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Master Thesis

Differential cryptanalysis with SAT solvers

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AFFIDAVIT

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Abstract

Hash functions are ubiquitous in the modern information age. They provide preimage, second preimage and collision resistance in a wide range of applications. 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.

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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

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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 it useful in a variety of applications.

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 1.1 (*Hash function*)

A *hash function* is a mapping $h : X \longrightarrow Y$ 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.

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 1.2 (*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 1.3 (*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 1.4 (*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 collisions is unavoidable [12]. 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 [15]. 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.

1.2 Cryptanalysis of Hash Functions

In August 2004, Wang et al. published results at Crypto'04 [15] 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 [13] 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 shown as powerful tool for cryptanalysis of hash algorithms. This thesis applies those ideas to satisfiability approaches.

1.3 Differential cryptanalysis

Definition 1.5 (*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 1.6

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

The following definition gives three basic boolean functions:

Definition 1.7

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 1.8

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 1.9

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 1.1

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 1.10

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 1.11

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 1.12

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.

In Chapter 5 we suggest future work based on our results.

“Just because it’s automatic
doesn’t mean it works.
—Daniel J. Bernstein”

Chapter 2

Differential cryptanalysis

2.1 MD4

MD4 is a cryptographic hash function originally described in RFC 1186 [9], updated in RFC 1320 [10] and declared obsolete by RFC 6150 [14]. 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 [11] and [6]. A Python 3 implementation derived from a previous Python version is available at github [8].

block size	512 bits	namely variable `block` in RFC 1320 [10]
digest size	128 bits	as per section 3.5 in RFC 1320 [10]
internal state size	128 bits	namely variables A, B, C and D
word size	32 bits	as per section 2 in RFC 1320 [10]

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.

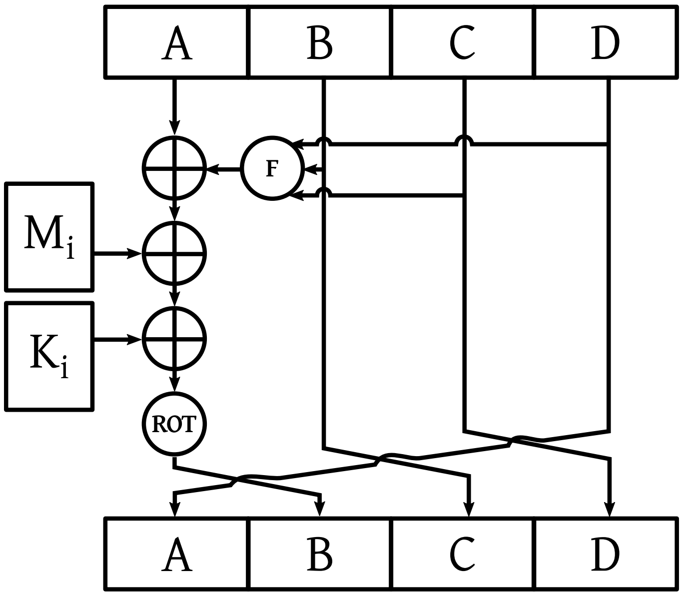


Figure 2.1: MD4 round function

Append those 64 bits to the input.

The message is split into 512-bit blocks (i.e. 16 32-bit words). Four state variables A, B, C and D are initialized with hexadecimal values:

$$[A]\ 01234567 \quad [B]\ 89abcdef \quad [C]\ fedcba98 \quad [D]\ 76543210$$

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

$$\mathrm{IF}(X, Y, Z) = (X \wedge Y) \vee (\neg X \wedge Z) \tag{2.1}$$

$$\mathrm{MAJ}(X, Y, Z) = (X \wedge Y) \vee (X \wedge Z) \vee (Y \wedge Z) \tag{2.2}$$

$$\mathrm{XOR}(X, Y, Z) = X \oplus Y \oplus Z \tag{2.3}$$

Definition 2.1

The boolean IF function behaves the following way: If the first argument is true, the second argument is returned. If the first argument is false, 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.

