University of Technology, Graz

Master Thesis

Differential cryptanalysis with SAT solvers

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Abstract

Hash functions are ubiquitous in the modern information age. They provide preimage, second preimage and collision resistance ensuring data and origin integrity. They are used as cryptographic primitives in protocols and applications.

In August 2006, Wang et al. showed efficient attacks against several hash function designs including MD4, MD5, HAVAL-128 and RIPEMD. With these results differential cryptanalysis has been proven useful to break collision resistance in hash functions. Over the years advanced attacks based on those differential approaches have been developed.

In this thesis we encode differential attack settings as SAT problems. SAT solvers are utilized to solve the problem revealing actual message collisions for a defined message difference.

Keywords: hash function, differential cryptanalysis, MD4, collision resistance, satisfiability, SAT solver

Affidavit

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master‘s thesis dissertation.

(digital signature)

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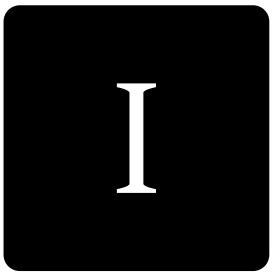
Also thanks to Roderick Bloem and Armin Biere who organized a meeting one year before submitting this work defining the main approaches involved in this thesis. Armin Biere released a custom lingeling version ats100 featuring more important clauses in lingeling.

And finally I am grateful for the support by Martina, who also supported me during good and bad days with this thesis, and my parents which provided a prosperous environment to me to be able to stand where I am today.

Thank you.
どもありがとうございました。

All source code is available at lukas-prokop.at/proj/megosat and published under terms and conditions of Free/Libre Open Source Software. This document was printed with LuaLaTeX and Linux Libertine Font.

Contents



Chapter 1

Introduction

Hash functions are used as cryptographic primitives in many applications and protocols. They take an arbitrary input message and provide a hash value. Input message and hash value are considered as byte strings in a particular encoding. The hash value is of fixed length and satisfies several properties which make them useful to enable data and origin integrity.

In this thesis we will consider the hash algorithms MD4 and SHA-256 and represent differential characteristics of hash collisions as SAT problem. If and only if satisfiability is given, the particular differential state is achievable using two different inputs leading to the same output. As far as SAT solvers return an actual model satisfying that state, we get a complete hash collision which can be verified and visualized. If the internal state of the hash algorithm is too large, the attack can be easily computationally simplified by modelling only a subset of steps of the hash algorithm or changing the modelled differential path.

Gaining experience with these kind of problems with previous non-SAT-based tools we try to apply best practices to a satisfiability setting. We will discuss which SAT techniques lead to best performance characteristics for our MD4 and SHA-256 testcases.

1.1 Preliminaries

Definition 1 (*Hash function*)

A *hash function* is a mapping $h : X \to Y$ with $X = \{0,1\}^*$ and $Y = \{0,1\}^n$ for some fixed $n \in {}_{\geq 1}$.

- Let $x \in X$, then $h(x)$ is called *hash value of* x.
- Let $h(x) = y \in Y$, then y is called *preimage of* y.

One example showing the use of hash functions as primitives is PKCS #5 specified in RFC 2898 [4]. Section 5.2 specifies PBKDF1 and PBKDF2 using an arbitrary pseudorandom function to derive password-based keys. Hash algorithms can be used as those pseudorandom functions. Given a minimum iteration count of 1000, as defined in section 4.2, yields the additional requirement that fast computation of hash values for given $x \in X$ is desirable.

A hash function has to satisfy the following security requirements:

Definition 2 (*Preimage resistance*)

Given $y \in Y$, a hash function h is *preimage resistant* iff it is computationally infeasible to find $x \in X$ such that $h(x) = y$.

Definition 3 (*Second-preimage resistance*)

Given $x \in X$, a hash function h is *second-preimage resistant* iff it is computationally infeasible to find $x_2 \in X$ with $x \neq x_2$ such that $h(x) = h(x_2)$. x_2 is called *second preimage*.

Definition 4 (*Collision resistance*)

A hash function h is *collision resistant* iff it is computationally infeasible to find any two $x \in X$ and $x_2 \in X$ with $x \neq x_2$ such that $h(x) = h(x_2)$.

