Improving Secure Hashing Algorithm 2 (SHA-2) Collisions Using Satisfiability Modulo Theory (SMT) Solvers

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Abstract

This work presents a detailed analysis on the performance differences among various Satisfiability Modulo Theory (SMT) solvers in generating collisions for the SHA-2 family of cryptographic hash functions. The focus of this project was to quantify which SMT solver is most effective at generating collisions for SHA-256, a widely adopted hash function critical for maintaining data integrity and security of protocols like TLS. Additionally, the research involved examining different arguments with these solvers, and their effects to the overall solving performance. Taking inspiration from recent works, I experimented with various encodings and developed my own theoretical differential encoding to enhance SMT reasoning. These findings provide both a methodological baseline and actionable insights regarding solver effectivness for future research in automated cryptanalysis.

Contents

Chapter 1

Introduction

1.1 Domain Problem

As part of this research project, my goal was to experiment and investigate potential measurable quantified performance differences in SMT solvers and their arguments – a novel contribution to SHA-2 collisions. My primary focus within the SHA-2 family is SHA-256.

Since this is an experimental science research project, which looked at different avenues, some research questions could not be answered declaratively within the timeframe. As such, no claims have been made that could not be proven.

1.1.1 What is a Hash Function?

A hash function is a deterministic mathematical algorithm that takes an input, known as the message, of an arbitrary size, and maps it to a fixed-size output, known as the hash value, digest or checksum. Hash functions are fundamental in computer science for data integrity verification, password storage, digital signatures and efficient data retrieval in hash tables.

They are designed in a manner to be efficient to compute, but computationally infeasible to reverse-engineer. In addition to that, they follow the avalanche effect principles – they are designed so that a minor change in the input propagates a huge output change.

1.1.2 Why SHA-2?

Secure Hashing Algorithm 2 (SHA-2) is a set of cryptographic hash functions published in 2001 by the National Security Agency. The main security applications are most notably the HTTPS/SSL/TLS protocols, cryptocurrencies such as Bitcoin, PGP, package authentication and more. Wikipedia Contributors [2025b]

This work will go into an in-depth explanation about SHA-2 in 3.3.1.

1.1.3 What is a Collision?

In cryptography, a collision refers to a scenario where two distinct inputs provide the same output. As desribed by Dang [2012] in 4.1, SHA-256 has a collision resistance of 2^{128}, meaning it is computationally infeasible. This mathematical strength is why SHA-2 continues to be trusted for critical security applications, despite being developed over two decades ago. Discovery of a full collision on SHA-2 algorithms would have a critical security impact on billions of users around the globe.

1.1.4 What is a Satisfiability Modulo Theory (SMT) Solver?

A Satisfiability Modulo Theory (SMT) solver is an automated reasoning tool that combines propositional logic with various computer science and mathematical theories. Given a specific mathematical/logical problem, a SMT checks if there exists a satisfying condition given the constraints. It is capable of reasoning about potential inputs to deduct potential computational paths – either represented as trees or

graphs depending on the core problem. Most (but not all) SMT solvers integrate a SAT solver backend, which handles the boolean structure of the problem. A standard input, widely accepted by many SMT solvers is the SMTLIB format. Barrett et al. [2017]

No additional knowledge in SMT solvers is required for the understanding of this work.

1.2 Research Questions (RQs)

RQ1 Does using a more effective SMT solver yield better SHA-256 collision results?

RQ2 Does using SMT solver arguments yield better SHA-256 collision results?

RQ3 How do different encodings impact SHA-256 collision results?

RQ4 Do principles of theory defined in Li et al. [2024] work in an SMT, and could they be improved?

1.2.1 Scope Alterations

These research questions have slightly deviated in order to become more meaningful and deterministic. All of them have remained closely related.

Li et al. [2024]'s research utilises somewhat complicated theory and representation. My original research question eagerly wanted to improve on it straight away. However, after analysing the situation, it proves a very difficult task on its own. Instead, it has been altered to look at potential theoretical improvements.

1.3 Beneficiaries

This research provides a formal verification; assurance that SHA-2 is still securely sound in the near-foreseeable future, while pushing the current field boundaries in SHA-2 SMT collisions, knowledge and benchmarks. Everyone indirectly is a beneficiary due to how prominent SHA-2 is. A

1.4 Work Performed

In order to answer and reason about the research questions, I developed a tool in Rust. 4.4 Using this tool, and an outlined benchmark methodology 4.5, I was able to visualise graphs to answer my questions. 5.1

Similarly, I reasoned about potential encodings and created a bit differential representation that could potentially improve on Li et al. [2024]. 4.9

1.5 Additional Information

During this research project, no assumptions have been made on previous works. When basing on previous research, the claims were taken with caution, until the results could be replicated. All mentioned and outlined information is correct as of my knowledge, and can be proven or externally verified if necessary. This ensures validity and corectness for the entirety of this work.

I assume, the reader has basic programming knowledge, knows about data structures and their differences, as well as the concepts of how to operate a Unix-based system to do the bare minimum. As part of that assumption, the reader should know what the Rust programming language is, and how it differs compared to other low-level languages such as C and C++ in design.

Aside from this, all critical parts for the understanding of this work have been outlined in a readible manner, throughout this paper before they are necessary.

Chapter 2

Output Summary

The primary output of this project is a suite of visualised graphs and tables aimed at addressing research questions RQ1, RQ2, and RQ3. The most substantial output can be found in Section 5.1 with the respective analysis in 5.1.3 Complete output, albeit without analysis, can be found in C.2.

As for RQ4 I investigated potential encodings, taking inspiration from Li et al. [2024]'s representation of differences. My complete encoding theory can be found in 4.9. This is promising, since it should be capable of reasoning fully about differences, including the non-linearity of SHA-2. Due to time constraints I was unable to develop and benchmark it.

These outputs primarily benefit the community of researchers by providing insight into different SMT tools and their performance.

2.1 Software Tool

A significant output of this project is the software tool, written entirely by me in Rust to facilitate reasoning about the research questions. This tool serves as a versatile CLI application for generating, benchmarking, and visualising results related to SHA-2 collisions using SMT solvers. It is designed to be extensible, allowing additional encodings and functionality implementations.

This software tool consists of approximately **5357** lines of Rust code (as shown by git `ls-files`). Torvalds and Contributors [2014] The full codebase can be found on GitHub mentioned in 4.4, or alternatively in D.3.

The intended recipients of this output are primarily researchers in cryptography, computer security, and formal verification looking for templates for their research. They will benefit from using this tool by having a base to reproduce and build results, as well as to develop new encoding strategies for SMT solvers.

Some screenshots of the output have been provided in E.

2.2 Open Source Contributions

While experiencing issues with SMT solvers, namely Bitwuzla, I decided to contribute to external repositories, in order to bring attention to these issues. More information about my contributions can be found in 4.7.3.

2.3 Additional Information

This report has been written in a manner and terminology to be convertible to a research paper. Its benefits (if approved) will serve the SMT2025 Workshop. SMT Workshop Organizers [2025]

Chapter 3

Context

3.1 Report Specific Term Disambiguation

SMT solvers inherently rely on logical constraints (not pure brute-force), making the distinction between "brute-force" and "guided search" ambiguous. This is a disambiguation to give meaning and context behind each term.

A **pure/true brute-force** attack is an attack where all possible hash combinations are attempted with no reasoning logic, attempted as is.

A **brute-force** attack, as used from here on, is an SMTLIB encoding that follows the SHA-2 mathematical algorithm, but does no additional processing or assertion. This means the underlying SAT/SMT implementation *may* still use heuristics or othwerise simplify the problem at hand. One way to think about this, is as a brute-force guided search.

3.2 Mathematical Notation

For all mathematical foundation described in this work, the following mathematical representation is in use:
$\gg$ represents a shift right (SHR).
$\ll$ represents a shift left (SHL).
$\oplus$ represents Exlusive Or (XOR).
$+$ represents modulo addition.

As common in Computer Science, all examples of iterators start from 0.

3.3 SHA-2 Collisions and Cryptographic Security

3.3.1 Overview of SHA-2

The SHA-2 family, designed by the National Security Agency (NSA) and standardised by NIST in 2001, comprises six primary hash functions: SHA-224, SHA-256, SHA-384, SHA-512, SHA-512/224, and SHA-512/256. These algorithms employ the Merkle–Damgård construction with a Davies–Meyer compression function, differing primarily in digest size (224 to 512 bits), initial values, and round counts (64 for SHA-256, 80 for SHA-512). National Institute of Standards and Technology (NIST) [2015] SHA-256 and SHA-512 remain widely adopted in TLS, DNSSEC, cryptocurrencies such as Bitcoin, PGP, package authentication and government applications. Wikipedia Contributors [2025b]

3.3.2 Inner Workings of SHA-2

The SHA-2 algorithm processes input through a series of deterministic transformations governed by its Merkle–Damgård structure.

Message Processing

Input messages undergo a pre-processing step to conform to the 512-bit block for SHA-256 (1024-bit block for SHA-512 respectively). This step is necessary only when converting an input message to a hash digest. However, this step is mostly irrelevant for automated reasoning tools like SMTs, which directly use arbitrary message blocks to reason about their values. As such, no additional knowledge is necessary about the preprocessing step.

Message Expansion

The pre-processed message only makes up the first 16 words. Remaining words, $16 \leq i \leq 63$, are expanded based on the mathematical foundation:

$$\begin{aligned} s_0 &= (w_{i-15} \gg 7) \oplus (w_{i-15} \gg 18) \oplus (w_{i-15} \gg 3) \\ s_1 &= (w_{i-2} \gg 17) \oplus (w_{i-2} \gg 19) \oplus (w_{i-2} \gg 10) \\ w_i &= w_{i-16} + s_0 + w_{i-7} + s_1 \end{aligned} \tag{3.1}$$

Function Definition

The SHA-2 standard utilises non-linear functions Maj and Ch, which introduce diffusion. These are defined as:

$$\begin{aligned} Maj(a,b,c) &= (a \wedge b) \oplus (a \wedge c) \oplus (b \wedge c) \\ Ch(e,f,g) &= (e \wedge f) \oplus (\neg e \wedge g) \end{aligned} \tag{3.2}$$

Constants and Initialisation

Each hash function part of the SHA-2 family uses different initialisation vectors (IVs), or otherwise known as H-constants. These serve as the initial hash values when starting the compression function. SHA-256 uses fractional parts of square roots from the first 8 primes, whereas SHA-512 uses cube roots.

The round constants, also known as K-constants, are derived from fractional parts of cube roots for the first 64 primes (SHA-256) or first 80 primes (SHA-512). These aim to break symmetry in message

scheduling during modular addition of the compression function.

Compression Function

Each H-constant updates one of eight 32-bit registers a–h, often referred as the "working variables", which are part of the 256-bit starting state.

The compression function employs 64 rounds (80 for SHA-512), where for each round, the following are executed:

Calculate temporary variables

$$T_1 = h + \Sigma_1(e) + Ch(e, f, g) + K_t + W_t$$
$$T_2 = \Sigma_0(a) + Maj(a, b, c)$$

Rotate working variables, calculate a and e

$$\begin{aligned} h &= g \\ g &= f \\ f &= e \\ e &= d + T_1 \\ d &= c \\ c &= b \\ b &= a \\ a &= T_1 + T_2 \end{aligned} \tag{3.3}$$

What is often referred to as a round-reduced model, is simply a compression with less iterations than standard. The number of iterations of this compression function, is what are often referred to as the number of "rounds" or "steps" of a collision.

For round-reduced models, a lot of K-constants and expanded messages are not required during compression to obtain the hash. As such, these can be removed from the SMTLIB encoding as they are redundant.

Finalisation

After processing all blocks, the final hash concatenates the eight registers' contents. At this stage, truncated variants trim the output size. For SHA-256, this produces a 64-character hexadecimal value.

3.3.3 Collision Fundamentals

A cryptographic collision occurs when distinct inputs $M \neq M'$ yield identical digests $H(M) = H(M')$. Such collisions violate the deterministic uniqueness expected of hash functions, enabling certificate forgery, blockchain double-spending, and data integrity breaches. As described in Dang [2012], due to SHA-2's collision resistance, a true brute-force collision requires $O(2^{n/2})$ operations for n-bit hashes. Reasoning and analytical attacks, such as Li et al. [2024], exploit weaknesses with the use of encodings and heuristics, to achieve practical breaks at reduced-rounds.

3.3.4 Classification of Collision Attacks

- **Free-Start Collisions (FS):** Attacker controls both message blocks and initialisation vectors (IVs). A collision occurs with either or both the message and/or IV are unique.
- **Semi-Free-Start Collisions (SFS):** Attacker chooses a fixed IV for both messages, while controlling the message blocks.
- **Classical/Standard Collisions (STD):** Attacker controls only the message blocks.

Satisfiability Theory

During my work, I observed that a standard collision is always unsatisfiable for the first 8 rounds. This is likely because the constants as part of the standard mathematically make this infeasible. Since there are 8 working variables, it takes exactly 8 rounds for a full rotation of a given variable, therefore from the 9th round onward at least one collision exists, but more likely many collisions exist. This does not hold true for SFS or FS collisions, which are satisfiable from the very start.

3.3.5 History of Collisions

Hash Function	CT	Rounds	Time	Memory	References
SHA-256		18	practical	practical	5.1
		31	$2^{49.8}$	2^{48}	Li et al. [2024]
	STD	28	practical	-	Dobraunig et al. [2016]
		31	$2^{65.5}$	-	Mendel et al. [2013]
		24	$2^{22.5}$	-	Sanadhya and Sarkar [2008]
	FS	39	practical	-	Li et al. [2024]
	SFS	38	$2^{19.2}$	-	Alamgir et al. [2024]
	SFS	38	2^{37}	-	Mendel et al. [2013]
SHA-512	STD	31	$2^{115.6}$	$2^{77.3}$	Li et al. [2024]
	STD	24	$2^{22.5}$	-	Sanadhya and Sarkar [2008]
	FS	39	practical	-	Dobraunig et al. [2016]
	SFS	38	$2^{40.5}$	-	Eichlseder et al. [2014]

Table 3.1: Historical SHA-256 and SHA-512 collisions from 2008 to present, including this paper's SHA-256 results for reference.

The pace of progression in this domain have been very slow moving, as can be seen by 3.1. Many researchers have attempted finding vulnerabilities since the big crash of MD4 and similarly structured hash functions. Wang et al. [2004]

3.3.6 Security Implications and Mitigations

The 2017 SHA-1 collision (SHAttered attack) Stevens et al. [2017] demonstrated real-world risks, prompting NIST to mandate SHA-2/3 migration for digital signatures. While full SHA-2 remains secure, reduced-round vulnerabilities highlight the importance of monitoring cryptanalytic advances.

Recent automated reasoning tool driven attacks underscore the role of SMTs in cryptanalysis. By encoding SHA-2's nonlinear functions and message expansion into SMT constraints, the tool can efficiently discover collisions with guaranteed certainty. Automated reasoning tools may also find differential characteristics, previously deemed intractable.

In the event of a full SHA-2 collision, NIST would most likely retire SHA-2 and urge for immediate adoption of post-quantum encryption standards defined in National Institute of Standards and Technology (NIST) [2024].

3.4 Recent Works

Alamgir et al. [2024] utilised a SAT + CAS approach. Their claim was that the SAT + CAS solver is capable of better performance as opposed to just a SAT approach. Despite this, Li et al. [2024] still beat Alamgir et al. [2024], but interestingly enough both of them used different encodings. It would be interesting to see how a SMT approach would fare against these, given a combination of both of these encodings. Alamgir et al. [2024]'s work makes use of a similar notation as Li et al. [2024].

RyotaK and Flatt Security Inc. [2024] made a direct attack targetting OpenWRT's implementation of SHA-256. As of my understanding, OpenWRT used only 12 characters out of the total output hash, where full collisions are more probable due to the smaller search space. The researcher was able to find a full collision for those 12 characters using true brute-force approaches, utilising a tool called HashCat. Hashcat Developers [2025] However, since this is not a reasoning tool, this can not be advanced any further – the only possible way would be to utilise more powerful compute, and would fall into the same category of NP-Hard as SAT solving.

Most interestingly, the researcher utilised GPU compute for their search instead of CPU compute. As of my awareness, there have been attempts to make a GPU accelerated SAT or SMT solver, but all failed or were outperformed by standard CPU alternatives. Osama M. and A. [2024] This work raises a question – could it be possible to make advances in reasoning tool that utilise GPU compute for cryptanalysis?

3.5 SMT Performance Claims

Bellini et al. [2024]'s research compared a wider variety of cryptanalysis tools, including SAT, SMT, MILP and CP for multiple different ciphers, permutations and hash functions. Their winner categorising strategy is described as: "The best solver for each cipher is the one with the highest number of wins. The winner of our competition (for every formalism) is the solver that performs best for the highest number of ciphers (more than 20, each from round 2 to 6)." Their claim is that "In the SMT solvers category, Z3 and MathSAT are always inferior to Yices2, which is thus clearly the best SMT solver in our testing".

As of my knowledge, no research has previously defined the baseline of what SMT solvers are capable of for SHA-2 collisions. No work has quantatively defined the floor of what is possible by simply doing nothing except stating the problem at hand. All research papers I read never mentioned any attempt at this, and made no comments if it was even feasible. It is likely that researchers who used SAT or SMT solvers were only able of getting a few rounds for collisions, and took this as an implied hard limit without the use of encodings. This creates the basis for RQ1 and RQ2, which aims to fill this knowledge gap.

3.6 Compilation Performance

Prior work demonstrates that binaries compiled from identical source code can exhibit performance or structural differences due to compiler optimizations, build environments, or platform-specific toolchains. For instance, Ren et al. [2021] showed that non-default optimisation sequences can amplify binary differences, while Dietrich et al. [2024] highlights the prevalence of non-bitwise equivalence in alternative builds. Due to this, all of my work attempts to generate performance equivalent artifacts by specifying exact build tools and their respective versions, as taken directly from the source websites (preferably GitHub releases).

Chapter 4

Method

4.1 Background

Prior to this work, I never utilised SMTLIB, and only briefly worked with Rust. I also never learnt anything about the security of SHA-2 or Hash Functions. This meant that my development journey was steep, and required a lot of research and trial and error. Despite this, I persevered; learnt topics that were required, read documentation on SMTLIB and Rust, and produced a viable software to answer my research questions. This section will mention and evaluate my full implementation methodology, benchmarking structure and mathematical encoding basis.

4.2 Project Methodology

During the development of this project I used a Kanban-styled board, split into multiple sprints. Each sprint consisted of tasks required towards a certain goal/subgoal of the project. As the project matured and I read more information from articles, research papers and different sources, tasks and their ordering somewhat changed. The Kanban-board came in handy for tracking these ad-hoc tasks.

Despite keeping everything organised, the scope of the project was too large at hand and required some alterations. I quickly found out that **quality** is more important than **quantity** in research. Unfortunately, it is quite hard to have accuracy, consistency and quality while working solo on a research project. Because of this, I stumbled into issues and oversights which I did not realise until later. Having had someone validate thins as the project went on, some of the traps I fell into could have been avoided. This gave me a wider understanding of why research is often conducted by multiple people.

4.3 Design

This project builds a binary providing a Command Line Interface (CLI). Design choices were still undertaken in various manners as described below.

