

UNIVERSITY OF TECHNOLOGY, GRAZ

MASTER THESIS

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# Differential cryptanalysis with SAT solvers

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*Author:*

Lukas Prokop

*Supervisor:*

Maria Eichlseder  
Florian Mendel

*A thesis submitted in fulfillment of the requirements  
for the master's degree in Computer Science*

*at the*

Institute of Applied  
Information Processing and  
Communications

August 16, 2016







Lukas Prokop, BSc BSc

## **Differential cryptanalysis with SAT solvers**

### **MASTER'S THESIS**

to achieve the university degree of

Master of Science

Master's degree programme: Computer Science

submitted to

**Graz University of Technology**

Supervisor

Dipl.-Ing. Dr.techn., Florian Mendel

Institute of Applied Information Processing and Communications

Second advisor: Maria Eichlseder

Graz, June 2016

## **AFFIDAVIT**

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# ABSTRACT

Hash functions are ubiquitous in the modern information age. They provide preimage, second preimage and collision resistance which are needed in a wide range of 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 shown useful to break collision resistance in hash functions. Over the years advanced attacks based on those differential approaches have been developed.

To find collisions like Wang et al., a cryptanalyst needs to specify a differential characteristic. Looking at the differential behavior of the underlying operations of the hash algorithm shows how differential values propagate in the algorithm. The goal is to find a differential characteristic whose differences cancel out in the output. Once such a differential characteristic was discovered, in a second step the actual values for those differences are defined yielding an actual hash collision.

Finding a differential characteristic can be a cumbersome and tedious task. Whereas propagation can be automated using dedicated tools, finding an initial differential characteristic is a difficult task as it can be specified with arbitrary levels of granularity.

SAT solvers inherently implement both tasks. They consecutively propagate values which narrow the search space. The probability to find a satisfiable assignment increases if the narrowed search space has many satisfiable assignments. And finally the assignment reveals initial values. On the other hand, SAT solvers have no notion of differential values and therefore problem encoding becomes an important topic.

In this thesis we look at differential characteristics and encode them as SAT problem. A SAT solver tells us whether a differential characteristic can represent a hash collision or not. We implemented a framework which allows us to verify differential behavior for integer operations. We then looked at the encoded problems in details and tried to change the encoding to improve the runtime of the SAT solver. We also provide a small CNF analysis library to compare an encoded problem with others.

**Keywords:** hash function, differential cryptanalysis, differential characteristic, MD4, SHA-256, collision resistance, satisfiability, SAT solver

## ACKNOWLEDGEMENTS

First of all I would like to thank my academic advisor for his continuous support during this project. Many hours of debugging were involved in writing this master thesis project, but thanks to Florian Mendel, this project came to a release with nice results. Also thanks for continuously reviewing this document.

I would also like to thank Maria Eichlseder for her great support. Her unique way to ask questions brought me back on track several times. Mate Soos supported me during my bachelor thesis with SAT related issues and his support continued with this master thesis in private conversations.

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 custom lingeling versions for us, e.g. featuring “more important” clauses in lingeling. He also provided further analysis for our testcases.

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](https://lukas-prokop.at/proj/megosat) and published under terms and conditions of Free/Libre Open Source Software. This document was printed with Lua<sup>A</sup>T<sub>E</sub>X and Linux Libertine Font.

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## Chapter 1

# Introduction

### 1.1 Overview

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 it useful in a variety of applications.

In this thesis we will consider the hash algorithms MD<sub>4</sub> and SHA-256. They use basic arithmetic functions like addition and bit-level functions such as XOR to transform an input to a hash value. We use a bit vector as input to this implementation and all operations applied to this bit vector will be represented as clauses of a SAT problem. Additionally we 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 an actual hash collision which can be verified and visualized. If the internal state of the hash algorithm is too large, the attack can be computationally simplified by modelling only a subset of steps of the hash algorithm or changing the modelled differential path.

Based on experience with these kind of problems with previous non-SAT-based tools we aim to apply best practices to a satisfiability setting. We will discuss which SAT techniques lead to best performance characteristics for our MD<sub>4</sub> and SHA-256 testcases.

## 1.2 Thesis Outline

This thesis is organized as follows:

**In Chapter 1** we briefly introduce basic subjects of this thesis. We explain our high-level goal involving hash functions and SAT solvers.

**In Chapter 2** we introduce the MD4 and SHA-256 hash functions. Certain design decisions imply certain properties which can be used in differential cryptanalysis. We discuss those decisions in this chapter after a formal definition of the function itself. Beginning with this chapter we develop a theoretical notion of our tools.

**In Chapter 3** we discuss approaches of differential cryptanalysis. We start off with work done by Wang, et al. and followingly introduce differential notation to simplify representation of differential states. This way we can easily dump hash collisions.

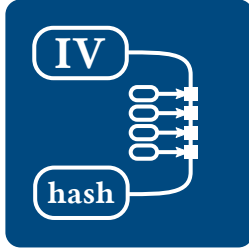
**In Chapter 4** we discuss SAT solving. We give a brief overview over used SAT solvers and discuss how we can speed up SAT solvers for cryptographic problems.

**In Chapter 5** we define SAT features which help us to classify SAT problems. This is a small subproject we did to look at properties of resulting DIMACS CNF files.

**In Chapter 6** we discuss how we represent a problem (i.e. the hash function and a differential characteristic) as SAT problem. This ultimately allows us to solve the problem using a SAT solver.

**In Chapter 7** we show data as result of our work. Runtimes are the main part of this chapter, but also results of the SAT features project are presented.

**In Chapter 8** we suggest future work based on our results.



## Chapter 2

# Hash algorithms

In this chapter we will define hash functions and their desired security properties. Followingly we look at SHA256 and MD4 as established hash functions. We will represent them with Boolean algebra (in chapter 6) to make it possible to reason about states in those hash functions using SAT solvers.

### 2.1 Preliminaries Redux

#### Definition 2.1 (*Hash function*)

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

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

Hash functions are considered as cryptographic primitives used as building blocks in cryptographic protocols. A hash function has to satisfy the following security requirements:

#### Definition 2.2 (*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 2.3 (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 2.4 (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  $h(x) = h(x_2)$ . Tuple  $(x, x_2)$  is called *collision*.

As far as hash functions accept input strings of arbitrary length, but return a fixed size output string, existence of collisions is unavoidable [20]. However, good hash functions make it very difficult to find collisions or preimages.

Any digital data can be hashed (i.e. used as input to a hash function) by considering it in binary representation. The format or encoding is not part of the hash function's specification.

**2.1.1 Merkle-Damgård designs**

The Merkle-Damgård design is a particular design of hash functions providing the following security guarantee:

**Definition 2.5 (Collision resistance inheritance)**

Let  $F_0$  be a collision resistant compression function. A hash function in Merkle-Damgård design is collision resistant if  $F_0$  is collision resistant.

This motivates thorough research of collisions in compression functions. The design was found independently by Ralph C. Merkle and Ivan B. Damgård. It was described by Merkle in his PhD thesis [13, p. 13–15] and followingly used in popular hash functions such as MD4, MD5 and the SHA2 hash function family. The single-pipe design works as follows:

1. Split the input into blocks of uniform block size. If necessary, apply padding to the last block to achieve full block size.
2. Compression function  $F_0$  is applied iteratively using the output  $y_{i-1}$  of the previous iteration and the next input block  $x_i$ , denoted  $y_i = F_0(y_{i-1}, x_i)$ .
3. An optional postprocessing function is applied.

**2.1.2 Padding and length extension attacks**

Hash functions of single-piped Merkle-Damgård design inherently suffer from length extension attacks. MD4 and SHA256 apply padding to their input to nor-

malize their input size to a multiple of its block size. The compression function is applied afterwards. This design is vulnerable to length extensions.

Consider some collision  $(x_0, x_1)$  with  $F_0(x_0) = y = F_0(x_1)$  where  $x_0$  and  $x_1$  have a size of one block. Let  $p$  be a suffix with size of one block. Then also  $(x_0 \parallel p, x_1 \parallel p)$  (where  $\parallel$  denotes concatenation) represents a collision in single-piped Merkle-Damgård designs, because it holds that:

$$F_0(F_0(x_0), p) = F_0(F_0(x_1), p) \iff F_0(y, p) = F_0(y, p)$$

Hence  $(x_0 \parallel p, x_1 \parallel p)$  is a collision as well. As far as  $F_0$  is applied recursively to every block,  $p$  can be of arbitrary size and  $(x_0, x_1)$  can be of arbitrary uniform size.

Because of this vulnerability, cryptanalysts only need to find a collision in compression functions. In our tests will only consider input of one block and padding will be neglected due to this vulnerability.

### 2.1.3 Example usage

One example showing the use of hash functions as primitives are JSON Web Tokens (JWT) specified in RFC 7519 [11]. Its application allows web developers to represent claims to be transferred between two parties.