As far as hash functions accept input strings of arbitrary length, but return a fixed size output string, existence of preimages and collisions is unavoidable [11]. However, good hash functions make it very difficult to determine collisions or preimages.

Most hash functions apply padding to their input to normalize the input size to a multiple of its block size before running a round function. In the following we always consider input of block size meaning the round function is run only for one block and padding is always considered part of this input message. Padding is negligible, because given two colliding blocks, we can add another incomplete block. Padding will occur only in the second block and with the same values in the second blocks it yield the same padded value. This results in a length extension attack, making input padding negligible for cryptanalysis.

Message 1			
4d7a9c83	**d6cb927a**	**29d5a578**	57a7a5ee
de748a3c	dcc366b3	b683a020	3b2a5d9f
c69d71b3	f9e99198	d79f805e	a63bb2e8
45dc8e31	97e31fe5	2794bf08	b9e8c3e9
Message 2			
4d7a9c83	**56cb927a**	**b9d5a578**	57a7a5ee
de748a3c	dcc366b3	b683a020	3b2a5d9f
c69d71b3	f9e99198	d79f805e	a63bb2e8
45dd8e31	97e31fe5	2794bf08	b9e8c3e9
Hash value of Message 1 and Message 2			
5f5c1a0d	71b36046	1b5435da	9b0d807a

TABLE 1.1: One of two MD4 hash collisions provided in [14]. Values are given in hexadecimal, message words are enumerated from left to right, top to bottom. Differences are highlighted with bold font for illustration purposes. For comparison the first bits of Message 1 are `11000001`... and the last bits are ...`10011101`. A message represents one block of 512 bits.

1.2 Cryptanalysis of Hash Functions

In August 2004, Wang et al. published results at Crypto'04 [14] which revealed that MD4, MD5, HAVAL-128 and RIPEMD can be broken practically using differential cryptanalysis. Their work is based on preliminary work by Hans Dobbertin [3]. On an IBM P690 machine, an MD5 collision can be computed in about one hour using this approach. Collisions for HAVAL-128, MD4 and RIPEMD were found as well. Patrick Stach's `md4coll.c` program [12] implements Wang's approach and can find MD4 collisions in few seconds on my Thinkpad x220 setup specified in Appendix B.

Let n denote the digest size, hence the size of the hash value $h(x)$ as number of bits. Due to the birthday paradox, a collision attack has a generic complexity of $2^{n/2}$ whereas pre-image and second pre-image attacks have generic complexities of 2^n.

Following results by Wang et al., differential cryptanalysis was discovered as powerful tool for cryptanalysis of hash algorithms. This thesis applies those ideas to satisfiability approaches.

1.3 Differential cryptanalysis

Definition 5 (*Hash collisoin*)

Given a hash function h, a hash collision is a pair (x, x_2) with $x \neq x_2$ such that $h(x) = h(x_2)$.

v_1	v_2	$f(v_1, v_2)$
1	1	1
1	0	0
0	1	0
0	0	0

(a) AND

v_1	v_2	$f(v_1, v_2)$
1	1	1
1	0	1
0	1	1
0	0	0

(b) OR

v	$f(v)$
1	0
0	1

(c) NOT

Figure 1.1: Truth tables for AND, OR and NOT

Differential cryptanalysis is based on the idea to consider two execution states of hash algorithms for slightly different input messages. We trace those difference to learn about the propagation of message differences.

Considering some hash function f, we look for two input messages x and x_2 such that the output values $h(x)$ and $h(x_2)$ correspond yielding a hash collision.

1.4 Satisfiability

Definition 6

A *boolean function* is a mapping $h : X \to Y$ with $X = \{0,1\}^n$ for $n \in {}_{\geq 1}$ and $Y = \{0,1\}$.

The following definition gives three basic boolean functions:

Definition 7

AND is a boolean function mapping $X = \{0,1\}^2$ to 1 if all values of X are 1. *OR* is a boolean function mapping $X = \{0,1\}^2$ to 1 if any value of X is 1. *NOT* is a boolean function mapping $X = \{0,1\}^1$ to 1 if the single value of X is 0. All functions return 0 in the other case.