4.3.1 Command Line Interface

Since the project mainly interfaces with SMT solvers, which are all CLI based – it made no sense to develop GUIs. Providing a packaged CLI binary allows reusability and shows intention that the code is ready to be used as is for further research and/or encodings.

For the design of subcommands, I took into consideration what functions were called most often with their respective arguments. Based on that, I derived default arguments and categorised functionality by subcommand. All subcommands with their respective arguments can be retrieved by appending `--help` to the command/subcommand invocation. An image representing this can be seen in E.

A Rust crate clap.rs was used for command functionality. K. and Clap Contributors [2025]

4.3.2 Graphs

Rust has somewhat limited visualisation libraries. Charming.rs provides very beautiful results, but has very limited control and otherwise uses an extremely heavy JavaScript backend. Zhang and Contributors [2025] Plotters.rs on the other hand, is a long standing and time tested visualisation crate, that gives almost all control over plotting, albeit with very verbose and hard to learn syntax. Plotters Development Team [2025] Due to the limited choice, I have chosen plotters as my graphing library.

I utilised the SVG backend to render images, using a colour pallette defined for consistency. Due to some graphs having a lot of relevant data, where up to 10 colours had to be used, some colours simply clash together – this was inevitable. My attempt at avoiding this was by ensuring contrasting colours where possible. No Rust visualisation crates support patterns (such as dashed lines), and utilising Python or alternative options would provide greater complexity, at the cost of having an extensible bundled software. Inevitably, some data could not be split, as it would become less meaningful. Due to this, some graphs might be harder to read. As an alternative, I have bundled tables in C.3, which contain the raw values.

4.3.3 Graph Filtering & Correction

All graph data is verified with the SHA-2 implementation. Any invalid results are automatically filtered out and removed from all plots.

Due to some issues in my SMTLIB generation code, all satisfiable SHA-512 results are invalid. As such, the SHA-512 graphs look very empty, despite investing around 30 hours of benchmark runtime. With the short timeframe to resolve this, I shifted focus towards other experiments. I make mention of this, since my software is capable of generating SMT for the entire SHA-2 family, given a proper implementation.

4.3.4 Understanding Graphs

In order to answer the research questions effectively, I created 3 different visualisation layouts.

Comparison Graph

With the main purpose of providing a side by side comparison of each solver baseline, the comparison graph plots data on a Cartesian2D line graph, where the compression rounds are displayed on the X-axis and $\log 2$ time on the Y-axis.

The timeout is the top of the graph. One way to understand this graph is – the line that goes the most to the right (more rounds), while staying low (less time) is the best. Additionally, the consistency and linearity of the line provides insight about the reasoning of the problem.

This graph is used to answer RQ1 in 5.1.

Baseline Graph

The baseline graph was designed to primarily reason and compare between different runs with variants. It utilises a Cartesian2D line graph, plotting a main baseline in the middle. Any missing or invalid data is skipped from plotting. Deviation data is then calculated from the baseline based on time difference, and represented as a percentage.

If no plot exists on baseline, but a valid deviation is plotted, $+\infty$ will be used as the deviation value. This can be interpreted as "This was infinitely faster than the nothing achieved (on baseline) within timeout". If a baseline exists, but no deviation for that round is present, the plot will be skipped.

A rough run-to-run variance is shown with a grey-ish colour near the middle. The green area with $-\%$ implies "this took $x\%$ less time, compared to baseline". Similarly, the red area with $+\%$ implies "this took $x\%$ more time, compared to baseline."

The graph scales with the results, and trims out at 100% in both directions. When a result is plotted on the edge of the graph, the deviation is $\geq 100\%$ (i.e. twice as long or half as long).

This graph was written with generics in mind, and was reused to visualise results for RQ2 and RQ3 in 5.1.

Detailed Graph

The detailed graph is more complex in terms of construction. Unlike other graphs, only a single benchmark run is plotted. It utilises a DualCartesian2D coordinate system, where the first line graph relates to time taken in $\log 2$, and the second to memory usage in Mibibytes (MiB).

Since SMT solving prefers more locality in memory hierarchy, this graph can help understand if the performance degradation is due to hardware limitations, such as saturating all CPU L3 cache. A graph for Bitwuzla with additional reruns can be seen in the full results C.2.

4.4 Implementation

All code was written in Rust (rustc version 1.85.1), compiled with the provided LLVM backend, and linked with mold (version 2.37.1). The Rust Project Developers [2025a] Ueyama [2025]

The code is licensed under CC BY-NC-SA 4.0, allowing free use with attribution, while limiting any commercial use. Commons [2013]

Repository for the code can be found below, with further build information in the README.md file:

`https://github.com/Supermarcel10/CSG-IN3007/tree/0.1.1`

At the time of submission, this repository is private

4.4.1 Functionality

The functionality of the tool is split into multiple parts. Each part is invoked by a separate subcommand.

SMTLIB Generation

The SHA-2 algorithm can be expressed as mathematical operations on a set of bits, where the Theory of Quantifier Free Bit Vector (QF_BV) is the primary foundation. This subcommand generates SMTLIB 2.6 files to talk with SMT solvers universally.

At present the code is capable of generating brute-force (purely modelling the SHA-2 algorithm), as well as differential encodings (Subsection 4.8.3). The generated files can also be written with Maj and Ch simplifications (Subsection 4.8.1), as well as alternative bitwise add (Subsection 4.8.2). Designed with extensibility in mind, the base 4 encoding (Subsection 4.9), which is partially implemented, can be easily added on by appending a new definition.

Rust does offer some SMTLIB based crates. Oliver Bøving and Mrmaxmeier [2025] However, these mostly interface directly with solvers, and provide no real way to of writing all instructions to a `.smt2` file. Because of this, no additional crates were used, and I manually wrote files using `std::fs` from an owned `std::String` containing my SMT code.

Load

The `load` subcommand reads (an) inputted result file(s) from a given dir/file path.

Loaded data is then deserialised into a `Benchmark` struct. The struct aims to preserve the original output of console out (cout) and console error (cerr), while storing additional metadata and information. By doing so, any additional data can be traced back, benchmarks can be reran with known parameters, and filtering is made simple.

One of my objectives mid-way was to migrate to rusqlite, a sqlite wrapper API for Rust. Rusqlite Developers [2025] This would allow cleaning up the hundreds of JSON result files, and make querying even easier. However, in doing so this would hinder the ablity to quickly view a result file without additional tools. With this consideration, I considered this a very low priority, and put the time aside for more experiments instead.

SHA-2

Written with National Institute of Standards and Technology (NIST) [2015] guidelines, this subcommand provides a partially deconstructed SHA-2 implementation. No established SHA-2 implementations allow control over the number of compression rounds, message digest or Initial Vector.

My original plan was to reuse parts of the Rust sha2 crate. RustCrypto Developers [2025] However, the inner workings utilise dark arts wizardry [1], with very optimised system calls based on architecture. Due to the complexity, I opted for my own implementations from scratch.

This implementation is not formally verified, but outputs the correct hash digest for standard variables against standard implementations. Due to SHA-2's avalanche effect mentioned in 1.1.1, this likely means the implementation is fully correct for the hash functions implemented.

My original implementation of SHA-2 utilised generics, and took in a 32 or 64 bit unsigned integer as the word type. This functioned correctly, and was somewhat simple to build, however was very restrictive. Having multiple components relying on the SHA-2 implementation, it hindered development by requiring those generics everywhere. To simplify this, I rewrote the entire SHA-2 functionality to use an enum structure with fields instead.

Benchmarking

The `benchmark` subcommand is the primary and most important part of the software. Given an input of a solver, round range, collision type, encoding and argument matrix, it calls the solver on the host machine and executes it with the `time` command.

Different SMT solvers output satisfiable (SAT) results in different bases, formats and patterns. To overcome this, I created a RegEx pattern to detect and process the input for boolean, decimal and hexadecimal. Additional formats can easily be defined in the `SmtOutputFormat` enum.

Another challenge was parsing the error codes returned from the SMT binary. There are no definitive standards related to output status of a solver. CVC5 as an example, returns an error code if the result is unsatisfiable, whereas some others return a success code. To overcome this, my output parser utilised the status code and console output to determine benchmark result.

A thread with a chrono timer is spawned right before a benchmark starts. This has minimum performance overhead, if any at all. When the thread wakes from sleep, the timeout period has elapsed. Consequently, the entire process stack is killed with `SIGTERM` (19), the output parser is ran and a `Benchmark` struct object is serialised. Benchmarking continues until all user options have been exhausted.

If the stop tolerance is hit, all benchmarks for the given solver are aborted, and benchmarking moves to the next viable solver (if applicable). This can happen for multiple reasons. One example of this, is if a SMT error is encountered. In such case, my result parser will return a `SMTError` for its status, and increment the stop hit count.

When a benchmark succeeds at finding a collision, or if no collision exists, the chrono thread is aborted and the parser reads the tokens and creates a new `Benchmark` object. This is then verified using the `sha2` subcommand, and the metadata is attached to the `Benchmark` struct. When complete, this is dumped to disk by deserialising the object and freeing memory for the next benchmark.

Graph Plotting

The `graph` subcommand is responsible for regenerating all the graphs from the filtered deserialised data. For designs and further information, refer to 4.3.2.

[1] Rust dark arts refers to "The Dark Arts of Unsafe Rust", defined by The Rustonomicon. The Rust Project Developers [2025b]

4.5 Benchmark Methodology

In order to obtain quantifiable results towards answering RQ1, RQ2 and RQ3 the `benchmark` subcommand described in 4.4.1 was used. This section goes in depth related to the methodologies and strategies employed for consistent, reproducible and reliable data.

A dedicated X86_64 machine was set up for running this workload, with no background tasks or workers, and an otherwise fresh installation of linux. Each benchmark run was invoked sequentially (one after the other), as to ensure no performance degradation. The machine was set up in a manner to provide the most reproducible results. The default parameters when running were `--round-range 1..21 --stop-tolerance 0 --continue-on-fail true`. A timeout period, of 15 minutes (default), was utilised for all benchmarks. The hardware, parameters and software versions are the basic configuration for all figures presented, unless otherwise specified.

	Runner Specification
CPU	AMD Ryzen 9 5900X
MEM	4 x 32GiB DDR4 3600MHz CL 36
OS	NixOS 25.05 (Warbler) x86_64
KERNEL	Linux Realtime 6.6.77-rt50

4.5.1 CPU and XMP Configuration

The primary task of my home lab prior to this research was to run 24/7 as a home server configuration with miscelaneous tasks. As such, some settings are tailored to lower power draw, better reliability and efficiency. These settings lock the core clock at base 3700MHz and disable any turbo boost clock. This reduces performance, but provides more consistent run-to-run performance and result reproducability.

The following BIOS settings have been applied:

Setting	**Value**
CPU Clock	37.00
CPU Clock Control	100.000 MHz
XMP	DDR4-3600 18-22-22-42-64-1.35V
CPU Vcore	0.818V
CPU Vcore Loadline Calibration	LOW
CSM Support	ENABLED

4.5.2 Kernel Choice

The runner utilises the Linux Realtime kernel, which aims to have predictable response times. One of the main differences is the task scheduling and interrupt handling. In short, the rt kernel uses a preemptible task assignment system, where in most cases high priority tasks cannot be interrupted by the kernel. Additionally, because of the scheduling, multi-threaded workloads often become slightly more deterministic and reproducible. This is all at the cost of some throughput loss.

In theory, it would be possible to test the differences between kernel choice, specifically for SMT solving. My current implementation would fully support this, and could produce a graph specific to answer this question. Producing a baseline run for all the solvers would take worst-case 40 hours per kernel to generate a graph towards a single SHA-2 hash function. This means producing data for 3-4 different kernels would take an additional 160 hours of benchmark runtime.

4.5.3 Reproducability

This runner can be rebuilt at any time, using the NixOS configuration found here:
`https://github.com/Supermarcel10/NixOSConfig/blob/f1d26ec/devices/E01/configuration.nix`

4.6 SMT Solver Choice

Selecting appropriate solvers for benchmarking is crucial to ensure comprehensive coverage and reliable results. To achieve this, I aimed to create an exhaustive list of currently available SMT solvers. The following table lists the solvers tested in this work, along with their versions and corresponding citations:

Solver	Version	Citation
Z3	4.13.4	de Moura and Bjørner [2008]
CVC5	1.2.1	Barbosa et al. [2022]
Yices	2.6.5	Dutertre [2014]
Bitwuzla	0.7.0	Niemetz and Preiner [2023]
Boolector	3.2.3	Brummayer and Biere [2009]
STP	2.3.4	Ganesh and Contributors [2018]
Colibri2	0.4-dirty	Frama C [N/D]
MathSAT	5.6.11 (1a1154baf0ab)	Cimatti et al. [2013]

4.7 Implementation Challenges

4.7.1 SMTLIB Compatibility

The current available version of the SMTLIB standard is 2.7. However, as of writing this report, most of the solvers do not support this version. Therefore, all encodings and `smt2` files in this work have been written using the SMTLIB 2.6 standard. Barrett et al. [2017]

Some solvers use an older version of SMTLIB 2.0, which does not provide the '`:left-assoc`' feature. This would require rewriting a significant portion of the SMT code to maintain compatibility, leading to those solvers being excluded from the benchmarks.

4.7.2 Compilation and Linking Issues

MathSAT

MathSAT dynamically links to libraries in the binary, which did not work as expected. To resolve this issue, I patched the ELF file considering its closed-source nature. Due to reproducability, MathSAT is present in the `solvers` directory with a `mathsat_patch.nix` file.

Colibri2

Colibri2 worked but exhibited some fundamental problems. It occasionally threw internal errors and sometimes generated output that failed SMTLIB assertions. This can only be seen in the JSON files part of the codebase.

As mentioned in 4.3.3, my graph implementation automatically filtered out invalid results, allowing all Colibri2 results to be included while displaying only valid ones.

4.7.3 Solver Issues

Bitwuzla

Bitwuzla was very strong from the beginning and ran without significant issues. However, during experimentation, I discovered an issue with memory handling that has since been resolved through creating an issue on their repository (`https://github.com/bitwuzla/bitwuzla/issues/169`).

Additionally, I encountered issues with the `nixpkgs` repository related to compiling the Kissat solver backend. I submitted a pull request to fix this issue, which has since been merged (`https://github.com/NixOS/nixpkgs/pull/400299`).

As mentioned in 3.6, different tools during compilation can have varying runtime performance. For benchmarking the Kissat solver backend in Bitwuzla, I used my built binary. Other backends performed within acceptable variance of the original runs.

4.8 Encodings

Each of the encodings, and their combinations were benchmarked. Their analysis can be seen in 5.1.3.

4.8.1 Simplifying Compression Functions

As described in 3.3.2, the SHA-2 compression function relies on two non-linear functions: the choice function $\mathrm{Ch}(e, f, g)$ and the majority function $\mathrm{Maj}(a, b, c)$. Both functions traditionally employ XOR operations to combine inputs as defined in the SHA-2 standard National Institute of Standards and Technology (NIST) [2015]. From my mathematical analysis, it is possible to replace XOR with OR in these functions, simplifying their implementation, while preserving logical behaviour.

The original definitions of the functions are:

$$\begin{aligned} Ch(e, f, g) &= (e \wedge f) \oplus (\neg e \wedge g) \\ Maj(a, b, c) &= (a \wedge b) \oplus (a \wedge c) \oplus (b \wedge c) \end{aligned} \tag{4.1}$$

In the simplified encoding, all XOR operations were substituted with OR:

$$\begin{aligned} Ch'(e, f, g) &= (e \wedge f) \vee (\neg e \wedge g) \\ Maj'(a, b, c) &= (a \wedge b) \vee (a \wedge c) \vee (b \wedge c) \end{aligned} \tag{4.2}$$

To validate equivalence, truth tables were constructed for all possible input combinations. Table 4.1 demonstrates identical outputs for both Ch and Ch', as well as Maj and Maj'. This arises because the sub-expressions in Ch are mutually exclusive: $e \wedge f$ and $\neg e \wedge g$ cannot simultaneously be 1. Consequently, OR and XOR produce identical results in this context. Similarly, for Maj, the OR operation captures the majority condition, as overlapping terms do not affect the final output.

Table 4.1: Truth table comparing original and modified Ch and Maj functions.

x	y	z	Ch	Ch′	Maj	Maj′
0	0	0	0	0	0	0
0	0	1	1	1	0	0
0	1	0	0	0	0	0
0	1	1	1	1	1	1
1	0	0	0	0	0	0
1	0	1	0	0	1	1
1	1	0	1	1	1	1
1	1	1	1	1	1	1

The substitution preserves non-linearity, as both OR and XOR are non-linear operations in Boolean algebra. Diffusion properties also remain unaffected, as the output dependence on input bits is unchanged.

This simplification aims to optimise the reasoning a solver might attempt. An XOR operation can be expressed using a combination of OR and AND logical operators alongside negation, specifically as $a \oplus b = (a \vee b) \wedge \neg(a \wedge b)$ Wikipedia Contributors [2025d]. By utilising my simplification methodology, the logical behaviour remains unchanged, while potentially reducing the search space.

4.8.2 Alternative Bitwise Add

Another potential idea for improving the reasoning of the solver was to use an alternative add encoding, distinct from the baseline bitvector addition `bvadd`. Naturally, since this encoding no longer runs at the hardware level, there will be significant runtime overhead. However, the hope with this encoding is for the solver to find new and potentially meaningful logic to reason about, pruning non-viable paths earlier.

The core implementation leveraged a bitwise carry-lookahead adder inspired by principles in Wikipedia Contributors [2025c] Kogge and Stone [1973]. For two BitVector (BV) operands a and b, the adder computed generate (g) and propagate (p) signals, where $i \leq length$, $length$ = number of input bits in BV:

$$g_0 = a \wedge b$$
$$p_0 = a \oplus b$$

$$\begin{aligned} g_{i+1} &= g_i \vee (p_i \wedge (g_i \ll 2^i)) \\ p_{i+1} &= p_i \wedge (p_i \ll 2^i) \end{aligned} \tag{4.3}$$

$$\text{bitadd-2}(a, b) = p_0 \oplus (g_{length} \ll 1)$$

For handling 3 or more operands, we can extend the base adder:

$$\text{bitadd-}n(x_1, \ldots, x_n) = \text{bitadd-2}(\bigoplus_{k=1}^{n} x_k, \ll \bigvee_{1 \leq i < j \leq n} (x_i \wedge x_j)) \tag{4.4}$$

This hierarchical structure, in theory, enables $O(\log n)$ carry propagation, though practical SMT constraints, in addition to lack of support for user-implemented `:left-assoc`, necessitated sequential left-to-right chaining for multi-operand cases. The SMTLIB implementation cascaded smaller adders through nested `let` bindings, avoiding combinatorial explosion in constraint generation. The full core adder SMTLIB implementation is available in D.1. The full multi-operand SMTLIB implementation is available in D.2.

The encoding drew inspiration from modern hardware optimisation techniques, particularly 3:2 compressor logic Wikipedia Contributors [2025a] and Wallace tree principles Wallace [1964].

4.8.3 Differential Encodings

In order to move to a differential reasoning model, I moved to using two differential encodings, with the primarily focus on reducing complexity by reasoning more about relative differences, thereby avoiding unnecessary constraints on absolute values. These encodings operated on the deltas between pairs of computation components rather than their absolute values, following established approaches that make the basis of research like Li et al. [2024].

