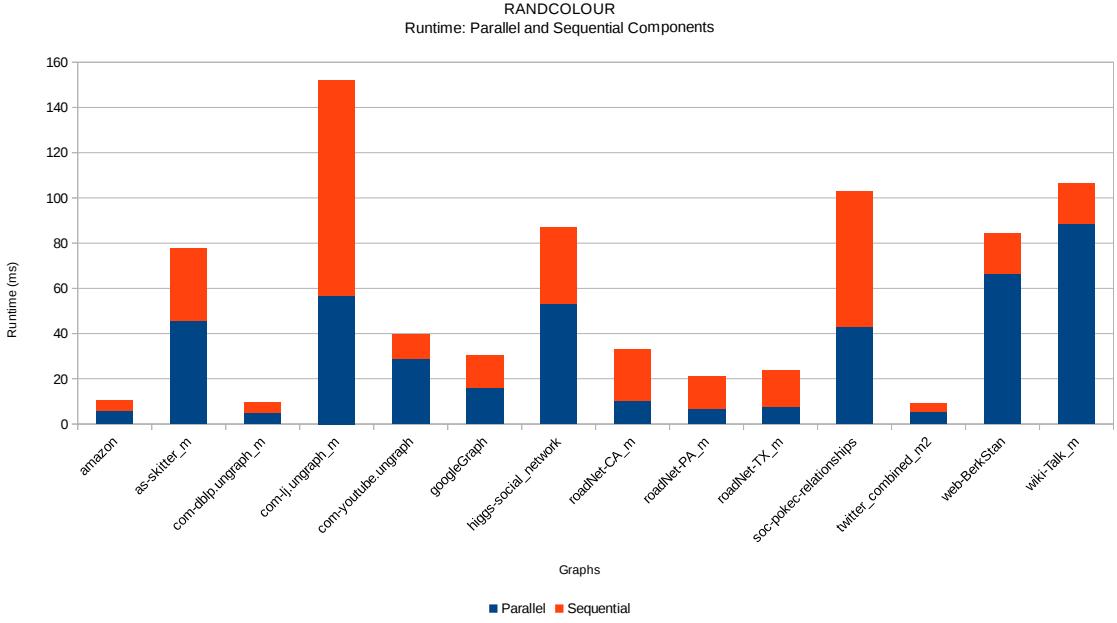


Figure 6.2: RANDCOLOUR: Parallel and Sequential Components of Runtime

6.3.4 RANDCOLOUR vs MAXCOLOUR vs MINMAXCOLOUR

We now compare the three implementations discussed. The runtime comparison is plotted in Figure 6.3. RANDCOLOUR clearly outperforms the other two in terms of runtime. This is in line with our idea for RANDCOLOUR- a quick algorithm for $\Delta + 1$ colouring. We can also see that MINMAXCOLOUR outperforms MAXCOLOUR in all cases.

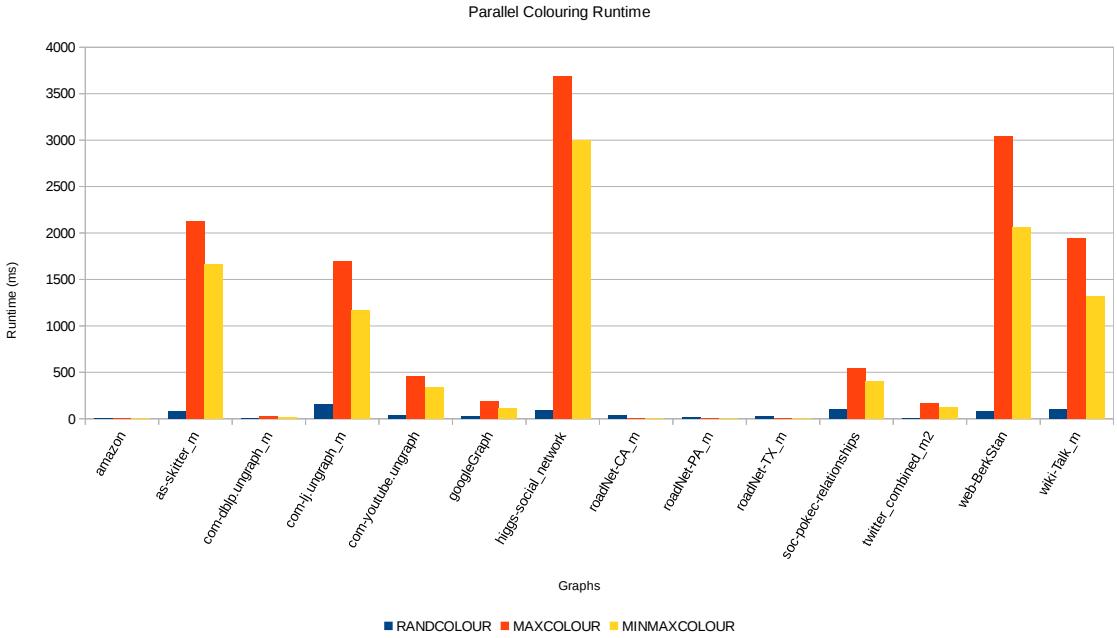


Figure 6.3: RANDCOLOUR vs MAXCOLOUR vs MINMAXCOLOUR: Runtime

We now compare the colour quality produced by the three implementations. This comparison is plotted in Figure 6.4. We can see that RANDCOLOUR is completely at a disadvantage here. It uses almost $\Delta + 1$ colours in all the cases whereas MAXCOLOUR and MINMAXCOLOURS use very few colours. This is again in lines with our approach to the problem. RANDCOLOUR was designed to compromise colour quality for faster runtime. Whereas MAXCOLOUR and MINMAXCOLOUR were designed to compromise runtime for better colour quality. We observe exactly the same from our experiments.

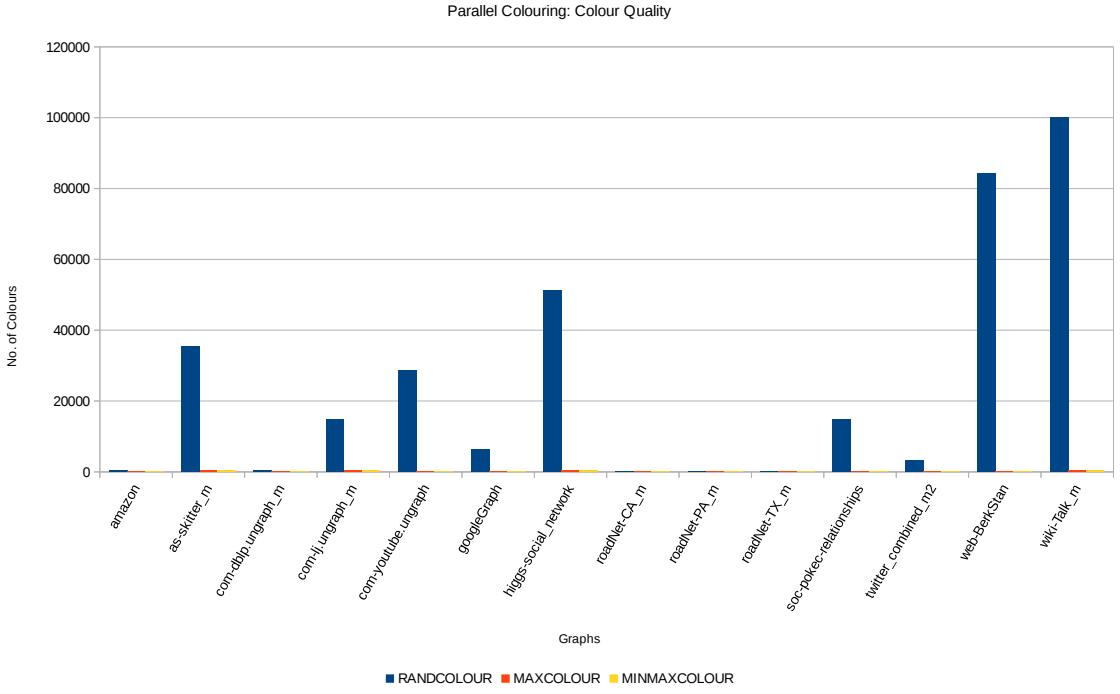


Figure 6.4: RANDCOLOUR vs MAXCOLOUR vs MINMAXCOLOUR: No. of Colours Used

6.3.5 MAXCOLOUR vs MINMAXCOLOUR

As we are ready to compromise runtime for big improvements in colour quality, we prefer MAXCOLOUR and MINMAXCOLOUR over RANDCOLOUR. As we have seen in Figure 6.3, MINMAXCOLOUR outperforms MAXCOLOURS in terms of runtime. Now, we try to see a possible reason for the same.

Both MAXCOLOUR and MINMAXCOLOUR are iterative algorithms which iterates until the whole graph is coloured. MAXCOLOUR finds one Maximal VIS in one iteration and MINMAXCOLOUR finds two Maximal VIS in one iteration. Hence,

MINMAXCOLOUR can possibly finish colouring the entire graph in lesser number of iterations. Lesser number of iterations imply lesser number of kernel calls. Invoking a CUDA Kernel takes some time and hence lesser number of kernel calls can mean lesser runtime for the implementation.

We try to plot the number of iterations endured by both the algorithms. This is given in Figure 6.5. We can clearly see that MINMAXCOLOUR runs for far less iterations compared to MAXCOLOUR. That improves the runtime of MINMAXCOLOUR over MAXCOLOUR as we have seen in Figure 6.3.

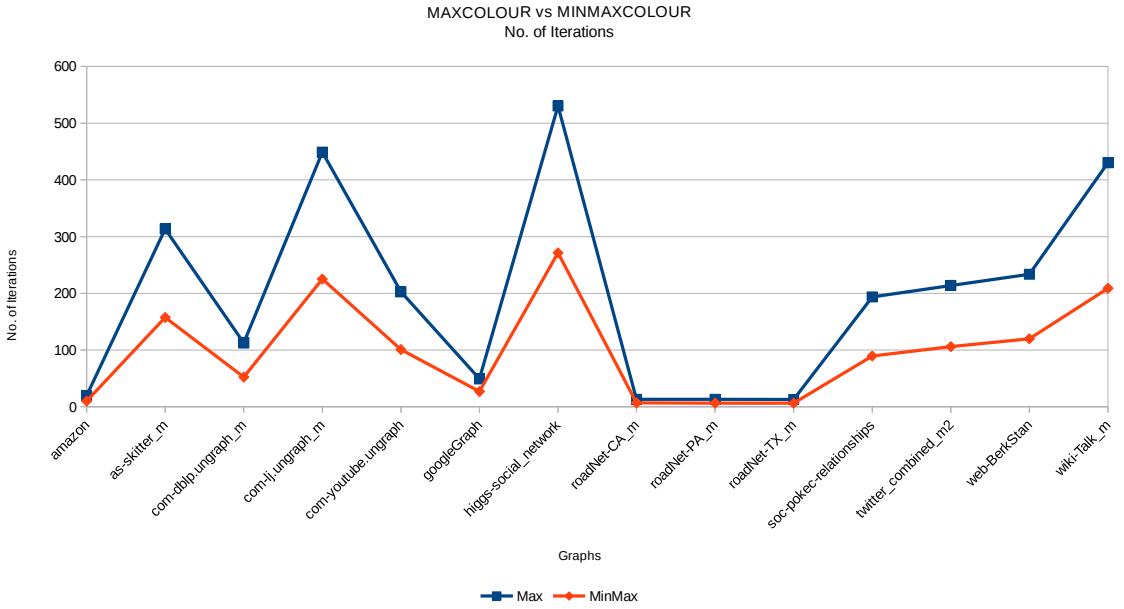


Figure 6.5: MAXCOLOUR vs MINMAXCOLOUR: No. of Iterations

So, we have seen that MINMAXCOLOUR has a better runtime compared to MAXCOLOUR possibly owing to the lesser number of iterations it runs for. But this doesn't necessarily mean MINMAXCOLOUR produces a better colouring compared to MAXCOLOUR. As we have seen in Figure 6.4, MINMAXCOLOUR and MAXCOLOUR produces very good colour quality compared to RANDCOLOUR. Now, we try to find out how their colouring compares to each other. We plot this in Figure 6.6.

As we can clearly see in Figure 6.6, MAXCOLOUR and MINMAXCOLOUR produces almost same colour quality. Still, we prefer MINMAXCOLOUR over MAXCOLOUR as it has a lesser runtime even though both of them produces similar colour quality.

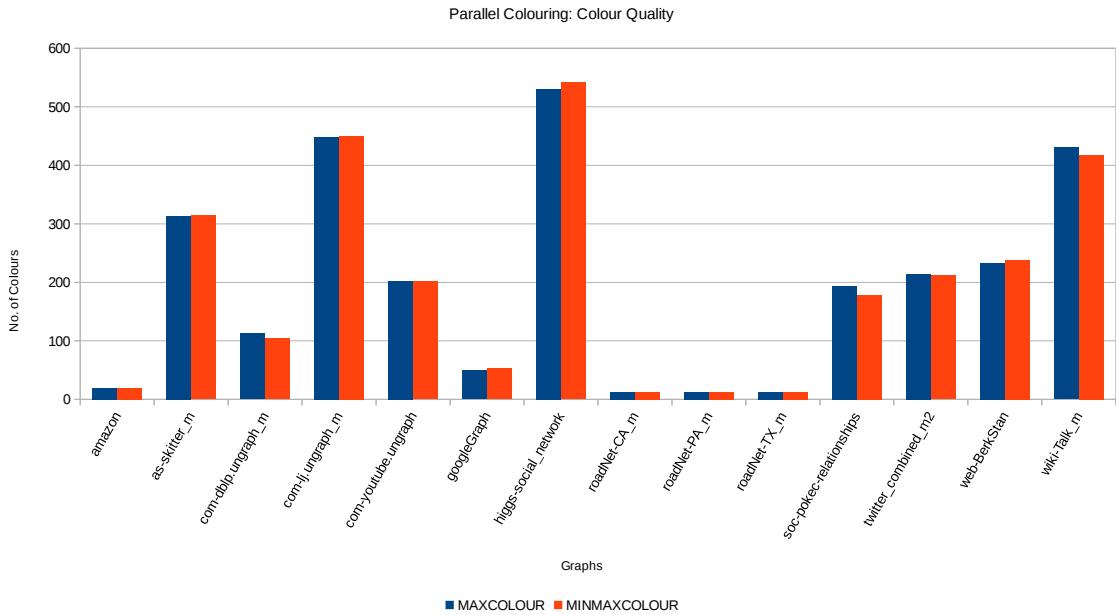


Figure 6.6: MAXCOLOUR vs MINMAXCOLOUR: No. of Colours Used

6.3.6 One Time Propagation

When we tried to implement One Time Propagation for our incremental and decremental implementations as in Algorithm 15, we realized that it can possibly improve the colour quality of MAXCOLOUR and MINMAXCOLOUR too. This is because MAXCOLOUR and MINMAXCOLOUR use different colours in each iteration irrespective of whether the vertices coloured in an iteration could use a colour already used. That approach helps MAXCOLOUR and MINMAXCOLOUR in possibly saving on runtime as less computations are involved. One Time Propagation brings in more computations for possible better colour quality.