Definition 8

A *truth table* unambiguously defines a boolean function by enlisting the evaluated truth value for all possible sets of inputs.

Table 1.1 shows truth tables for AND, OR and NOT.

In the following we discuss how boolean functions are related to computation in general and hash algorithms specifically.

Definition 9

An *algorithm* is a step-wise set of instructions to solve a problem.

One specific set of algorithms transform a given input to some output according to some rules. Such algorithms are said to satisfy the *I/O property*. Hash algorithms satisfy the I/O property.

Theorem 1

Every algorithm can be represented as boolean function.

This is trivial to see considering that computers are built from logic gates. However, in practice physical properties are used to employ storage of values, which does not exist in the model of boolean algebra. This can be mapped to our boolean model by constants for stored values and assuming an infinite memory.

Definition 10

A boolean function is *satisfiable* iff there exists at least one input $x \in X$ such that $h(x) = 1$. Every input $x \in X$ satisfying this property is called *model*. Every element of X is called *assignment*.

In the following we will establish some theory to reach the following property:

Definition 11

A boolean function is *satisfiable* iff a certain state in two hash algorithm instances is achievable.

The generic complexity of SAT determination is given by 2^n for n boolean variables. The corresponding tool to determine satisfiability is defined in the following.

Definition 12

A *SAT solver* is a tool to determine satisfiability of a boolean function. If satisfiability is given, it returns some model.

1.5 Thesis Outline

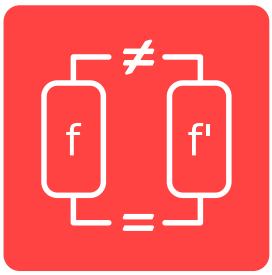
This thesis is organized as follows:

In Chapter 1 we discussed the basic properties and fundamentals of the tools in discussion including hash functions and SAT solvers.

In Chapter 2 we introduce the MD4 and SHA-256 hash functions and discuss possible approaches in differential cryptanalysis.

In Chapter 3 we discuss SAT solving and potential approaches to speed up SAT solvers for cryptographic problems.

In Chapter 4 we show results of our work and discuss its implications.



Chapter 2

Differential cryptanalysis

2.1 MD4

MD4 is a cryptographic hash function originally described in RFC 1186 [8], updated in RFC 1320 [9] and obsoleted by RFC 6150 [13]. It was invented by Ronald Rivest in 1990 with properties given in Table 2.1. Since 1995 [3] successful attacks have been found to break collisions, preimage and second-preimage resistance in MD4; including but not limited to [10] and [6]. A Python 3 implementation derived from a previous Python version is available at github [7].

block size	512 bits	namely variable `block` in RFC 1320 [9]
digest size	128 bits	as per section 3.5 in RFC 1320 [9]
internal state size	128 bits	namely variables A, B, C and D
word size	32 bits	as per section 2 in RFC 1320 [9]

Table 2.1: MD4 hash algorithm properties

In the following a quick overview over MD4's design is given.

First of all, padding is applied. A single bit 1 is appended to the input. As long as the input does not reach a length congruent 448 modulo 512, bit 0 is appended. Followingly, length appending takes place. Represent the length of the input (without the modifications of the previous step) in binary and take its first 64 bits. Append those 64 bits to the input.