Section 8 defines implementation requirements and refers to RFC 7518 [7], which specifies cryptographic algorithms such as “HMAC SHA-256” to be implemented. It is (besides “none”) the only required signature and MAC algorithm.

## 2.2 MD4

MD4 is a cryptographic hash function originally described in RFC 1186 [17], updated in RFC 1320 [18] and declared obsolete by RFC 6150 [22]. It was invented by Ronald Rivest in 1990 with properties given in Table 2.1. In 1995 [4] successful full-round attacks have been found to break collision resistance. Followingly preimage and second-preimage resistance in MD4 have been broken as well. Some of those attacks are described in [19] and [14]. We derived a Python 3 implementation based on a Python 2 implementation and made it available on github [16].

block size	512 bits	namely variable block in RFC 1320 [18]
digest size	128 bits	as per Section 3.5 in RFC 1320 [18]
internal state size	128 bits	namely variables $A$ , $B$ , $C$ and $D$
word size	32 bits	as per Section 2 in RFC 1320 [18]

TABLE 2.1: MD4 hash algorithm properties

MD4 uses three auxiliary Boolean functions:

**Definition 2.6**

The Boolean IF function is defined as follows: If the first argument is true, the second argument is returned. Otherwise the third argument is returned.

The Boolean MAJ function returns true if the number of Boolean values true in arguments is at least 2. The Boolean XOR function returns true if the number of Boolean values true in arguments is odd.

Using the logical operators  $\wedge$  (AND),  $\vee$  (OR) and  $\neg$  (NEG) we can define them as (see section 4.1 for a thorough discussion of these operators):

$$\text{IF}(X, Y, Z) := (X \wedge Y) \vee (\neg X \wedge Z) \quad (2.1)$$

$$\text{MAJ}(X, Y, Z) := (X \wedge Y) \vee (X \wedge Z) \vee (Y \wedge Z) \quad (2.2)$$

$$\begin{aligned} \text{XOR}(X, Y, Z) &:= (X \wedge \neg Y \wedge \neg Z) \vee (\neg X \wedge Y \wedge \neg Z) \\ &\quad \vee (\neg X \wedge \neg Y \wedge Z) \vee (X \wedge Y \wedge Z) \\ &:= (X \oplus Y \oplus Z) \end{aligned} \quad (2.3)$$

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

**Padding and length extension.** 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 previous modifications) in binary and take its first 64 less significant bits. Append those 64 bits to the input.

**Initialization.** The message is split into 512-bit blocks (i.e. 16 32-bit words). Four state variables  $A_i$  with  $-4 \leq i < 0$  are initialized with these hexadecimal values:

$$[A_{-4}] \ 01234567 \quad [A_{-1}] \ 89abcdef \quad [A_{-2}] \ fedcba98 \quad [A_{-3}] \ 76543210$$

**Round function with state variable updates.** The round function is applied in three rounds with 16 iterations. In every iteration values  $A_{-1}$ ,  $A_{-2}$  and  $A_{-3}$  are taken as arguments to function  $F$ . Function  $F$  is IF in round 1, followed by MAJ for round 2 and XOR for the final round 3. The resulting value is added to  $A_{-1}$ , current message block  $M$  and constant  $X$ . Finally the 32-bit sum will be left-rotated by  $p$  positions. Left rotation is formally defined in Definition 2.7. The values of  $X$  and  $p$  are defined as follows:

Let  $i$  be the iteration counter between 1 and 16 and  $r$  the round between 1 and 3. Then  $X$  takes the value of the  $i$ -th column and  $r$ -th row of matrix  $C$ .  $p$  takes the value of row  $r$  and column  $i \bmod 4$  of matrix  $P$ .



$$C = \begin{pmatrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \\ 0 & 4 & 8 & 12 & 1 & 5 & 9 & 13 & 2 & 6 & 10 & 14 & 3 & 7 & 11 & 15 \\ 0 & 8 & 4 & 12 & 2 & 10 & 6 & 14 & 1 & 9 & 5 & 13 & 3 & 11 & 7 & 15 \end{pmatrix}$$

$$P = \begin{pmatrix} 3 & 7 & 9 & 11 \\ 3 & 5 & 9 & 13 \\ 3 & 9 & 11 & 15 \end{pmatrix}$$

This round function design is visualized in Figure 2.1.

## 2.3 SHA-256

SHA-256 is a hash function from the SHA-2 family designed by the National Security Agency (NSA) and published in 2001 [6]. It uses a Merkle-Damgård construction with a Davies-Meyer compression function. The best known preimage attack was found in 2011 and breaks preimage resistance for 52 rounds [8]. The best known collision attack breaks collision resistance for 31 rounds of SHA-256 [12] and pseudo-collision resistance for 46 rounds [9].

block size	512 bits	as per Section 1 of the standard [6]
digest size	256 bits	mentioned as Message Digest size [6]
internal state size	256 bits	as per Section 1 of the standard [6]
word size	32 bits	as per Section 1 of the standard [6]

TABLE 2.2: SHA-256 hash algorithm properties

### Definition 2.7 (*Shifts, rotations and a notational remark*)

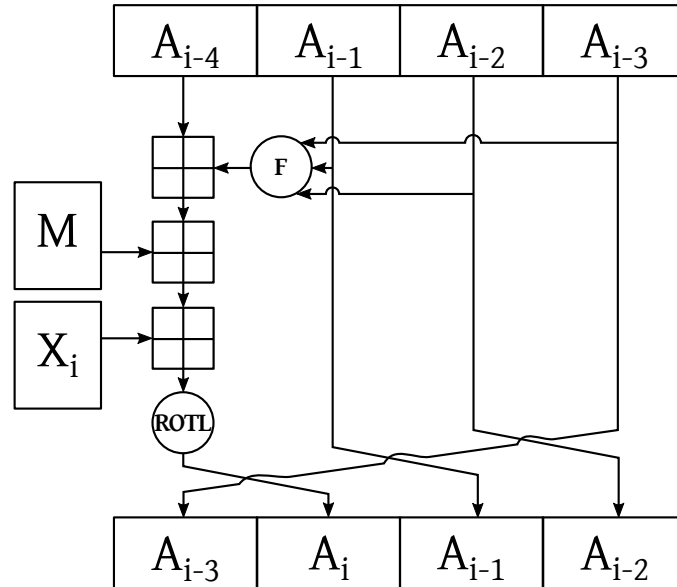
Consider a 32-bit word  $X$  with 32 binary values  $b_i$  with  $0 \leq i \leq 31$ .  $b_0$  refers to the least significant bit. Shifting ( $\ll$  and  $\gg$ ) and rotation ( $\lll$  and  $\ggg$ ) creates a new 32-bit word  $Y$  with 32 binary values  $a_i$ . We define the following notations:

$$Y := X \ll n \iff a_i := b_{i-n} \text{ if } 0 \leq i - n < 32 \text{ and } 0 \text{ otherwise}$$

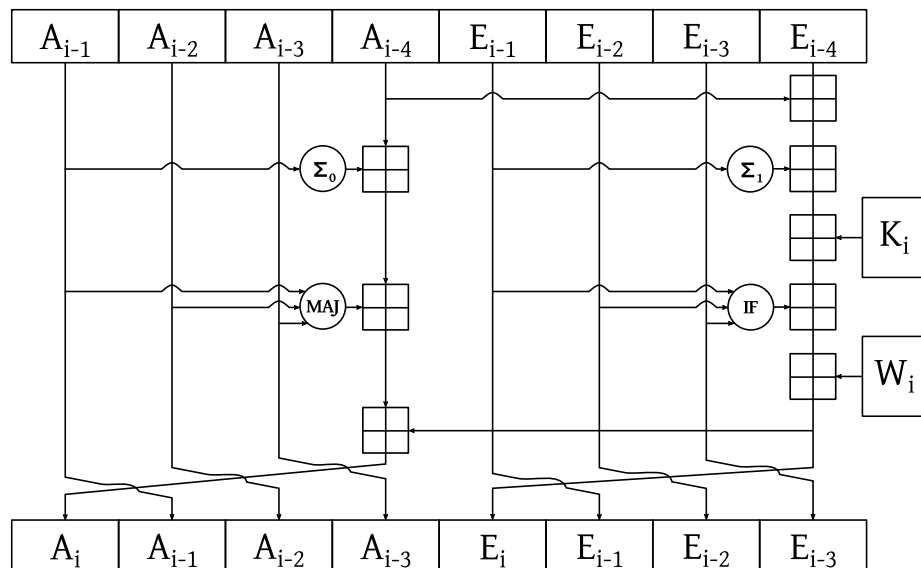
$$Y := X \gg n \iff a_i := b_{i+n} \text{ if } 0 \leq i + n < 32 \text{ and } 0 \text{ otherwise}$$

$$Y := X \lll n \iff a_i := b_{i-n \bmod 32} \text{ as used in MD}_4$$

$$Y := X \ggg n \iff a_i := b_{i+n \bmod 32}$$



**Figure 2.1:** MD<sub>4</sub> round function updating state variables



**Figure 2.2:** SHA-256 round function as characterized in [5]

Besides MD4's MAJ and IF, another four auxiliary functions are defined. Recognize that  $\oplus$  denotes the XOR function whereas  $\boxplus$  denotes 32-bit addition.

$$\begin{aligned}\Sigma_0(X) &:= (X \ggg 2) \oplus (X \ggg 13) \oplus (X \ggg 22) \\ \Sigma_1(X) &:= (X \ggg 6) \oplus (X \ggg 11) \oplus (X \ggg 25) \\ \sigma_0(X) &:= (X \ggg 7) \oplus (X \ggg 18) \oplus (X \gg 3) \\ \sigma_1(X) &:= (X \ggg 17) \oplus (X \ggg 19) \oplus (X \gg 10)\end{aligned}$$

**Padding and length extension.** The padding and length extension scheme of MD4 is used also in SHA-256. Append bit 1 and followed by a sequence of bit 0 until the message reaches a length of 448 modulo 512 bits. Afterwards the first 64 bits of the binary representation of the original input are appended.