Two differential encodings were created for this:

- **Delta Subtraction** (DSub) $\Delta_{-} = x - x'$
- **Delta Exclusive OR** (DXOR) $\Delta_{\oplus} = x \oplus x'$

Both encodings were systematically applied to:

- Message block differences during expansion (via the $w_i t$ variables),
- Working variables (a-h) in the compression function,
- Round-specific constants (K_i),
- Final digest segments.

For collision assertions, I required all hash digest differences to satisfy $\Delta_{\text{hash}} = 0$, ensuring identical outputs. Message or initial vector differences, depending on collision type, were constrained with $\Delta_{\text{input}} \neq 0$ to enforce at least one distinct chunk.

Notably, the implementation did not introduce additional assertions beyond these difference constraints. The base SHA-2 algorithm's logical operations and modular arithmetic were preserved in both encodings. All the underlying absolute values were still present and being calculated for each variable to ensure compliance with the SHA-2 definition.

While this preserved flexibility for mixed constraints, I considered (but did not implement) a pure delta encoding that would reason exclusively about differences. Such an approach would require reconstructing original values from deltas during constraint solving. However, this introduces challenges like handling the non-linear interaction propagation through Ch and Maj functions described in 3.3.2.

4.9 Base 4 Encoding

The base 4 encoding addresses the challenge of the DSub and DXOR representations. Binary uses a base 2 system, and comparing two bits creates a 2×2 matrix with four possible variations. Thus, using a base 4 system ensures that all operations are non-lossy and revertible to absolute values if needed.

This encoding can overcome the issue of non-linearity in OR and XOR logic by providing deterministic outcomes without requiring any absolute values. Although this work is only theoretical, due to time constraints for implementation and testing, it has the potential to perform well.

For simplicity, this work uses symbols a through d to represent different states instead of numerical values. In addition to the base 4 system, shorthand symbols are used to provide an abstraction and generalisation of underlying differences and their original values.

These shorthands include:

- $e \Leftrightarrow a \vee b$: both values equal
- $f \Leftrightarrow b \vee d$: right bit is 1
- $g \Leftrightarrow c \vee d$: left bit is 1

(x, x')	a	b	c	d	e	f	g
$(0,0)$	+				+		
$(0,1)$		+				+	
$(1,0)$			+				+
$(1,1)$				+	+	+	+

Table 4.2: Representation of base 4 symbols including shorthand operators (e, f, g). A '+' indicates whether a specific value pair is possible for (x, x'). Table design inspired by Alamgir et al. [2024].

Each representation becomes a separate variable in SMTLIB format. This way, it is possible to continue using the theory of BitVectors. Each variable can then be used for the most suited logical operation according to SHA-2's rules, as described in 3.3.1. Alternatively, it is also possible to experiment with the `declare-datatype` SMTLIB instruction to define this encoding.

In order to maintain corectness, these have been tested with AND, OR and XOR operations. No counter-examples have been found. D.3 D.4 D.5

Chapter 5

Results

5.1 Graphs

This section presents a comprehensive analysis of the most significant findings from my experiments. For an exhaustive set of results, please refer to C.2 and C.3 for most raw data.

All visualisations included in this document were generated using the implementation process detailed in 4.4. This ensures consistency and reproducibility across all graphs. The experiments described here were conducted following the benchmarking methodologies outlined in 4.5. Adhering to these strategies enabled me to obtain reliable and comparable results.

5.1.1 Significant Graphs

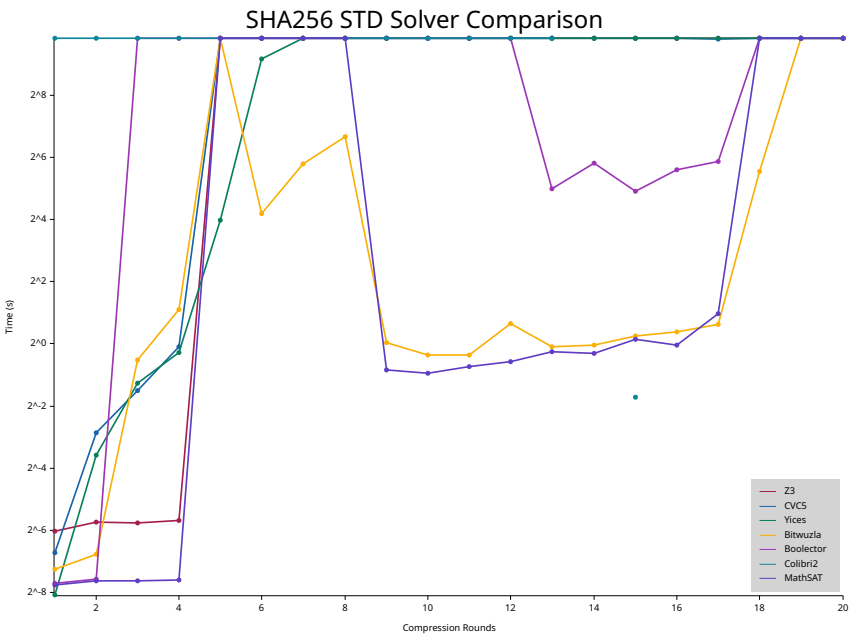

Figure 5.1: Graph representing SHA-256 standard collisions from 1 to 20 rounds using brute-force, where each colour line represents a separate solver. Results ran with arguments `--round-range 1..21 --continue-on-fail true`.

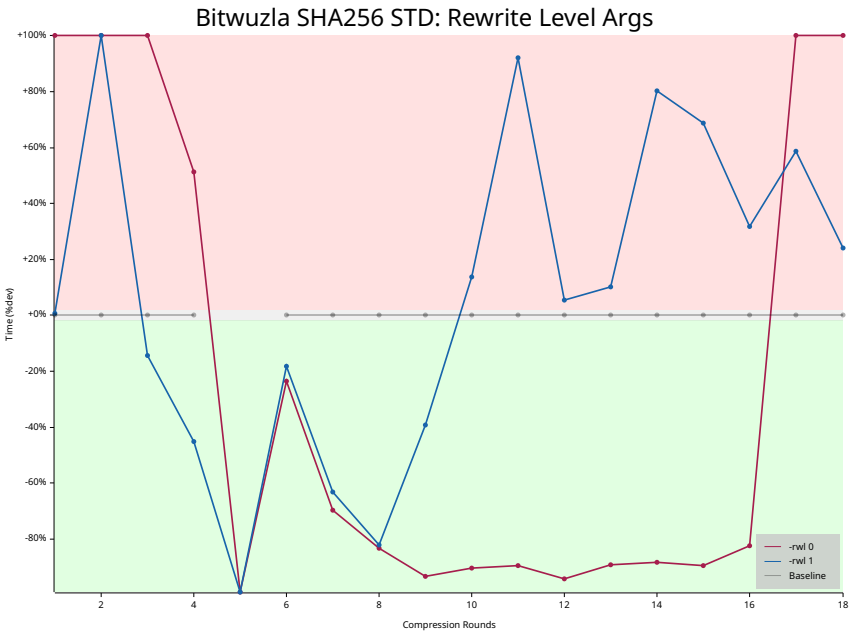

Figure 5.2: Bitwuzla SHA-256 standard collisions from 1 to 18 rounds using brute-force, where each colour line represents a different solver argument related to rewrite level. Results ran with arguments `--round range 1..19 --continue-on-fail true`

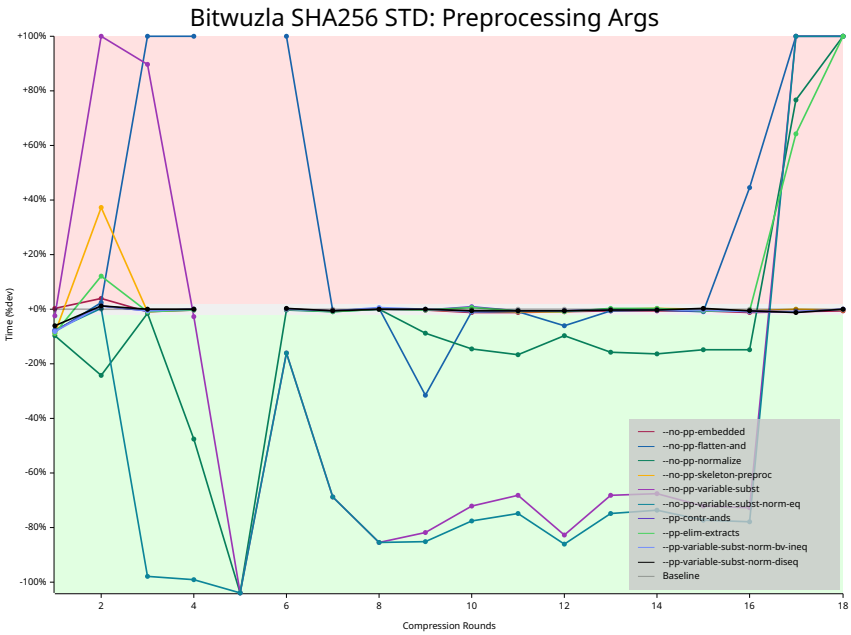

Figure 5.3: Bitwuzla SHA-256 standard collisions from 1 to 18 rounds using brute-force, where each colour line represents a different solver argument related to preprocessing. Results ran with arguments `--round range 1..19 --continue-on-fail true`

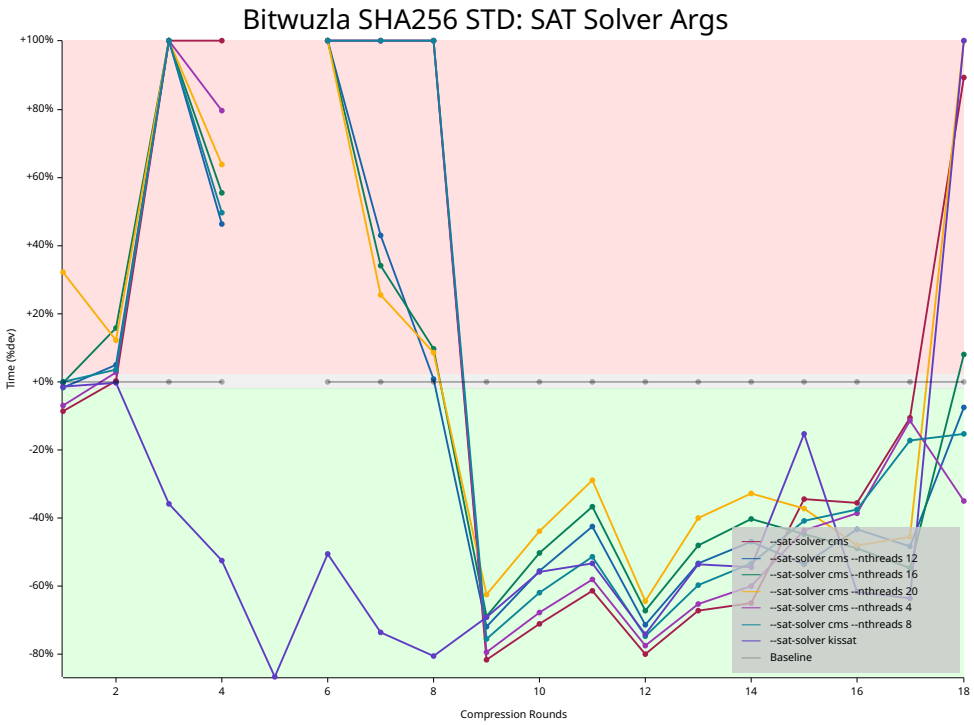

Figure 5.4: Bitwuzla SHA-256 standard collisions from 1 to 18 rounds using brute-force, where each colour line represents a different solver argument related to the backend SAT solver. Results ran with arguments `--round range 1..19 --continue-on-fail true`

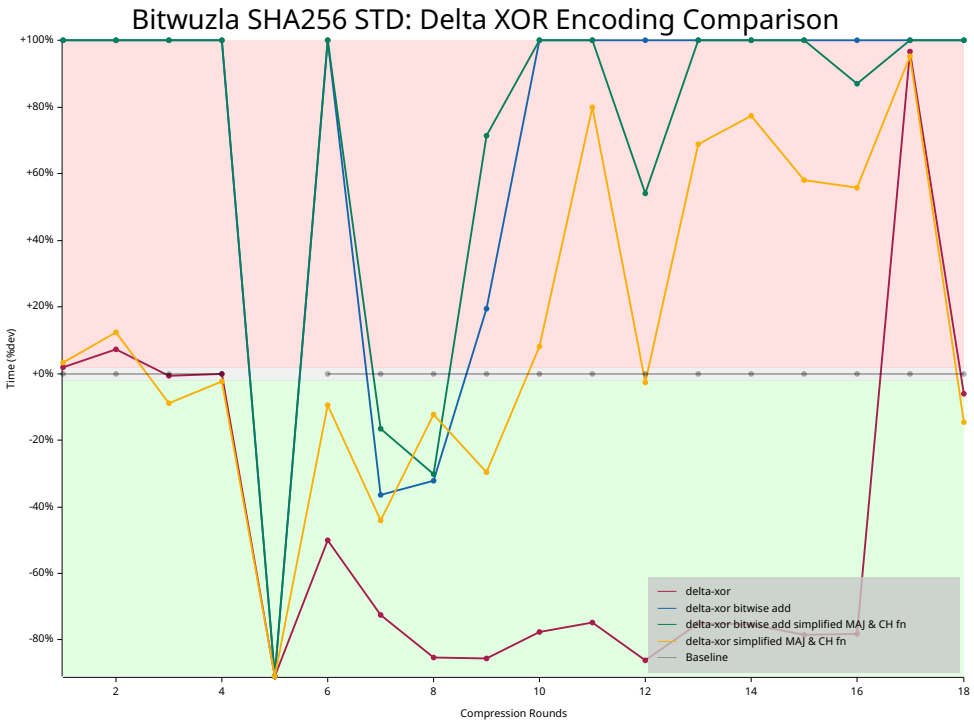

Figure 5.5: Bitwuzla SHA-256 standard collision from 1 to 20 rounds using $\Delta_{\oplus}$ encoding. Where each colour line represents a different encoding variant. Results ran with arguments `--round-range 1..19 --stop-tolerance 0 --continue-on-fail true`

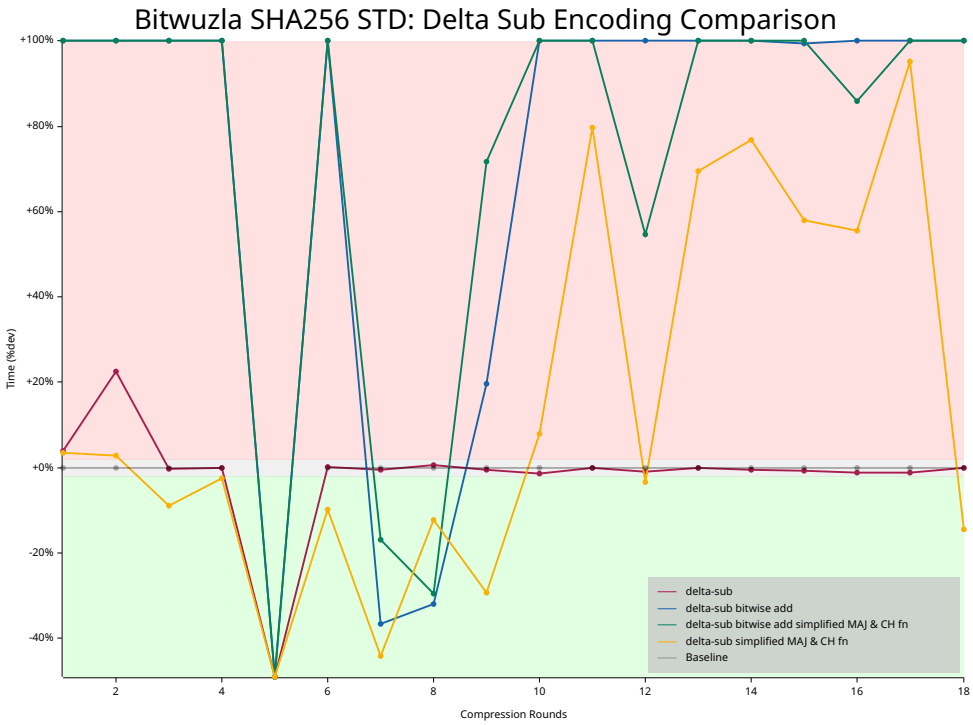

Figure 5.6: Bitwuzla SHA-256 standard collision from 1 to 20 rounds using Δ_{-} encoding. Where each colour line represents a different encoding variant. Results ran with arguments `--round-range 1..19 --stop-tolerance 0 --continue-on-fail true`

5.1.2 Significant Console Output

Both of these outputs showcase the differential graphs with notation as Li et al. [2024]. The Δ and $_i$ notation has been escaped due to being invalid UTF-8 in LaTeX.