The message is split into 512-bit blocks (i.e. 16 32-bit words). Four state

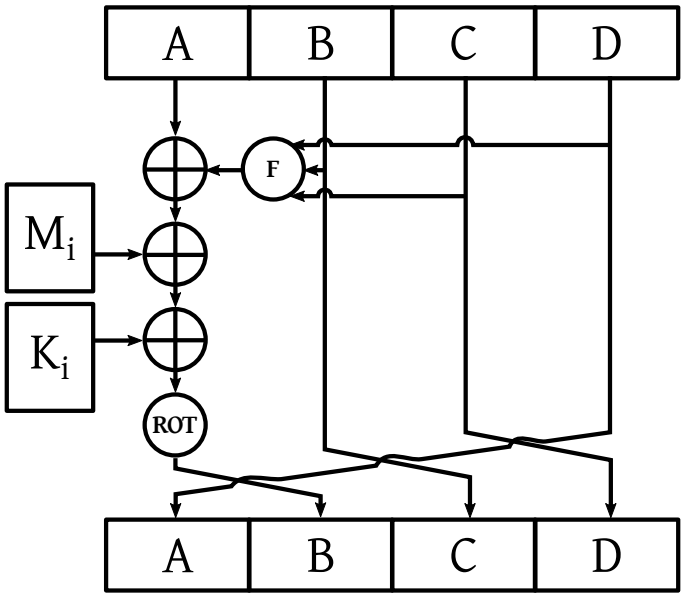


Figure 2.1: MD4 round function

variables A, B, C and D are initialized with hexadecimal values:

[**A**] `01234567` [**B**] `89abcdef` [**C**] `fedcba98` [**D**] `76543210`

To process one block, three auxiliary boolean functions are defined:

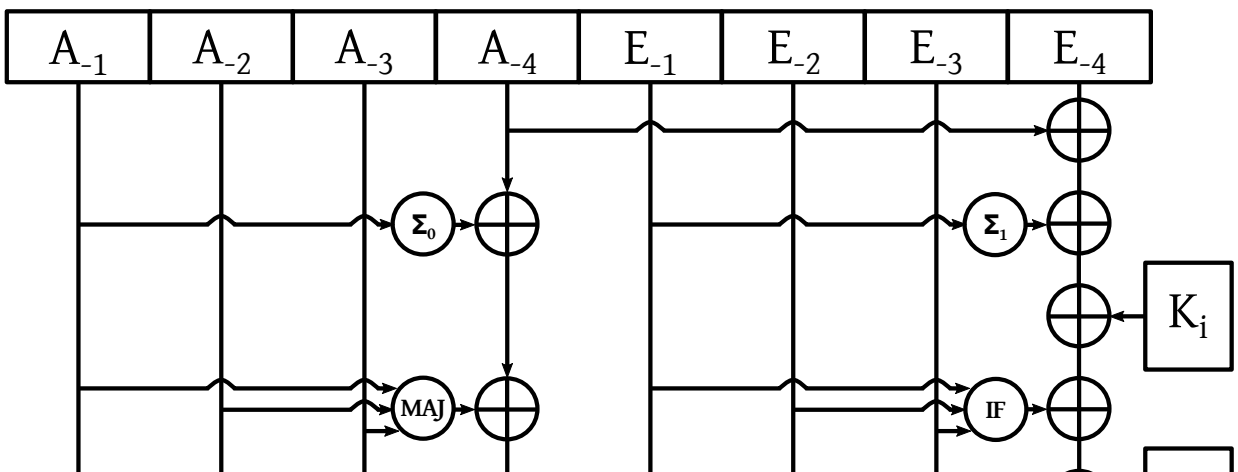
$$F(X,Y,Z) = (X \wedge Y) \vee (\neg X \wedge Z) \tag{2.1}$$
$$G(X,Y,Z) = (X \wedge Y) \vee (X \wedge Z) \vee (Y \wedge Z) \tag{2.2}$$
$$H(X,Y,Z) = X \oplus Y \oplus Z \tag{2.3}$$

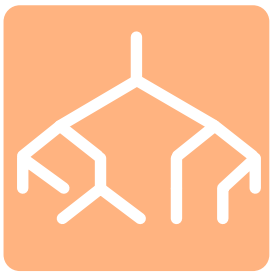
2.2 SHA-256

2.3 Differential notation

2.4 Addition example

2.5 Differential path


A-1
A-2
A-3
A-4
E-1
E-2
E-3
E-4
Σ0
Σ1
Ki
MAJ
IF



"What idiot called them
logic errors rather than
bool shit?"

Chapter 3

Satisfiability

3.1 SAT features and CNF analysis

At the very beginning I was very intrigued with the question "What is an 'average' SAT problem?". Answers to this question can help to optimize SAT solver memory layouts. But originally I was wondering whether our differential cryptanalysis SAT problems distinguish from "average" SAT problems. First of all, we need to elaborate on the question itself.