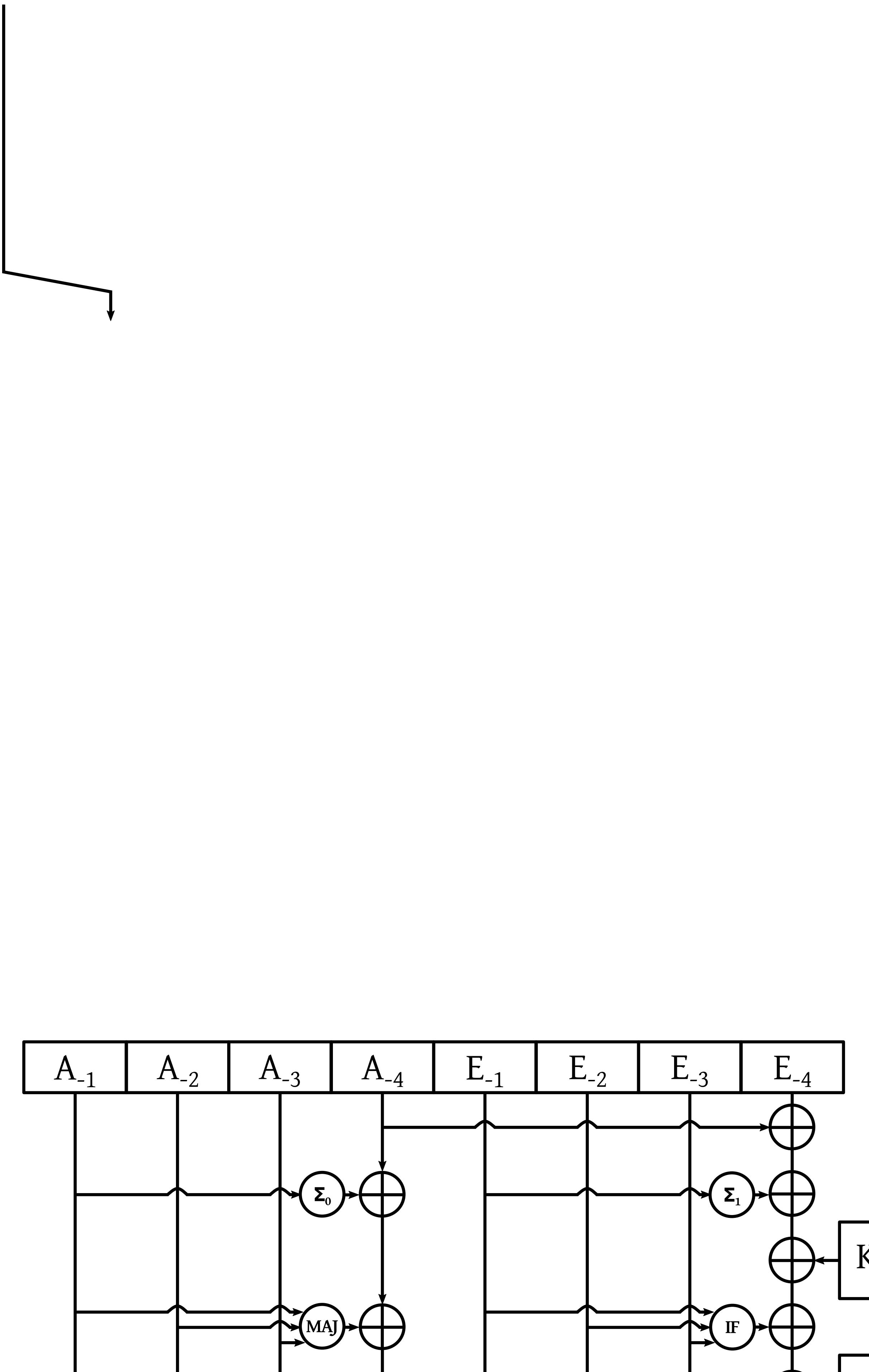
2.2 SHA-256

2.3 Differential notation

[**char-2006**]

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
MAJ
IF

“What idiot called them logic errors rather than bool shit?
—Unknown”

Chapter 3

Satisfiability

3.1 DIMACS quasi-standard

Definition 3.1

> 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.

$$(a \vee b) \wedge (\neg a \vee \neg b) \tag{3.1}$$

Display 3.1 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 3.1

> Every boolean function can be represented as CNF.