We try to plot the change in colour quality of MAXCOLOUR and MINMAXCOLOUR on following themselves with a One Time Propagation. This is given in Figures 6.7 and 6.8. As we can clearly see, One Time Propagation definitely helps in improving the colour quality of both algorithms by a long way.

This improvement in colour quality using One Time Propagation comes with its own cost. As discussed earlier, One Time Propagation involves a decent amount of computation. Hence, it could affect the runtime of the algorithms drastically. So, we try to plot the impact of One Time Propagation on the runtime of MAXCOLOUR and MINMAXCOLOUR in Figures 6.9 and 6.10.

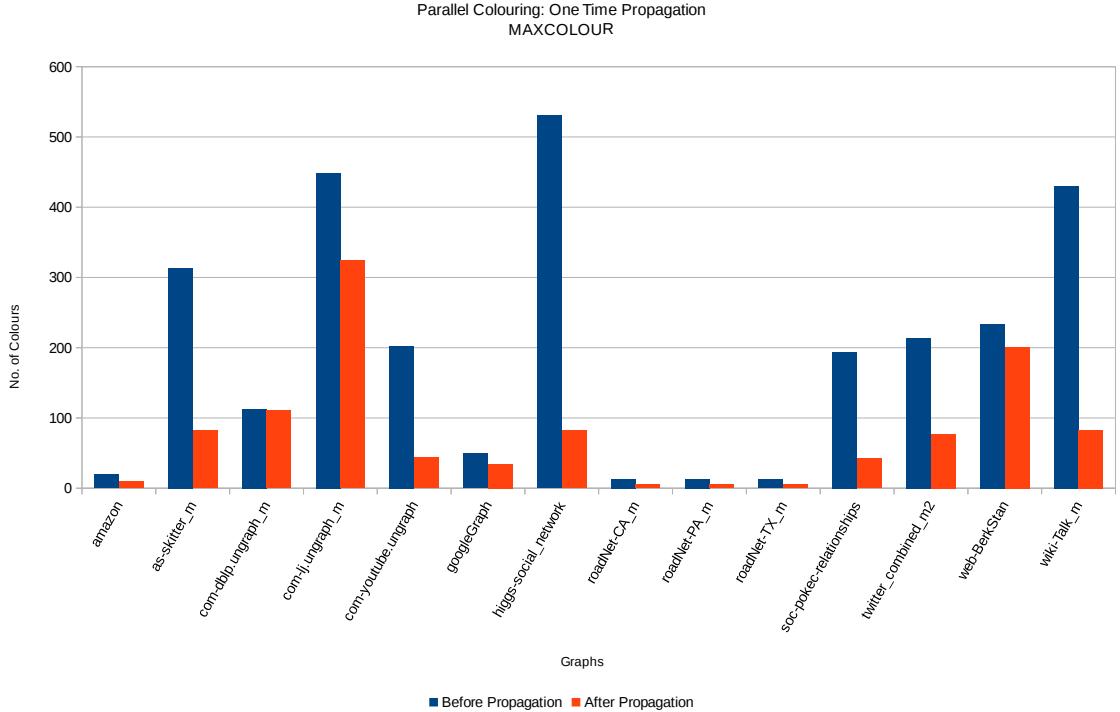


Figure 6.7: MAXCOLOUR: Effect of One Time Propagation on No. of Colours Used

As we can clearly see, One Time Propagation almost doubles the runtime of MAXCOLOUR and MINMAXCOLOUR. So, it depends on our application to decide if we should do a One Time Propagation, thus bettering colour quality and compromising the runtime, or not.

6.4 Incremental Parallel Graph Colouring on GPU

6.4.1 2-Thread Incremental Colouring

We implemented Algorithm 11, which, as we discussed earlier, uses two threads to handle a newly added edge. Number of edges incremented and the respective runtime by 2-Thread Incremental Colouring for our test graphs are tabulated in Table 6.4.

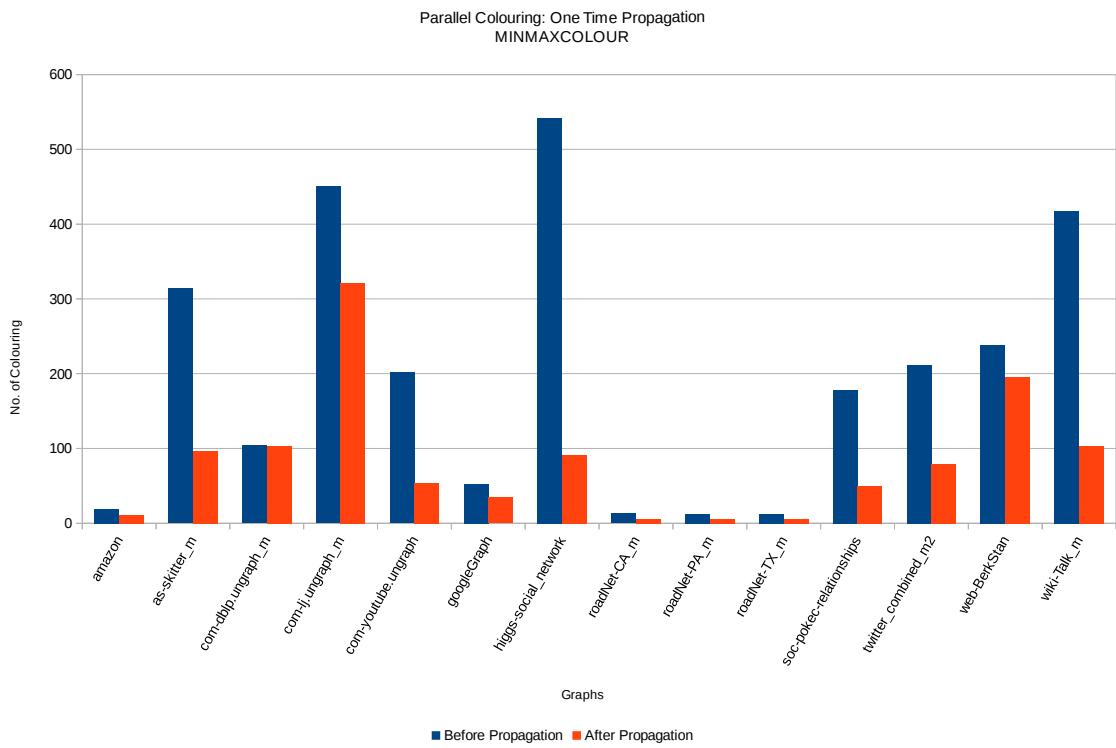


Figure 6.8: MINMAXCOLOUR: Effect of One Time Propagation on No. of Colours Used

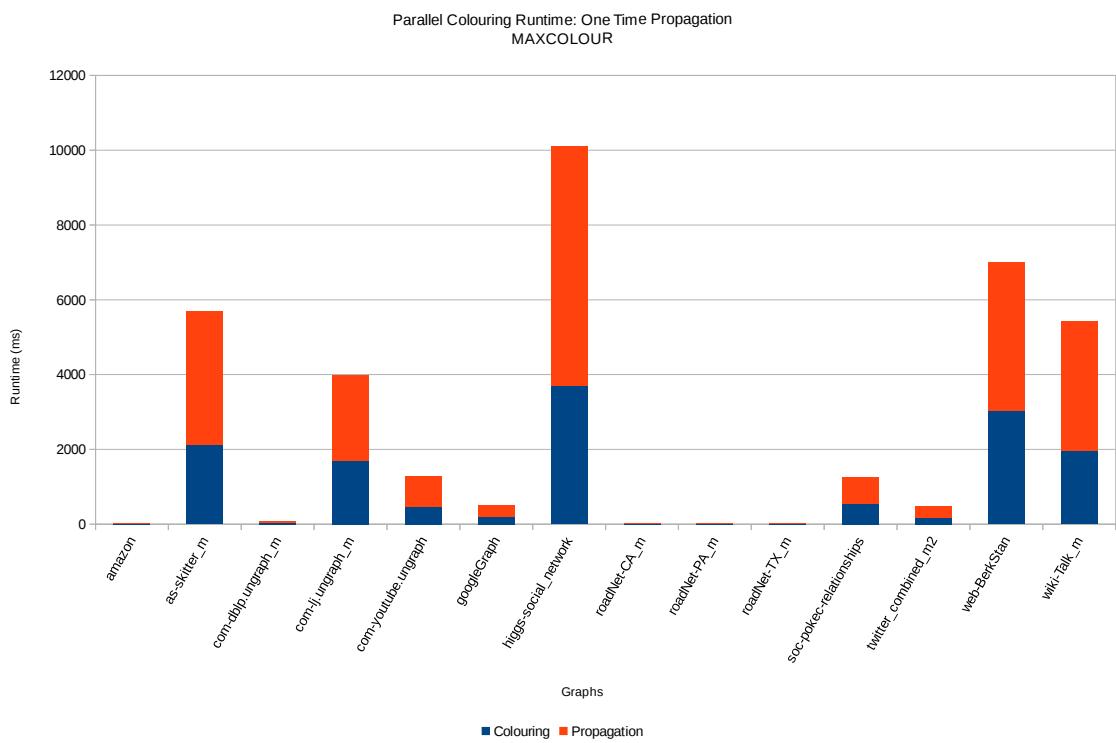


Figure 6.9: MAXCOLOUR: Effect of One Time Propagation on Runtime

No	Name	n	m	Δ	Source
1	amazon	600000	925872	549	Leskovec and Krevl (2014)
2	as-skitter_m	1696415	11095298	35455	Leskovec and Krevl (2014)
3	com-dblp.ungraph_m	425957	1049866	343	Leskovec and Krevl (2014)
4	com-lj.ungraph_m	4036538	34681189	14815	Leskovec and Krevl (2014)
5	com-youtube.ungraph	1157827	2987624	28754	Leskovec and Krevl (2014)
6	facebook	4039	88234	1045	Leskovec and Krevl (2014)
7	gcol1	100	2487	61	Beasley (1990)
8	gcol2	100	2487	70	Beasley (1990)
9	gcol3	100	2482	62	Beasley (1990)
10	gcol4	100	2503	62	Beasley (1990)
11	gcol5	100	2450	63	Beasley (1990)
12	gcol6	100	2537	67	Beasley (1990)
13	gcol7	100	2505	61	Beasley (1990)
14	gcol8	100	2479	63	Beasley (1990)
15	gcol9	100	2486	62	Beasley (1990)
16	gcol10	100	2506	68	Beasley (1990)
17	gcol11	100	2467	60	Beasley (1990)
18	gcol12	100	2531	60	Beasley (1990)
19	gcol13	100	2467	61	Beasley (1990)
20	gcol14	100	2524	65	Beasley (1990)
21	gcol15	100	2528	62	Beasley (1990)
22	gcol16	100	2493	64	Beasley (1990)
23	gcol17	100	2503	63	Beasley (1990)
24	gcol18	100	2472	61	Beasley (1990)
25	gcol19	100	2527	62	Beasley (1990)
26	gcol20	100	2420	59	Beasley (1990)
27	gcol21	300	22482	173	Beasley (1990)
28	gcol22	300	22569	177	Beasley (1990)
29	gcol23	300	22393	175	Beasley (1990)
30	gcol24	300	22446	172	Beasley (1990)
31	gcol25	300	22360	177	Beasley (1990)
32	gcol26	300	22601	179	Beasley (1990)
33	gcol27	300	22327	183	Beasley (1990)
34	gcol28	300	22472	176	Beasley (1990)
35	gcol29	300	22520	176	Beasley (1990)
36	gcol30	300	22543	176	Beasley (1990)
37	googleGraph	916428	4322051	6332	Leskovec and Krevl (2014)
38	higgs-social_network	456626	12508413	51386	Leskovec and Krevl (2014)
39	roadNet-CA_m	1971281	2766607	12	Leskovec and Krevl (2014)
40	roadNet-PA_m	1090920	1541898	9	Leskovec and Krevl (2014)
41	roadNet-TX_m	1393383	1921660	12	Leskovec and Krevl (2014)
42	soc-pokec-relationships	1632803	22301964	14854	Leskovec and Krevl (2014)
43	soc-Slashdot0811_m	77360	469180	2539	Leskovec and Krevl (2014)
44	soc-Slashdot0902_m	82168	504230	2552	Leskovec and Krevl (2014)
45	twitter_combined_m2	81306	1342296	3383	Leskovec and Krevl (2014)
46	web-BerkStan	685230	6649470	84230	Leskovec and Krevl (2014)
47	wiki-Talk_m	2394385	4659565	100029	Leskovec and Krevl (2014)

Graph	Runtime (ms)	No. of Colours Used
amazon	8.47027	20
as-skitter_m	2131.9	313
com-dblp.ungraph_m	28.1163	112
com-lj.ungraph_m	1691.93	449
com-youtube.ungraph	461.461	203
googleGraph	188.109	49
higgs-social_network	3682.62	530
roadNet-CA_m	5.62559	13
roadNet-PA_m	3.29859	13
roadNet-TX_m	4.07131	13
soc-pokec-relationships	543.96	194
twitter_combined_m2	168.604	214
web-BerkStan	3038.64	234
wiki-Talk_m	1943.2	430

Table 6.2: MAXCOLOUR

Graph	Runtime (ms)	No. of Colours Used
amazon	6.12398	19
as-skitter_m	1662.08	314
com-dblp.ungraph_m	16.3007	104
com-lj.ungraph_m	1171.55	450
com-youtube.ungraph	337.952	202
googleGraph	116.477	53
higgs-social_network	3000.45	542
roadNet-CA_m	5.0902	13
roadNet-PA_m	2.92264	12
roadNet-TX_m	3.65121	12
soc-pokec-relationships	404.37	178
twitter_combined_m2	121.206	212
web-BerkStan	2067.15	239
wiki-Talk_m	1313.37	417