**Initialization.** In a similar manner to MD4, initialization of internal state variables (called “working variables” in [6, Section 6.2.2]) takes place before running the round function. The eight state variables are initialized with the following hexadecimal values:

$$\begin{aligned}A_{-1} &= 6a09e667 & A_{-2} &= bb67ae85 & A_{-3} &= 3c6ef372 & A_{-4} &= a54ff53a \\ E_{-1} &= 510e527f & E_{-2} &= 9b05688c & E_{-3} &= 1f83d9ab & E_{-4} &= 5be0cd19\end{aligned}$$

Furthermore SHA-256 uses 64 constant values in its round function. We initialize step constants  $K_i$  for  $0 \leq i < 64$  with the following hexadecimal values (which must be read left to right and top to bottom):

428a2f98	71374491	b5c0fbcf	e9b5dba5	3956c25b	59f111f1
923f82a4	ab1c5ed5	d807aa98	12835b01	243185be	550c7dc3
72be5d74	80deb1fe	9bdc06a7	c19bf174	e49b69c1	efbe4786
0fc19dc6	240ca1cc	2de92c6f	4a7484aa	5cb0a9dc	76f988da
983e5152	a831c66d	b00327c8	bf597fc7	c6e00bf3	d5a79147
06ca6351	14292967	27b70a85	2e1b2138	4d2c6dfc	53380d13
650a7354	766a0abb	81c2c92e	92722c85	a2bfe8a1	a81a664b
c24b8b70	c76c51a3	d192e819	d6990624	f40e3585	106aa070
19a4c116	1e376c08	2748774c	34b0bcb5	391c0cb3	4ed8aa4a
5b9cca4f	682e6ff3	748f82ee	78a5636f	84c87814	8cc70208
90bffffa	a4506ceb	bef9a3f7	c67178f2		

**Precomputation of W.** Let  $W_i$  for  $0 \leq i < 16$  be the sixteen 32-bit words of the padded input message. Then compute  $W_i$  for  $16 \leq i < 64$  the following way:

$$W_i := \sigma_1(W_{i-2}) + W_{i-7} + \sigma_0(W_{i-15}) + W_{i-16}$$

**Round function.** For every block of 512 bits, the round function is applied. The eight state variables are updated iteratively for  $i$  from 0 to 63.

$$\begin{aligned}E_i &:= A_{i-4} + E_{i-4} + \Sigma_1(E_{i-1}) + \text{IF}(E_{i-1}, E_{i-2}, E_{i-3}) + K_i + W_i \\ A_i &:= E_i - A_{i-4} + \Sigma_0(A_{i-1}) + \text{MAJ}(A_{i-1}, A_{i-2}, A_{i-3})\end{aligned}$$

$W_i$  and  $K_i$  refer to the previously initialized values.

**Computation of intermediate hash values.** Intermediate hash values for the Davies-Meyer construction are initialized with the following values:

$$\begin{array}{llll} H_0^{(0)} := A_{-1} & H_1^{(0)} := A_{-2} & H_2^{(0)} := A_{-3} & H_3^{(0)} := A_{-4} \\ H_4^{(i)} := E_{-1} & H_5^{(i)} := E_{-2} & H_6^{(i)} := E_{-3} & H_7^{(i)} := E_{-4} \end{array}$$

Every block creates its own  $E_i$  and  $A_i$  values for  $60 \leq i < 64$ . These are used to compute the next intermediate values:

$$\begin{array}{ll} H_0^{(j)} := A_{63} + H_0^{(i-1)} & H_4^{(j)} := E_{63} + H_4^{(i-1)} \\ H_1^{(j)} := A_{62} + H_1^{(i-1)} & H_5^{(j)} := E_{62} + H_5^{(i-1)} \\ H_2^{(j)} := A_{61} + H_2^{(i-1)} & H_6^{(j)} := E_{61} + H_6^{(i-1)} \\ H_3^{(j)} := A_{60} + H_3^{(i-1)} & H_7^{(j)} := E_{60} + H_7^{(i-1)} \end{array}$$

**Finalization.** The final hash digest of size 256 bits is provided as

$$H_0^{(N)} \parallel H_1^{(N)} \parallel H_2^{(N)} \parallel H_3^{(N)} \parallel H_4^{(N)} \parallel H_5^{(N)} \parallel H_6^{(N)} \parallel H_7^{(N)}$$

where  $N$  denotes the index of the last block and operator  $\parallel$  denotes concatenation. Hence  $H_0^{(N)}$  are the four least significant bytes of the digest.



“JUST BECAUSE IT’S AUTOMATIC DOESN’T  
MEAN IT WORKS.”  
—Daniel J. Bernstein

## Chapter 3

# Differential cryptanalysis

In chapter 2 we defined two hash functions. In this chapter we consider such functions from a differential perspective. Differential considerations will turn out to yield successful collision attacks on hash functions. We introduce a notation to easily represent differential characteristics.

### 3.1 Motivation

In August 2004, Wang et al. published results at Crypto’04 [23] 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 [4]. 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 [21] 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, i.e. the size of the hash value  $h(x)$  in bits. Due to the birthday paradox, a collision attack has a generic complexity of  $2^{n/2}$  whereas preimage and second preimage attacks have generic complexities of  $2^n$ . In other words it is computationally easier to find any two colliding hash values than the preimage or second preimage for a given hash value.

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

Message 1			
4d7a9c83	<b>d6cb927a</b>	<b>29d5a578</b>	57a7a5ee
de748a3c	dcc366b3	b683a020	3b2a5d9f
c69d71b3	f9e99198	d79f805e	a63bb2e8
<b>45dc8e31</b>	97e31fe5	2794bf08	b9e8c3e9
Message 2			
4d7a9c83	<b>56cb927a</b>	<b>b9d5a578</b>	57a7a5ee
de748a3c	dcc366b3	b683a020	3b2a5d9f
c69d71b3	f9e99198	d79f805e	a63bb2e8
<b>45dd8e31</b>	97e31fe5	2794bf08	b9e8c3e9
Hash value of Message 1 and Message 2			
5f5c1a0d	71b36046	1b5435da	9bod807a

TABLE 3.1: One of two MD4 hash collisions provided in [23]. Values are given in hexadecimal, message words are enumerated from left to right, top to bottom. Differences are highlighted in bold 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.

## 3.2 Fundamentals

### Definition 3.1 (*Hash collision*)

Given a hash function  $h$ , a hash collision is a pair  $(x_1, x_2)$  with  $x_1 \neq x_2$  such that  $h(x_1) = h(x_2)$ .

Pseudo-collisions are also often considered when attacking hash functions. A *pseudo collision* is given if a hash collision can be found for a given hash function, but the initial vectors (IV) can be chosen arbitrarily.

Hash algorithms consume input values as blocks of bits. As far as the length of the input must not conform to the block size, padding is applied. Now consider such a block of input values and another copy of it. We use those two blocks as inputs for two hash algorithm implementations, but provide slight modifications in few bits. Differential cryptanalysis is based on the idea to consider those execution states and tracing those difference to learn about the propagation of message differences. Compare this setup with Figure 3.1.

At the very beginning only the few defined differences are given. But as the hash algorithm progresses in computation, differences are propagated to more and more bits. Most likely the final value will differ in many bits, because of a desirable hash algorithm property called *Avalanche effect*. A small difference in the input should lead to a visually recognizable difference in the output.