Theorem 3.1 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 $b_{i,l}$ if $r_{i,l}$ is true.

As far as f is an arbitrary k-ary boolean function, any function can be represented as CNF.

SAT problems are usually represented in

Definition 3.2

> 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.
>
> Positive clause, negative clause, empty clause and mixed clause: A clause that has no negative literals is a positive clause and a clause that has no positive literals is a negative clause. An empty clause or a null clause has zero positive and zero negative literals. A mixed clause has at least one positive and at least one negative literal.
>
> Horn clause: A Horn clause is a clause with at most one positive literal. A set of Horn clauses makes a Horn set.
>
> Definite clause

3.2 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 in some very basic properties. First of all, we need to elaborate on the question itself.

Definition 3.3 (*SAT feature*)

> A *SAT feature* is a statistical value (named *feature value*) retrievable from some

given SAT problem in some well-defined encoding.

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 retrieve 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 suggested limit is only given with polynomial complexity 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 $P \neq NP$. Hence the number of valid models cannot be a SAT feature as far as satisfiability needs to be determined. But no actual hard boundary for runtime requirements is given. Previous work has shown that expensive algorithms can provide useful data in a small time frame if they are limited to a constant subproblem size.

The most similar resource I found looking at SAT features was the SATzilla project [7, 16] in 2012. The authors systematically defined 138 SAT features categorized in 12 groups. The features themselves are not defined formally, but an implementation is provided bundled with example data.

POSNEG_RATIO_CLAUSE_mean	ratio of positive to negative clauses, mean

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.

POSNEG-RATIO-CLAUSE-mean

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

3.3 SAT features in comparison

Proposition 3.1

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.

3.4 Basic SAT solving techniques

3.5 SAT solvers in use

3.6 Encodings

3.6.1 STP approach

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

Chapter 4

Results

4.1 Benchmark results

4.2 Related work

4.3 Conclusion

Chapter 5

Summary and Future Work

5.1 Summary of results

5.2 Future work

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:	011101100100111111110111100u110001	W:	u1010110110010111001001001111010
2	A:	1010101101000000001110u01n1110010	W:	n01n1001110101011010010101111000
3	A:	101011u1001111010101001001010001	W:	01010111101001111010010111101110
4	A:	00101100011000110101010111110010	W:	11011110011101001000101000111100
5	A:	0001101001100010 10u1101000000001	W:	11011100110000110110011010110011
6	A:	0001101100unuu110001000001111010	W:	10110110100000111010000000100000
7	A:	00101011100000010unn011001010000	W:	00111011001010100101110110011111
8	A:	01110011001000 1u1111111110110000	W:	11000110100111010111000110110011
9	A:	101011n01unnu0001111100110011111	W:	11111001111010011001000110011000
10	A:	10n00100100001010100000001 0101110	W:	11010111100111111000000001011110
11	A:	u1000110101101100100101011111111	W:	10100110001110111011001011101000
12	A:	001011u00u1010111111110001111011	W:	0100010111011110n100011100011000 1
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:	11110011101100000101111111010100		
22	A:	01011101110011010011001100111010		
23	A:	01010000111011101100011110001111		
24	A:	00000010000100100011011100011010		
25	A:	10110000100101100001010011101010		
26	A:	00001010100010010111011101000001		
27	A:	00000110111011110101101010110011		
28	A:	10110110010111010110110000100101		
29	A:	10100010000011010100100001101001		
30	A:	00101001110101111110001110110001 1		
31	A:	11111100100100101101011110110110		
32	A:	01001111111010010011010000010111 1		
33	A:	00111000000111101011011101110010 0		
34	A:	00100000001110101111010000000101 01		
35	A:	n0100000000110011000000100011100 10		
36	A:	n0000111111010111101111001011001		
37	A:	11001000000110100100001100001100		
38	A:	10110000001100111111010011010110 0		
39	A:	00010010000001010000110110001110 0		
40	A:	11000000001001000011100011000010 1		
41	A:	00000110100001101111010100100110		
42	A:	01001110110111011111111010000110		
43	A:	01010000001100011110100000110110 1		
44	A:	11111000000010110111101110000110 0		
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:	00010000000110010010101000111010		
-2	A:	10011000101110101101110011111110		
-1	A:	11101111111001101101010111000100		
0	A:	x-------------------------------	W:	---x----------------------------
1	A:	--------------------------------	W:	--------------------------------
2	A:	---------------------x----------	W:	x-------------------------------
3	A:	xxx-----------------------------	W:	--------------------------------
4	A:	------------------------------xx	W:	x-------------------------------
5	A:	-------xxxxxxxxxxxxxxxx-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:	01100111010001010010001100000001		
-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 nehalem192go specification [2]