Definition 13 (*SAT feature*)

Given a SAT problem, a *SAT feature* is a statistical value (named *feature value*) which can be retrieved from the given problem in polynomial time.

A SAT feature is called *dynamic* if new clauses need to be formulated to evaluate a SAT feature value. Other SAT features are called *static*. A SAT feature is called *performance-driven* if the runtime of any computation contributes to the feature value.

The most basic example of a SAT feature is the number of variables and clauses of a given SAT problem. This SAT feature is stored in the CNF header of a SAT problem encoded in the DIMACS format.

It should be computationally easy to evaluate SAT features of a given SAT problem. The general goal is to write a tool which evaluates several SAT features at the same time and prints them for comparison with other problems. A SAT feature is expected to be computable in linear time and memory with the number of variables and number of clauses. But a hard limit is only given with polynomial complexity for evaluation algorithms. This implies that evaluation of satisfiability must not be necessary to evaluate a SAT feature under the assumption that $\mathcal{P} \neq \mathcal{NP}$. Hence the number of valid models is not a SAT feature as far as satisfiability needs to be determined.

The most similar resource I found looking at SAT features was the SATzilla project 3.1 in 2012. The authors systematically defined 138 SAT features categorized in 12 groups.

Many SAT solvers collect feature values to improve algorithm selection, restart strategies and estimate problem sizes. Recent trends to apply Machine Learning to SAT solving imply feature evaluation. SAT features and the resulting satisfiability runtime are used as training data for Machine Learning. One example using SAT features for algorithm selection is ASlib [1].

However, most of these SAT features are performance-driven. Examples for performance-driven SAT features include the number of restarts within a certain time frame or evaluation of local minima.

In the following section we want to evaluate SAT features and compare test cases.

3.2 SAT features in comparison

Proposition 1

> The set of public benchmarks in SAT competitions between 2008 and 2015 represent average SAT problems

Define a large set of SAT features. Present data. Categorize data.

Given a set of clauses, return a subset of clauses satisfying given criterion	
clauses_allLitsNeg	all literals are negative
clauses_oneLitNeg	exactly one literal is negative
clauses_geqOneLitNeg	more than one literal is negative
clauses_allLitsPos	all literals are positive
clauses_oneLitPos	exactly one literal is positive
clauses_geqOneLitPos	more than one literal is positive
clauses_length1	clause contains exactly one literal ("unit clause")
clauses_length2	clause contains exactly two literals
clauses_unique	clause did not yet occur
clauses_tautological	clause contains some literal and its negation
Given a set of literals/variables, return boolean property	
literals_existential	literal does not occur negated
literals_unit	literal occurs in clause of length 1
literals_contradiction	literal occurs with its negation on one clause
literals_1occ	literal occurs only in one clause once
literals_2occs	literal occurs two times in clauses
literals_3occs	literal occurs three times in clauses
variables_unit	variable occurs in clause of length 1
Given a set of clauses, return real number based on this clause	
clauses_mapLength	number of literals in clause
clauses_mapRatioPosNeg	number of positive literals divided by total number of literal
clauses_mapNumPos	number of positive literals in clause
Given one clause, return boolean property	
clauselits_someEx	any is literal existential
clauselits_allEx	all literals are existential
clauselits_someUnit	contains unit variable
clauselits_someContra	contains contradiction variable
clauselits_all1occ	all variables occur only once in all clauses
clauselits_all12occ	all variables occur only once or twice in all clauses
Given all clauses, return the following property	
concomp_variable	number of connected components where two variables are in the same component iff they occur in at least one clause together
concomp_literal	number of connected components where two literals are in the same component iff they occur in at least one clause together
xor2_count	Number of clause pairs $(a \vee b, \neg a \vee b)$ for two variables a and b