Table 6.3: MINMAXCOLOUR

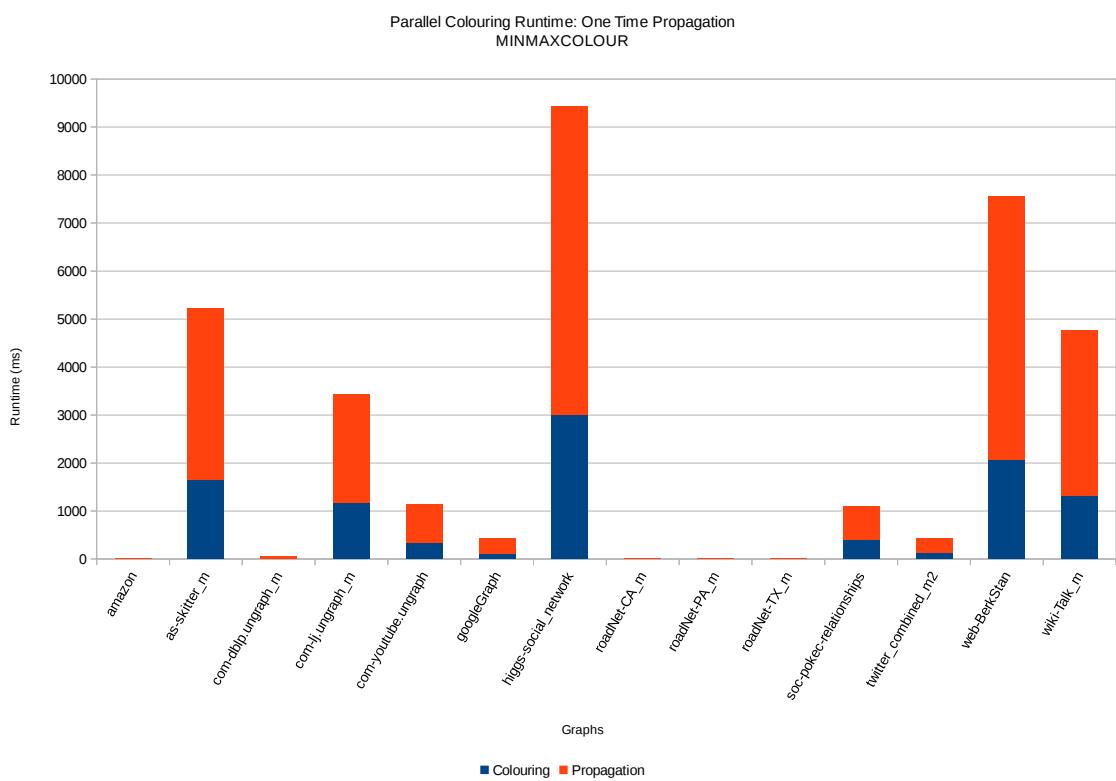


Figure 6.10: MINMAXCOLOUR: Effect of One Time Propagation on Runtime

Graph	No. of Edge Additions	Incremental Runtime (ms)
amazon	30018	808.10
as-skitter_m	29724	34399.40
com-dblp.ungraph_m	30122	1057.09
com-lj.ungraph_m	30032	2919.95
com-youtube.ungraph	29802	12169.20
googleGraph	29877	4739.38
higgs-social_network	29752	55435.40
roadNet-CA_m	29819	772.53
roadNet-PA_m	30111	785.72
roadNet-TX_m	30013	782.08
soc-pokec-relationships	29963	2226.85
twitter_combined_m2	30164	3926.37
wiki-Talk_m	29806	61138.70

Table 6.4: 2-Thread Incremental Colouring

Graph	No. of Edge Additions	Incremental Runtime (ms)
amazon	30018	1030.13
as-skitter_m	29724	387355.00
com-dblp.ungraph_m	30122	2688.64
com-lj.ungraph_m	30032	16552.40
com-youtube.ungraph	29802	72534.60
googleGraph	29877	15921.50
higgs-social_network	29752	392153.00
roadNet-CA_m	29819	386.82
roadNet-PA_m	30111	399.70
roadNet-TX_m	30013	388.68
soc-pokec-relationships	29963	8345.85
twitter_combined_m2	30164	59531.60
wiki-Talk_m	29806	508009.00

Table 6.5: Many Thread Incremental Colouring

6.4.2 Many Thread Incremental Colouring

We implemented Algorithm 12, which, as we discussed earlier, tries to parallelize the 2-Thread Incremental Colouring. Number of edges incremented and the respective runtime by Many Thread Incremental Colouring for our test graphs are tabulated in Table 6.5.

6.4.3 2-Thread Incremental vs Many Thread Incremental

The 2-Thread model (Algorithm 11) uses only two threads per addition of a new edge. Whereas, the Many Thread model (Algorithm 12) tries to maximize the number of threads used by clubbing upto 1024 newly added edges together for processing. So, the Many Thread Model tries to decrease the number of kernel calls, increase the number of threads spawned and increase parallelism. But this comes at a cost. The process by which Many Thread model clubs different edges together for parallel processing is computation intensive.

We try to plot the number of kernel calls by both implementations for our test graphs. This is given in Figure 6.11. As we can clearly see, Many Threads model calls the kernel much fewer times compared to the 2-Threads model.

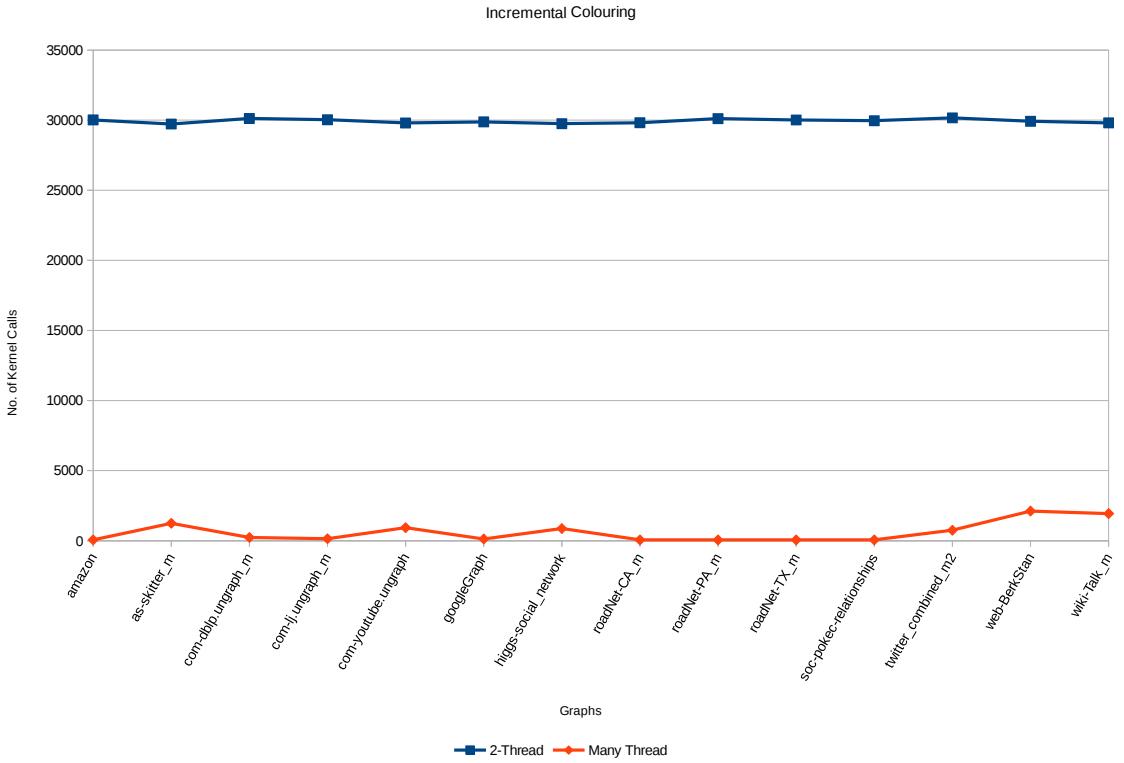


Figure 6.11: 2-Thread Incremental vs Many Thread Incremental: No. of Kernel Calls

Many Thread model calling the kernel much fewer times needn't necessarily point to a smaller runtime as the process employed by the Many Thread model to achieve the same is computation intensive. So, we plot the runtime of 2-Thread model and Many Thread model for our test graphs. This is given in Figure 6.12.

We can see that the Many Thread model is computationally very intensive and the

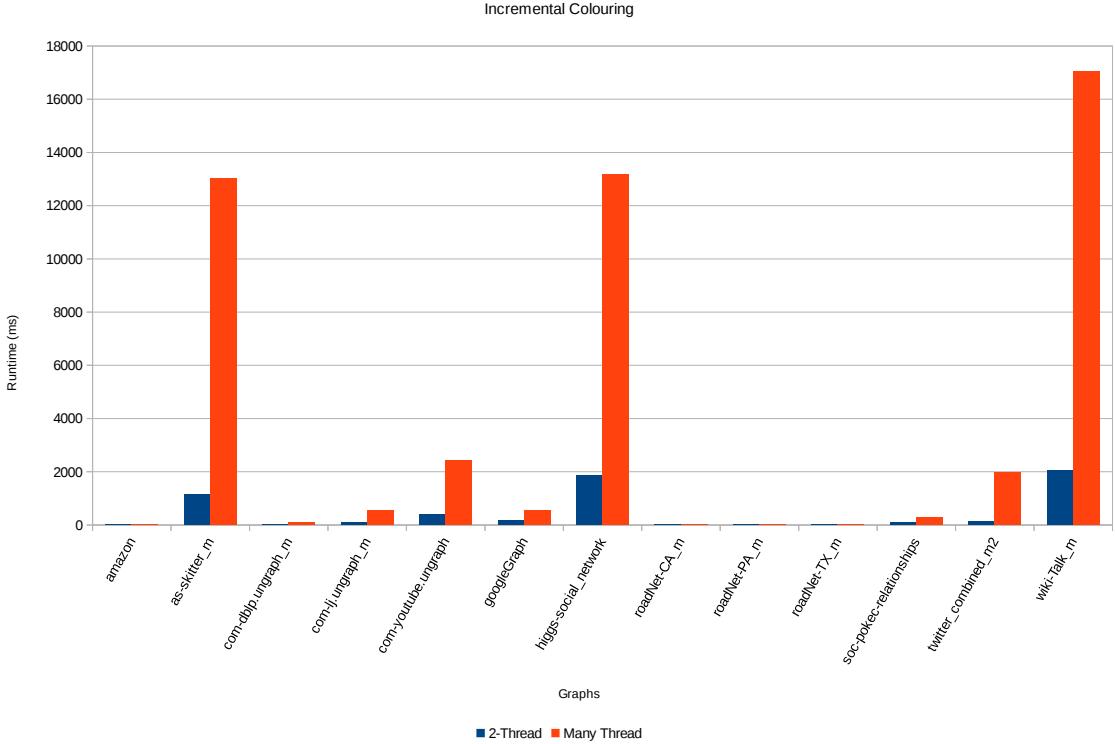


Figure 6.12: 2-Thread Incremental vs Many Thread Incremental: Runtime

runtime is very high compared the 2-Thread model. As the Many Thread model is technically just a parallelized version of the already parallel 2-Thread model, both algorithms should produce similar colour quality. We try to verify this by plotting the colour quality produced by both approaches. This is given in Figure 6.13. We can see that both the models produce similar colour quality.

6.4.4 One Time Propagation

Now that we have identified that the 2-Thread Model is better than the Many Thread Model, we try to improve the colouring produced by the 2-Thread Model by employing One Time Propagation as in Algorithm 15.

Incremental colouring assumes that the initial graph is already coloured. After the addition of edges, the colour quality can possibly get worse. We try to plot the difference in colour quality brought upon by the 2-Thread Model on our test graphs and the impact One Time Propagation has on bettering the colour quality. This is given in Figure 6.14.

Though we have established Many Thread Incremental Colouring is a computation-

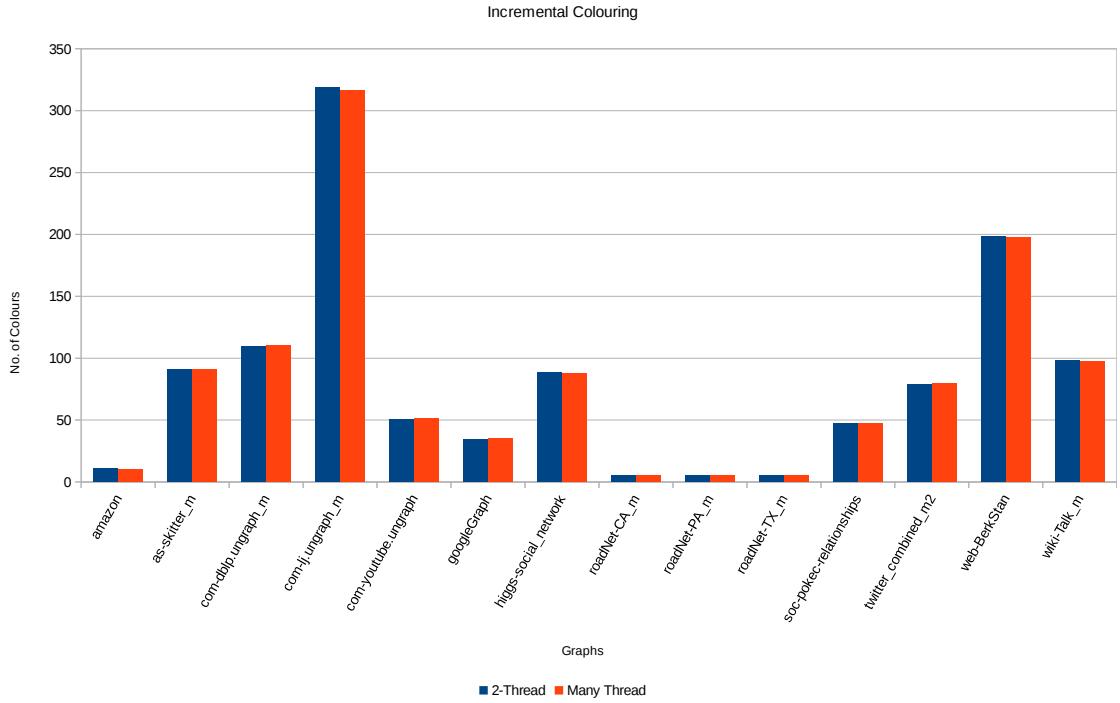


Figure 6.13: 2-Thread Incremental vs Many Thread Incremental: No. of Colours Used

ally bad model, we try to plot the impact of One Time Propagation on the colour quality in its case also. It's given in Figure 6.15.