Visualizing those differences helps the cryptanalyst to find modifications yielding a small number of differences in the evaluation state. The propagation of



**Figure 3.1:** Typical attack setting for a collision attack: Hash function  $f$  is applied to two inputs  $M$  and  $M^*$  which differ by some predefined bits.  $M$  describes the difference between these values. A hash collision is given if and only if output values  $C$  and  $C^*$  show the same value. In differential cryptanalysis we observe the differences between two instances applying function  $f$  to inputs  $M$  and  $M^*$ .

differences in a particular hash algorithm is called *differential path*. Empirical results in differential cryptanalysis indicate that sparse paths are desirable, because it is easier to cancel out few differences in the output compared to many differences. The cryptanalyst consecutively modifies the input values to eventually receive a collision in the output value.

### Theorem 3.1

Assuming the number of differences in a differential path is small, this path is expected to result in a hash collision with higher probability.

### Definition 3.2

The propagation of differences in a particular function is called *differential path*. The complete differential state during a computation is called *differential characteristic*.

bit	binary	hexadecimal representation / differential notation
$x_0$	d6cb927a	11010110110010111001001001111010
$x_1$	29d5a578	0010100111010101010010101111000
$x_2$	45dc8e31	01000101110111001000111000110001
$x_0^*$	56cb927a	01010110110010111001001001111010
$x_1^*$	b9d5a578	1011100111010101010010101111000
$x_2^*$	45dd8e31	01000101110111011000111000110001
$\Delta x$		u1010110110010111001001001111010 n01n100111010101010010101111000 010001011101110n1000111000110001

TABLE 3.2: The three words different between Message 1 and Message 2 of the original MD4 hash collision by Wang et al. The last three lines show how differences can be written down using bit conditions. As far as 4 symbols are not from the set  $\{0, 1\}$  it holds that the messages differ by 4 bits.

### 3.3 Differential notation

Differential notation helps us to visualize differential characteristics by defining so-called *generalized bit conditions*. It was introduced by Christian Rechberger and Christophe de Cannière in 2006 [2, Section 3.2], inspired by *signed differences* by Wang et al. and is shown in Table 3.3.

Consider two hash algorithm implementations. Let  $x_i$  be some bit from the first implementation and let  $x_i^*$  be the corresponding bit from the second implementation. Differences are computed using a XOR and commonly denoted as  $\Delta x = x_i \oplus x_i^*$ . Bit conditions allow us to encode possible relations between bits  $x_i$  and  $x_i^*$ .

For example, let us take a look at the original Wang et al. hash collision in MD4 provided in Table 3.1. We extract all values with differences and represent them using differential notation. This gives us Table 3.2.

The following properties hold for bit conditions:

- If  $x_i = x_i^*$  holds and some value is known,  $\{0, 1\}$  contains its bit condition.
- If  $x_i \neq x_i^*$  holds and some value is known,  $\{u, n\}$  contains its bit condition.
- If  $x_i = x_i^*$  holds and the values are unknown, its bit condition is  $-$ .
- If  $x_i \neq x_i^*$  holds and the values are unknown, its bit condition is  $x$ .

Applying this notation to hash collisions means that arbitrary bit conditions (except for  $\#$ ) can be specified for the input values. In one of the intermediate iterations, we enforce a difference using one of the bit conditions  $\{u, n, x\}$ . This excludes trivial solutions with no differences from the set of possible solutions. And the final values need to lack differences thus are represented using a dash  $-$ .



$(x_i, x_i^*)$	(0, 0)	(1, 0)	(0, 1)	(1, 1)	$(x_i, x_i^*)$	(0, 0)	(1, 0)	(0, 1)	(1, 1)
?	✓	✓	✓	✓	3	✓	✓		
-	✓			✓	5	✓		✓	
x		✓	✓		7	✓	✓	✓	
0	✓				A		✓		✓
u		✓			B	✓	✓		✓
n			✓		C			✓	✓
1				✓	D	✓		✓	✓
#					E		✓	✓	✓

TABLE 3.3: Differential notation as introduced in [2]. The left-most column specifies a symbol called “bit condition” and right-side columns indicate which bit configurations are possible for two given bits  $x_i$  and  $x_i^*$ .

$\Delta x$	conjunctive normal form	$\Delta x$	conjunctive normal form
#	$(x) \wedge (\neg x)$	1	$(x) \wedge (x^*)$
0	$(\neg x) \wedge (\neg x^*)$	-	$\neg(x \oplus x^*)$
u	$(x) \wedge (\neg x^*)$	A	$(x)$
3	$(\neg x^*)$	B	$(x \vee \neg x^*)$
n	$(\neg x) \wedge (x^*)$	C	$(x^*)$
5	$(\neg x)$	D	$(\neg x \vee x^*)$
x	$(x \oplus x^*)$	E	$(x \vee x^*)$
7	$(\neg x \vee \neg x^*)$	?	

TABLE 3.4: All bit conditions represented as CNF using two boolean variables  $x$  and  $x^*$  to represent two bits.

### 3.4 A simple addition example

Using this notation, we can now reason about the behavior of functions on differential values. We start with 1-bit addition as most basic exercise to the reader. Consider a matrix with two input rows and one output row. The values of the first two rows are added such that the bit difference at the third row is created.

Figure 3.5 illustrates this example. Remember that symbols such as  $-$  and  $\emptyset$  underlie semantics defined in Table 3.3. It is also interesting to see how propagation of values can work. In Figure 3.6 we see how an underspecified value  $?$  can be strengthened once we have checked which values can be taken. Recognize that the system is constrained by the function in use and the definition of the differential symbols.

Finally we can extend our testcases to 4 bits and retrieve testcases such as Table 3.7 and 3.8.

### 3.5 Differential characteristics in action

In the previous section we illustrated how propagation with differential values works and how differential characteristics are written down. It is always important to keep in mind which function the characteristic illustrates, because this is not documented with the characteristic.

Now consider MD4 as defined in section 2.2. MD4 takes some input message (in our case limited to size of one block), the state variables are initialized and iteratively new  $A_i$  are computed.

Similarly, SHA-256 takes a message block  $M$  and initializes eight variables with an initial vector (IV). The remaining  $W_i$  are computed and iteratively, values  $A_i$  and  $E_i$  are computed.

Those values are structured in differential characteristics illustrated in Figure 3.2. Those layouts are used to specify our hash collisions we want to evaluate. Table 3.9 is also gives an application of the layout.

-	⇒	00	00	00	00	11	11	11	11
-		00	00	11	11	00	00	11	11
-		00	11	00	11	00	11	00	11

TABLE 3.5: A simple 1-bit addition example: On the left the differential characteristic is given. Two dashes, by definition, denote a missing difference in both input arguments. The result of the addition also must not show a difference. This yields eight possible bit configurations where two values close to each other denote  $(M, M^*)$  of Figure 3.1. Due to the behavior of addition, we know that configurations 2, 3, 5 and 8 (from left to right) are not possible.

-	⇒	00	00	11	11
-		00	11	00	11
?		00	11	11	00

TABLE 3.6: Like Figure 3.5, but any difference value for the result bit is possible. As such we consider any possible bit configuration, but eventually recognize that only four bit configurations are consistent with the behavior of addition. Because all resulting configurations show no bit difference in the output bit, we can strengthen ? by replacing it with -. This illustrates how knowledge about differential states can be propagated.

A: 0011	A: ---x	A: ---x	A: ---x
B: 0101	B: ---x	B: ---x	B: ---x
S: 1000	S: ????	S: ???-	S: x???

A: 0011	A: ---x	A: ----
B: 0101	B: ---x	B: ---x
S: 0000	S: ???x	S: x-??

TABLE 3.7: The upper line shows valid differential characteristics for 4bit addition whereas the lower line show invalid ones for 4bit addition. The rows are conventionally named using capital letters.

A: ----	A: 7C-3	A: 0uCD
S: 0000	S: -3u?	S: ADC7

A: ---x	A: xxxx
S: 0000	S: 0000

TABLE 3.8: Differential characteristics for the SHA-2 Sigma function. The upper line shows valid states. The lower line shows invalid ones.