Listing 5.1: 14 round collision output obtained by running `sha2-collision benchmark --solver bitwuzla --hash-function sha256 --collision-type std --round-range 14..15 -R true -E bruteforce::true`

```
14 rounds; SHA256 STD collision; Bitwuzla; SMT solver PID: 57943
File: smt/SHA256_STD_14_ALTADD.smt2
CV   : 6a09e667 bb67ae85 3c6ef372 a54ff53a 510e527f 9b05688c 1f83d9ab 5be0cd19
CV'  : 6a09e667 bb67ae85 3c6ef372 a54ff53a 510e527f 9b05688c 1f83d9ab 5be0cd19
M    : ffffffff ffffffff ffffffff ffffffff ffffffff ffffffff ffffffff ffffffff ffffffff ffffffff ffffffff ffffffe9
    00000000 00000000
M'   : 7fffffff ddf3fdbf 7c8b10a7 de0fffbf a1ec023f 9dec01bf ffffffff 7fffffff 7fffffff ffffffff ffffffff ffffffff ffffffe9
    00000000 00000000
Hash : 1121e8fd ad9d9f9f 5e16068c 8acbfb6b 9cde4233 a73a2f5f dc9ced0a d8f47aa2 (Valid? true)
Hash': 1121e8fd ad9d9f9f 5e16068c 8acbfb6b 9cde4233 a73a2f5f dc9ced0a d8f47aa2 (Valid? true)


 i |                A                 |                E                 |                W
 0 | ================================ | ================================ | u================================
 1 | u================================ | u================================ | ==u===u=====uu========u==u======
 2 | ================================ | =nn==========n========u========= | u=====uu=uuu=u==uuu=uuuu=u=uu===
 3 | ================================ | u================================ | ==u====uuuuu=============u======
 4 | ================================ | n================================ | =u=uuuu====u==uuuuuuuu=uuu======
 5 | ================================ | u================================ | =uu===u====u==uuuuuuuuu==u======
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 9 | ================================ | ================================ | ================================
10 | ================================ | ================================ | ================================
11 | ================================ | ================================ | ================================
12 | ================================ | ================================ | ================================
13 | ================================ | ================================ | ================================
```

Listing 5.2: 14 round collision output obtained by running `sha2-collision benchmark --solver bitwuzla --hash-function sha256 --collision-type std --round-range 14..15 -R true -E bruteforce::`

```
14 rounds; SHA256 STD collision; Bitwuzla; SMT solver PID: 58100
File: smt/SHA256_STD_14.smt2
CV   : 6a09e667 bb67ae85 3c6ef372 a54ff53a 510e527f 9b05688c 1f83d9ab 5be0cd19
CV'  : 6a09e667 bb67ae85 3c6ef372 a54ff53a 510e527f 9b05688c 1f83d9ab 5be0cd19
M    : 00000000 00269eb0 073a5f45 870a253d 10cf61c3 340c932a 252046ec a8e31d41 3bf4e7e6 ba76205e 9c4e594a 38c84784 c504f3aa f3ea62bc
    00000000 00000000
M'   : 00900018 a97b43d8 bc209ac8 bb2001f0 a79d7d46 fe43c1a8 38304343 860d9489 7b9b7537 d7879422 20a912e5 227a74d1 6e52b216 6efc2748
    00000000 00000000
Hash : 2d09ea67 bb67ae85 3c6ef372 a54ff53a 8550d704 9f05689c b00572e3 a5670f5a (Valid? true)
Hash': 2d09ea67 bb67ae85 3c6ef372 a54ff53a 8550d704 9f05689c b00572e3 a5670f5a (Valid? true)


 i |                 A                |                 E                |                 W
 0 | ================================ | ================================ | ========n==n================nn===
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 2 | nu===nuu==nn=n=nnn=n=n=u=un===== | ==nuuuu==nn=u=n=n==u=nnn==nnn=== | n=nnn=uu===uu=u=nu===u=un===nu=u
 3 | u=n====nn=nu=nunnn===nnunu=n==u= | ==u=unun===u===nnu==nunuu==nnu== | ==nnnu====n=u=u===u==u==nn==uu=u
 4 | unn=nu=u==uu=u===uuu==nu=uu==n=u | ===nnn=uuu==u===n==un======un=un | n=nu=nnn=u=n==u====nnn==u====n=u
 5 | n=u=uu=nnn===n=======nn========= | ==u=n=====n=u===nn====nn==n=u=== | nn==n=n==n==uunn=n=u==u=n=====u=
 6 | u===nu=n===u==u==n===u==u==u=n== | nuun==nn=n===n=n======u===n=nnnn | ===nnu=u===n=========u=nu=u=uunn
 7 | ================================ | u=u===u===n=u===u=u=n==n=n=nnn=n | ==u=unn=uuu=nnu=n===u==unu==n===
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 9 | ================================ | =n=n===nnn===n=======nn====n==== | =nu=un=nnuuu===nn=un=n===unuuu==
10 | ================================ | u====n=n==u=nnn==n===u==u==u=n== | u=nuuu==nun==uun=u==u=nun=n=unun
11 | ================================ | ================================ | ===uu=n=u=nn==n===nn==uu=n=n=u=n
12 | ================================ | ================================ | u=n=n=nu=n=n=un==u=====uu=unun==
13 | ================================ | ================================ | u==unn=u===n=nu==u===n=nunuu=u==
```

5.1.3 Analysis

Figure 5.1 helps answer RQ1 and showcases interesting aspects of SMT solver choice. The first eight rounds are UNSAT, meaning no collisions exist. As mentioned in 3.3.4, this could be due to how the IV combined with rotational working variables work.

Bitwuzla was the most consistent SMT solver, being the only one capable of finding a collision for 7 and 8 rounds. This suggests that Bitwuzla likely has stronger reasoning capabilities for UNSAT cores as opposed to its competitors.

As most solvers struggled with higher-round collisions, Bitwuzla and MathSAT were capable of pushing through and delivering 18 and 17 rounds respectively. Bitwuzla is the definitive winner, being both more consistent and able to deliver the most rounds within the timeout period. This means Bitwuzla is the baseline SMT solver to beat.

Measuring Bitwuzla's brute-force capabilities, with a 12 hour timeout, no collision was found for 19 rounds. C.2

Arguments

To answer RQ2, I ran all arguments available on the most promising SMT solver, Bitwuzla. Figures 5.2 and 5.3 proved that adjusting Bitwuzla's arguments can significantly impact performance. Despite this, the solvability of consecutive rounds was not meaningfully improved.

Setting the rewrite level to 0 or disabling `variable-subst` improved short-running collisions but hindered long-running ones.

Adjusting Bitwuzla's SAT solver backend arguments influenced performance. The Kissat SAT solver backend outperformed the baseline (CaDiCal) in lower UNSAT rounds but struggled with higher-round collisions, as can be seen in 5.4.

Enabling `--bv-solver prop` negated all of Bitwuzla's performance gains against the competition. C.2 This is likely what gives Bitwuzla most of the edge compared to other solvers.

Enabling multithreading via CryptoMiniSat improved overall performance, though increasing threads beyond four (the lowest tested) led to diminishing returns. As described in 4.5.2, the runner's Linux Kernel could have impacted this. However, more likely at scale, this is caused by practical trade-offs related to SMT parallelism and SMT solver memory characteristics.

Encodings

To answer RQ3, all combinations of implemented differential encodings, mentioned in 4.8, have been benchmarked. While there were no significant performance improvements, insights can be gathered from 5.5 and 5.6.

The delta subtract encoding, did not allow the solver to reason more freely as expected, and performed within margin of error. It did however influence the solvability of round 5, where previously no satisfiable result was found within the timeout period.

On the other hand, the delta XOR encoding proved to be impactful, especially in short-running collisions. It did however see a noticeable spike after round 17, but on round 18 returned slightly below baseline brute-force run, remaining a promising solution to expand on.

As for the alternative bitwise add, it almost always performed worse. However, some output collisions were simpler with less altered bits, implying the SMT solver has managed to reason more effectively to

negate the effects of SHA-2's collision resistance. A good example of this can be seen in 5.1, as opposed to the exact same parameters without the alternative bitwise add in 5.2.

Maj and Ch simplification proved to have some effect, but did not paint a clear enough picutre to make a conclusive answer. In combination with other encodings, it could prove to be more useful.

Chapter 6

Conclusions and Discussion

6.1 Conclusion

This work has quantatively assessed solving times for SHA-2 collisions using different SMT solvers, their arguments, and encodings.

The graphs, provided in 5.1, undoubtedly answer RQ1: Bitwuzla Niemetz and Preiner [2023] stands out as the most promising SMT solver among those tested. While MathSAT Cimatti et al. [2013] performed closely, it fell short in terms of round solvability.

It is plausible that an alternative set of arguments could improve MathSAT's or another solver's performance, leaving RQ2 partially unanswered. However, it is conclusive that default arguments for Bitwuzla seem to be the most stable for round solvability and solving time.

As for RQ3, I have explored some basic encodings to provide insights. Reasoning about differences by subtraction simply does not work – it should not be attempted in any future work, since it seems like a dead end and waste of time.

For RQ4, I have provided a theoretical representation of reasoning about bits in 4.9. This approach could potentially perform well, and in combination with other encodings could be on par with Li et al. [2024]'s representation.

Using brute-force approaches proved ineffective, as expected, but performed significantly better than previous literature would imply. As seen in 3.1, the magnitude of the attack for 18 rounds is nowhere near the current capabilities. By identifying the most promising reasoning tools (RQ1) and their arguments (RQ2), I have established a starting point that future research can build upon.

As previously discussed in 3.5, Bellini et al. [2024] claim that MathSAT is always inferior to Yices2. While it is plausible for other hash functions in combination with their categorising strategy, my experiments using SHA-2 yielded results that contradict their claim. It might potentially hold true under specific encodings; however, the performance gap observed in my benchmarks suggests this is unlikely. This is certainly not possible for a larger number of rounds, which was not taken into account with their methodology. Consequently, one should not assert that MathSAT is always inferior to Yices2, since this is an eager generalisation.

As stated before in 3.5, no previous work has definitively and quantatively set out a baseline specific to finding the best tool for SHA-2 collisions – therefore, this is a new and meaningful contribution to the current knowledge.

My theory mentioned in 3.3.4 seems to hold true, I was unable to find any historical work to prove or disprove this. An unsat result is always a worst-case scenario after running all possible combinations. Therefore there exists no combinations where a collision is possible with the standard IV for under 8 rounds.

Additionally, throughout the project, I discovered underlying issues with Bitwuzla and the upstream distribution repository. I submitted an issue and a pull request (respectively), as mentioned in (4.7.3),

thereby contributing to open-source during this project.

6.2 Future Work

6.2.1 Encoding Based Work

To build upon the findings from my research, I propose replicating encodings from Li et al. [2024] or Alamgir et al. [2024], or a combination of both, and translating them to SMTLIB. Running these encodings on Bitwuzla, the most promising SMT solver identified in my research, would allow for comparing results with the SAT or SAT + CAS approaches outlined in their respective papers. This comparison might reveal improvements due to heuristics at the SMT level. To implement this, I suggest adding relevant encodings to the encoding section of the program and generating files for running on SMT solvers.

In addition to this, the 4.9 could be completed and ran in comparison to these encodings to more effectively answer RQ4.

6.2.2 SMT Argument Exploration Work

During my research, time constraints limited me to exploring only the most promising solver, Bitwuzla. However, it is plausible that other SMT solvers such as MathSAT could outperform Bitwuzla with the right combination of arguments. To investigate this, future work could involve benchmarking each argument for interested solvers and comparing results to identify potential improvements over the baseline performance. The current software can accommodate these tasks, given sufficient time.

6.2.3 Hardware Based Work

It is highly possible that processors with increased L3 cache, such as the AMD Ryzen 7 9800X3D Advanced Micro Devices, Inc. [2025], may benefit solving performance due to reduced miss penalties. SMT solving is very memory heavy, and the locality of memory hierarchy has a major performance impact. Even in gaming and certain workstation workloads, larger L3 caches have shown to improve performance significantly. Steve Burke and GamersNexus Team [2024] However, there is a trade-off between cache size and retrieval time. Shanthi A. P. [n.d.] To date, no research has quantatively assessed the effects of cache size or core clock speed on SAT/SMT solving time. Therefore, potential future work could involve quantifying these effects and plotting correlations between hardware parameters and solving times. The current software can run these benchmarks, but it may require additional fields in the Benchmark struct to differentiate hardware-level changes.

6.2.4 Rust Language Improvements

As mentioned in 4.3.2, Rust options for visualisation crates are very limited. Additional contributions to open source could improve the situation by making the syntax a lot simpler. Functionality, such as different line plot styles could be improved.

The smt crate, mentioned in 4.4.1, lacks trivial features like the ability to export to files. It also has poor documentation compared to the standard of the Rust ecosystem, where everything is verbosely documented. This is another potential area to contribute additional work to, helping shape the ecosystem of Rust and cryptography.

Glossary

Brute-force A **brute-force** attack, as used from here on, is an SMTLIB encoding that follows the SHA-2 mathematical algorithm, but does no additional processing or assertion. This means the underlying SAT/SMT implementation *may* still use heuristics or othwerise simplify the problem at hand. One way to think about this, is as a brute-force guided search.. 8, 34

Chaining Vector (CV) Intermediate state values created during message expansion, and used as input for processing each given block iteratively. 34

Collision A security vulnerability where two distinct inputs produce the same hash digest. 34

Compression A function that combines the current chaining vector and a message block to produce the next state. 34

Differential Controlled differences in input messages analyzed to trace propagation through hash rounds. 34

encoding An encoding is a guidance to allow the solver to either reason better or to prune the search space.. 34

Expansion Preprocessing step where the message block is expanded into a schedule of words for use in hash computation rounds. 34

Free-start collision (FS) A free-start collision involves finding two messages, either distinct or identical, that produce identical hash digests, where each message utilies its own distinct chosen IV. 34

Hash Digest Also known as simply "hash", is a fixed-size output produced by a hash function. 34

Hash Function A cryptographic algorithm that deterministically maps arbitrary-length input data to a fixed-size hash digest, ensuring properties like collision resistance, preimage resistance, and computational efficiency for verifying data integrity and authenticity. 34

Initial Vector (IV) Predefined initial constants, based on hash function used, to initialize the algorithm's state before processing the input message. 34

Message Input data processed by the hash function, padded and divided into fixed-size blocks for hashing. 34

Pure Brute-force A **pure/true brute-force** attack is an attack where all possible hash combinations are attempted with no reasoning logic, attempted as is.. 8, 34

Secure Hashing Algorithm 2 (SHA-2) DEFINE ME!. 34

Semi-free-start collision (SFS) A semi-free-start collision involved finding two distinct messages that produce identical hash digests under a chosen IV. 34

SMT A Satisfiability Modulo Theory (SMT) solver is a tool that determines the satisfiability of logical formulas with respect to combinations of background theories. 34

Standard collision (STD) A standard collision involves finding two distinct messages that produce identical hash digests under a fixed initial value. This is the classic collision resistance security property required of cryptographic hash functions. 34

Truncation The process of shortening the final hash digest to a specified bit-length. 34

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Appendix A

Project Definition Document

The below 14 PDD pages have been included using `includepdf`. Page numbering, TOC, styling and appendix have remained together, as in the original PDD.

Improving SHA-2 Collisions Using Satisfiability Modulo Theory (SMT) Solvers

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General Information

The project idea originated from a City academic (Nyx-Brain, 2024), posted both on Moodle, as well as outside their office. This makes Martin Nyx Brain a supervisor on this project.

The project does not involve any external clients, or create any arrangements involving outside help as of this time. Outside collaborators, such as field experts, may involve themselves by providing additional insight, information or potential resources, such as computing power like a Virtual Machine (VM), **but will not directly contribute to the codebase of the project**.

This document makes use of Open Sans font for better compatibility, due to the lack of out-of-box presence of Times New Roman on most Unix based distributions.

This document contains approximately 1800 words, excluding the cover sheet, references, ToC, ethics checklist and appendix. Excluding titles, figure captions and other aspects not part of general “content” yields about 1750 words, about +3%, which is within City’s policy of word count deviation.

Document Version: 1.0

Version	Date
1.0	2025-02-02

Table of Contents

Solved Problem

This research project aims to utilise unexplored opportunities that have arisen from advances in *"New Records in Collision Attacks on SHA-2"* (Li, Y. Liu, F. And Wang, G, 2024). This research will expand on the novel concept of using a Satisfiability Modulo Theory (SMT) solver for practical SHA-2 collisions, using the principles and mathematics described, in addition to their code as a reference.

Project Objectives

The main purpose of this research is to investigate potential measurable quantified performance differences in SMT solvers and their parameters for SHA-2 collisions.

Research Questions

This project consists of two primary research questions (RQs):

1. **RQ1:** Does using a more effective SMT solver yield better SHA-256 collision results?
2. **RQ2**: Can encodings provided in the research (Li, Y. Liu, F. And Wang, G, 2024) be improved upon, aiming for better practical SHA-256 collisions?
   2.1. Using the *ESPRESSO logic minimizer* (Wikipedia, 2024) heuristic?
   2.2. Using better parallelism?

Justification

Li, Y. Liu, F. And Wang, G, 2024 research has proved that an SMT solver, a well-known NP-Hard problem (Wikipedia, 2024), can be utilised to solve SHA-2; thus implying SHA-2 collision is only as complex as SMT in complexity space. The research did however lack vast experimentation with different SMTs and respective parameters – which could in turn provide better results. **RQ1** shall provide benchmark insights and analysis of the differences and similarities noted.

Li, Y. Liu, F. And Wang, G, 2024 research encodings can potentially be expanded on to provide better efficiency. The longest running aspect of the code is the SMT solver. Number of clauses and variables directly exponentially influence the search space; creating more concise clauses would reduce the search space, and could allow for better throughput. One example of this is the *ESPRESSO logic minimizer* heuristic (Wikipedia, 2024), aiming to remove the "don't-care terms".

The Rust language is built targetting concurrent programming, as defined by one of its values - “Fearless Concurrency” (ch16-00, ‘The Rust Programming Language’, Rust Project Contributors, 2025). The emphasis on correct memory structure and power of concurrency could allow for a potential “*Cube-and-Conquer*” approach when interacting with the SMT solver. (Marijn, Heule, J., Kullmann, O., Wieringa, S. and Biere, A.)

These heuristics and encoding efficiencies can be combined, in addition to other methods, not mentioned here for brevity. **RQ2** shall provide findings on potential heuristics and encoding efficiencies, not limited or confined to these two examples. It shall describe what has been attempted, how it affected benchmarks and an explanation of proving/disproving any performance uplift.

Additional Notes

It is important to note, as this is research, either proving or disproving any of the RQs is seemed as a valid outcome. For example: failure to find an SMT as effective or better, could provide vital information as to explain what key characteristics in SMT are crucial specific to SHA-2 collisions. This knowledge would potentially open a path for future research around the basis of those key characteristics.

During research, additional questions may arise, but will not be the primary concern of this research.

Project Beneficiaries

“The SHA-2 hash function is implemented in some widely used security applications and protocols, including TLS and SSL, PGP, SSH, S/MIME, and IPsec.” (sec. *“Applications”* para. 1, Wikipedia, 2025)

This research will provide a formal verification; assurance that SHA-2 is still securely sound in the near-foreseeable future, while pushing the current field boundaries in SHA-2 SMT collisions, knowledge and benchmarks. In the very unlikely event of a breakthrough, the project can become a research publication, **outside of the scope of this project**, in order to create pressure and emphasis on moving away from SHA-2 onto more secure, quant-safe standards for the public.

Project Plan

As for project methodology, a Kanban-styled board, split into **multiple sprints** is in use for this project. Downtime and work pressure is accounted for, with two 2-week sprints followed by a 1-week break. The project splits very effectively into these sprints; as an **agile-esque Kanban approach** allows out-of-order task completion – including, but not limited to documentation, development, research and testing. This ensures everything is accounted for as outlined by requirements.

Since this out-of-order task approach does not work very well with a gantt chart, one has not been used for this project. Instead, it is possible to define tasks as dependencies where necessary, but a sprint-planning approach should reduce the need for dependency nested tasks.

I have decided to use GitHub's in-built "project" boards, since they tie in directly to the repository, allowing for easy access and referencing throughout, where necessary.

The GitHub Kanban board (private) can be found here.

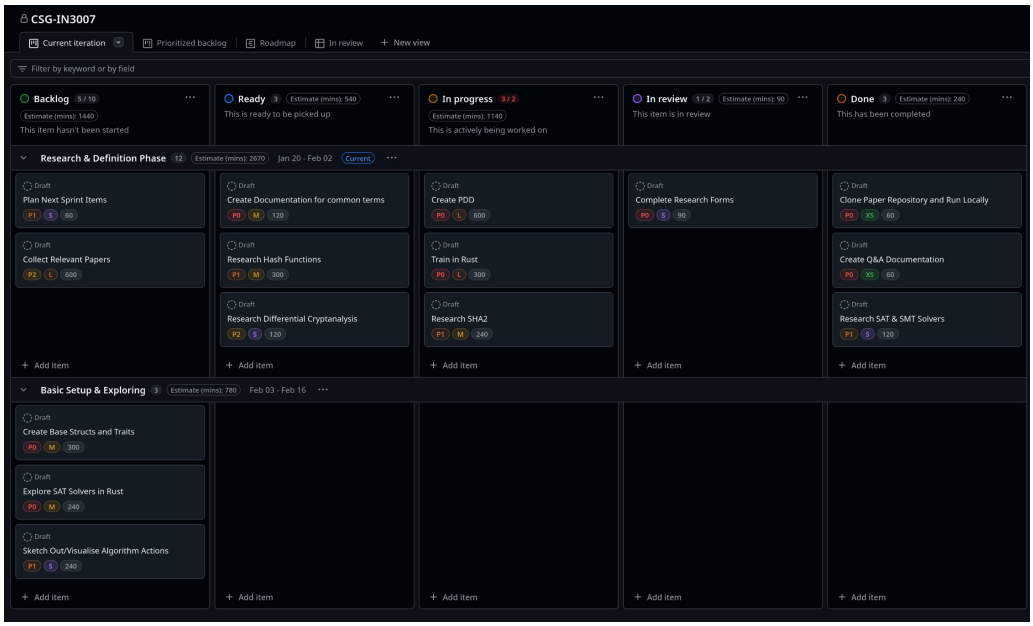


Figure 1: Current Project Board

Risks Affecting the Project

The **lack of supervisor time** could result in lack of deeper understanding in the topic, slowing down the research. RQ1 has been chosen to avoid extreme depth in SHA-2 and SMTs, in order to reduce the risk; my current knowledge and prior base research, would be sufficient to answer this RQ. However, as for RQ2, I would require depth of knowledge and would require weekly time with my supervisor. As an alternative, I can utilise public knowledge such as publications, contact other researchers in the field and find out more information, gaining help through other routes.