From Figure 6.14, we can see that the locally optimizing technique of the 2-Thread Model does well enough to maintain the colour quality of the graph on addition of new edges. We also see that One Time Propagation doesn't really have much of an impact on the colour quality. In most cases, it betters the colour quality by a very small extent. On an average, it improves the colouring produced by the 2-Thread Incremental model by 2 colours.

We now try to evaluate the impact of One Time Propagation on the runtime of 2-Thread Incremental Model. We plot the runtime with the One Time Propagation component separated in Figure 6.16. As we can see, One Time Propagation doesn't have much of an overhead on the runtime of 2-Thread Incremental Model. But whatever extra runtime it brings in might not always justify the 2 colours it saves on average. So, again, it is application dependent as to if we should use One Time Propagation or not.

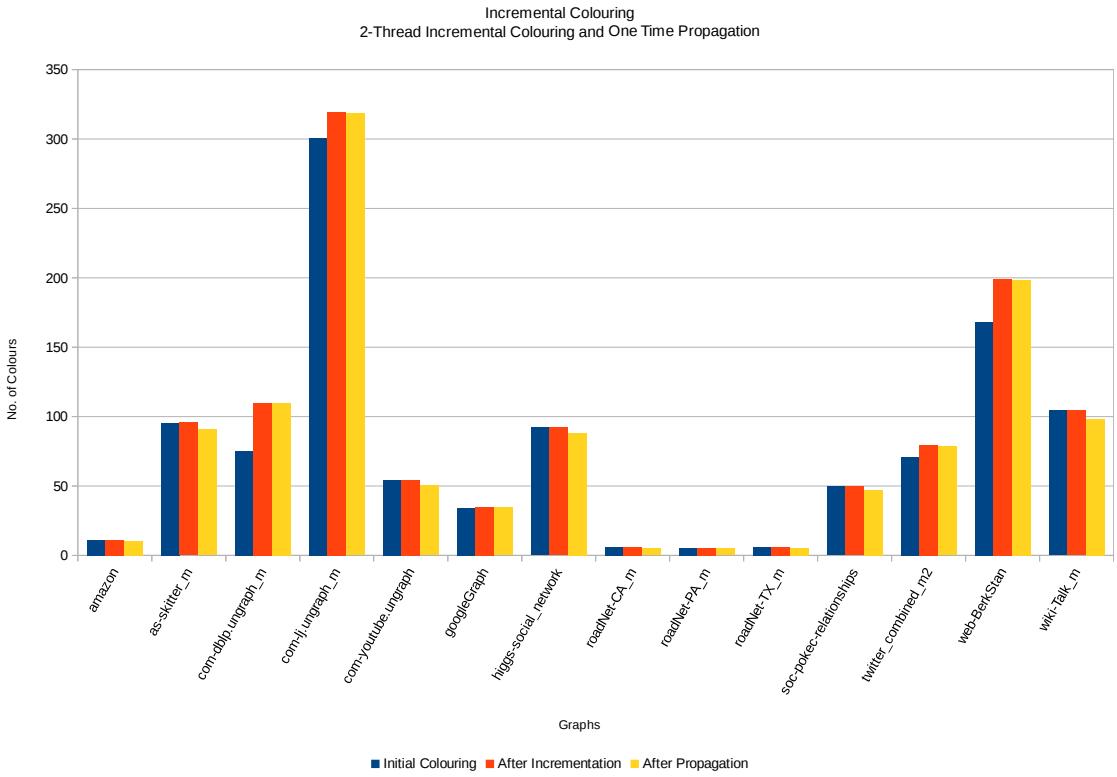


Figure 6.14: 2-Thread Incremental Model and One Time Propagation: No. of Colours Used

6.4.5 One Time Propagation vs Wave Propagation

We have already theoretically established that Wave Propagation can be computationally heavy because of the way it handles the ripple effect. Here, we try to see if Wave Propagation actually does better than One Time Propagation or not and how really heavy it is on computation.

First of all, we compare the percentage increase in colour quality that both propagation technique brings in. That is, we try to see the percentage decrease in the total number of colours used. We plot it for both our 2-Thread Incremental Model and the Many Thread Incremental Model in Figures 6.17 and 6.18.

We can establish here from our experiments that, on an average, Wave Propagation is only as effective as One Time Propagation if not negligently better.

As discussed earlier, Wave Propagation comes with its own overhead on runtime. We plot the same for both our 2-Thread Incremental Model and the Many Thread Incremental Model in Figures 6.19 and 6.20. We can see that Wave Propagation is very

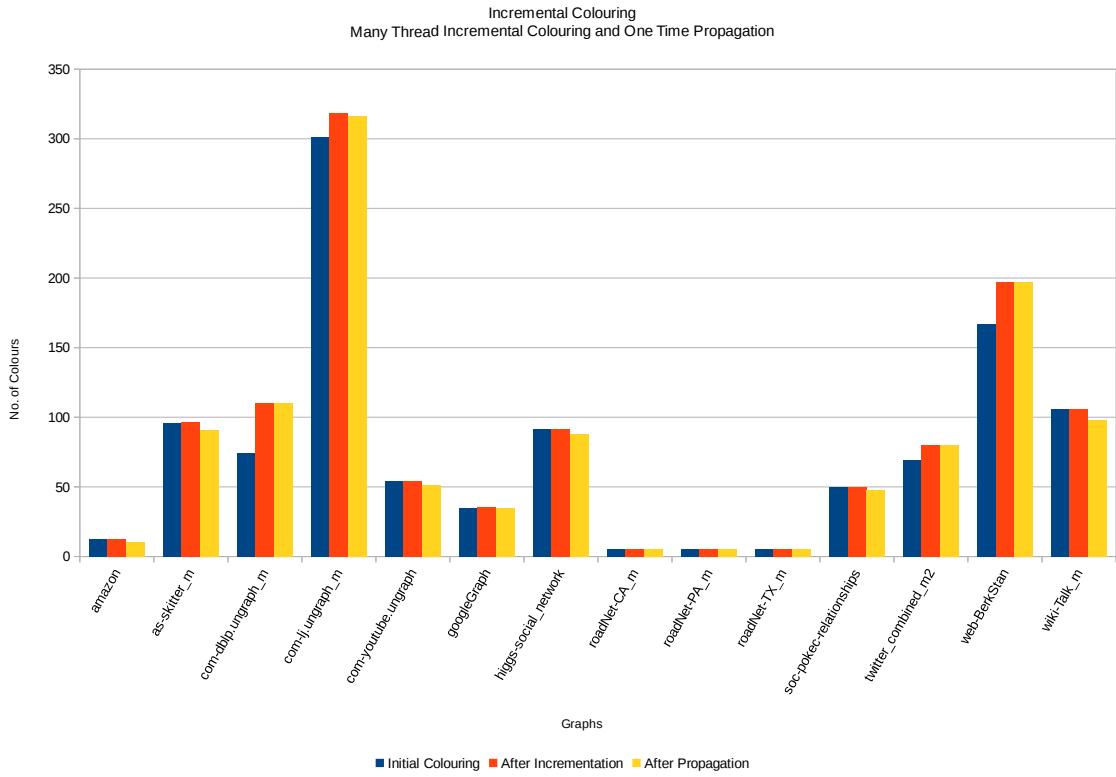


Figure 6.15: Many Thread Incremental Model and One Time Propagation: No. of Colours Used

expensive in terms of runtime.

6.5 Decremental Parallel Graph Colouring on GPU

6.5.1 2-Thread Decremental Colouring

We implemented Algorithm 13, which, as we discussed earlier, uses two threads to handle a newly deleted edge. Number of edges decremented and the respective runtime by 2-Thread Decremental Colouring for our test graphs are tabulated in Table 6.6.

6.5.2 Many Thread Decremental Colouring

We implemented Algorithm 14, which, as we discussed earlier, tries to remove a set of edges in parallel. Number of edges decremented and the respective runtime by Many Thread Decremental Colouring for our test graphs are tabulated in Table 6.7.

Graph	No. of Edge Deletions	Decremental Runtime (ms)
amazon	30018	771.47
as-skitter_m	29724	82801.70
com-dblp.ungraph_m	30122	1215.35
com-lj.ungraph_m	30032	6378.97
com-youtube.ungraph	29802	28674.60
googleGraph	29877	10598.10
higgs-social_network	29752	139029.00
roadNet-CA_m	29819	303.67
roadNet-PA_m	30111	306.49
roadNet-TX_m	30013	304.56
soc-pokec-relationships	29963	5117.94
twitter_combined_m2	30164	8654.66
web-BerkStan	29922	233072.00
wiki-Talk_m	29806	157034.00

Table 6.6: 2-Thread Decremental Colouring

Graph	No. of Edge Deletions	Decremental Runtime (ms)
amazon	30018	0.45
as-skitter_m	29724	14.32
com-dblp.ungraph_m	30122	0.37
com-lj.ungraph_m	30032	5.87
com-youtube.ungraph	29802	11.79
googleGraph	29877	3.68
higgs-social_network	29752	34.57
roadNet-CA_m	29819	0.24
roadNet-PA_m	30111	0.22
roadNet-TX_m	30013	0.23
soc-pokec-relationships	29963	6.35
twitter_combined_m2	30164	2.44
web-BerkStan	29922	46.35
wiki-Talk_m	29806	40.47

Table 6.7: Many Thread Decremental Colouring

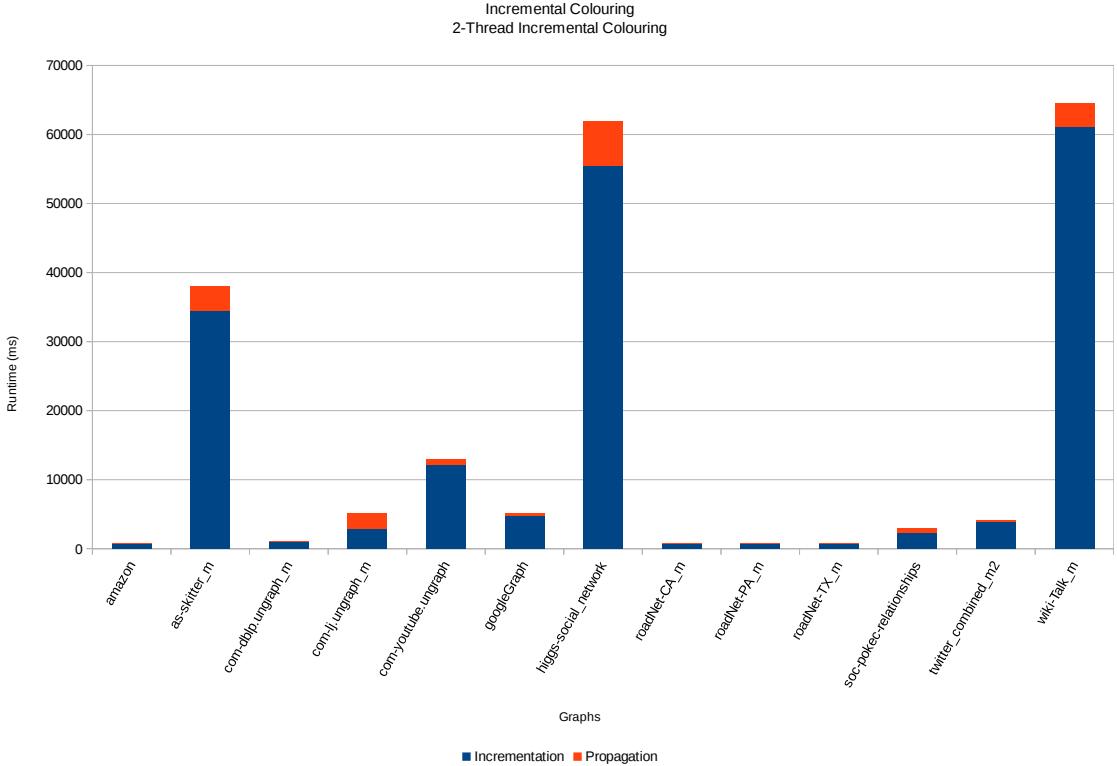


Figure 6.16: 2-Thread Incremental Model and One time Propagation: Runtime

6.5.3 2-Thread Decremental vs Many Thread Decremental

The 2-Thread model (Algorithm 13) uses only two threads per deletion of a new edge. Whereas, the Many Thread model (Algorithm 14) clubs many edges and deletes them together. The Many Thread Model maximises parallelism and calls the kernel only once. But it does no effort to improve the colouring unlike the 2-Thread Decremental model which tries to locally optimize colouring.

The Many Thread Decremental model must run really fast as it decrements all the edges together in one parallel process and does no computation to improve colouring. The 2-Thread Decremental Model must definitely be slower as it calls the kernel for each edge deletion and also tries to locally optimize colouring in each kernel call. We plot the runtime of both the algorithms for our test graphs. This is given in Figure 6.21.