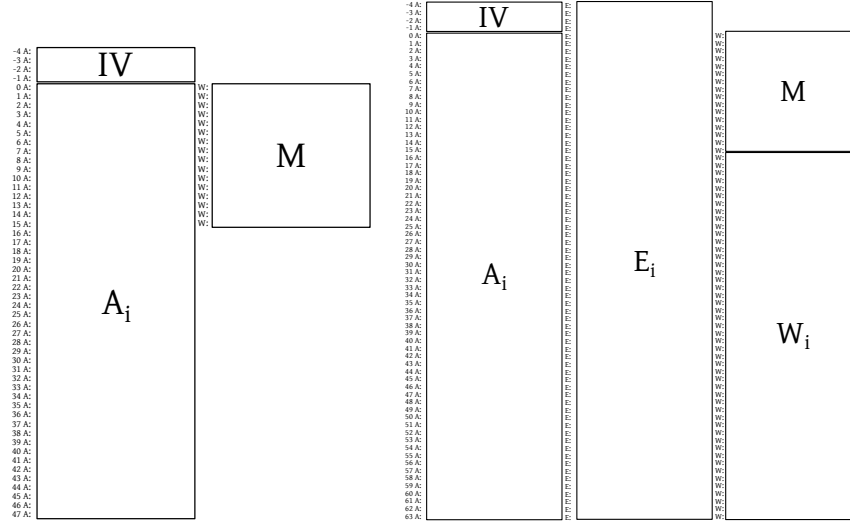


Figure 3.2: Layout of MD4 and SHA256 differential characteristics

$i$	$VS_{i,0}$	$VS_{i,1}$	$VS_{i,2}$	$i$	$VS_{i,0}$	$VS_{i,1}$	$VS_{i,2}$
-4 A	01100111010001010001100000001			-4 A	01100111010001010001100000001		
-3 A	00010000001100100101010001110110			-3 A	00010000001100100101010001110110		
-2 A	1001100001011010101110011111110			-2 A	1001100001011010101110011111110		
-1 A	11101111100110101010110001001			-1 A	11101111100110101010110001001		
0 A	0110101111010100111001000010010	WE	010011010111010100111001000011	0 A	0110101111010100111001000010010	WE	010011010111010100111001000011
1 A	01110110010011111101100110001	WE	101010110110010110010001110110	1 A	01110110010011111101100110001	WE	101010110110010110010001110110
2 A	101010110100000001110101110010	WE	01010011101001110100101110010	2 A	101010110100000001110101110010	WE	01010011101001110100101110010
3 A	1010110011101010010010010001	WE	11011100111010010010001110010	3 A	1010110011101010010010010001	WE	11011100111010010010001110010
4 A	001010001100011010101011110010	WE	110111001100011010101010011	4 A	001010001100011010101011110010	WE	110111001100011010101010011
5 A	0001010010001010110100000001	WE	101011001100011010101010011	5 A	0001010010001010110100000001	WE	101011001100011010101010011
6 A	0001100100110001000000111010	WE	101011001100011010101010011	6 A	0001100100110001000000111010	WE	101011001100011010101010011
7 A	0010101110000001010010010000	WE	00111010010101001011011001111	7 A	0010101110000001010010010000	WE	00111010010101001011011001111
8 A	????????????????????????????	WE	110001101001101011100011010011	8 A	01110011001000111111111010000	WE	110001101001101011100011010011
9 A	????????????????????????????	WE	111110011101001100100011001000	9 A	101011010100000011100110011111	WE	111110011101001100100011001000
10 A	101010100100010101100000001110	WE	101011100111001110000000101110	10 A	101010100100010101100000001110	WE	101011100111001110000000101110
11 A	10001101010101010101010101010	WE	1010011000110101001011101000	11 A	10001101010101010101010101010	WE	1010011000110101001011101000
12 A	00101100101011010101010101010	WE	0100010110110100011000110001	12 A	00101100101011010101010101010	WE	0100010110110100011000110001
13 A	10010100100010001000100010001	WE	10010111100011000111111100101	13 A	10010100100010001000100010001	WE	10010111100011000111111100101
14 A	0000101001010001-----110	WE	001001111001010010111100001000	14 A	0000101001010001-----110	WE	001001111001010010111100001000
15 A	00011101010101-----100	WE	101100111101000110000111101001	15 A	00011101010101-----100	WE	101100111101000110000111101001
16 A	00010101010101-----111			16 A	00010101010101-----111		
17 A	00011110011010-----110			17 A	00011110011010-----110		
18 A	01010110000101-----100			18 A	01010110000101-----100		
19 A	10100000001011-----100			19 A	10100000001011-----100		
20 A	1101001111110110100000010100			20 A	1101001111110110100000010100		
21 A	111100111010000001011111010100			21 A	111100111010000001011111010100		
22 A	01011011001001001001001101010			22 A	01011011001001001001001101010		
23 A	010100001101101010001110001111			23 A	010100001101101010001110001111		
24 A	00000010000101000101100011010			24 A	00000010000101000101100011010		
25 A	10110000100101000010101101010			25 A	10110000100101000010101101010		
26 A	000010101000100101101101000001			26 A	000010101000100101101101000001		
27 A	00000101101101110101010101011			27 A	00000101101101110101010101011		
28 A	1010100101101010110000100101			28 A	1010100101101010110000100101		
29 A	101000100000101010010000101001			29 A	101000100000101010010000101001		
30 A	0010100110101111000110100011			30 A	0010100110101111000110100011		
31 A	11111001001001010101110101010			31 A	11111001001001010101110101010		
32 A	010011111010010101000010111			32 A	010011111010010101000010111		
33 A	00110000011101010101101100100			33 A	00110000011101010101101100100		
34 A	00100000011010111010000010101			34 A	00100000011010111010000010101		
35 A	01000000010011000001000110010			35 A	01000000010011000001000110010		
36 A	000001111010111011100101001			36 A	000001111010111011100101001		
37 A	11001000000101010000110000100			37 A	11001000000101010000110000100		
38 A	101100000100011111010011010100			38 A	101100000100011111010011010100		
39 A	000100100000101000010110001100			39 A	000100100000101000010110001100		
40 A	1100000001001000011000110000101			40 A	1100000001001000011000110000101		
41 A	0000010100001011101010010010			41 A	0000010100001011101010010010		
42 A	0100110101101111110100001010			42 A	0100110101101111110100001010		
43 A	01010000010001111010000010101			43 A	01010000010001111010000010101		
44 A	1111000000101011101100001000			44 A	1111000000101011101100001000		
45 A	1000010101010100101000000100			45 A	1000010101010100101000000100		
46 A	10000010100100101000101110010			46 A	10000010100100101000101110010		
47 A	10000001110010101010001011101			47 A	10000001110010101010001011101		

TABLE 3.9: One of the original MD4 collision by Wang et al, with a few bits underspecified (left) and propagated values (right). The question marks indicate that any bit configuration for the two bits are possible. Dashes indicate that the bits have the same configuration in both instances, but the value itself is unknown. However, it turns out the description with missing values in iteration 6 (message) and iterations 8–19 is complete enough such that missing values can be deduced by other values the description of the algorithm.



“WHAT IDIOT CALLED THEM LOGIC  
ERRORS RATHER THAN BOOL SHIT?”  
—Unknown

## Chapter 4

# Satisfiability

Boolean algebra allows us to describe functions over two-valued variables. Satisfiability is the question for an assignment such that a function evaluates to true. Satisfiability problems are solved by SAT solvers. We discuss the basic theory behind satisfiability. We will learn that any computation can be represented as satisfiability problem. In Chapter 6 we will represent a differential cryptanalysis problem such that it is solvable iff the corresponding SAT problem is satisfiable.

### 4.1 Basic notation and definitions

#### Definition 4.1 (*Boolean function*)

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

#### Definition 4.2 (*Assignment*)

A  $k$ -*assignment* is an element of  $\{0, 1\}^k$ .  
Let  $f$  be some  $k$ -ary Boolean function. An *assignment for function  $f$*  is any  $k$ -assignment.

#### Definition 4.3 (*Truth table*)

Let  $f$  be some  $k$ -ary Boolean function. The *truth table of Boolean function  $f$*  assigns truth value 0 or 1 to any assignment of  $f$ .

Boolean functions are characterized by their corresponding truth table.

$x_1$	$x_2$	$f(x_1, x_2)$	$x_1$	$x_2$	$f(x_1, x_2)$	$v$	$f(v)$
1	1	1	1	1	1	1	0
1	0	0	1	0	1	0	1
0	1	0	0	1	1	(c) NOT	
0	0	0	0	0	0		

(A) AND

(B) OR

TABLE 4.1: Truth tables for AND, OR and NOT

Table 4.1 shows example truth tables for the Boolean AND, OR and NOT functions. A different definition of the three functions is given the following way:

**Definition 4.4**

Let AND, OR and NOT be three Boolean functions.

- AND maps  $X = \{0, 1\}^2$  to 1 if all values of  $X$  are 1.
- OR maps  $X = \{0, 1\}^2$  to 1 if any value of  $X$  is 1.
- NOT maps  $X = \{0, 1\}^1$  to 1 if the single value of  $X$  is 0.

All functions return 0 in the other case.

Those functions are denoted  $a_0 \wedge a_1$ ,  $a_0 \vee a_1$  and  $\neg a_0$  respectively, for input parameters  $a_0$  and  $a_1$ .

It is interesting to observe, that any Boolean function can be represented using only these three operators. This can be proven by complete induction over the number of arguments  $k$  of the function.

Let  $k = 1$ . Then we consider any possible 2-assignment for one input variable  $x_1$  and one value of  $f(x_1)$ . Then four truth tables are possible listed in Table 4.2. The description shows the corresponding definition of  $f$  using AND, OR and NOT only.