The project will use Rust as the primary language. As of my knowledge, at present, there is no natively written SMTs or SHA-2 collisions in Rust, only bindings exist. As this is research, anything can happen; it may occur that Rust is an incredibly **poor choice of programming language** for this use case. This in turn would add complications as to requiring a rewrite in a known and trusted language in this field, C++. This is unlikely, since Rust and C++ have direct out-of-box compatibility with linkers, and in fact as defined by '*The Rustonomicon*' (Rust Project Contributors, 2025) the "Repr(C)" trait aims to reproduce C code where possible. This in theory would allow Rust code to be interchangeable with C++, and as of my knowledge, some of it has already been achieved through open-source contributions. Additionally, the community for Rust is very open to answering questions. Specifically related to this project, the Discord community server has #cryptography-and-security and #dark-arts channels, these are very active and have a lot of Rust knowledgable users. In the worst case scenario, a direct fork of the Li, Y. Liu, F. And Wang, G, 2024 research, in C++ and Python, with alterations could be utilised as a base for the project.

A **high-performance HVM** will be required to match the performance benchmarks of the original paper. My aim is to obtain such HVM from outside collaborators potentially interested in this research. As an alternative, I am aware that City does have a HVM, but it does fall short of my needs for longer-term high-performance throughput. I own a X86 24-thread 128GB RAM home-lab, as well as have access to an always-free Oracle Cloud Infrastructure ARM Ampere A1 4-thread 24GB RAM VM. Either of these could be utilised to continue creation of benchmarks, working around the limitations and providing comparable benchmarks. There still would be a conceivable difference based on implementations; "algorithm progress, [...] is sometimes orders of magnitude more important than hardware." (Thompson, N.C., Ge, S. and Sherry, Y.M., 2021)

LSEP Issues

Prefix Notes

To note, it is **nearly impossible** a breakthrough occurs. It is **impossible** to determine the probability of advancements and how large they would be. Based on previous research in this field, which has been very slow-progressing, it is predictable that the performance will not be too dissimilar, to that of current records, set out by Li, Y., Liu, F. and Wang, G. (2024). Since this risk is **nearly impossible**, but **extremely consequential**, I believe this project does **not** pose any **probable** high-risk, similarly to how CVE categorises risk based on knowledge requirement and likely-hood.

Legal

General Data Protection Act (GDPR) does not directly apply to the scope of this project. However, a breakthrough in SHA-2 collisions could be used to break the security of many GDPR compliant companies. Therefore, ethical and responsible disclosure would be required in such scenario.

NCSC does not clearly define any legal requirement to disclose a vulnerability. It does make mention of "Vulnerability Reporting with a UK government online service" – which this project could apply to, but makes no legal obligations. (NCSC, 2018)

ENISA makes mention of the "Coordinated Vulnerability Disclosure" mentioning "the Cybersecurity Act (2019), the NIS2 Directive (2022), and the upcoming Cyber Resilience Act (2024)." (ENISA. n.d.)

As such, if the project were to require vulnerability disclosure, the national bodies responsible for the UK/EU would be contacted, ensuring an ethical, legal and responsible disclosure.

Social

This research will have benefits in progressing the cryptography field, ensuring the safety of public data. It will either create a formal verification that SHA-2 is still secure sound with present knowledge. Alternatively it could disprove the security of SHA-2, showing it is potentially near end-of-life; in this case putting pressure for the world to push for, ideally quant-safe, better alternatives to replace it.

In the **extremely unlikely** scenario that a breakthrough occurs, practical reproducible polynomial-time SHA-2 collisions would pose a real-time threat to many protocols, users and all electronically stored information behind encryption, requiring a mass-scale action of all international security bodies. It would also permanently break some

cryptocurrencies, that are embedded in SHA-2 too deeply to change, potentially crashing the cryptocurrency market. It is more positive for a research to discover and disclose this ethically, rather than a user with malicious intent - where it may be too late causing international harm.

Ethical

The original codebase provided by Li, Y., Liu, F. and Wang, G. (2024) does not contain a licence. Their paper does make note that "The source code to search for the differential characteristics and verify the (SFS/FS) collisions for SHA-256 and SHA-512 is available [...]", but it does not set out if forking and working on-top of it would be permissible. By default copyright standards, it is assumed that such property is reserved for the copyright owners. The original research paper has the **CC BY 4.0** licence, which allows for sharing and adapting the principles enclosed as long as attribution is given (CreativeCommons, n.d.). However, it may be unethical to assume that this same licence applies to the code hyperlinked in the paper. This has been mitigated by the decision to create a new codebase in Rust, and use the principles of the paper.

Professional

One professional risk for me, is potential to release skewed benchmarks, misleading others. One way of preventing misleading benchmarks, is to ensure all variables remain the same, and only the SMT or its parameters change for **RQ1.** This would provide a like-for-like benchmark, and with enough runs for averages and standard deviations could prove to be an accurate representation of best algorithmically performing SMTs to answer **RQ1**.

Ethics Review

Part A: Ethics Checklist

A.1: If you answer YES to any of the questions in this block, your consultant/supervisor must have obtained approval for the project from an appropriate external ethics committee, and you need to have received written confirmation of this from him/her. Students cannot themselves apply for ethics approval in this case as the project is considered high risk". This type of research is not covered by City's process, and external approval from an appropriate institution is required.		**Answer**
1.1	Does your research require approval from the National Research Ethics Service (NRES)?	NO
1.2	Will you recruit participants who are covered by the Mental Capacity Act 2005?	NO
1.3	Will you recruit any participants who are covered by the Criminal Justice System, for example, people on remand, prisoners and those on probation?	NO

A.2: If you answer YES to any of the questions in this block your consultant/supervisor must have obtained appropriate ethics committee approval.		Answer
2.1	Does your research involve participants who are unable to give informed consent?	NO
2.2	Is there a risk that your research might lead to disclosures from participants concerning their involvement in illegal activities?	NO
2.3	Is there a risk that obscene and or illegal material may need to be accessed for your research study (including online content and other material)?	NO
2.4	Does your project involve participants disclosing information about protected characteristics (as identified by the Equality Act 2010)?	NO
2.5	Does your research involve you travelling to another country outside of the UK, where the Foreign & Commonwealth Office has issued a travel warning that affects the area in which you will study?	NO
2.6	Does your research involve invasive or intrusive procedures?	NO
2.7	Does your research involve animals?	NO
2.8	Does your research involve the administration of drugs, placebos or other substances to study participants?	NO

A.3: If you answer YES to any of the questions in this block, then unless you are applying to an external ethics committee or the Senate Research Ethics Committee (SREC), you must apply for approval from the Computer Science Research Ethics Committee (CSREC) through Research Ethics Online - https://researchmanager.city.ac.uk/. Depending on the level of risk associated with your application, it may be referred to the Senate Research Ethics Committee (SREC).		**Answer**
3.1	Does your research involve participants who are under the age of 18?	NO
3.2	Does your research involve adults who are vulnerable because of their social, psychological or medical circumstances (vulnerable adults)?	NO
3.3	Are participants recruited because they are staff or students of City, University of London?	NO
3.4	Does your research involve intentional deception of participants?	NO
3.5	Does your research involve participants taking part without their informed consent?	NO
3.5	Is the risk posed to participants greater than that in normal working life?	NO
3.7	Is the risk posed to you, the researcher(s), greater than that in normal working life?	NO
A.4 If you answer YES to the following question and your answers to all other questions in sections A1, A2 and A3 are NO, then your project is deemed to be of MINIMAL RISK. **If this is the case, then you can apply for approval through your supervisor under PROPORTIONATE REVIEW. You do so by completing PART B of this form.** **If you have answered NO to all questions on this form, then your project does not require ethical approval. You should submit and retain this form as evidence of this.**		**Answer**
4	Does your project involve human participants or their identifiable personal data?	NO

Part B: Ethics Proportionate Review Form

Omitted for brevity due to not being applicable. The answer to A.4 is “No”, since no human participants or their data will be involved. All testing and benchmarking will be done on generated SHA-2 pairs, unrelated to anyone or anything.

References

[1] Nyx-Brain, M. (2024) 'Improving Attacks on the SHA-2 Algorithms'. Available at: https://moodle4.city.ac.uk/pluginfile.php/1093061/mod_folder/content/0/%5BSecurity%5D%5BCryptography%5DImproving-Attacks-on-the-SHA-2-Algorithms.docx accessed on 2025-01-30.

[2] Li, Y., Liu, F. and Wang, G. (2024) 'New Records in Collision Attacks on SHA-2'. Available at: https://eprint.iacr.org/2024/349 accessed on 2025-01-30.

[3] Thompson, N.C., Ge, S. and Sherry, Y.M. (2021) 'Building the algorithm commons: Who discovered the algorithms that underpin computing in the modern enterprise?', Global Strategy Journal, 11(1), pp. 17–33. Available at https://onlinelibrary.wiley.com/doi/epdf/10.1002/gsj.1393 accessed on 2025-02-02.

[4] Rust Project Contributors (2025) 'The Rust Programming Language'. Available at: https://github.com/rust-lang/book/blob/main/src accessed on 2025-01-31, with latest commit SHA fa312a3.

[5] Rust Project Contributors (2025) 'The Rustonomicon'. Available at: https://github.com/rust-lang/nomicon accessed on 2025-01-31, with latest commit SHA bc22988.

[6] Wikipedia Contributors (2025) 'SHA-2'. Available at: https://en.wikipedia.org/w/index.php?title=SHA-2&oldid=1271918606 accessed on 2025-01-31.

[7] Wikipedia Contributors (2024) 'Satisfiability modulo theories'. Available at: https://en.wikipedia.org/w/index.php?title=Satisfiability_modulo_theories&oldid=1250965920 accessed on 2025-02-02.

[8] Wikipedia Contributors (2024) 'Espresso heuristic logic minimizer'. Available at: https://en.wikipedia.org/w/index.php?title=Espresso_heuristic_logic_minimizer&oldid=1251095784 accessed on 2025-02-02.

[9] Marijn, Heule, J., Kullmann, O., Wieringa, S. and Biere, A. (n.d.) 'Cube and Conquer: Guiding CDCL SAT Solvers by Lookaheads'. Available at: https://www.cs.utexas.edu/~marijn/publications/cube.pdf accessed on 2025-02-02.

[10] National Cyber Security Centre (NCSC) (2018) 'Vulnerability Reporting'. Available at: https://www.ncsc.gov.uk/information/vulnerability-reporting accessed on 2025-02-02.

[11] European Network and Information Security Agency (ENISA) (n.d.) 'Vulnerability Disclosure'. Available at: https://www.enisa.europa.eu/topics/vulnerability-disclosure accessed on 2025-02-02.

[12] CreativeCommons (n.d.) 'Attribution 4.0 International Deed (CC BY 4.0)'. Available at: https://creativecommons.org/licenses/by/4.0/ accessed on 2025-02-02.

Appendix

No client information sheet is provided, since the project does not involve a client.

No AI tools have been utilised as part of this PDD.

For category 3, section 4.5.7 "Legal, Social, Ethical and Professional Issues (LSEPI)" a "Prefix Notes" section has been used instead of an Appendix for better clarity.

Appendix B

Reuse Summary

No code has been directly reused.

The codebase bundles Colibri2 and MathSAT with their respective licences, but does not statically or dynamically link to the binaries. Usage of these bundled binaries is optional, and the code assumes nothing exists on the host, thus making checks that an SMT solver is present on the device. For the sake of generating results, these bundled tools, in addition to all previously mentioned SMT solvers, have been used with their respective licences.

The SHA-2 implementation part of my code, was written fully by me as per guidelines of National Institute of Standards and Technology (NIST) [2015], and is otherwise an open widely used standard.

Rust being a streamlined low-level embedded language, provides the basic building blocks, known as the standard (`std`) library. Similarly, like with other languages, Rust requires the use of other external libraries, known as "crates", to extend functionality. This project makes use of multiple crates to supplement functionality of the `std` Rust library.

Unlike C or C++, Rust does not utilise header files which may be provided by libraries, and instead directly links statically these crates built externally of the project target. All provided code is fully written by me using these imported building blocks.

Full information regarding licences; for all solvers (including bundled ones), as well as crates; can be found in the README.md file of the source code, accessible both on GitHub and via the submission.

Appendix C

Produced Output

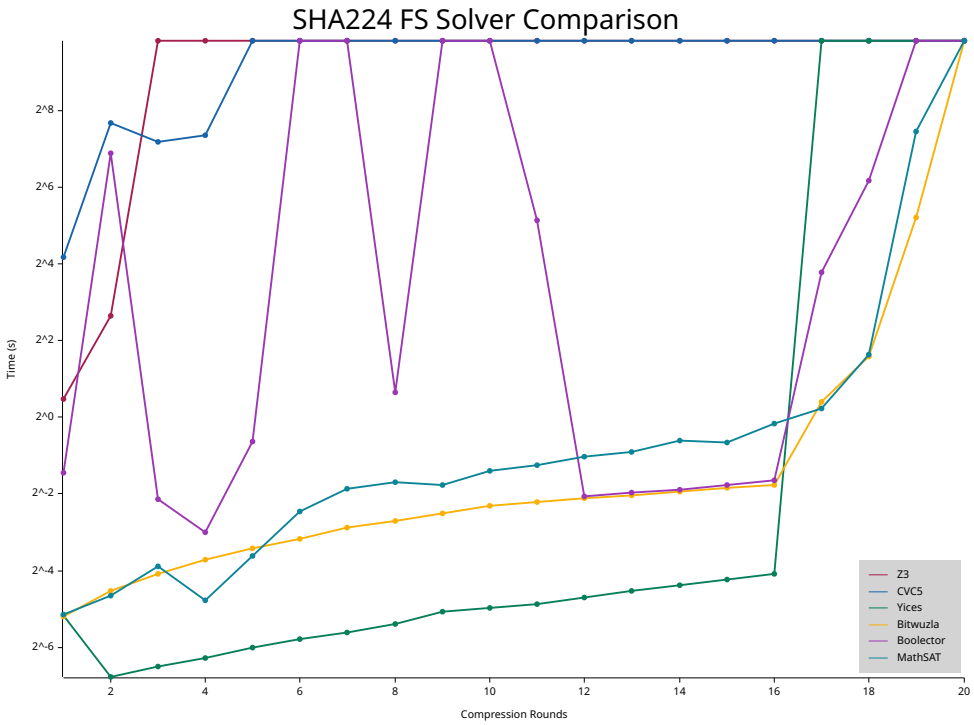
C.1 Notes

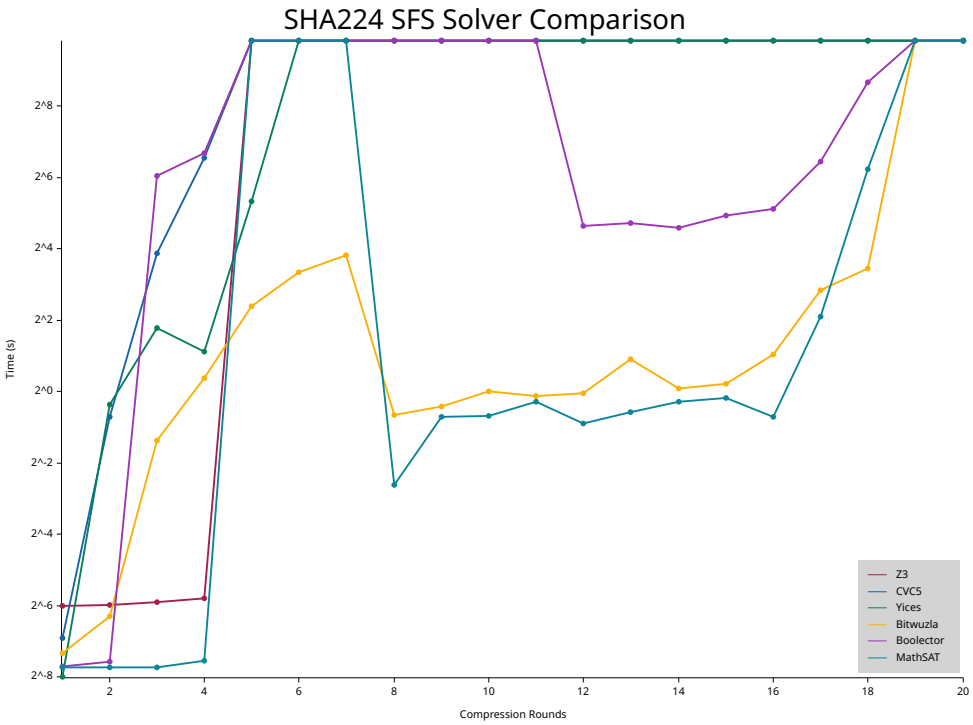
This report was written in TeX and compiled to PDF. The tables have been created using an online tool TablesGenerator.com [N/D].