We can clearly see that Many Thread Decremental Colouring outperforms the 2-Thread Decremental Model by a big margin in terms of runtime. The Many Thread model takes very less time, as expected, as it is fully parallelized and involves very less computation. But it's not really fair to compare the both as the 2-Thread model spends

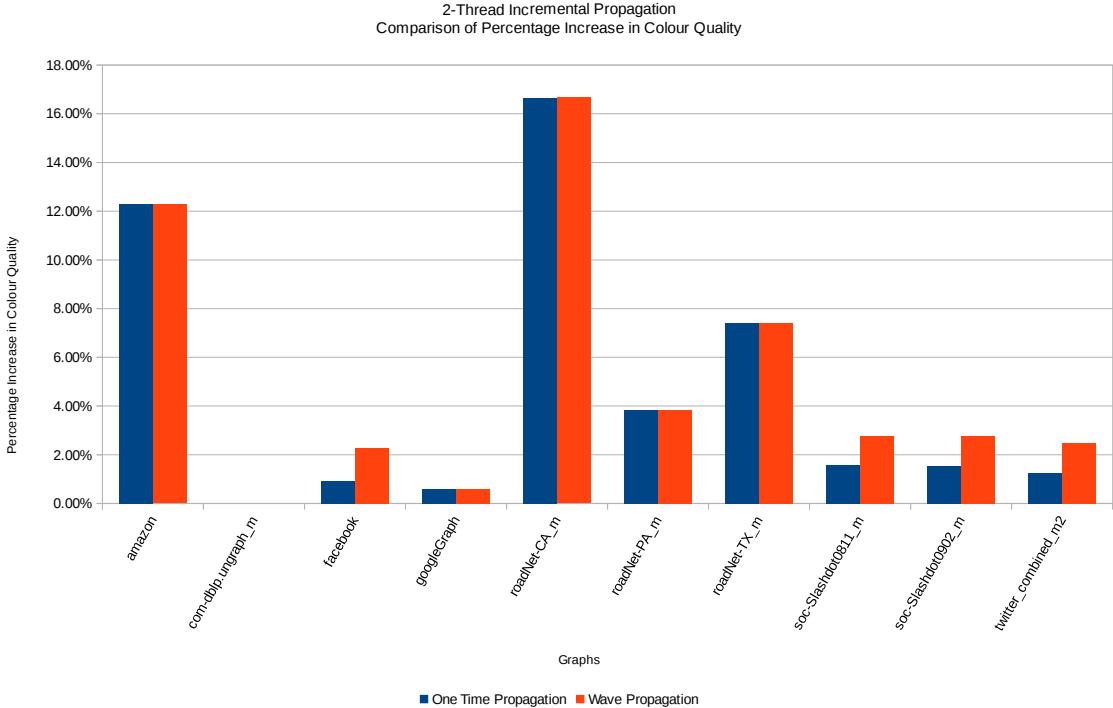


Figure 6.17: One time Propagation vs Wave Propagation: 2-Thread Model, Colour Quality

time in trying to improve the colouring. The Many Thread model has to depend on propagation to improve the colouring. So, we plot the colour quality produced by the two models without propagation. This is given in Figure 6.22.

The Many Thread Model ofcourse just keeps the existing colouring whereas the 2-Thread model tries to locally improve it. This can be observed from the plot.

6.5.4 One Time Propagation

So, we have established that the Many Thread model is really fast compared to the 2-Thread model. But then, the Many Thread model doesn't improve the existing colouring which might be possible as edges are deleted. Chances of improvement in colouring is definitely higher during deletion of edges compared to addition of edges.

In the case of the 2-Thread model, after the deletion of edges, the colour quality can possibly improve. We try to plot the difference in colour quality brought upon by the 2-Thread Model on our test graphs and the impact One Time Propagation has on bettering the colour quality. This is given in Figure 6.23.

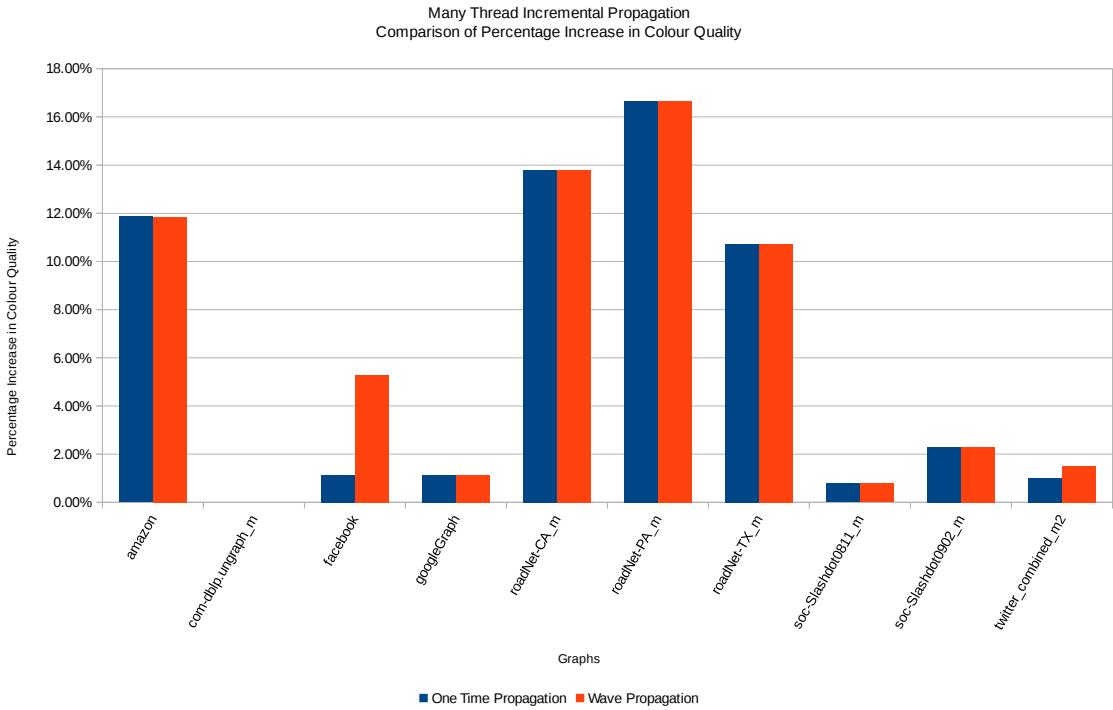


Figure 6.18: One time Propagation vs Wave Propagation: Many Thread Model, Colour Quality

We can clearly see the local optimization of colouring by the 2-Thread model. It improves the colouring after the deletion of edges. One Time Propagation helps in improving the colour quality further. In most cases, the improvement in colouring done by the 2-Thread model itself is significant.

In the case of the Many Thread model, after the deletion of edges, the colouring is not changed. We try to plot the maintenance of initial colouring by the Many Thread Model on our test graphs and the impact One Time Propagation has on bettering the colour quality. This is given in Figure 6.24.

We can see that the Many Thread model merely keeps the initial colouring untouched and that the One Time Propagation improves the colour quality significantly.

We now compare the colour quality produced by both the models after One Time Propagation. This is given in 6.25. We can see that both the models perform nearly similarly.

As we have already established, the Many Thread model outperforms the 2-Thread model with a big margin in terms of runtime. One Time Propagation itself contributes to the runtime. As we have established that the 2-Thread model itself can improve the

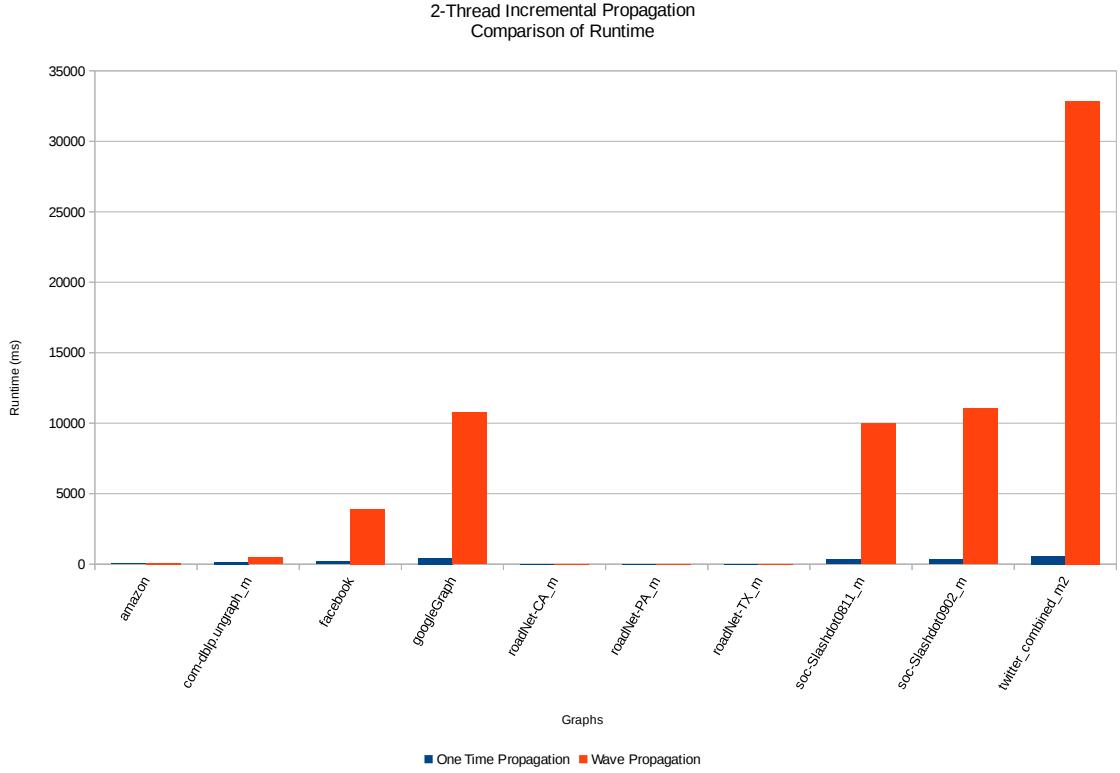


Figure 6.19: One time Propagation vs Wave Propagation: 2-Thread Model, Runtime

colouring significantly without the help of One Time Propagation and that its runtime is already much higher than that of the Many Thread model, from here on, we will consider the 2-Thread model without One Time Propagation and the Many Thread model with One Time Propagation.

We first compare the runtime of the 2-Thread model without One Time Propagation and the Many Thread model with One Time Propagation. This is given in Figure 6.26.

From the figure, we can see that Many Thread model with One Time Propagation outperforms 2-Thread model without One Time Propagation by a big margin in terms of runtime. We will now try to compare their colour quality. This is given in Figure 6.27.

We can see that the number of colours used by both the approaches are very similar. The Many Thread model has a slightly better colouring, thanks to the One Time Propagation. Also, as we have that it performs much better than the 2-Thread model in terms of runtime, Many Thread Decremental Colouring followed by One Time Propagation seems to be the best option for decremental colouring.

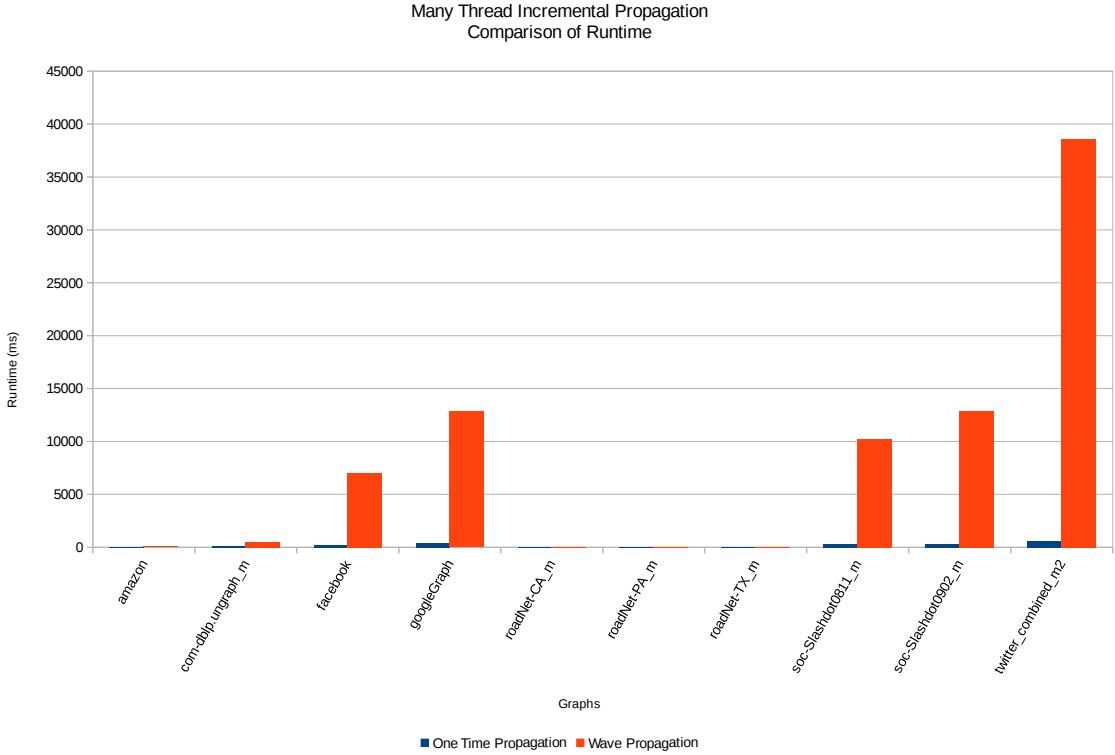


Figure 6.20: One time Propagation vs Wave Propagation: Many Thread Model, Runtime

6.5.5 One Time Propagation vs Wave Propagation

We already know how computationally heavy Wave Propagation is. We try to see if it can bring in a significant improvement in colouring so as to justify the cost involved in terms of runtime.

First of all, we compare the percentage increase in colour quality that both propagation technique brings in. That is, we try to see the percentage decrease in the total number of colours used. We plot it for both our 2-Thread Decremental Model and the Many Thread Decremental Model in Figures 6.28 and 6.29.

As discussed in the incremental colouring section, we can establish from our experiments that, on an average, Wave Propagation is only as effective as One Time Propagation if not slightly better.

As discussed earlier, Wave Propagation comes with its own overhead on runtime. We plot the same for both our 2-Thread Decremental Model and the Many Thread Decremental Model in Figures 6.30 and 6.31. We can see that Wave Propagation is very expensive in terms of runtime.