3.3 Basic SAT solving techniques

3.4 SAT solvers in use

3.5 Encodings

3.5.1 STP approach

Chapter 4

Results

4.1 Benchmark results

4.2 Related work

4.3 Conclusion

Appendices

Appendix A

Illustration

i		$\nabla S_{i,0}$	$\nabla S_{i,1}$	$\nabla S_{i,2}$
-4	A:	01100111010001010010001100000001		
-3	A:	00010000001100100101010001110110		
-2	A:	10011000101110101101110011111110		
-1	A:	11101111110011011010101110001001		
0	A:	01101011110101001110010000010010	W:	01001101011110101001110010000011
1	A:	01110111001111111101111000110001	W:	01010110110010111001001001111010
2	A:	10101011010000000011100011110010	W:	10111001110101011010010101111000
3	A:	10101101001111010101001001010001	W:	01010111101001111010010111101110
4	A:	00101100011000110101010111110010	W:	11011110011101001000101000111100
5	A:	00011010011000101001101000000001	W:	11011100110000110110011010110011
6	A:	00011011000100110001000001111010	W:	10110110100000011101000000100000
7	A:	00101011100000010011011001010000	W:	00111011001010100101110110011111
8	A:	01110011001000101111111110110000	W:	11000110100111010111000110110011
9	A:	10101110101100001111100110011111	W:	11111001111010011001000110011000
10	A:	10100100100001010100000010101110	W:	11010111100111111000000001011110
11	A:	01000110101101100100101011111111	W:	10100110001110111011001011101000
12	A:	00101100001010111111111000111011	W:	01000101110111011000111000110001
13	A:	10011101001100010100000111100101	W:	10010111111000110001111111100101
14	A:	00001010010100011000100011010110	W:	00100111100101001011111100001000
15	A:	00011110101010010110011011010100	W:	10111001111010001100001111101001
16	A:	10010010110100101001101101011111		
17	A:	00011111001110100001001000011110		
18	A:	01010111000011010000000010010100		
19	A:	01110000000101111001101011000100		
20	A:	11011001111111101110100000110100		
21	A:	11110011101100000101111111010100		
22	A:	01011101110011010011001100111010		
23	A:	01010000111011101100011110001111		
24	A:	00000010000100100011011100011010		
25	A:	10110000100101100001010011101010		
26	A:	00001010100010010111011101000001		
27	A:	00000110111011111010110101110011		
28	A:	10110110010111010110110000100101		
29	A:	10100010000011010100100001101001		
30	A:	00101001110101111100011101100011		
31	A:	11111100100100101101111110110110		
32	A:	01001111110100100110100000101111		
33	A:	00111000001111010110111011100100		
34	A:	00100000011101011110100000010101		
35	A:	10100000000110011000001000111010		
36	A:	10000111111010111101111001011001		
37	A:	11001000000110100100001100001100		
38	A:	10110000011001111110100110101100		
39	A:	00010010000010100001101100011100		
40	A:	11000000010010000111000110000101		
41	A:	00000110100001101111010100100110		
42	A:	01001110110111011111111010000110		
43	A:	01010000011000111101000001101101		
44	A:	11111000000101101111011100001100		
45	A:	10001010110110110010110000000100		
46	A:	10000010100110010101100011011100		
47	A:	10000001111001011011010010111101		

TABLE A.1: One of the original MD4 collision given by Wang, et al.

Appendix B

Testcases

Figures A.1, A.2, A.3 and A.4 show testcases used to test performance measures.