Index

Bibliography

[1] Bernd Bischl et al. “ASlib: A benchmark library for algorithm selection”. In: *Artificial Intelligence* 237 (2016), pp. 41 –58. ISSN: 0004-3702. DOI: http://dx.doi.org/10.1016/j.artint.2016.04.003. URL: http://www.sciencedirect.com/science/article/pii/S0004370216300388.

[2] Intel Corporation. *Intel Xeon Processor X5690 (12M Cache, 3.46 GHz, 6.40 GT/s Intel QPI) Specifications*. URL: http://ark.intel.com/products/52576/Intel-Xeon-Processor-X5690-12M-Cache-3_46-GHz-6_40-GTs-Intel-QPI (visited on 04/05/2016).

[3] Hans Dobbertin. “Cryptanalysis of MD4”. In: *Journal of Cryptology* 11.4 (1998), pp. 253–271. ISSN: 1432-1378. DOI: 10.1007/s001459900047. URL: http://dx.doi.org/10.1007/s001459900047.

[4] B. Kaliski. *PKCS #5: Password-Based Cryptography Specification Version 2.0*. RFC 2898. The Internet Engineering Task Force, 2000, pp. 9–11. URL: https://tools.ietf.org/html/rfc2898#section-5.2 (visited on 03/29/2016).

[5] Lenovo Group Ltd. *ThinkPad X220 Tablet (4299) - Onsite (2011)*. URL: http://www.lenovo.com/shop/americas/content/pdf/system_data/x220t_tech_specs.pdf (visited on 04/05/2016).

[6] Yusuke Naito et al. “Improved Collision Attack on MD4”. In: (2005), pp. 1–5. URL: http://eprint.iacr.org/.

[7] Eugene Nudelman et al. “Satzilla: An algorithm portfolio for SAT”. In: *Solver description, SAT competition* 2004 (2004).

[8] prokls. *MD4 in pure Python 3.4*. URL: https://gist.github.com/prokls/86b3c037df19a8c957fe.

[9] Ronald Rivest. *The MD4 Message Digest Algorithm*. RFC 1186. The Internet Engineering Task Force, 1990, pp. 1–18. URL: https://tools.ietf.org/html/rfc1186.

[10] Ronald Rivest. *The MD4 Message-Digest Algorithm*. RFC 1320. The Internet Engineering Task Force, 1992, pp. 1–20. URL: https://tools.ietf.org/html/rfc1320.

[11] Yu Sasaki et al. "New Message Difference for MD4". In: (2007), pp. 1–20. URL: http://www.iacr.org/archive/fse2007/45930331/45930331.pdf.

[12] Martin Schläffer and Elisabeth Oswald. "Searching for differential paths in MD4". In: *Fast Software Encryption*. Springer. 2006, pp. 242–261.

[13] Patrick Stach. *MD4 collision generator*. URL: http://crppit.epfl.ch/documentation/Hash_Function/Fastcoll_MD4/md4coll.c (visited on 04/05/2016).

[14] S. Turner and L. Chen. *The MD4 Message Digest Algorithm*. RFC 6150. The Internet Engineering Task Force, 2011, pp. 1–10. URL: https://tools.ietf.org/html/rfc6150 (visited on 03/15/2016).

[15] Xiaoyun Wang et al. "Collisions for Hash Functions MD4, MD5, HAVAL-128 and RIPEMD." In: *IACR Cryptology ePrint Archive* 2004 (2004), p. 199.

[16] Lin Xu et al. "SATzilla: portfolio-based algorithm selection for SAT". In: *Journal of Artificial Intelligence Research* (2008), pp. 565–606.