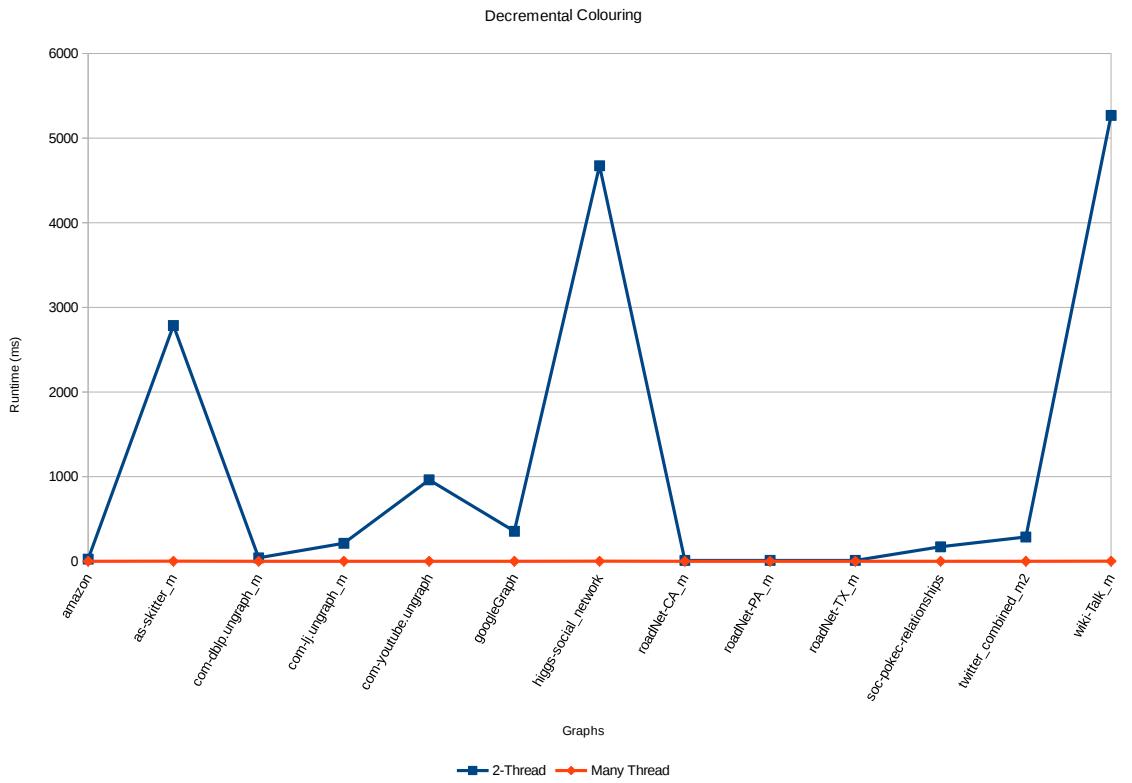


Figure 6.21: 2-Thread Decremental vs Many Thread Decremental: Runtime

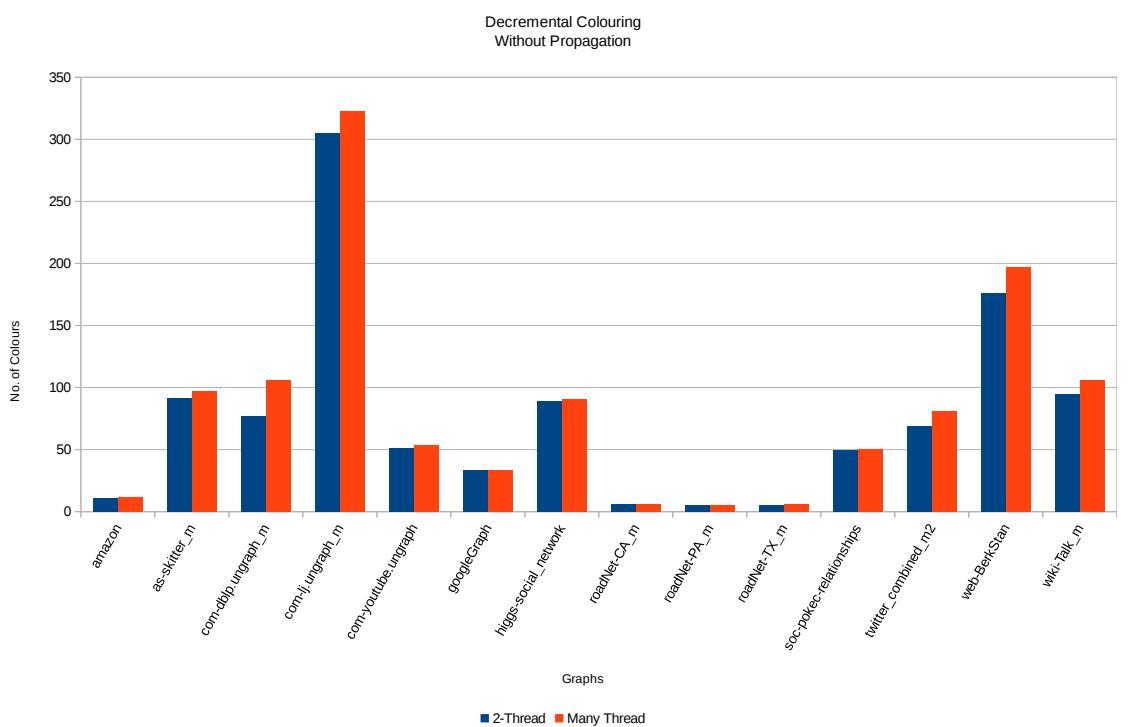


Figure 6.22: 2-Thread Decremental vs Many Thread Decremental: No. of Colours Used

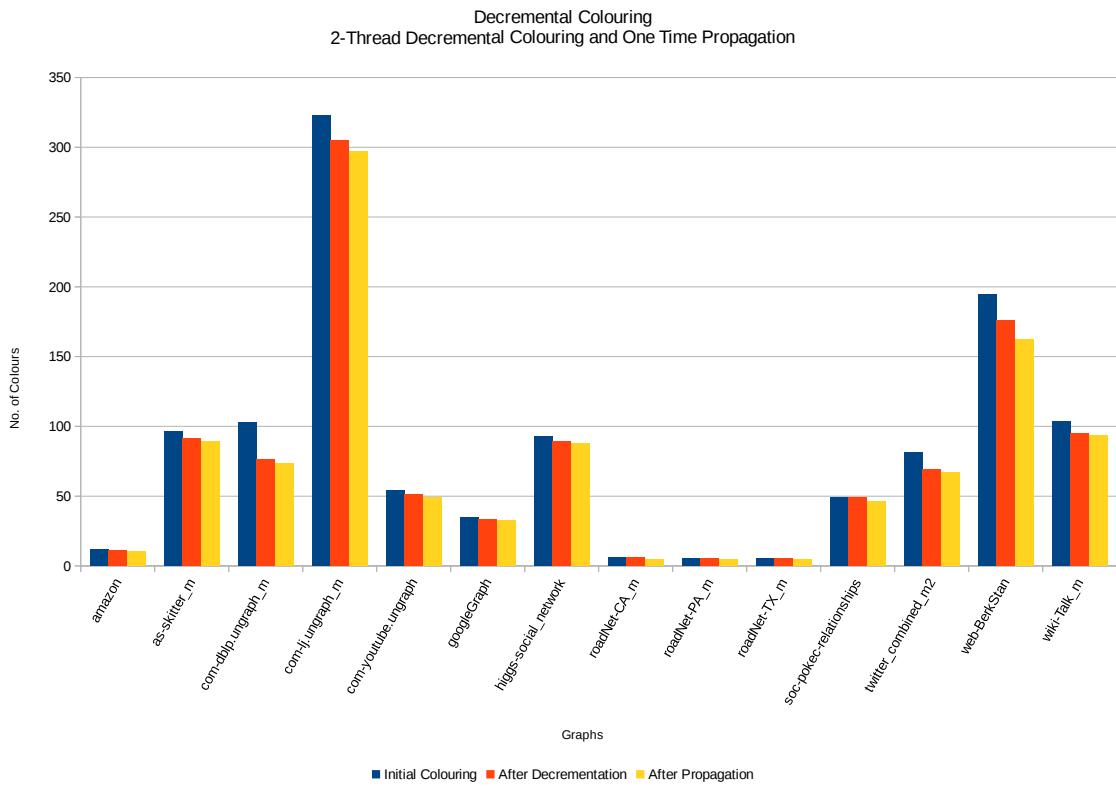


Figure 6.23: 2-Thread Decremental and One Time Propagation: No. of Colours Used

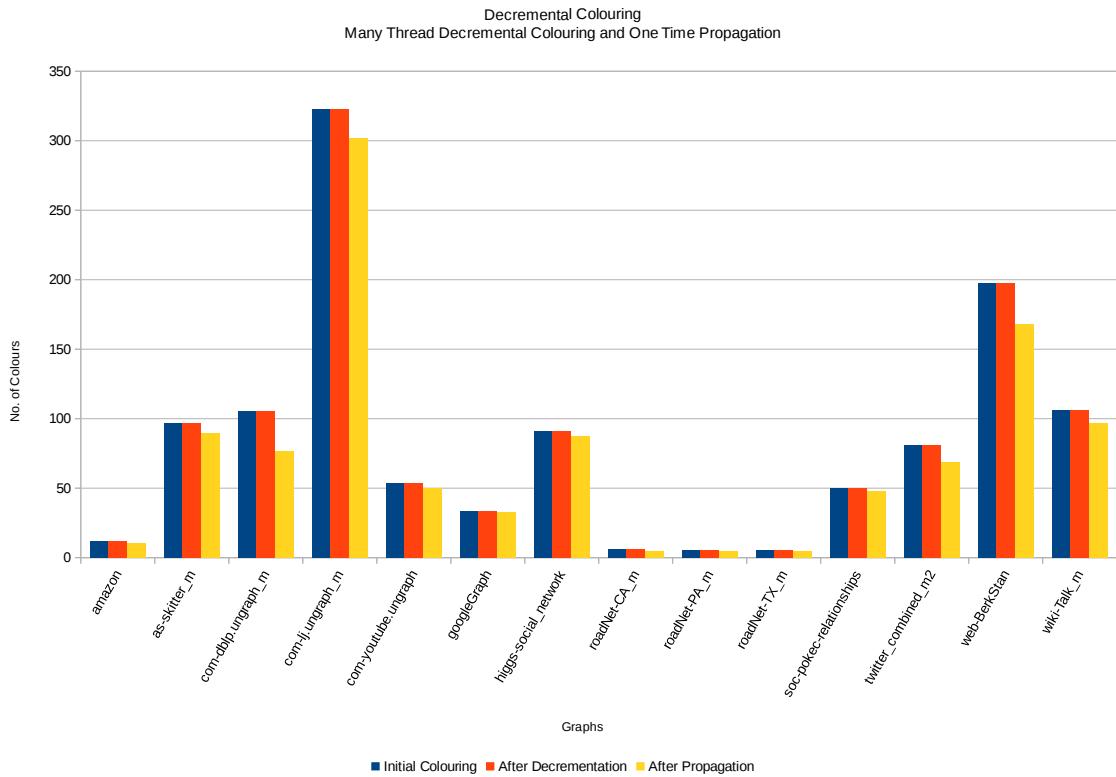


Figure 6.24: Many Thread Decremental and One Time Propagation: No. of Colours Used

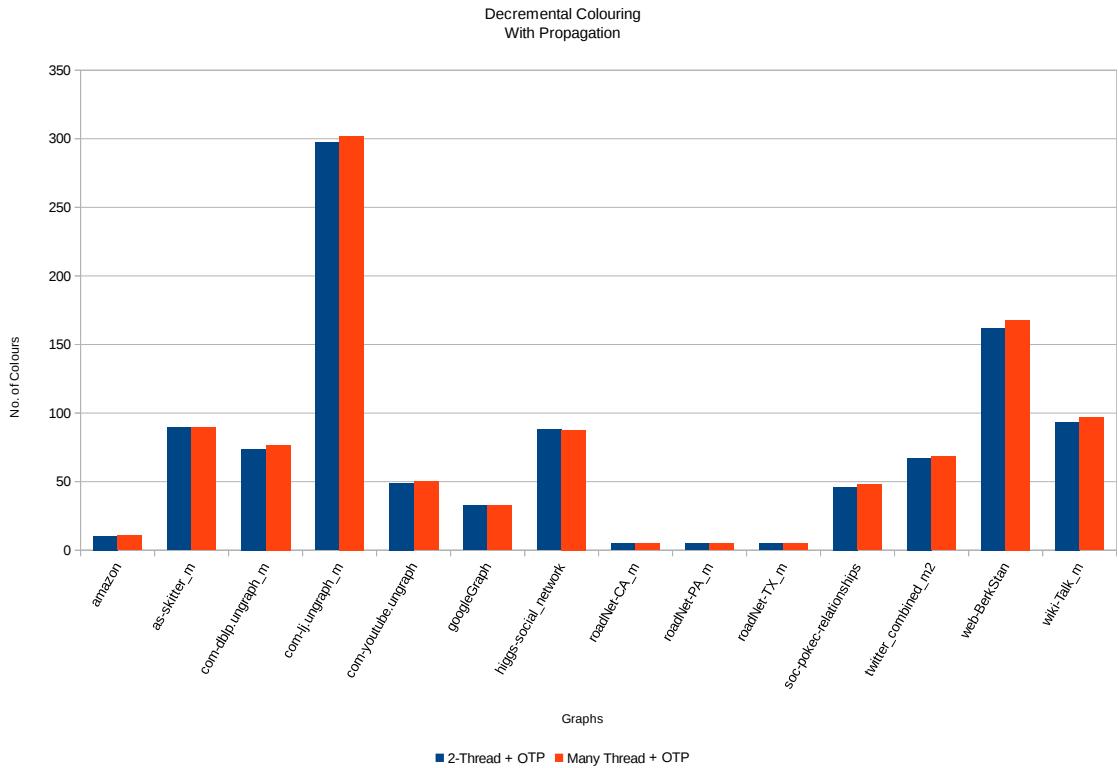


Figure 6.25: 2-Thread Decremental vs Many Thread Decremental: No. of Colours Used After One Time Propagation