i		$\nabla S_{i,0}$	$\nabla S_{i,1}$	$\nabla S_{i,2}$
-4	A:	01100111010001010010001100000001		
-3	A:	00010000001100100101010001110110		
-2	A:	10011000101110101101110011111110		
-1	A:	11101111110011011010101110001001		
0	A:	x------------------------------	W:	---x-------------------------
1	A:	------------------------------	W:	------------------------------
2	A:	--------------------x---------	W:	x------------------------------
3	A:	xxx---------------------------	W:	------------------------------
4	A:	----------------------------xx	W:	x------------------------------
5	A:	------xxxxxxxxxxxxxxx-x-------	W:	------------------------------
6	A:	x-------x----------x-x-xxxx--x	W:	------------------------------
7	A:	--------x-----x---------------	W:	------------------------------
8	A:	--------x------x-x-x---------	W:	x------------------------------
9	A:	----------------x---x---------	W:	------------------------------
10	A:	------x----x--xxx-xxx---------	W:	------------------------------
11	A:	x--------------xxx-x----------	W:	------------------------------
12	A:	---x-x----------------------	W:	x------------------------------
13	A:	------------------------------	W:	------------------------------
14	A:	-x----------------------------	W:	------------------------------
15	A:	x-x---------x----------------	W:	------------------------------
16	A:	-xxx----------------------------		
17	A:	------------------------------		
18	A:	------------------------------		
19	A:	x-----------------------------		
20	A:	x-----------------------------		
21	A:	------------------------------		
22	A:	------------------------------		
23	A:	------------------------------		
24	A:	------------------------------		
25	A:	------------------------------		
26	A:	------------------------------		
27	A:	------------------------------		
28	A:	------------------------------		
29	A:	------------------------------		
30	A:	------------------------------		
31	A:	------------------------------		
32	A:	x-----------------------------		
33	A:	------------------------------		
34	A:	------------------------------		
35	A:	------------------------------		
36	A:	------------------------------		
37	A:	------------------------------		
38	A:	------------------------------		
39	A:	------------------------------		
40	A:	------------------------------		
41	A:	------------------------------		
42	A:	------------------------------		
43	A:	------------------------------		
44	A:	------------------------------		
45	A:	------------------------------		
46	A:	------------------------------		
47	A:	------------------------------		

TABLE B.1: TODO description

i		$\nabla S_{i,0}$	$\nabla S_{i,1}$	$\nabla S_{i,2}$
-4	A:	01100111010001010010001100000001		
-3	A:	00010000001100100101010001110110		
-2	A:	10011000101110101101110011111110		
-1	A:	11101111110011011010101110001001		
0	A:	????????????????????????????????	W:	---x----------
1	A:	????????????????????????????????	W:	----------
2	A:	????????????????????????????????	W:	x----------
3	A:	????????????????????????????????	W:	----------
4	A:	????????????????????????????????	W:	x----------
5	A:	????????????????????????????????	W:	----------
6	A:	????????????????????????????????	W:	----------
7	A:	????????????????????????????????	W:	----------
8	A:	????????????????????????????????	W:	x----------
9	A:	????????????????????????????????	W:	----------
10	A:	????????????????????????????????	W:	----------
11	A:	????????????????????????????????	W:	----------
12	A:	????????????????----------	W:	x----------
13	A:	????????????????----------	W:	----------
14	A:	????????????????----------	W:	----------
15	A:	????????????????----------	W:	----------
16	A:	???x----------		
17	A:	?----------		
18	A:	?----------		
19	A:	?----------		
20	A:	x----------		
21	A:	----------		
22	A:	----------		
23	A:	----------		
24	A:	----------		
25	A:	----------		
26	A:	----------		
27	A:	----------		
28	A:	----------		
29	A:	----------		
30	A:	----------		
31	A:	----------		
32	A:	x----------		
33	A:	----------		
34	A:	----------		
35	A:	----------		
36	A:	----------		
37	A:	----------		
38	A:	----------		
39	A:	----------		
40	A:	----------		
41	A:	----------		
42	A:	----------		
43	A:	----------		
44	A:	----------		
45	A:	----------		
46	A:	----------		
47	A:	----------		