Now let  $g$  be some  $k$ -ary function. Let  $(a_0, a_1, \dots, a_k)$  be the  $k$  input arguments to  $g$  and  $x_1 := g(a_0, a_1, \dots, a_k)$ . Then we can again look at Table 4.2 to discover that 4 cases are possible: 2 cases where the return value of our new  $(k + 1)$ -ary function depends on value  $x_1$  and 2 cases where the return value is constant.

This completes our proof.

$x_1$	$f(x_1)$	$x_1$	$f(x_1)$	$x_1$	$f(x_1)$	$x_1$	$f(x_1)$
1	1	1	1	1	0	1	0
0	1	0	0	0	1	0	0
(A) $f : x \mapsto 1$		(B) $f : x \mapsto x$		(C) $f : x \mapsto \neg x$		(D) $f : x \mapsto 0$	

TABLE 4.2: Unary  $f$  and its four possible cases

Boolean functions have an important property which is described in the following definition:

**Definition 4.5**

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

The corresponding tool to determine satisfiability is defined as follows:

**Definition 4.6**

A *SAT solver* is a tool to determine satisfiability (SAT or UNSAT) of a Boolean function. If satisfiability is given, it returns some model.

### 4.1.1 Computational considerations

The generic complexity of SAT determination is given by  $2^n$  for  $n$  Boolean variables.

Let  $n$  be the number of variables of a Boolean function. No known algorithm exists to determine satisfiability in polynomial runtime. This means no algorithm solves the SAT problem with runtime behavior which depends polynomially on the growth of  $n$ .

This is known as the famous  $\mathcal{P} \stackrel{?}{\neq} \mathcal{NP}$  problem.

However, SAT solver can take advantage of the problem's description. For example consider function  $f$  in Display 4.1.

$$f(x_0, x_1, x_2) = x_0 \wedge (\neg x_1 \vee x_2) \quad (4.1)$$

Instead of trying all possible 8 cases for 3 Boolean variables, we can immediately see that  $x_0$  is required to be 1. So we don't need to test  $x_0 = 0$  and can skip 4 cases. This particular strategy is called *unit propagation*.

### 4.1.2 SAT competitions

SAT research is heavily concerned with finding good heuristics to find some model for a given SAT problem as fast as possible. Biyearly [SAT competitions](#) take place to challenge SAT solvers in a set of benchmarks. The committee evaluates the most successful SAT solvers solving the most problems within a given time frame.

SAT 2016 is currently ongoing, but in 2014 lingeling by Armin Biere has won first prize in the Application benchmarks track and second prize in the Hard Combinatorial benchmarks track for SAT and UNSAT instances respectively. Its parallelized sibling plingeling and Cube & Conquer sibling treengeling have won prizes in parallel settings.

In chapter 7 we will look at runtime results shown by (but not limited to) those SAT solvers.

## 4.2 The DIMACS de-facto standard

### Definition 4.7

A *conjunction* is a sequence of Boolean functions combined using a logical OR. A *disjunction* is a sequence of Boolean functions combined using a logical AND. A *literal* is a Boolean variable (*positive*) or its negation (*negative*).

A SAT problem is given in *Conjunctive Normal Form* (CNF) if the problem is defined as conjunction of disjunctions of literals.

A simple example for a SAT problem in CNF is the exclusive OR (XOR). It takes two Boolean values  $a$  and  $b$  as arguments and returns true if and only if the two arguments differ.

$$(a \vee b) \wedge (\neg a \vee \neg b) \quad (4.2)$$

Display 4.2 shows one conjunction (denoted  $\wedge$ ) of two disjunctions (denoted  $\vee$ ) of literals (denoted  $a$  and  $b$  where prefix  $\neg$  represents negation). This structure constitutes a CNF.

Analogously we define a *Disjunctive Normal Form* (DNF) as disjunction of conjunctions of literals. The negation of a CNF is in DNF, because literals are negated and conjunctions become disjunctions, vice versa.

### Theorem 4.1

Every Boolean function can be represented as CNF.

Theorem 4.1 is easy to prove. Consider the truth table of an arbitrary Boolean function  $f$  with  $k$  input arguments and  $j$  rows of output value false. We represent  $f$  as CNF.

Consider Boolean variables  $b_{i,l}$  with  $0 \leq i \leq j$  and  $0 \leq l \leq k$ . For every row  $i$  of the truth table with assignment  $(r_i)$ , add one disjunction to the CNF. This disjunction contains  $b_{i,l}$  if  $r_{i,l}$  is false. The disjunction contains  $\neg b_{i,l}$  if  $r_{i,l}$  is true.

As far as  $f$  is an arbitrary  $k$ -ary Boolean function, we have proven that any function can be represented as CNF.

SAT problems are usually represented in the DIMACS de-facto standard. Consider a SAT problem in CNF with  $nbclauses$  clauses and enumerate all variables from 1 to  $nbvars$ . A DIMACS file is an ASCII text file. Lines starting with “c” are skipped (comment lines). The first remaining line has to begin with “p cnf” followed by  $nbclauses$  and  $nbvars$  separated by spaces (header line). All following non-comment lines are space-separated indices of Boolean variables optionally



prefixed by a minus symbol. Then one line represents one clause and must be terminated with a zero symbol after a space. All lines are conjuncted to form a CNF.

Variations of the DIMACS de-facto standard also allow multiline clauses (the zero symbol constitutes the end of a clause) or arbitrary whitespace instead of spaces. The syntactical details are individually published on a per competition basis.

LISTING 4.1: Display 4.2 represented in DIMACS format

```
p cnf 2 2
a b
-a -b
```

### 4.3 Terminology

Given a conjunctive structure of disjunctions, we can define terms related to this structure:

#### Definition 4.8

A *clause* is a disjunction of literals. A *k-clause* is a clause consisting of exactly *k* literals. A *unit clause* is a 1-clause. A *Horn clause* is a clause with at most one positive literal. A *definite clause* is a clause with exactly one positive literal. A *goal clause* is a clause with no positive literal.

#### Definition 4.9

Given a literal, its *negated literal* is the literal with its sign negated. A literal is *positive*, if its sign is positive. A literal is *negative* if its sign is negative. An *existential literal* is a literal which occurs exactly once and its negation does not occur. A *used variable* is a variable which occurs at least once in the CNF.

The *literal frequency* is the number of occurrences of a literal in the CNF divided by the number of clauses declared. Equivalently *variable frequency* defines the number of variable occurrences divided by the number of clauses declared.

#### Definition 4.10

The *clause length* of a clause is the number of literals contained. A clause is called *tautological* if a literal and its negated literal occurs in it.

### 4.4 Basic SAT solving techniques

**Definition 4.11**

Given two CNFs  $A$  and  $B$ , they are called *equisatisfiable* if and only if  $A$  is satisfiable if and only if  $B$ .

**4.4.1 Boolean constraint propagation (BCP)**

One of the most basic techniques to SAT solving is *Boolean Constraint Propagation*, also called *unit propagation*. It is so fundamental that SATzilla, introduced in section 5.2, applies it immediately before looking at SAT features.

Let  $l$  be the literal of a unit clause in a CNF. Remove any clause containing  $l$  and replace any occurrences of  $\neg l$  from the CNF. It is easy to see, that the resulting CNF is equisatisfiable, because due to the unit clause  $l$  must be true. So any clause containing  $l$  is satisfied and  $\neg l$  yields false, where  $A \vee \perp$  is equivalent to  $A$  for any boolean function  $A$ .

**4.4.2 Watched literals**

Watched Literals are another fundamental concept in SAT solving. It is very expensive to check satisfiability of all clauses for every value of a literal. Watched Literals is a neat technique to reduce the number of checks.

Consider the solver assigns a value for literal  $l$ . Instead of looking at all clauses and testing whether the clause is falsified by  $l$ , only clauses containing  $l$  are checked if  $l$  is one of the watched literals of the clause. This empirical approach was established with the Chaff and zChaff SAT solvers and has proven useful in various variants.

**4.4.3 Remark**

The previous two techniques shall illustrate basic approaches, but actual SAT solving research requires decades of development to tune individual SAT solvers. Memory models and concurrency strategies lead to fundamentally different run-time behaviours of SAT solvers.

As such an initial idea to initiate an individual SAT solver specifically designed for solving problems in differential cryptanalysis was dropped, because development time is expected too long for a master thesis to be fruitful. As such we focused on popular and established SAT solvers of the SAT community.