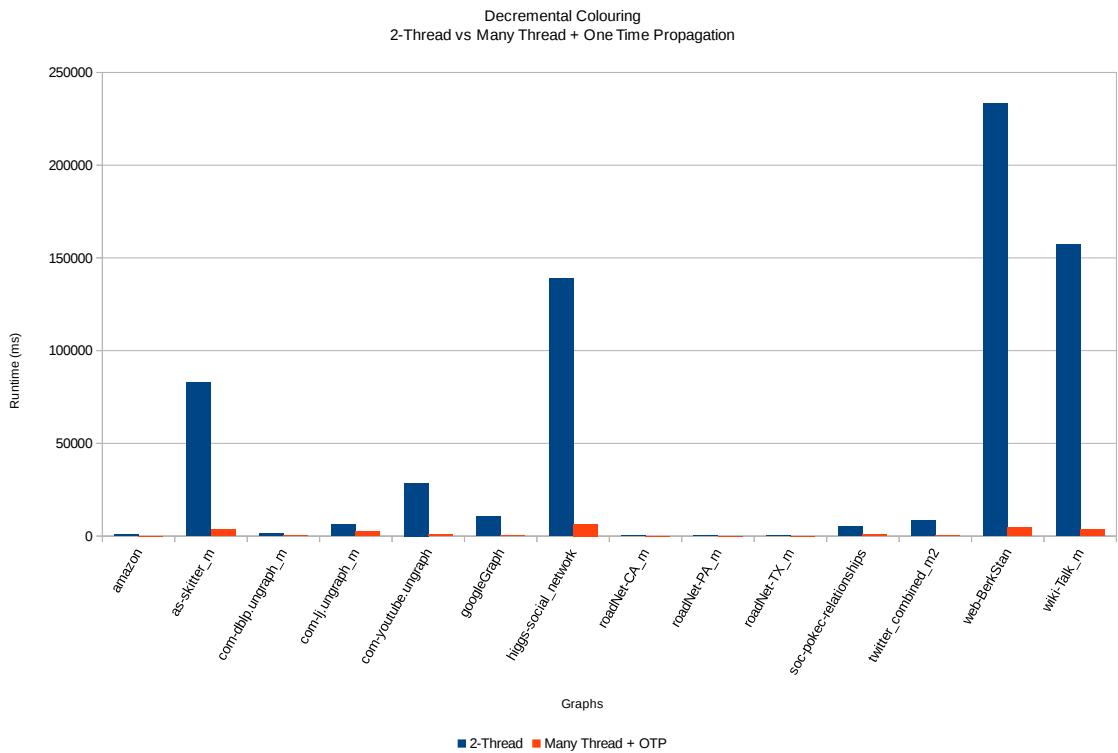


Figure 6.26: 2-Thread Decremental vs Many Thread Decremental + OTP: Runtime

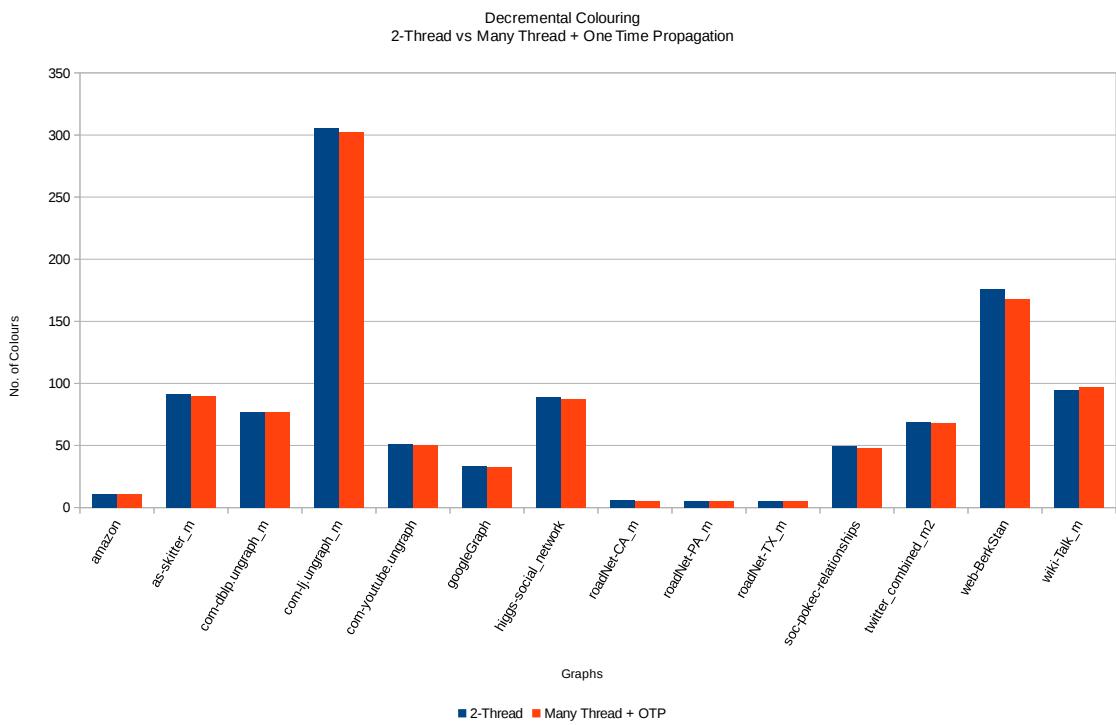


Figure 6.27: 2-Thread Decremental vs Many Thread Decremental + OTP: No. of Colours Used

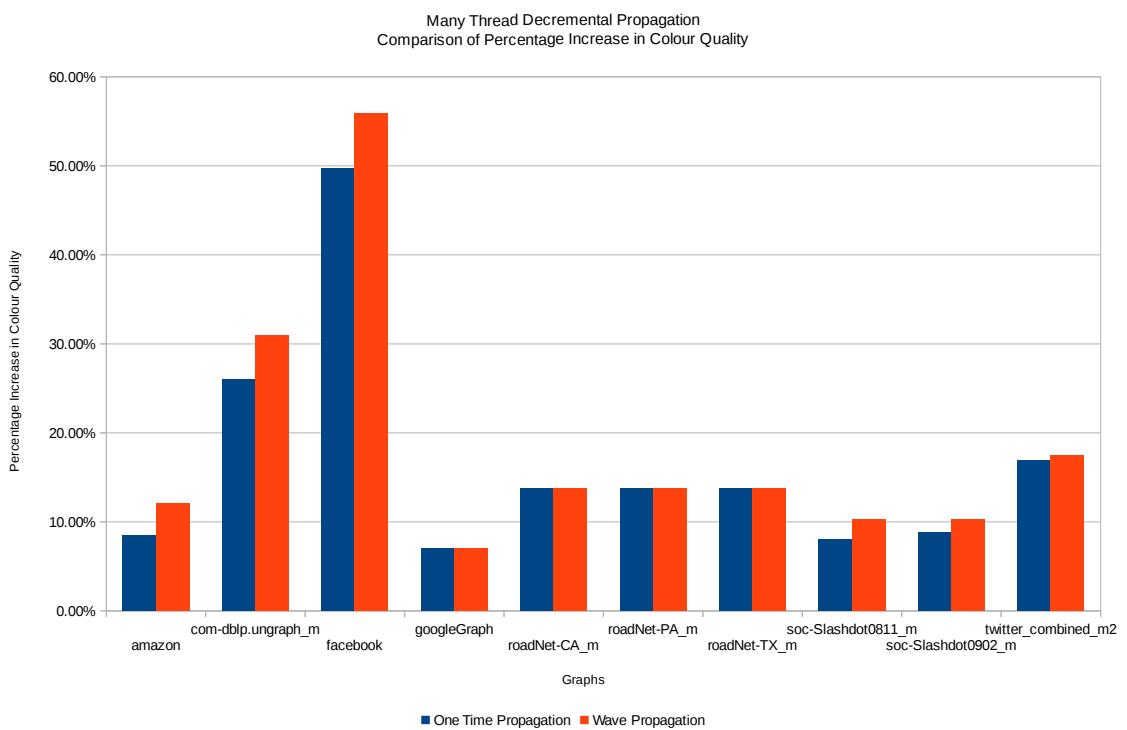


Figure 6.28: One time Propagation vs Wave Propagation: 2-Thread Model, Colour Quality

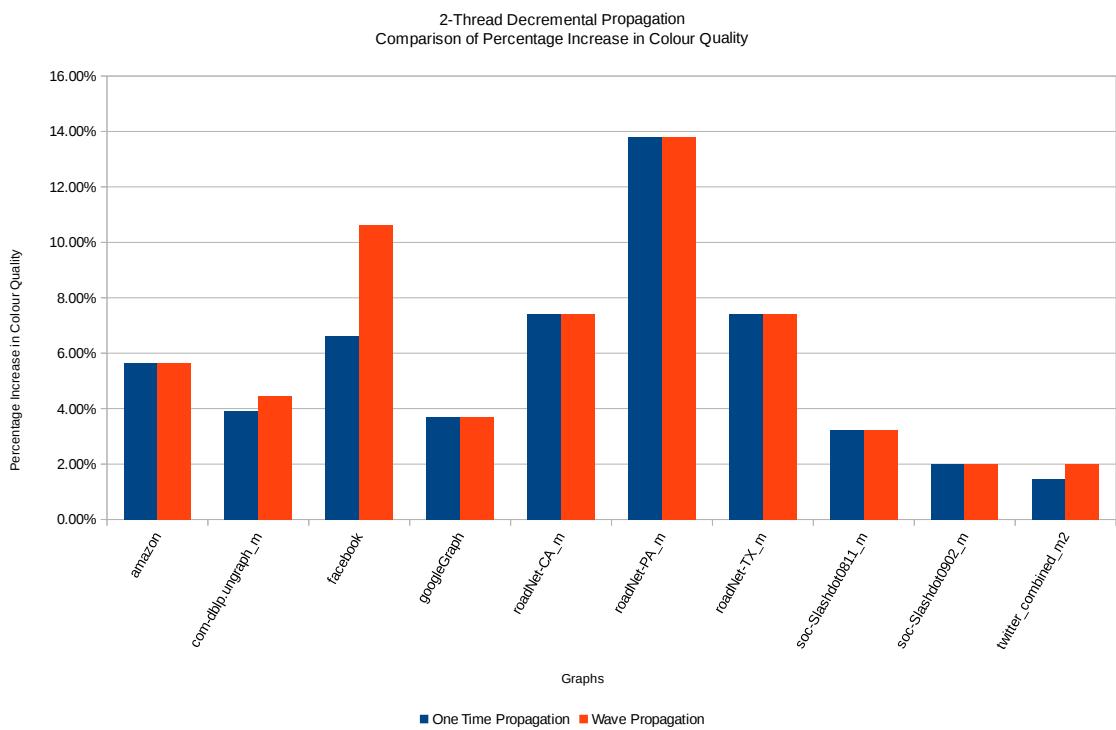


Figure 6.29: One time Propagation vs Wave Propagation: Many Thread Model, Colour Quality

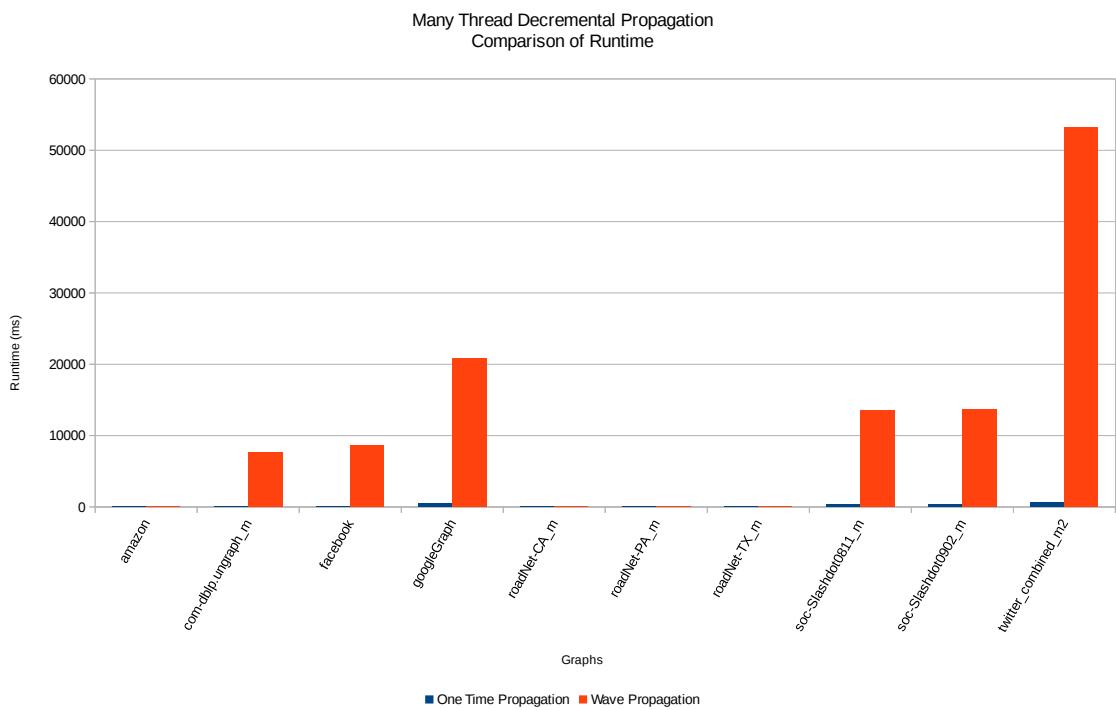


Figure 6.30: One time Propagation vs Wave Propagation: 2-Thread Model, Runtime

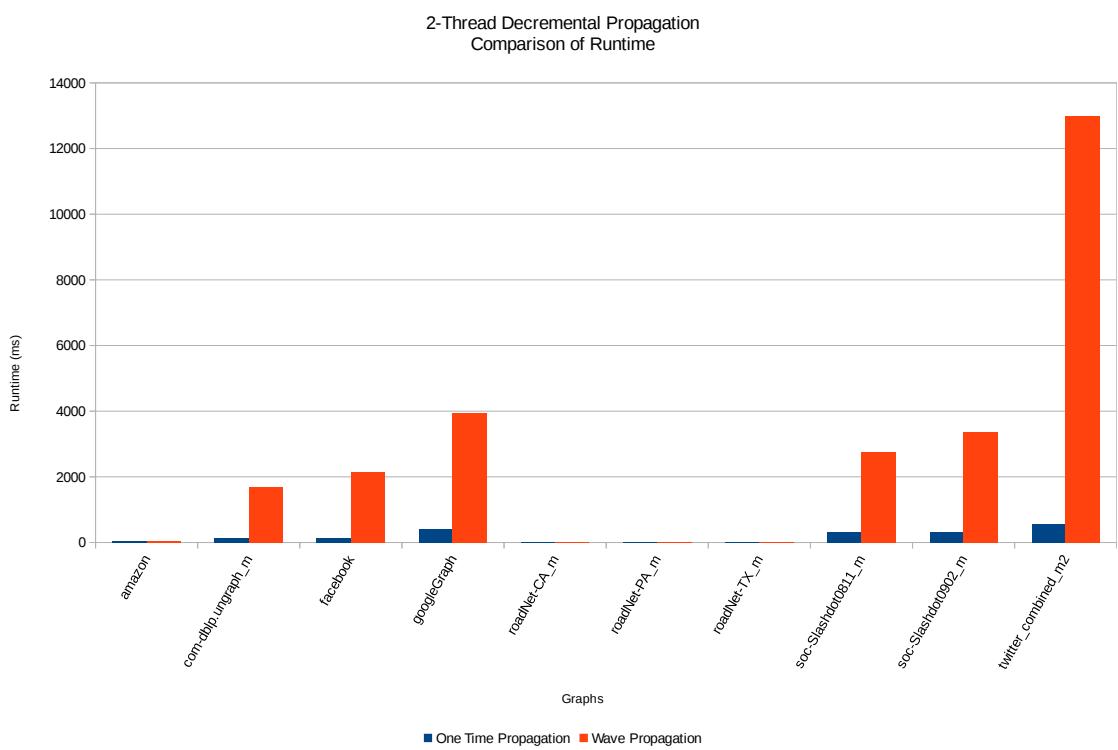


Figure 6.31: One time Propagation vs Wave Propagation: Many Thread Model, Runtime

CHAPTER 7

CONCLUSION AND FUTURE WORK

Our three approaches to parallel graph colouring on GPUs delivered expected results with RANDCOLOUR producing a very fast $\Delta + 1$ colouring, as intended, and MAXCOLOUR and MINMAXCOLOUR producing much better colour quality at a compromised runtime. RANDCOLOUR performed at an average runtime of 52 ms with an average graph having 1.3 million vertices and 7.8 million edges. We have seen that lower Max Degree generally leads to higher number of conflicts in graphs of comparable dimensions and a higher number of conflicts imply a larger sequential component of runtime, which in general, is larger than the parallel component of runtime. MINMAXCOLOUR beats MAXCOLOUR in terms of runtime in all our experiments possibly owing to lesser number of iterations the algorithm endures. MAXCOLOUR performed at an average runtime of 992 ms and MINMAXCOLOUR at 730 ms. So, even though MINMAXCOLOUR and MAXCOLOUR produces similar colour quality, we prefer MINMAXCOLOUR owing to its reduced runtime. Both MAXCOLOUR and MINMAXCOLOUR used 198 colours on average compared to 24296 colours by RANDCOLOUR. We have also seen how One Time Propagation can significantly improve the colouring produced by MINMAXCOLOUR, which in order to save on computation brings in 2 new colours in every iteration. One Time Propagation comes at a cost in terms of runtime and it depends upon our application for the algorithm to decide if we should go for a better colour quality with One Time Propagation, thus compromising on runtime, or not. One Time Propagation improves the colouring produced by MINMAXCOLOUR by 60% on an average.