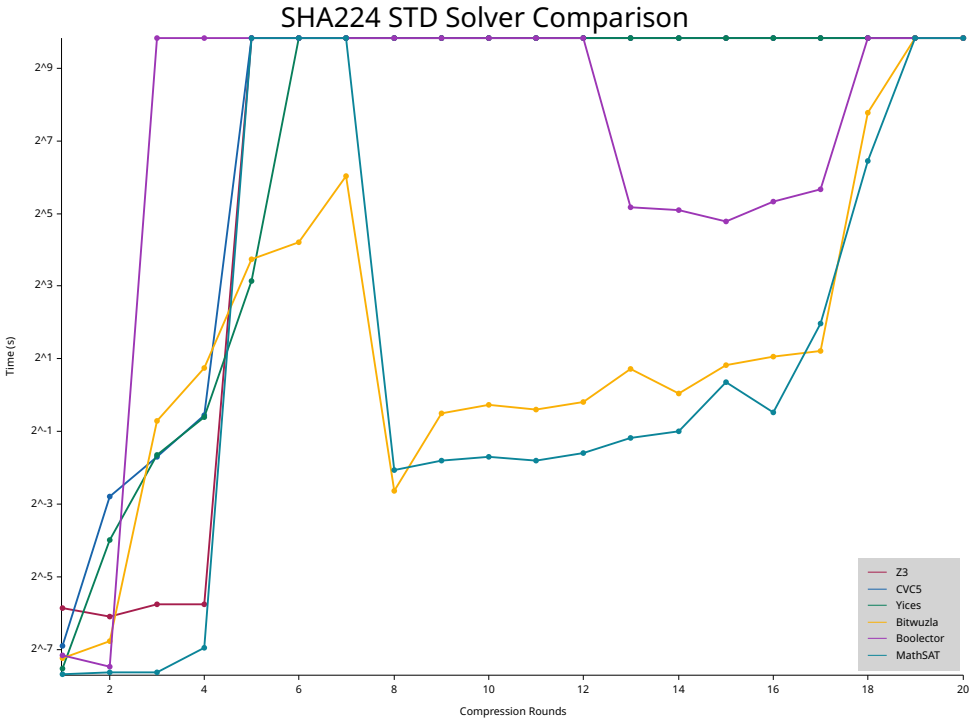
C.2 Result Graphs

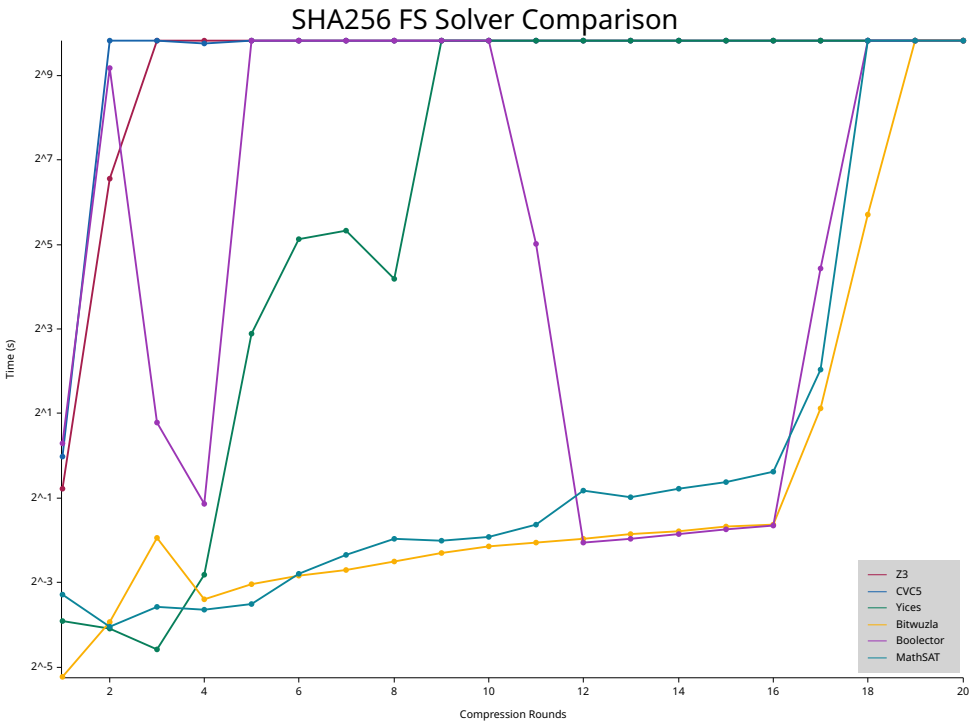
All graph data can be found in the form of tables in C.3.

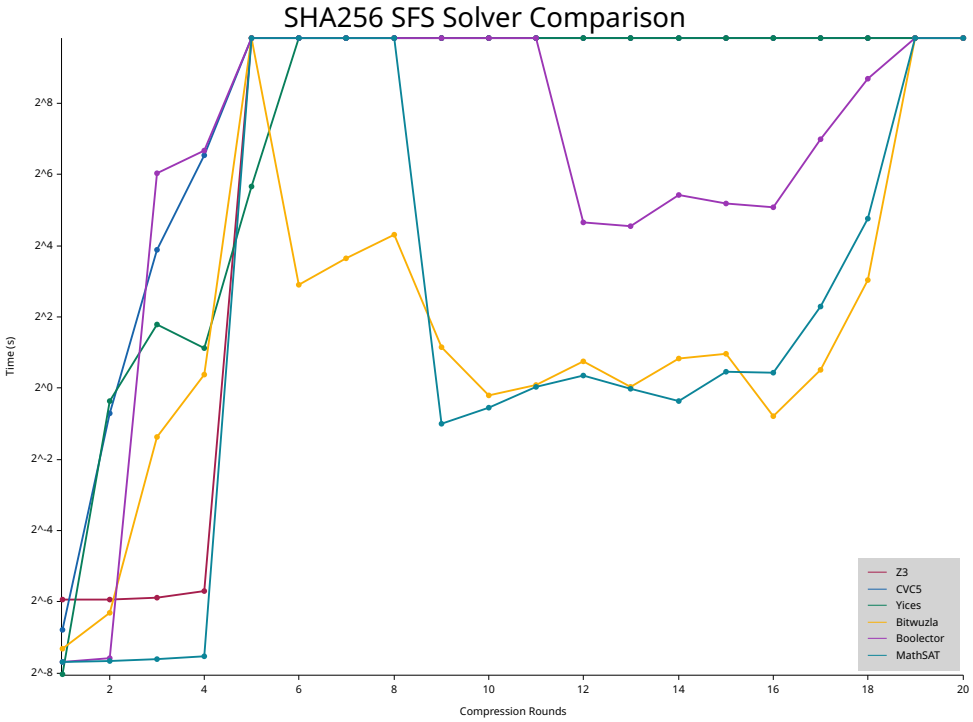
C.2.1 Solver Comparison Graphs

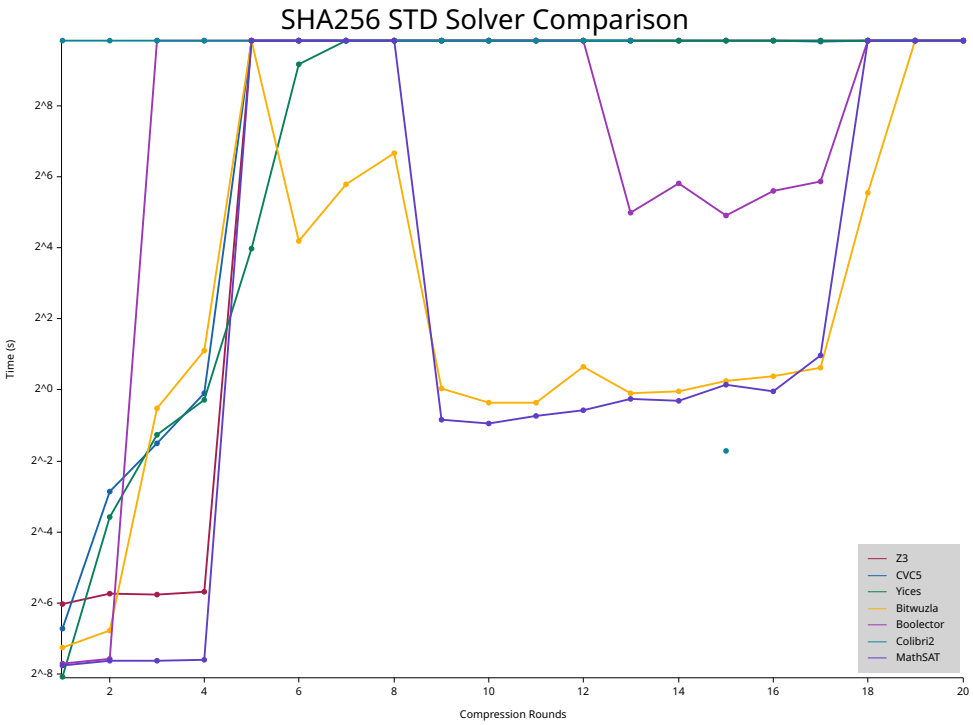


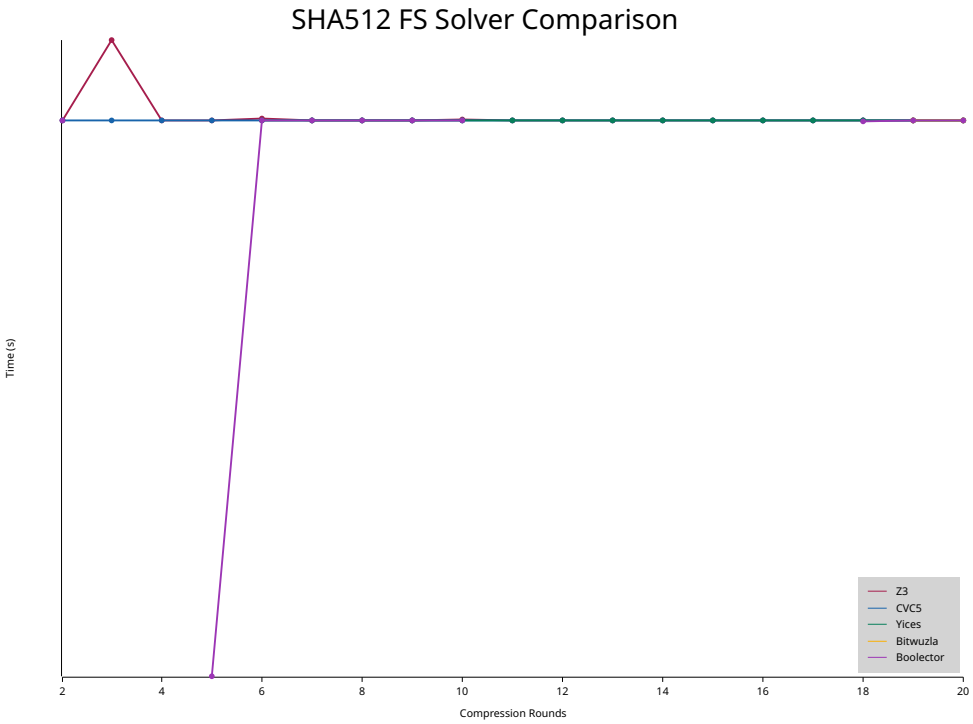

SHA224 SFS Solver Comparison
Time (s)
2^8
2^6
2^4
2^2
2^0
2^-2
2^-4
2^-6
2^-8
2
4
6
8
10
12
14
16
18
20
Compression Rounds
Z3
CVC5
Yices
Bitwuzla
Boolector
MathSAT

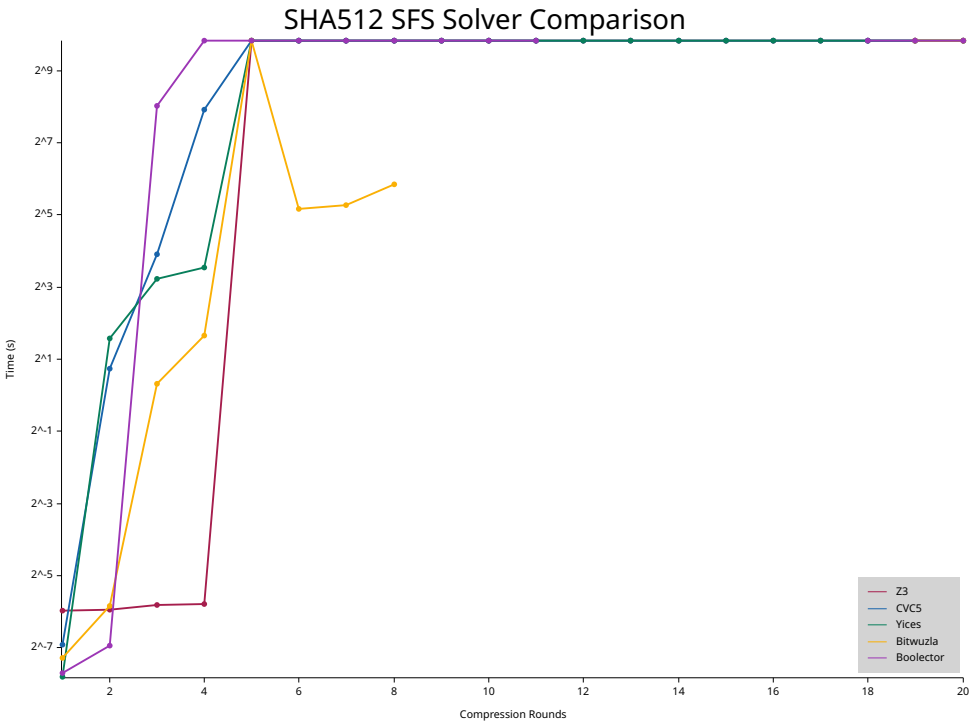

SHA224 STD Solver Comparison
Time (s)
2^9
2^7
2^5
2^3
2^1
2^-1
2^-3
2^-5
2^-7
2
4
6
8
10
12
14
16
18
20
Compression Rounds
Z3
CVC5
Yices
Bitwuzla
Boolector
MathSAT

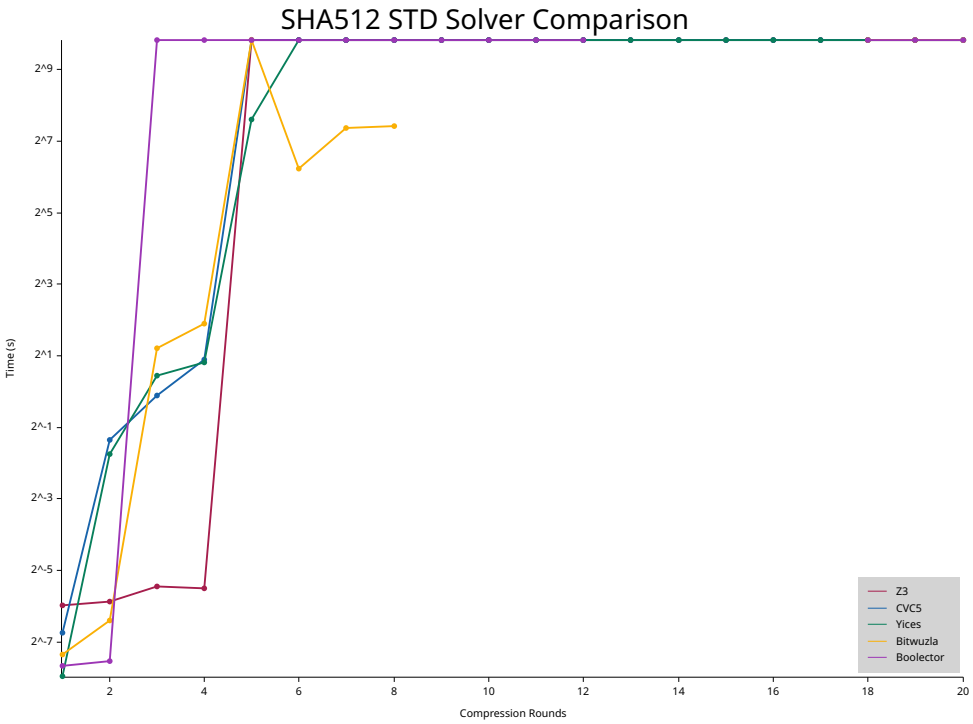

SHA256 FS Solver Comparison
Time (s)
2^9
2^7
2^5
2^3
2^1
2^-1
2^-3
2^-5
2
4
6
8
10
12
14
16
18
20
Compression Rounds
Z3
CVC5
Yices
Bitwuzla
Boolector
MathSAT


SHA256 SFS Solver Comparison
Time (s)
2^8
2^6
2^4
2^2
2^0
2^-2
2^-4
2^-6
2^-8
2
4
6
8
10
12
14
16
18
20
Compression Rounds
Z3
CVC5
Yices
Bitwuzla
Boolector
MathSAT

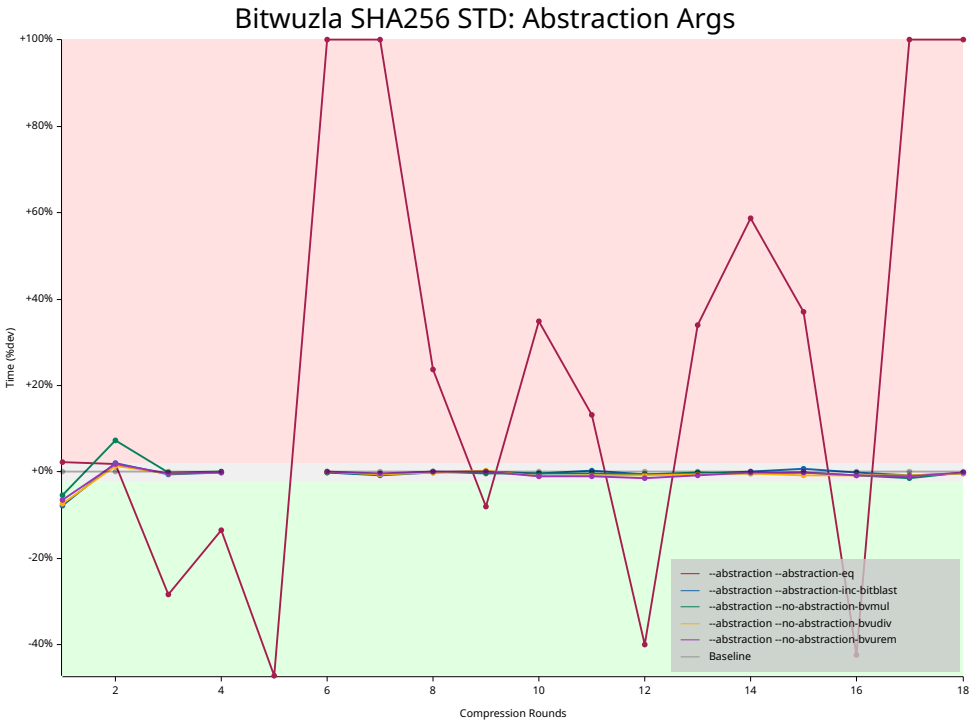

SHA256 STD Solver Comparison
Time (s)
2^8
2^6
2^4
2^2
2^0
2^-2
2^-4
2^-6
2^-8
2
4
6
8
10
12
14
16
18
20
Compression Rounds
Z3
CVC5
Yices
Bitwuzla
Boolector
Colibri2
MathSAT

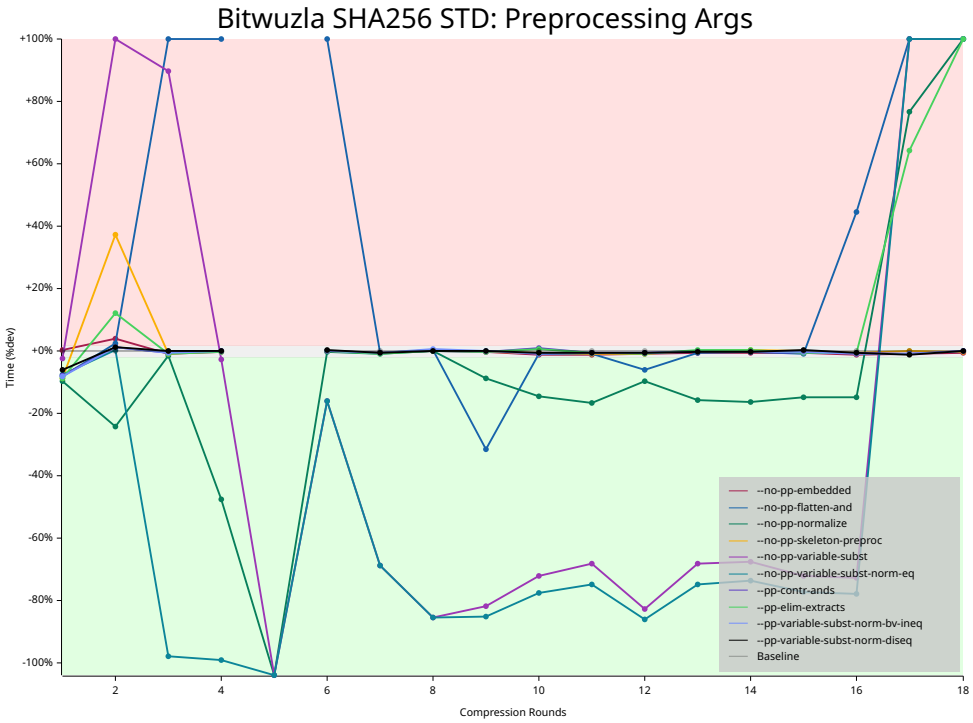

SHA512 FS Solver Comparison
Time (s)
2
4
6
8
10
12
14
16
18
20
Compression Rounds
Z3
CVC5
Yices
Bitwuzla
Boolector