## 4.5 SAT solvers in use

In this thesis we consider the several SAT solvers. They have been selected either by their popularity or their good results at previous SAT competitions:

- MiniSat 2.2.0
- treengeling, lingeling and plingeling, in versions:
  - lingeling ats1
  - lingeling ats101
  - lingeling ats102
  - lingeling ats104
  - lingeling baz
- CryptoMiniSat 4.5
- CryptoMiniSat 5
- glucose syrup

Specifically this means the hash collision attacks we looked have run with these SAT solvers. The results are discussed in section 7 and provided in Appendix D.

lingeling ats101, ats102 and ats104 are non-public releases of lingeling. They have been developed in private communication with Armin Biere. Our main goal was to achieve a separation between two sets of variables. First all variables of the first need to be assigned in the best possible way. Afterwards the second set of variables is considered. Specifically variables modelling the differences between the two hash algorithm instances should constitute the first set.

ats101 implements that difference variables are guessed with false first and usual heuristics apply for all other variables. Our intermediate results with incomplete CNF files showed a high number of restarts. Therefore ats102 disables backjumping and therefore skips decisions for important variables. Finally ats104 is not expected to distinguish from ats102. It only provides further debugging information.

The SAT solvers have generally been run without any special options, except for

- MiniSat was run with `pre=once` as it is generally recommended to run with the builtin preprocessor.
- Lingeling has been generally run with `phase=-1` to prefer false as initial assignment to literals. However, lingeling ats101 implements this with more forceful strategy.





“WHAT IDIOT CALLED THEM LOGIC  
ERRORS RATHER THAN BOOL SHIT?”  
—Unknown

## Chapter 5

# SAT features

At the very beginning I was very intrigued by the question “What is an ‘average’ SAT problem?”. Answers to this question can help to optimize SAT solver memory layouts. Specifically for this thesis I wanted to find out whether our problems distinguish from “average” problems in any way such that we can use this distinction for runtime optimization.

I came up with 8 questions related to basic properties of SAT problems we will discuss in depth in this section:

1. Given an arbitrary literal. What is the percentage it is positive?
2. What is the variables / clauses ratio?
3. How many literals occur only either positive or negative?
4. What is the average and longest clause length among CNF benchmarks?
5. How many Horn clauses exist in a CNF?
6. Are there any tautological clauses?
7. Are there any CNF files with more than one connected variable component?
8. How many variables of a CNF are covered by unit clauses?

We will now define the terms used in those questions.

## 5.1 SAT features and CNF analysis

### Definition 5.1 (*SAT feature*)

A *SAT feature* is a statistical value (named *feature value*) retrievable from some given SAT problem.

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.

The general goal is to write a tool which evaluates several SAT features at the same time and retrieve them for comparison with other problems. Therefore it should be computationally easy to evaluate SAT features of a given SAT problem. A suggested computational limit is given with polynomial complexity in terms of number of variables and number of clauses for memory as well as runtime for evaluation algorithms. Sticking to this convention 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 cannot be a SAT feature as far as satisfiability needs to be determined. But no actual hard computational limit is defined.

## 5.2 Related work

The most similar resource I found looking at SAT features was the SATzilla project [15, 24] in 2012. The authors systematically defined 138 SAT features categorized in 12 groups. Some features are only evaluated conditionally. The features themselves are not defined formally, but an implementation is provided bundled with example data. The following list provides an excerpt of the features:

**nvarsOrig** number of variables defined in the CNF header

**nvars** number of active variables

**reducedVars**  $\text{nvarsOrig} - \text{nvars}$ , divided by  $\text{nvars}$

**vars-clauses-ratio**  $\text{nvars}$  divided by number of active clauses

**POSNEG-RATIO-CLAUSE-mean** mean of  $2 \cdot \left\| 0.5 - \frac{\text{pos}}{\text{length}} \right\|$  where  $\text{pos}$  is the number of positive literals and  $\text{length}$  clause length of a specific clause

**POSNEG-RATIO-CLAUSE-entropy** like POSNEG-RATIO-CLAUSE-mean but entropy

**TRINARY+** number of clauses with clause length 1, 2 or 3 divided by number of active clauses

**HORNY-VAR-min** minimum number of times a variable occurs in a Horn clause

**cluster-coeff-mean** let neighbors of a clause be all clauses containing any literal negated and let clauses  $c_1$  and  $c_2$  be conflicting if  $c_1$  contains literal  $l$  and  $c_2$  contains  $\neg l$ , then return the mean of 2 times the number of conflicting neighbors of a clause  $c$  divided by the number of unordered pairs of neighbors, returned iff computable within 20 seconds for all clauses

Please recognize that active clauses are the unsatisfied clauses after BCP has been applied. Equivalently active variables are remaining variables after application of BCP.

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].

### 5.3 Statistical features

For our SAT features we need to define some basic statistical terminology. Let  $x_1, x_2, \dots, x_n$  be a finite sequence of numbers ( $n \in \mathbb{N}$ ).

**Arithmetic mean** (or short: mean) is defined as

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

**Standard deviation** (or short: sd) with mean  $\bar{x}$  is defined as

$$\sigma(x) = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2}$$

**Median** with  $x_1 \leq x_2 \leq \dots \leq x_n$  (i.e. sorted ascendingly) is defined as

$$m = \begin{cases} x_{\text{mid}} & \text{if } n \text{ odd} \\ \frac{x_{\text{mid}} + x_{\text{mid}+1}}{2} & \text{if } n \text{ even} \end{cases} \quad \text{with } \text{mid} = \frac{n}{2}$$

and often considered more “robust” than the arithmetic mean.

**Entropy** is defined according to Claude Shannon’s information theory:

$$H(x) = - \sum_{i=1}^n x_i \cdot \log_2(x_i)$$

where  $0 \cdot \log_2(0) := 0$ .

Furthermore *count* refers to the number of elements  $n$ , *largest* refers to the maximum element  $\max_{1 \leq i \leq n}(x_i)$  and *smallest* refers to the minimum element  $\min_{1 \leq i \leq n}(x_i)$ .

## 5.4 Suggested SAT features

We wrote a tool called *cnf-analysis*. The evaluated features are partially inspired by SATzilla and *lingeling*. The latter prints basic statistics for every CNF it evaluates.

A summary of our suggested SAT features is given:

**clause\_variables\_sd\_mean**

mean of sd of variables in a clause

**clauses\_length\_(largest, smallest, mean, median, sd)**

statistics related to the clause length

**connected\_(literal, variable)\_components\_count**

two literals (variables) are connected if they occur in some clause together, count the number of connected components

**definite\_clauses\_count**

number of definite clauses in the CNF

**existential\_literals\_count**

number of existential literals in the CNF

**existential\_positive\_literals\_count**

number of positive, existential literals in the CNF

**(false, true)\_trivial**

is the CNF satisfied if all variables are claimed to be false (true)?

**goal\_clauses\_count**

number of goal clauses in the CNF

**literals\_count**

number of literals in the CNF (i.e. sum of clause lengths)

**literals\_frequency\_k\_to\_k + 5**

let  $n_l$  be the literal frequency of literal  $l$ , count the number of  $n_l$  satisfying  $\frac{k}{100} \leq n_l < \frac{k+5}{100}$  where  $k$  is a variable in  $\{0, 5, 10, \dots, 90, 95\}$  and  $k = 95$  counts  $\frac{k}{100} \leq n_l \leq \frac{k+5}{100}$ .

**literals\_frequency\_(largest, smallest, mean, median, sd)\_entropy**

statistics related to literal frequencies



**literals\_occurrence\_one\_count**

number of literals with occurrence 1

**nbclauses, nbvars** number of clauses (variables) as defined in the CNF header**negative\_literals\_in\_clause\_(smallest, largest, mean)**

statistics related to number of negative literals in clauses

**(positive, negative)\_unit\_clause\_count**

number of unit clauses with a positive (negative) literal

**positive\_literals\_count**

number of positive literals in CNF

**positive\_literals\_in\_clause\_(largest, smallest, mean, median, sd)**

statistics related to number of positive literals in clauses

**positive\_negative\_literals\_in\_clause\_ratio\_(mean, entropy)**let  $r_c$  be the number of positive literals divided by clause length of clause  $c$ ,  
mean and related of all  $r_c$ **positive\_negative\_literals\_in\_clause\_ratio\_mean**mean of all  $r_c$ **tautological\_literals\_count**

number of clauses which contain a tautological literal

**two\_literals\_clause\_count**

number of clauses with two literals

**variables\_frequency\_k\_to\_k + 5**

same as literals\_frequency\_k\_to\_k + 5 but for variables

**variables\_frequency\_(largest, smallest, mean, median, sd, entropy)**

same as literals\_frequency but for variables

**variables\_used\_count**

number of variables with occurrence greater o

## 5.5 Evaluation efficiency

The resource requirements of those features have been classified:

**Type 1** read the files as bytes, a DIMACS parser is not necessary, constant memory is used

**Type 2** features understand what a clause is, but still need constant memory

**Type 3** subquadratic runtime and linear memory

**Type 4** unrestricted

Memory and runtime is always considered in comparison with the filesize.