For incremental colouring, we tried two approaches namely the 2-Thread Incremental Model and the Many Thread Incremental Model. As expected, the Many Thread Incremental Model involves much lesser kernel calls compared to the 2-Thread Incremental Model. But whatever this saves on runtime is negligible compared to the runtime cost finding independent edges to be processed in parallel inflicts. The Many Thread

Incremental Model in its current form is impractically slow compared to the 2-Thread Model even though both algorithms produce similar colour quality. We also saw that One Time Propagation doesn't have much effect on the colour quality produced by 2-Thread Incremental Colouring as the 2-Thread algorithm itself tries to locally optimize the colouring every time an edge is added. In our experiments, One Time Propagation on average bettered the colouring produced by 2 colours at an average run time cost of 727 ms. The payout doesn't seem to justify its cost. So, for incremental colouring, the 2-Thread Incremental Model without One Time Propagation performed the best in our experiments with an average runtime of 196 ms per 1000 edge insertions.

For decremental colouring, we tried two approaches namely the 2-Thread Decremental Model and the Many Thread Decremental Model. In terms of run time the Many Thread Decremental Model outperformed the 2-Thread Decremental Model by a huge margin, as expected, as it involved very less computation and massive parallelism. But the Many Thread Decremental Model doesn't improve existing colouring unlike the local optimization of colouring carried out by the 2-Thread Decremental Model. So, the Many Thread Decremental Model is dependent on some form of propagation to possibly improve the colouring as edges get deleted. We saw that the Many Thread Decremental Colouring is extremely fast with an average runtime of 0.4 ms per 1000 deletions of edges. Compared to this the 2-Thread Decremental Model takes 440 ms per 1000 deletions of edges. But the colouring produced by 2-Thread Decremental Model is superior to that of the Many Thread Model. So, we employ One Time Propagation for the Many Thread Model. We saw that the Many Thread Decremental Colouring followed by One Time Propagation performs equally or slightly better than the 2-Thread Decremental Model in terms of colour quality. Even with the One Time Propagation cost, our Many Thread Decremental Model performs really well with an average runtime of 24 ms per 1000 deletions of edges with an average 12% improvement in colouring.

We also tried Wave Propagation which we expected to be really computation intensive. From all our experiments with Wave Propagation, we could see that Wave Propagation doesn't significantly improve the colouring compared to One Time Propagation and performs significantly slower compared to One Time Propagation. In the case of Many Thread Decremental Model, in our experiments, Wave Propagation took

a whooping 11745 ms to run compared to 197 ms by One Time Propagation. Similar results were achieved with incremental models also. So, in its current state, Wave Propagation is impractical to use.

7.1 Future Work

Parallel incremental and decremental graph colouring is a not so explored space as far as the author understands. Atleast not in the realm of GPGPUs. So, our work was an attempt at exploring and understanding the problem. Our humble attempt at solving the problem has many shortcomings which can possibly be improved with further research.

Our CUDA implementations are not thoroughly optimized. Optimizing our CUDA programs might help us to make the maximum use underlying NVIDIA GPUs. Also, our implementations might involve warp divergences. We can possibly improve the performance by employing a warp-centric approach to our problem as proposed by Hong *et al.* (2011).

Our incremental approach uses only two threads at a time. It could be better if we can exploit the massive parallelism offered by the GPUs by spawning more threads. Our attempt at this, the Many Threads model, is impractically slow. We can possibly optimize it by parallelizing the phase where we find non-conflicting edges which is currently the bottleneck. More research needs to be done in order to increase the parallelism involved in incremental colouring.

Our approach to Wave Propagation is extremely slow and it seems to perform only marginally better than One Time Propagation. Probably there could be other approaches faster than One Time Propagation to propagate colouring information across the graph.

REFERENCES

1. **Amdahl, G. M.**, Validity of the single processor approach to achieving large scale computing capabilities. In *Proceedings of the April 18-20, 1967, Spring Joint Computer Conference, AFIPS '67 (Spring)*. ACM, New York, NY, USA, 1967. URL <http://doi.acm.org/10.1145/1465482.1465560>.
2. **Appel, K.** and **W. Haken** (1977). Every planar map is four colorable. part i: Discharging. *Illinois J. Math.*, **21**(3), 429–490. URL <http://projecteuclid.org/euclid.ijm/1256049011>.
3. **Beasley, J. E.** (1990). Or-library: Distributing test problems by electronic mail. *J Oper Res Soc*, **41**(11), 1069–1072. ISSN 0160-5682. URL <http://dx.doi.org/10.1057/jors.1990.166>.
4. **Bozdag, D.**, **Ü. V. Çatalyürek**, **A. H. Gebremedhin**, **F. Manne**, **E. G. Boman**, and **F. Özgüner**, A parallel distance-2 graph coloring algorithm for distributed memory computers. In **L. T. Yang**, **O. F. Rana**, **B. D. Martino**, and **J. Dongarra** (eds.), *High Performance Computing and Communications, First International Conference, HPCC 2005, Sorrento, Italy, September 21-23, 2005, Proceedings*, volume 3726 of *Lecture Notes in Computer Science*. Springer, 2005. ISBN 3-540-29031-1. URL http://dx.doi.org/10.1007/11557654_90.
5. **Bozdag, D.**, **A. H. Gebremedhin**, **F. Manne**, **E. G. Boman**, and **Ã. V. ÃGatalyÃ¡jrek** (2008). A framework for scalable greedy coloring on distributed-memory parallel computers. *J. Parallel Distrib. Comput.*, **68**(4), 515–535. URL <http://dblp.uni-trier.de/db/journals/jpdc/jpdc68.html#BozdagGMBC08>.
6. **Briggs, P.**, **K. D. Cooper**, **K. Kennedy**, and **L. Torczon** (2004). Coloring heuristics for register allocation. *SIGPLAN Not.*, **39**(4), 283–294. ISSN 0362-1340. URL <http://doi.acm.org/10.1145/989393.989424>.
7. **Brooks, R. L.**, *Classic Papers in Combinatorics*, chapter On Colouring the Nodes of a Network. Birkhäuser Boston, Boston, MA, 1987. ISBN 978-0-8176-4842-8, 118–121. URL http://dx.doi.org/10.1007/978-0-8176-4842-8_7.
8. **Çatalyürek, U. V.**, **J. Feo**, **A. H. Gebremedhin**, **M. Halappanavar**, and **A. Pothen** (2012). Graph coloring algorithms for multi-core and massively multithreaded architectures. *Parallel Comput.*, **38**(10-11), 576–594. ISSN 0167-8191. URL <http://dx.doi.org/10.1016/j.parco.2012.07.001>.
9. **Cohen, J.** and **P. Castonguay** (2012). Efficient graph matching and coloring on the gpu. *GTC on-demand S0332*, 1–10.
10. **Fleurent, C.** and **J. A. Ferland** (). Genetic and hybrid algorithms for graph coloring. *Annals of Operations Research*, **63**(3), 437–461. ISSN 1572-9338. URL <http://dx.doi.org/10.1007/BF02125407>.
11. **Gebremedhin, A. H.** and **F. Manne** (2000). Scalable parallel graph coloring algorithms. *Concurrency: Practice and Experience*, **12**(12), 1131–1146. ISSN 1096-9128. URL [http://dx.doi.org/10.1002/1096-9128\(200010\)12:12<1131::AID-CPE528>3.0.CO;2-2](http://dx.doi.org/10.1002/1096-9128(200010)12:12<1131::AID-CPE528>3.0.CO;2-2).

12. **Grosset, A. V. P., P. Zhu, S. Liu, S. Venkatasubramanian, and M. Hall** (2011). Evaluating graph coloring on gpus. *SIGPLAN Not.*, **46**(8), 297–298. ISSN 0362-1340. URL <http://doi.acm.org/10.1145/2038037.1941597>.
13. **GyÅarfÅas, A. and J. Lehel** (1988). On-line and first fit colorings of graphs. *Journal of Graph Theory*, **12**(2), 217–227. ISSN 1097-0118. URL <http://dx.doi.org/10.1002/jgt.3190120212>.
14. **Herzberg, A. M. and M. R. Murty** (2007). Sudoku squares and chromatic polynomials. *Notices of the AMS*, **54**(6), 708–717.
15. **Hong, S., S. K. Kim, T. Oguntebi, and K. Olukotun** (2011). Accelerating cuda graph algorithms at maximum warp. *SIGPLAN Not.*, **46**(8), 267–276. ISSN 0362-1340. URL <http://doi.acm.org/10.1145/2038037.1941590>.
16. **Hovland, R. J.** (2008). Latency and bandwidth impact on gpu-systems. *Norwegian University of Science and Technology*.
17. **Jensen, T. R. and B. Toft**, *Graph coloring problems*, volume 39. John Wiley & Sons, 2011.
18. **Jones, M. T. and P. E. Plassmann** (1993). A parallel graph coloring heuristic. *SIAM J. Sci. Comput.*, **14**(3), 654–669. ISSN 1064-8275. URL <http://dx.doi.org/10.1137/0914041>.
19. **Khor, S.** (2009). Application of graph coloring to biological networks. *arXiv preprint arXiv:0912.3461*.
20. **Lakshman, T., A. Bagchi, and K. Rastani** (1994). A graph-coloring scheme for scheduling cell transmissions and its photonic implementation. *Communications, IEEE Transactions on*, **42**(234), 2062–2070.
21. **Lee, V. W., C. Kim, J. Chhugani, M. Deisher, D. Kim, A. D. Nguyen, N. Satish, M. Smelyanskiy, S. Chennupaty, P. Hammarlund, R. Singhal, and P. Dubey** (2010). Debunking the 100x gpu vs. cpu myth: An evaluation of throughput computing on cpu and gpu. *SIGARCH Comput. Archit. News*, **38**(3), 451–460. ISSN 0163-5964. URL <http://doi.acm.org/10.1145/1816038.1816021>.
22. **Leighton, F. T.** (1979). A graph coloring algorithm for large scheduling problems. *Journal of research of the national bureau of standards*, **84**(6), 489–506.
23. **Leskovec, J. and A. Krevl** (2014). SNAP Datasets: Stanford large network dataset collection. <http://snap.stanford.edu/data>.
24. **Luby, M.**, A simple parallel algorithm for the maximal independent set problem. In *Proceedings of the Seventeenth Annual ACM Symposium on Theory of Computing*, STOC '85. ACM, New York, NY, USA, 1985. ISBN 0-89791-151-2. URL <http://doi.acm.org/10.1145/22145.22146>.
25. **Naumov, M., P. Castonguay, and J. Cohen** (2015). Parallel graph coloring with applications to the incomplete-lu factorization on the gpu. *NVIDIA Technical Report*, **001**. URL <https://research.nvidia.com/publication/parallel-graph-coloring-applications-incomplete-lu-factorization-gpu>.
26. **NVIDIA Corporation** (2016a). Cuda toolkit documentation. URL <http://docs.nvidia.com/cuda/parallel-thread-execution/#ptx-machine-model>. [Online; accessed on 22 April, 2016].

27. **NVIDIA Corporation** (2016b). curand: Cuda toolkit documentation. URL <http://docs.nvidia.com/cuda/curand/#axzz475iTZCEH>. [Online; accessed on 22 April, 2016].
28. **Sengupta, S.**, Parallel graph coloring algorithms on the gpu using opencl. In *Computing for Sustainable Global Development (INDIACom), 2014 International Conference on*. 2014.
29. **Sutter, H.** (2005). The free lunch is over: A fundamental turn toward concurrency in software. *Dr. Dobb's Journal*, **30**(3). URL <http://www.gotw.ca/publications/concurrency-ddj.htm>.
30. **Thomas, R.** (1998). An update on the four-color theorem. *Notices of the American Mathematical Society*, **45**(7), 848–859.
31. **Welsh, D. J. A. and M. B. Powell** (1967). An upper bound for the chromatic number of a graph and its application to timetabling problems. *The Computer Journal*, **10**(1), 85–86. URL <http://comjnl.oxfordjournals.org/content/10/1/85.abstract>.
32. **Wikipedia, the free encyclopedia** (2016). Moore's law. URL https://en.wikipedia.org/wiki/Moore%27s_law#/media/File:Transistor_Count_and_Moore%27s_Law_-_2011.svg. [Online; accessed on 22 April, 2016].
33. **Wilson, R. J.**, *Four Colors Suffice: How the Map Problem Was Solved*. 2014. ISBN 9780691158228 0691158223.
34. **Zaman, L.** (2011). Parallel first-fit graph coloring in java. URL <http://www.cse.yorku.ca/~zaman/pdfs/6490A.pdf>.
35. **Zuckerman, D.**, Linear degree extractors and the inapproximability of max clique and chromatic number. In *Proceedings of the Thirty-eighth Annual ACM Symposium on Theory of Computing*, STOC '06. ACM, New York, NY, USA, 2006. ISBN 1-59593-134-1. URL <http://doi.acm.org/10.1145/1132516.1132612>.