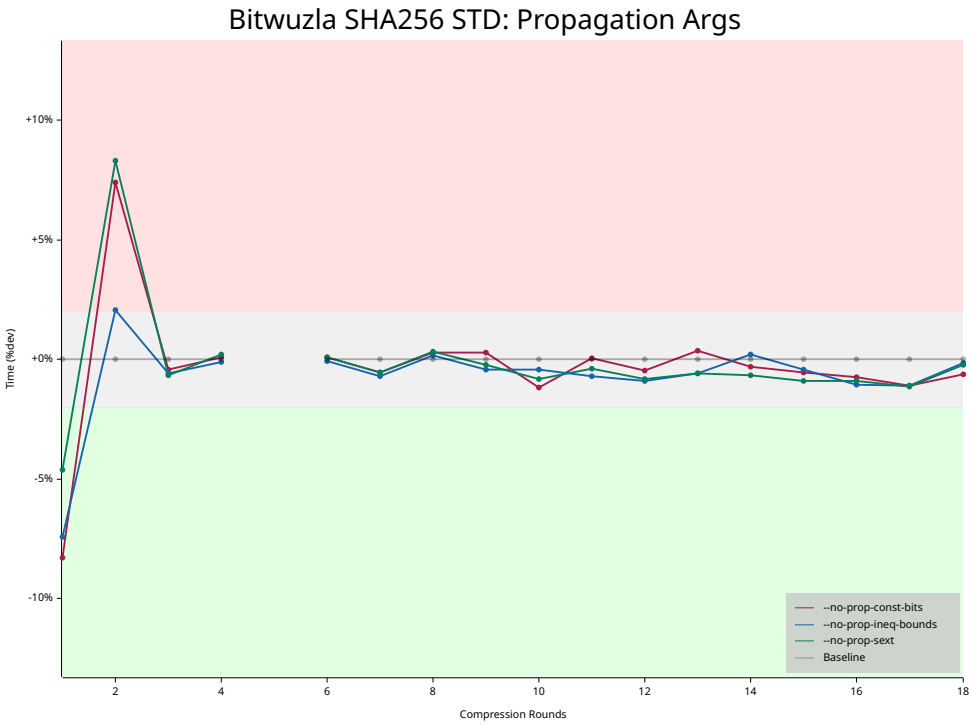

SHA512 SFS Solver Comparison
Time (s)
2^9
2^7
2^5
2^3
2^1
2^-1
2^-3
2^-5
2^-7
2
4
6
8
10
12
14
16
18
20
Compression Rounds
Z3
CVC5
Yices
Bitwuzla
Boolector

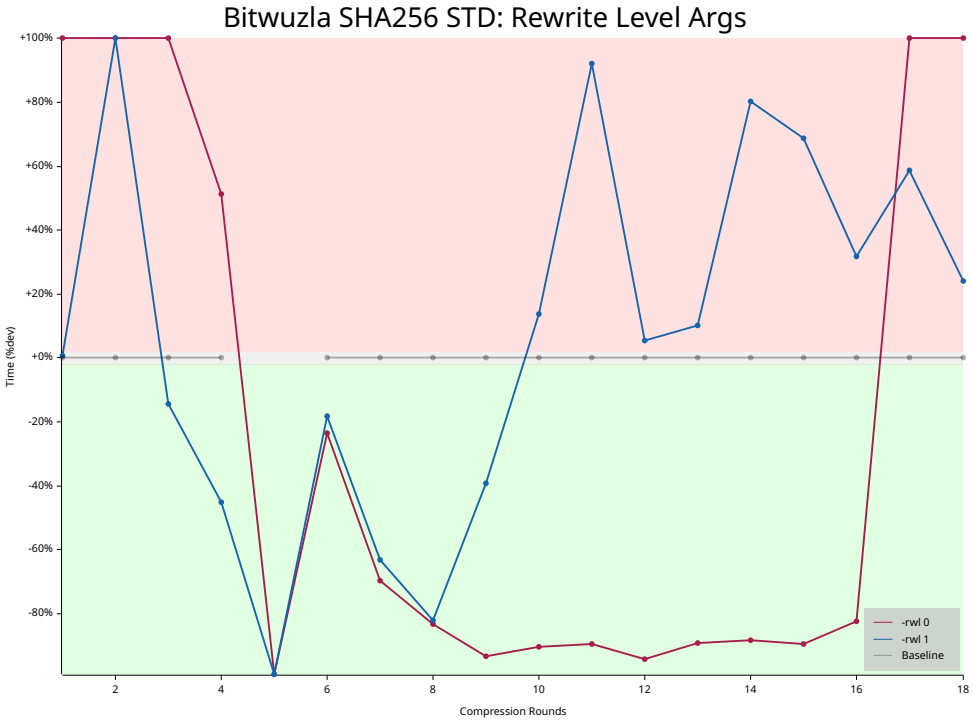

SHA512 STD Solver Comparison
Time (s)
2^9
2^7
2^5
2^3
2^1
2^-1
2^-3
2^-5
2^-7
2
4
6
8
10
12
14
16
18
20
Compression Rounds
Z3
CVC5
Yices
Bitwuzla
Boolector

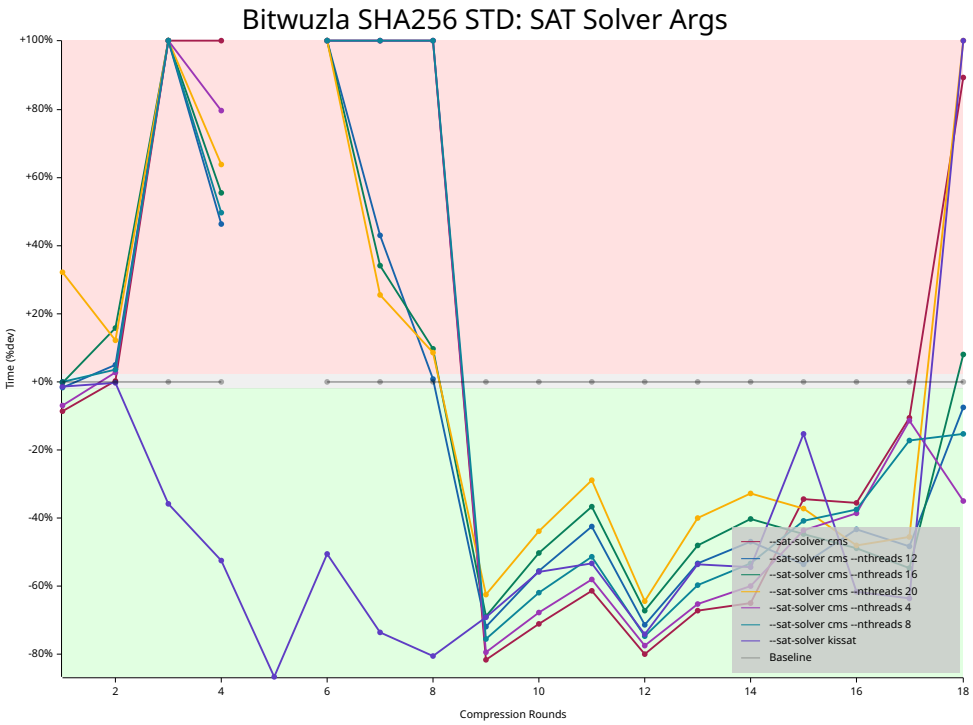
C.2.2 Bitwuzla Arguments

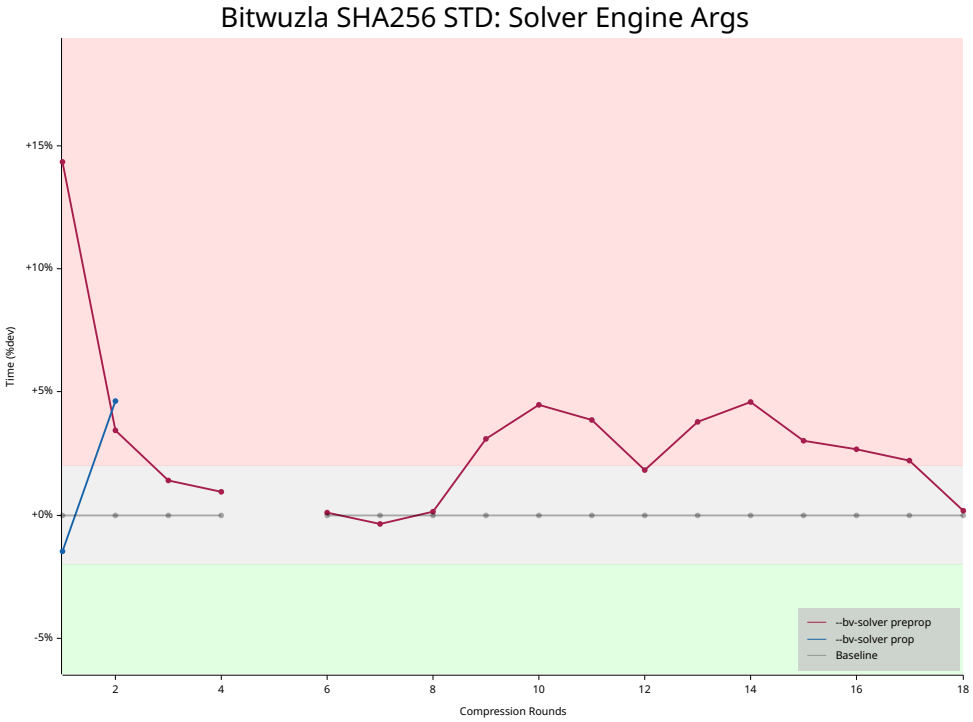




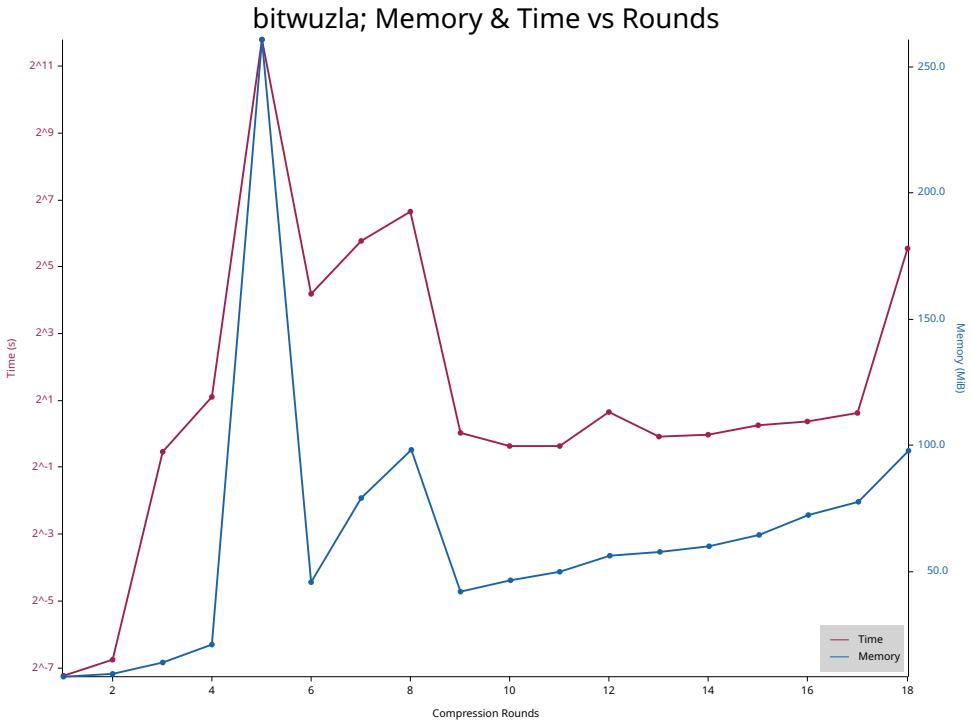

Bitwuzla SHA256 STD: Propagation Args
+10%
+5%
+0%
-5%
-10%
Time (%dev)
2
4
6
8
10
12
14
16
18
Compression Rounds
--no-prop-const-bits
--no-prop-ineq-bounds
--no-prop-sext
Baseline


Bitwuzla SHA256 STD: Rewrite Level Args
+100%
+80%
+60%
+40%
+20%
+0%
-20%
-40%
-60%
-80%
Time (%dev)
2
4
6
8
10
12
14
16
18
Compression Rounds
-rwl 0
-rwl 1
Baseline

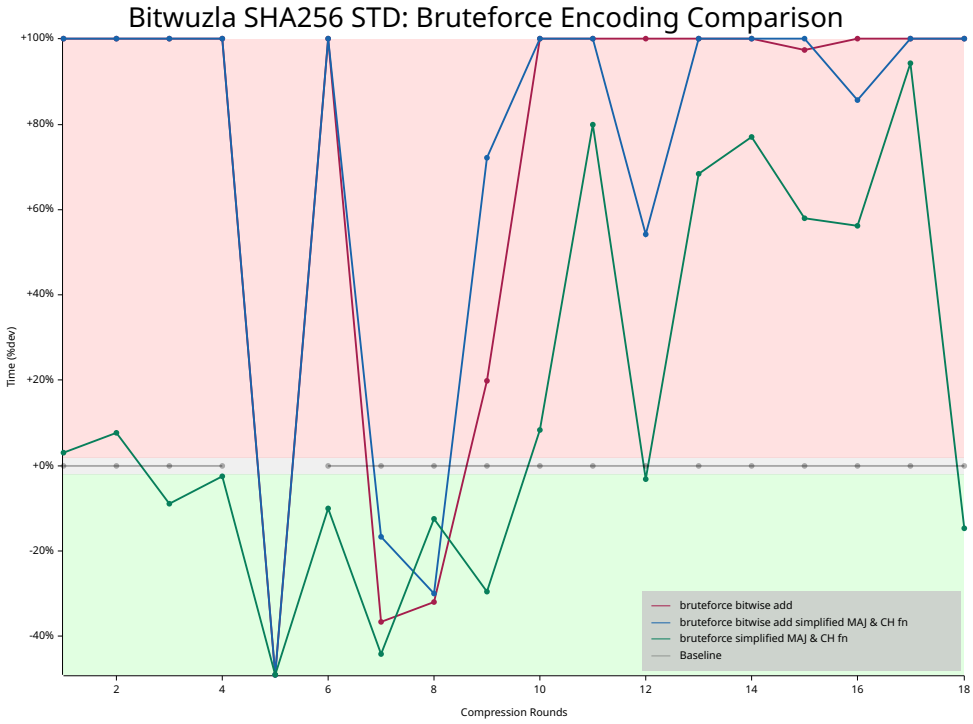

Bitwuzla SHA256 STD: SAT Solver Args
+100%
+80%
+60%
+40%
+20%
+0%
-20%
-40%
-60%
-80%
Time (%dev)
2
4
6
8
10
12
14
16
18
Compression Rounds
--sat-solver cms
--sat-solver cms --nthreads 12
--sat-solver cms --nthreads 16
--sat-solver cms --nthreads 20
--sat-solver cms --nthreads 4
--sat-solver cms --nthreads 8
--sat-solver kissat
Baseline

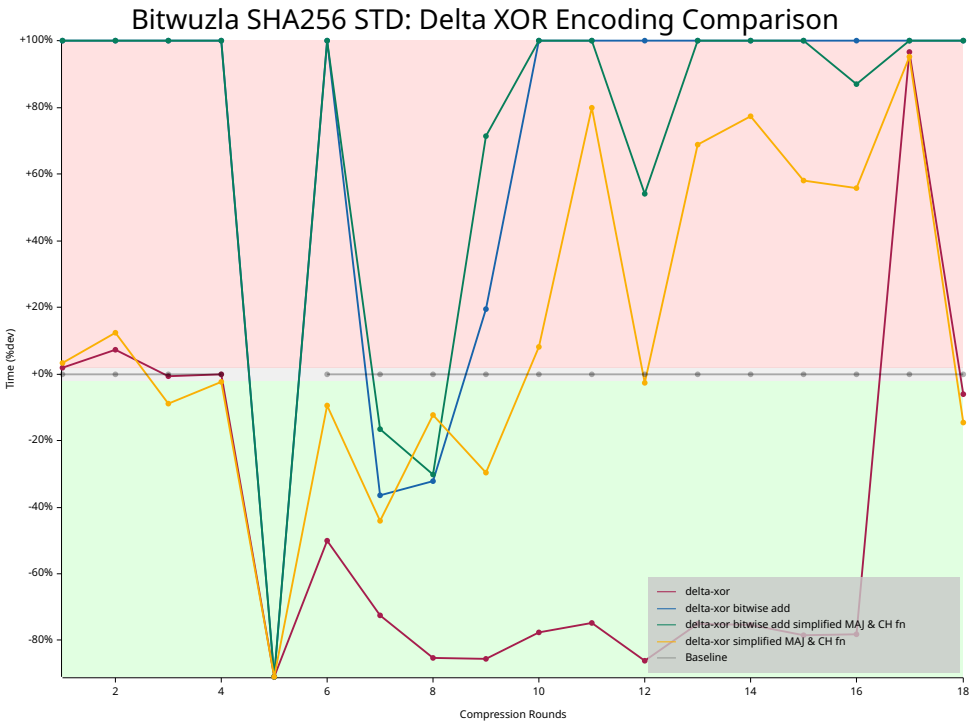

Bitwuzla SHA256 STD: Solver Engine Args
+15%
+10%
+5%
+0%
-5%
Time (%dev)
2
4
6
8
10
12
14
16
18
Compression Rounds
--bv-solver preprop
--bv-solver prop
Baseline

