

# Contents

<b>Acknowledgements</b>	<b>I</b>
<b>Contents</b>	<b>II</b>
<b>Index</b>	<b>V</b>
<b>List of Figures</b>	<b>VII</b>
<b>List of Tables</b>	<b>IX</b>
<b>List of Algorithms</b>	<b>XI</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Overview . . . . .	1
1.2 Motivation . . . . .	2
1.3 Contents of the PhD thesis . . . . .	3
<b>2 State of the Art</b>	<b>5</b>
2.1 Backward search with the FM-Index . . . . .	5
2.1.1 BWT calculation . . . . .	6
2.1.2 Suffix Array sorting algorithms . . . . .	7
2.1.3 FM-Index data structures . . . . .	8
2.1.4 FM-Index of the complementary strand . . . . .	9
2.1.5 Recursive Backward Search algorithm . . . . .	9
2.1.6 Iterative Backward Search algorithm . . . . .	13
2.2 General Purpose GPU . . . . .	14
2.3 Sensitivity (TPR) . . . . .	17
2.4 Sequence alignment tools . . . . .	18
<b>3 Objectives and contributions</b>	<b>25</b>
3.1 Objectives . . . . .	25

<b>4 FM-Index search on hybrid CPU-GPU environments</b>	<b>29</b>
4.1 FM-Index compression . . . . .	29
4.2 GPU exact search algorithm . . . . .	30
4.2.1 Implementation details . . . . .	31
4.2.2 Pthread multi GPU version . . . . .	32
4.2.3 Experimental results . . . . .	33
4.3 Hybrid CPU-GPU inexact search algorithm . . . . .	39
4.3.1 Implementation details . . . . .	41
4.3.2 Bounding techniques explanation . . . . .	44
4.3.3 Experimental results . . . . .	45
4.3.4 Conclusions . . . . .	48
<b>5 Faster and more accurate inexact mapping using advanced tree exploration on backward search methods</b>	<b>51</b>
5.1 Suffix Array compression . . . . .	52
5.1.1 Vector S compression . . . . .	52
5.1.2 Vector R compression . . . . .	53
5.2 Search tree exploration prototype . . . . .	55
5.3 Search tree exploration complete algorithm . . . . .	59
5.4 Compatibility interface . . . . .	62
5.5 Experimental results . . . . .	64
5.5.1 Comparison with other FM-Index only algorithms . . . . .	64
5.5.2 Preprocessing step for modern aligners . . . . .	66
5.5.3 Comparison between BWT and <i>csalib</i> runtimes . . . . .	67
5.5.4 Asymptotic analysis . . . . .	69
5.6 Conclusions . . . . .	70
<b>6 General conclusions</b>	<b>71</b>
6.1 Exact mapping on GPU algorithm . . . . .	71
6.2 Hybrid CPU-GPU pair-end algorithm . . . . .	72
6.3 Advanced search tree exploration inexact mapping algorithm . . . . .	73
<b>7 Relevant publications and source code</b>	<b>77</b>
<b>Bibliography</b>	<b>79</b>

# List of Figures

2.1	Nvidia Tesla GPU architecture . . . . .	21
2.2	Nvidia GPU memory hierarchy . . . . .	22
2.3	Nvidia kernel . . . . .	23
4.1	Multiple threads in CPU . . . . .	33
4.2	Profiling of the algorithm without operative system disk cache . . .	35
4.3	Profiling of the algorithm with operative system disk cache . . . .	35
4.4	Obtaining the optimum GPU block size . . . . .	37
4.5	Speedup impact of the number of reads per GPU kernel execution	37
4.6	Short sequence mapping tools comparison finding only the first occurrence . . . . .	40
4.7	Short sequence mapping tools comparison finding all occurrences . .	40
4.8	Hybrid CPU-GPU, execution times . . . . .	47
4.9	Hybrid CPU-GPU, mapping locations found . . . . .	47
5.1	Number of partial solutions. Values of <i>res</i> during a forward search of string “AGGATC” against the reference “AGGAGC\$” . . . . .	57
5.2	Complete inexact search algorithm. Example for 2 errors. . . . .	59
5.3	BWT only tools. 2 Million 250bps reads. Execution times from 0 to 7 errors. . . . .	65
5.4	BWT and SW tools. 2 Million 250bps reads. Execution times comparing the new algorithm, the modern mappers and the combination of both. . . . .	68
5.5	BWT and SW tools. 2 Million 400bps reads. Execution times comparing the new algorithm, the modern mappers and the combination of both. . . . .	68
5.6	BWT and csalib runtimes. 2 Million 250bps reads. Execution times from 0 to 7 errors. . . . .	69

# List of Tables

4.1 Effectiveness of the hybrid model . . . . .	45
4.2 Sequential execution of the hybrid CPU-GPU algorithm . . . . .	46
4.3 Comparison with SOAP3-dp. . . . .	48
5.1 Results for Soap 2, Bowtie 1 and the new algorithm. The dataset contains 2 million 250bps reads. . . . .	66

# List of Algorithms

2.1	Exact Backward Search . . . . .	14
2.2	Search iteration with the FM-Index . . . . .	14
4.1	Matrix $O$ decompression . . . . .	30
4.2	GPU exact search algorithm . . . . .	31
4.3	Sequential execution . . . . .	41
4.4	Backward Vector GPU . . . . .	42
4.5	Backward Helper CPU . . . . .	43
5.1	Vector $S$ decompression . . . . .	52
5.2	Vector $R$ decompression . . . . .	54
5.3	Search prototype . . . . .	56
5.4	Exact Subroutine . . . . .	57
5.5	Branch Subroutine . . . . .	58
5.6	Complete Inexact Search (Step I figure 5.2) . . . . .	61
5.7	Calculate D forward (Step I figure 5.2) . . . . .	63