This classification should support future considerations regarding feature evaluation tools. The suggested SAT features above have been explicitly selected to avoid Type 4 implementations to limit the time to compute features. The Python implementation triggered MemoryErrors on a computer with 4 GB RAM for a 770 MB CNF file. Followingly a much more efficient Go implementation was implemented which requires much less memory and is much faster. `bench_573.smt2.cnf` took 1 second in Go instead of 2 minutes in Python. However, the data evaluated is less accurate compared to Python, because Python unlike Go provide nice implementation of statistical tools in the standard library.

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

## 5.6 CNF dataset

To evaluate CNF features of a representative set of CNF files, it was necessary to identify equivalent CNF files in the best possible way. Therefore I defined a hashing algorithm standardizing the CNF input provided to a SHA1 instance. Every CNF file is identifiable by its “cnfhash 2.0.0” hash value.

In the next step a complete set of CNF files of previous SAT competitions was collected. The following CNF file collections have been considered:

- SAT Race 2008
- SAT09 Competition
- SAT-Race 2010
- SAT11 Competition
- SAT Challenge 2012
- SAT Competition 2013
- SAT Competition 2014
- SAT-Race 2015
- SAT Competition 2016

- SATlib

The benchmarks are mostly contributed by the participants of the associated conferences. Others are reused from previous years. Individual projects allow to generate CNF files for specific problems in a selectable problem size; such as

Some files turned out to be problematic. In SATlib, 3 gzipped files couldn't be decompressed and several files contain empty clauses. Empty clauses are assumed to immediately falsify the CNF and are therefore pointless. I removed trailing zeros in CNFs. Variants of the DIMACS standard also expect lines with a percent symbol to terminate the CNF. Besides those minor issues documented as part of the cnf-analysis project, many feature files have been determined.

TODO: Illustrate basic properties about those CNF files

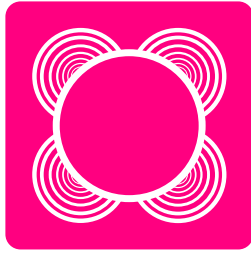
## 5.7 The average SAT problem

### **Proposition 5.1**

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

TODO: what is an average SAT problem?

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 $b$



“THERE IS CONSENSUS THAT ENCODING  
TECHNIQUES USUALLY HAVE A DRAMATIC  
IMPACT ON THE EFFICIENCY OF THE SAT  
SOLVER”

—Magnus Björk

## Chapter 6

# Problem encoding

We already discussed how SAT solvers work and which input they take. We also sketched how hash algorithm properties got broken using differential cryptanalysis. In this section we combine those subjects and describe how we designed an attack setting.

### 6.1 STP approach

TODO: describe approach

### 6.2 Two instances and its difference

TODO: we wrote a tool called `algotocnf` for our differential needs

TODO:

- reference to Magnus Daum's thesis ( $\neq$  signed bit diff desc)

### 6.3 Approach with a differential description

TODO: approach with differential desc

## 6.4 Influencing evaluation order



## Chapter 7

# Results

### 7.1 SAT features results

TODO: do cryptoproblems distinguish from other problems?

TODO: do our benchmark distinguish from other problems?

TODO: answer the 8 questions posed previously

### 7.2 Attack results

TODO: is simplification worth it?

TODO: discuss runtime and development, tuning by doing difference variables first, diff desc makes a difference

Appendix [D](#) provide a more exhaustive list of runtimes retrieved.

### 7.3 Related work

### 7.4 Conclusion

TODO: we attacked MD<sub>4</sub> and SHA<sub>2</sub>, but can see the problems with

## 7.5 Contributions

To strengthen Reproducible Research, the source code and data resulting from this thesis is available online. It allows the reader to run the experiments again and verify our claims. We did our best to describe our hardware setup as accurately as possible. At the following website, any results part of this project are collected:

<http://lukas-prokop.at/proj/megosat/>

Several subprojects are part of this master thesis:

### **algotocnf**

A python library implementing the encoding described in chapter 6.

**Python3 library and program:** <https://github.com/prokls/algotocnf>

### **cnf-hash**

A standardized way to produce a unique hash for CNF files

**Go implementation:** <https://github.com/prokls/cnf-hash-go>

**Python3 implementation:** <https://github.com/prokls/cnf-hash-py>

**Testsuite:** <https://github.com/prokls/cnf-hash-tests2>

### **cnf-analysis**

Evaluate SAT features for a given CNF file.

**Go implementation:** <https://github.com/prokls/cnf-analysis-go>

**Python3 implementation:** <https://github.com/prokls/cnf-analysis-py>

**Testsuite:** <https://github.com/prokls/cnf-analysis-tests>



## **Chapter 8**

# **Summary and Future Work**

### **8.1 Summary of results**

### **8.2 Future work**



# **Appendices**



## **Appendix A**

### **Illustration**

$i$		$VS_{i,0}$	$VS_{i,1}$	$VS_{i,2}$
-4	A:	01100111010001010010001100000001		
-3	A:	00010000001100100101010001110110		
-2	A:	10011000101110101101110011111110		
-1	A:	1110111110011011010101110001001		
0	A:	01101011110101001110010000010010	W:	01001101011110101001110010000011
1	A:	011011001001111111011100u110001	W:	u1010110110010111001001001111010
2	A:	101010110100000001110u01n1110010	W:	n01n100111010101101001010111000
3	A:	101011u1001111010101001001010001	W:	0101011110100111101001011110110
4	A:	00101100011000110101010111110010	W:	1101110011101001000101000111100
5	A:	000110100110001010u1101000000001	W:	1101100110000110110011010110011
6	A:	0001101100unuu110001000001111010	W:	1011011010000011010000000100000
7	A:	00101011100000010unnn011001010000	W:	001110110010100101110110011111
8	A:	011100110010001u1111111110110000	W:	11000110100111010111000110110011
9	A:	101011n01unnnu000111110011001111	W:	11111001111010011001000110011000
10	A:	10n00100100001010100000010101110	W:	11010111100111111000000001011110
11	A:	u1000110101101100100101011111111	W:	10100110001110111011001011101000
12	A:	001011u00u101011111110001111011	W:	010001011101110n1000111000110001
13	A:	10un1n01001100010100000111100101	W:	10010111111000110001111111100101
14	A:	00001010010100011000100011010110	W:	00100111100101001011111100001000
15	A:	0001111010101u010110011011010100	W:	10111001111010001100001111101001
16	A:	n00n0un0110100101001101101011111		
17	A:	00011111001110100001001000011110		
18	A:	01010111000011010000000010010100		
19	A:	u1n10000000101111001101011000100		
20	A:	n1un1001111111011101000000110100		
21	A:	1111001110110000010111111010100		
22	A:	01011101110011010011001100111010		
23	A:	01010000111011101100011110001111		
24	A:	00000010000100100011011100011010		
25	A:	10110000100101100001010011101010		
26	A:	00001010100010010111011101000001		
27	A:	00000110111011101011010110011		
28	A:	10110110010111010110110000100101		
29	A:	10100010000011010100100001101001		
30	A:	00101001110101111100011101100011		
31	A:	1111110010010010101011110110110		
32	A:	01001111110100100110100000101111		
33	A:	00111000001111010110111011100100		
34	A:	00100000011101011110100000010101		
35	A:	n0100000001100110000010001110010		
36	A:	n0000111111010111101111001011001		
37	A:	11001000000110100100001100001100		
38	A:	10110000011001111110100110101100		
39	A:	00010010000010100001101100011100		
40	A:	1100000010010000111000110000101		
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 MD<sub>4</sub> collision given by Wang, et al.

## Appendix B

### 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”.

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

TABLE B.1: Thinkpad x220 Tablet specification [10]

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

TABLE B.2: Cluster node nehalem192go specification [3]





## Appendix C

### Testcases

Figures C.1, C.2, C.3 and C.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:	-----xxxxxxxxxxxxx-x-----	W:	-----
6	A:	x-----x-----x-x-xxxx--x	W:	-----
7	A:	-----x--x-x-----	W:	-----
8	A:	-----x-----x-x-x-----	W:	x-----
9	A:	-----x-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 C.1: TODO description

$i$		$\nabla S_{i,0}$	$\nabla S_{i,1}$	$\nabla S_{i,2}$
-4	A:	01100111010001010010001100000001		
-3	A:	0001000000110010010101010001110110		
-2	A:	10011000101110101101110011111110		
-1	A:	1110111110011011010101110001001		
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 C.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:	1110111110011011010101110001001		
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 C.3: TODO description

$i$		$VS_{i,0}$	$VS_{i,1}$	$VS_{i,2}$
-4	A:	01100111010001010010001100000001		
-3	A:	00010000001100100101010001110110		
-2	A:	100110001011101010110011111110		
-1	A:	1110111110011011010101110001001		
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 C.4: TODO description



## **Appendix D**

### **Runtimes retrieved**





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