TABLE B.2: TODO description

i		$\nabla S_{i,0}$	$\nabla S_{i,1}$	$\nabla S_{i,2}$
-4	A:	01100111010001010010001100000001		
-3	A:	00010000001100100101010001110110		
-2	A:	10011000101110101101110011111110		
-1	A:	11101111110011011010101110001001		
0	A:	????????????????????????????????	W:	---x----------
1	A:	????????????????????????????????	W:	----------
2	A:	????????????????????????????????	W:	x----------
3	A:	????????????????????????????????	W:	----------
4	A:	????????????????????????????????	W:	x----------
5	A:	????????????????????????????????	W:	----------
6	A:	????????????????????????????????	W:	----------
7	A:	????????????????????????????????	W:	----------
8	A:	????????????????????????????????	W:	x----------
9	A:	????????????????????????????????	W:	----------
10	A:	????????????????????????????????	W:	----------
11	A:	????????????????????????????????	W:	----------
12	A:	????????????????????????????????	W:	x----------
13	A:	????????????????????????????????	W:	----------
14	A:	????????????????????????????????	W:	----------
15	A:	????????????????????????????????	W:	----------
16	A:	????????????????????????????????		
17	A:	????????????????????????????????		
18	A:	????????????????????????????????		
19	A:	????????????????????????????????		
20	A:	????????????????????????????????		
21	A:	----------		
22	A:	----------		
23	A:	----------		
24	A:	----------		
25	A:	----------		
26	A:	----------		
27	A:	----------		
28	A:	----------		
29	A:	----------		
30	A:	----------		
31	A:	----------		
32	A:	x----------		
33	A:	----------		
34	A:	----------		
35	A:	----------		
36	A:	----------		
37	A:	----------		
38	A:	----------		
39	A:	----------		
40	A:	----------		
41	A:	----------		
42	A:	----------		
43	A:	----------		
44	A:	----------		
45	A:	----------		
46	A:	----------		
47	A:	----------		

TABLE B.3: TODO description

i		$\nabla S_{i,0}$	$\nabla S_{i,1}$	$\nabla S_{i,2}$
-4	A:	01100111010000101001000011000000001		
-3	A:	00010000001100100101010001110110		
-2	A:	10011000101110101101110011111110		
-1	A:	11101111110011011010101110001001		
0	A:	????????????????????????????????????	W:	????????????????????????????????????
1	A:	????????????????????????????????????	W:	????????????????????????????????????
2	A:	????????????????????????????????????	W:	????????????????????????????????????
3	A:	????????????????????????????????????	W:	????????????????????????????????????
4	A:	????????????????????????????????????	W:	????????????????????????????????????
5	A:	????????????????????????????????????	W:	????????????????????????????????????
6	A:	????????????????????????????????????	W:	????????????????????????????????????
7	A:	????????????????????????????????????	W:	????????????????????????????????????
8	A:	????????????????????????????????????	W:	????????????????????????????????????
9	A:	????????????????????????????????????	W:	????????????????????????????????????
10	A:	????????????????????????????????????	W:	????????????????????????????????????
11	A:	????????????????????????????????????	W:	????????????????????????????????????
12	A:	????????????????????????????????????	W:	????????????????????????????????????
13	A:	????????????????????????????????????	W:	????????????????????????????????????
14	A:	????????????????????????????????????	W:	????????????????????????????????????
15	A:	????????????????????????????????????	W:	????????????????????????????????????
16	A:	????????????????????????????????????		
17	A:	????????????????????????????????????		
18	A:	????????????????????????????????????		
19	A:	????????????????????????????????????		
20	A:	????????????????????????????????????		
21	A:	----------		
22	A:	----------		
23	A:	----------		
24	A:	----------		
25	A:	----------		
26	A:	----------		
27	A:	----------		
28	A:	----------		
29	A:	----------		
30	A:	----------		
31	A:	----------		
32	A:	x????????????????????????????????		
33	A:	----------		
34	A:	----------		
35	A:	----------		
36	A:	----------		
37	A:	----------		
38	A:	----------		
39	A:	----------		
40	A:	----------		
41	A:	----------		
42	A:	----------		
43	A:	----------		
44	A:	----------		
45	A:	----------		
46	A:	----------		
47	A:	----------		

Table B.4: TODO description

Appendix C

Hardware setup

In the following we introduce two hardware setups which were used to run our testcases. The first setup is referred to as "Thinkpad x220" throughout the document whereas the second setup is referred to as "Cluster".

Type model	Thinkpad Lenovo x220 tablet, 4299-2P6
Processor	Intel i5-2520M, 2.50 GHz, dual-core, Hyperthreaded
RAM	16 GB (extension to common retail setup)
Memory	160 GB SSD
L3 cache size	3072 KB

Table C.1: Thinkpad x220 Tablet specification [5]

Processor	Intel Xeon X5690, 3.47 GHz, 6 cores, Hyperthreaded
RAM	192 GB
L3 cache size	12288 KB

Table C.2: Cluster node nehalem192g0 specification [2]

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