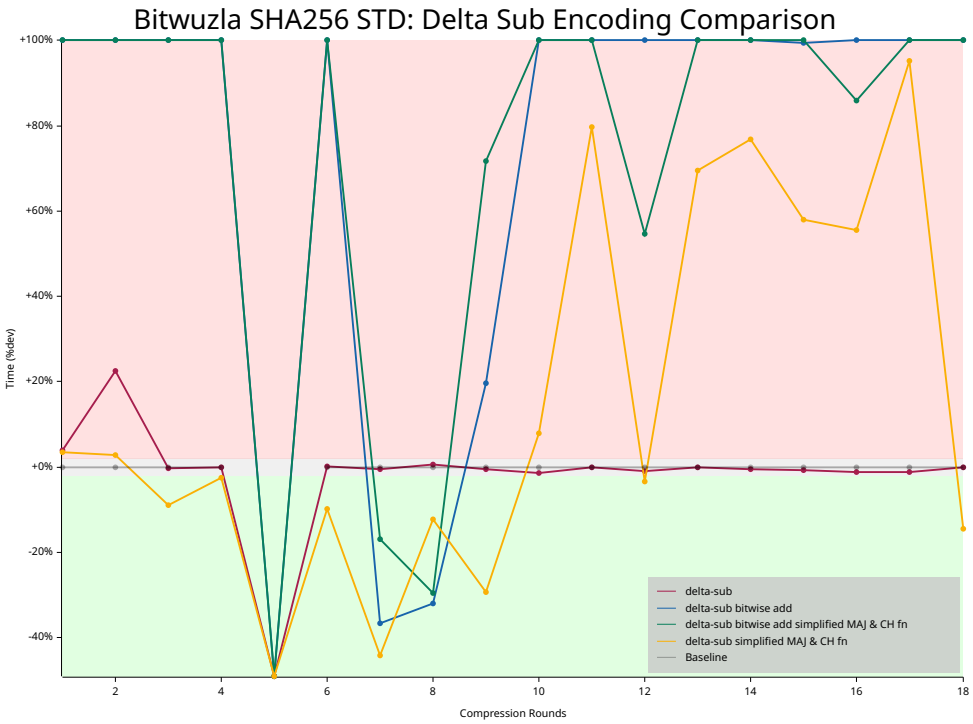
C.2.3 Detailed Bitwuzla Graph



C.2.4 Encoding Graphs




Bitwuzla SHA256 STD: Delta XOR Encoding Comparison
Time (%dev)
+100%
+80%
+60%
+40%
+20%
+0%
-20%
-40%
-60%
-80%
2
4
6
8
10
12
14
16
18
Compression Rounds
delta-xor
delta-xor bitwise add
delta-xor bitwise add simplified MAJ & CH fn
delta-xor simplified MAJ & CH fn
Baseline


Bitwuzla SHA256 STD: Delta Sub Encoding Comparison
Time (%dev)
+100%
+80%
+60%
+40%
+20%
+0%
-20%
-40%
2
4
6
8
10
12
14
16
18
Compression Rounds
delta-sub
delta-sub bitwise add
delta-sub bitwise add simplified MAJ & CH fn
delta-sub simplified MAJ & CH fn
Baseline

C.3 Result Tables

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.0	0.7	2.2	3515.7	18.3	54.7	100.7	1.0	0.8	0.8	1.6	0.9	1.0	1.2	1.3	1.5	46.2	36000.1	900.1
Memory (MiB)	8258	9410	14082	21482	266754	46862	80986	100662	43066	47394	50894	57722	59262	61474	65806	73986	79482	100186	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.1: Bitwuzla result table for standard collisions using brute-force encoding.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.0	0.0	0.0	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1
Memory (MiB)	28610	29378	29570	29570	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O

Table C.2: Z3 result table for standard collisions using brute-force encoding.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.1	0.4	0.8	15.7	571.0	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1
Memory (MiB)	4226	5186	6338	7682	23042	93890	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O

Table C.3: Yices result table for standard collisions using brute-force encoding.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.1	0.4	0.9	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1
Memory (MiB)	21506	27394	33062	41198	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O

Table C.4: CVC5 result table for standard collisions using brute-force encoding.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.0	0.0	0.0	900.1	900.1	900.1	900.1	0.6	0.5	0.6	0.7	0.8	0.8	1.1	1.0	1.9	900.1	900.1	900.1
Memory (MiB)	10370	10562	10562	10754	-	-	-	-	40090	39598	43870	45514	49922	50306	53998	60650	68038	-	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	T/O	T/O	T/O	T/O	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O	T/O

Table C.5: MathSAT result table for standard collisions using brute-force encoding.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	15	18	19	20
Time (s)	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	0.3	900.1	900.1	900.1
Memory (MiB)	-	-	-	-	-	-	-	-	-	-	-	-	-	33982	-	-	-
Result	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	SAT	T/O	T/O	T/O

Table C.6: Colibri2 result table for standard collisions using brute-force encoding.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.0	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	900.1	31.4	56.6	30.0	48.4	57.9	900.1	900.1	900.1
Memory (MiB)	6146	6146	-	-	-	-	-	-	-	-	-	-	71562	98562	67390	84042	87206	-	-	-
Result	UNSAT	UNSAT	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	T/O	SAT	SAT	SAT	SAT	SAT	T/O	T/O	T/O

Table C.7: Boolector result table for standard collisions using brute-force encoding.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.9	2.9	5.4	6.4	21.0	66.9	34.6	68.4	1.2	2.7	1.9	3.4	3.7	2.3	2.4	4.1	5.8	362.3	900.1	900.1
Memory (MiB)	15142	22682	34802	42634	56926	106686	79210	115822	68262	79234	85202	88370	95298	102930	106790	116470	133174	242386	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.8: Bitwuzla result table for standard collisions using brute-force encoding with alternative bitwise add.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.0	0.6	2.1	11.2	16.5	30.5	88.2	0.7	0.8	1.4	1.5	1.6	1.7	1.9	2.0	3.0	39.4	900.1	900.1
Memory (MiB)	8066	9602	14214	21898	36646	44738	53554	100974	42670	46362	50462	53946	57698	64506	65374	70610	78422	107846	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.9: Bitwuzla result table for standard collisions using brute-force encoding with simplified Maj and Ch functions.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.9	2.9	5.4	6.5	22.1	70.5	45.5	70.5	1.8	3.5	1.9	2.4	3.7	2.3	4.2	2.4	10.2	356.0	900.1	900.1
Memory (MiB)	14970	23042	35358	40478	55666	105262	83890	123002	68954	77498	81406	87630	92902	103742	107810	114602	126794	282186	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.10: Bitwuzla result table for standard collisions using brute-force encoding with simplified Maj and Ch functions, and alternative bitwise add.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.9	2.9	5.4	6.4	21.0	67.1	34.8	68.3	1.2	2.7	1.9	3.4	3.7	2.3	2.4	4.1	5.9	361.8	900.1	900.1
Memory (MiB)	14910	25158	35174	41354	56822	112482	81246	118758	69246	79494	84626	89470	95594	106794	114206	116626	132430	240878	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.11: Bitwuzla result table for standard collisions using delta XOR encoding with alternative bitwise add.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.0	0.6	2.1	11.3	16.6	30.5	88.4	0.7	0.8	1.4	1.5	1.6	1.7	1.9	2.0	3.0	39.5	900.1	900.1
Memory (MiB)	8066	9410	15050	22922	36534	44286	55890	103570	42950	46390	51910	53990	57538	64138	65426	70958	76566	102770	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.12: Bitwuzla result table for standard collisions using delta XOR encoding with simplified Maj and Ch functions.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.9	2.9	5.4	6.5	22.2	70.3	45.6	70.2	1.8	3.5	1.9	2.4	3.7	2.3	4.2	2.4	10.2	352.8	900.1	900.1
Memory (MiB)	14954	22870	36734	39682	56962	103294	85238	117686	69726	77530	81894	87786	92934	103886	111798	114642	123514	282870	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.13: Bitwuzla result table for standard collisions using delta XOR encoding with simplified Maj and Ch functions, and alternative bitwise add.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.0	0.7	2.2	900.1	18.3	54.4	101.2	1.0	0.8	0.8	1.6	0.9	1.0	1.2	1.3	1.5	46.2	900.1	900.1
Memory (MiB)	8258	9218	14386	22938	-	47222	80618	100766	43286	47134	51994	55050	64386	61514	67266	71586	80502	103022	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	T/O	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.14: Bitwuzla result table for standard collisions using delta Sub encoding.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.9	2.9	5.4	6.4	21.0	66.9	34.6	68.4	1.2	2.7	1.9	3.4	3.7	2.3	2.4	4.1	5.8	361.9	900.1	900.1
Memory (MiB)	14946	25358	34334	39762	56798	91638	84022	117454	69234	78310	85198	88210	94246	102958	114958	116706	130694	239462	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.15: Bitwuzla result table for standard collisions using delta Sub encoding with alternative bitwise add.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.0	0.0	0.6	2.1	11.3	16.5	30.5	88.3	0.7	0.8	1.4	1.5	1.6	1.7	1.9	2.0	3.0	39.6	900.1	900.1
Memory (MiB)	8450	9602	13822	23038	41230	42910	55442	94750	42422	47602	51038	53902	57954	64262	63514	69850	77074	107982	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.16: Bitwuzla result table for standard collisions using delta Sub encoding with simplified Maj and Ch functions.

Round	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Time (s)	0.9	2.9	5.4	6.5	22.1	70.7	45.5	71.0	1.8	3.5	1.9	2.4	3.7	2.3	4.2	2.4	10.2	354.8	900.1	900.1
Memory (MiB)	15066	23026	36178	43438	57914	106126	83238	123038	69950	77426	81874	88110	93382	100990	105074	114586	129902	283446	-	-
Result	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	UNSAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	SAT	T/O	T/O

Table C.17: Bitwuzla result table for standard collisions using delta Sub encoding with simplified Maj and Ch functions, and alternative bitwise add.

Appendix D

Source Code

D.1 Notes

This tex document makes use of the lstlisting-rust provided under the BSD-3 licence. Denki [2025]

D.2 Proofs

D.2.1 Bitwise Adder

Listing D.1: Core adder in SMTLIB2 for 32-bit BV

```
(define-fun bitadd-2 ((a (_ BitVec 32)) (b (_ BitVec 32))) (_ BitVec 32)
  (let (
    (p0 (bvxor a b))
    (g0 (bvand a b))
  )
  (
    let (
      (g1 (bvor g0 (bvand p0 (bvshl g0 #x00000001))))
      (p1 (bvand p0 (bvshl p0 #x00000001)))
    )
    (
      let (
        (g2 (bvor g1 (bvand p1 (bvshl g1 #x00000002))))
        (p2 (bvand p1 (bvshl p1 #x00000002)))
      )
      (
        let (
          (g3 (bvor g2 (bvand p2 (bvshl g2 #x00000004))))
          (p3 (bvand p2 (bvshl p2 #x00000004)))
        )
        (
          let (
            (g4 (bvor g3 (bvand p3 (bvshl g3 #x00000008))))
            (p4 (bvand p3 (bvshl p3 #x00000008)))
          )
          (
            let (
              (g5 (bvor g4 (bvand p4 (bvshl g4 #x00000010))))
              (p5 (bvand p4 (bvshl p4 #x00000010)))
            )
            (
              let (
                (g6 (bvor g5 (bvand p5 (bvshl g5 #x00000020))))
                (p6 (bvand p5 (bvshl p5 #x00000020))) ; Redundant
              )
              (
                bvxor p0 (bvshl g6 #x00000001)
              )
```

```
            )
          )
        )
      )
    )
  ))
)
```

Listing D.2: multiple operand adder in smtlib2 for 32-bit bv

```
(define-fun bitadd-3 ((a (_ bitvec 32)) (b (_ bitvec 32)) (c (_ bitvec 32))) (_ bitvec
    32)
  (let (
    (sum (bvxor a b c))
    (carry (bvshl (bvor (bvand a b) (bvand a c) (bvand b c)) #x00000001))
  )
  (
    bitadd-2 sum carry
  ))
)
(define-fun bitadd-4 ((a (_ bitvec 32)) (b (_ bitvec 32)) (c (_ bitvec 32)) (d (_ bitvec
    32))) (_ bitvec 32)
  (let (
    (sum (bvxor a b c))
    (carry (bvshl (bvor (bvand a b) (bvand a c) (bvand b c)) #x00000001))
  )
  (
    bitadd-3 sum carry d
  ))
)
(define-fun bitadd-5 ((a (_ bitvec 32)) (b (_ bitvec 32)) (c (_ bitvec 32)) (d (_ bitvec
    32)) (e (_ bitvec 32))) (_ bitvec 32)
  (let (
    (sum1 (bvxor a b c))
    (carry1 (bvshl (bvor (bvand a b) (bvand a c) (bvand b c)) #x00000001))
    (sum2 (bvxor d e))
    (carry2 (bvshl (bvand d e) #x00000001))
  )
  (
    bitadd-4 sum1 carry1 sum2 carry2
  ))
)
(define-fun bitadd-6 ((a (_ bitvec 32)) (b (_ bitvec 32)) (c (_ bitvec 32)) (d (_ bitvec
    32)) (e (_ bitvec 32)) (f (_ bitvec 32))) (_ bitvec 32)
  (let (
    (sum1 (bvxor a b c))
    (carry1 (bvshl (bvor (bvand a b) (bvand a c) (bvand b c)) #x00000001))
    (sum2 (bvxor d e f))
    (carry2 (bvshl (bvor (bvand d e) (bvand d f) (bvand e f)) #x00000001))
  )
  (
    bitadd-4 sum1 carry1 sum2 carry2
  ))
)
```

D.2.2 BASE4 Proofs

Listing D.3: AND logic proof

```
(set-option :produce-models true)
(set-logic QF_BV)

(define-sort BV4 () (_ BitVec 4))


; Input Variables
(declare-fun LEFT_X () BV4)
(declare-fun RIGHT_X () BV4)
(declare-fun LEFT_Y () BV4)
(declare-fun RIGHT_Y () BV4)


; Differential variables for X
(define-fun X_a () BV4 (bvand (bvnot LEFT_X) (bvnot RIGHT_X)))
(define-fun X_b () BV4 (bvand (bvnot LEFT_X) RIGHT_X))
(define-fun X_c () BV4 (bvand LEFT_X (bvnot RIGHT_X)))
(define-fun X_d () BV4 (bvand LEFT_X RIGHT_X))
(define-fun X_f () BV4 (bvor X_b X_d))  ; f = b OR d
(define-fun X_g () BV4 (bvor X_c X_d))  ; g = c OR d


; Differential variables for Y
(define-fun Y_a () BV4 (bvand (bvnot LEFT_Y) (bvnot RIGHT_Y)))
(define-fun Y_b () BV4 (bvand (bvnot LEFT_Y) RIGHT_Y))
(define-fun Y_c () BV4 (bvand LEFT_Y (bvnot RIGHT_Y)))
(define-fun Y_d () BV4 (bvand LEFT_Y RIGHT_Y))
(define-fun Y_f () BV4 (bvor Y_b Y_d))  ; f = b OR d
(define-fun Y_g () BV4 (bvor Y_c Y_d))  ; g = c OR d


; Theory Diff
(define-fun LEFT_XY () BV4 (bvand LEFT_X LEFT_Y))
(define-fun RIGHT_XY () BV4 (bvand RIGHT_X RIGHT_Y))


; Actual
(define-fun a_XY () BV4 (bvand (bvnot LEFT_XY) (bvnot RIGHT_XY)))
(define-fun b_XY () BV4 (bvand (bvnot LEFT_XY) RIGHT_XY))
(define-fun c_XY () BV4 (bvand LEFT_XY (bvnot RIGHT_XY)))
(define-fun d_XY () BV4 (bvand LEFT_XY RIGHT_XY))


; Logic
(define-fun d2 () BV4 (bvand X_d Y_d))
(define-fun b2 () BV4 (bvand (bvand X_f Y_f) (bvnot d2)))
(define-fun c2 () BV4 (bvand (bvand X_g Y_g) (bvnot d2)))
(define-fun a2 () BV4 (bvnot (bvor d2 (bvor c2 b2))))


; Assert mismatch
(assert (not (and
    (= a2 a_XY)
    (= b2 b_XY)
    (= c2 c_XY)
    (= d2 d_XY)
)))

```

```
59
60 (check-sat)
```

Listing D.4: OR logic proof

```
1  (set-option :produce-models true)
2  (set-logic QF_BV)
3
4  (define-sort BV4 () (_ BitVec 4))
5
6
7  ; Input Variables
8  (declare-fun LEFT_X () BV4)
9  (declare-fun RIGHT_X () BV4)
10 (declare-fun LEFT_Y () BV4)
11 (declare-fun RIGHT_Y () BV4)
12
13
14 ; Differential variables for X
15 (define-fun X_a () BV4 (bvand (bvnot LEFT_X) (bvnot RIGHT_X)))
16 (define-fun X_b () BV4 (bvand (bvnot LEFT_X) RIGHT_X))
17 (define-fun X_c () BV4 (bvand LEFT_X (bvnot RIGHT_X)))
18 (define-fun X_d () BV4 (bvand LEFT_X RIGHT_X))
19 (define-fun X_f () BV4 (bvor X_b X_d))  ; f = b OR d
20 (define-fun X_g () BV4 (bvor X_c X_d))  ; g = c OR d
21
22
23 ; Differential variables for Y
24 (define-fun Y_a () BV4 (bvand (bvnot LEFT_Y) (bvnot RIGHT_Y)))
25 (define-fun Y_b () BV4 (bvand (bvnot LEFT_Y) RIGHT_Y))
26 (define-fun Y_c () BV4 (bvand LEFT_Y (bvnot RIGHT_Y)))
27 (define-fun Y_d () BV4 (bvand LEFT_Y RIGHT_Y))
28 (define-fun Y_f () BV4 (bvor Y_b Y_d))  ; f = b OR d
29 (define-fun Y_g () BV4 (bvor Y_c Y_d))  ; g = c OR d
30
31
32 ; Theory Diff
33 (define-fun LEFT_XY () BV4 (bvor LEFT_X LEFT_Y))
34 (define-fun RIGHT_XY () BV4 (bvor RIGHT_X RIGHT_Y))
35
36
37 ; Actual
38 (define-fun a_XY () BV4 (bvand (bvnot LEFT_XY) (bvnot RIGHT_XY)))
39 (define-fun b_XY () BV4 (bvand (bvnot LEFT_XY) RIGHT_XY))
40 (define-fun c_XY () BV4 (bvand LEFT_XY (bvnot RIGHT_XY)))
41 (define-fun d_XY () BV4 (bvand LEFT_XY RIGHT_XY))
42
43
44 ; Logic
45 (define-fun a2 () BV4 (bvand X_a Y_a))
46 (define-fun b2 () BV4 (bvnot (bvor X_g Y_g a2)))
47 (define-fun c2 () BV4 (bvnot (bvor X_f Y_f a2)))
48 (define-fun d2 () BV4 (bvnot (bvor a2 b2 c2)))
49
50
51 ; Assert mismatch
52 (assert (not (and
53     (= a2 a_XY)
54     (= b2 b_XY)
```

```
    (= c2 c_XY)
    (= d2 d_XY)
)))


(check-sat)
```

Listing D.5: XOR logic proof

```
(set-option :produce-models true)
(set-logic QF_BV)

(define-sort BV4 () (_ BitVec 4))


; Input variables
(declare-fun LEFT_X () BV4)
(declare-fun RIGHT_X () BV4)
(declare-fun LEFT_Y () BV4)
(declare-fun RIGHT_Y () BV4)


; Differential variables for X
(define-fun X_a () BV4 (bvand (bvnot LEFT_X) (bvnot RIGHT_X)))
(define-fun X_b () BV4 (bvand (bvnot LEFT_X) RIGHT_X))
(define-fun X_c () BV4 (bvand LEFT_X (bvnot RIGHT_X)))
(define-fun X_d () BV4 (bvand LEFT_X RIGHT_X))


; Differential variables for Y
(define-fun Y_a () BV4 (bvand (bvnot LEFT_Y) (bvnot RIGHT_Y)))
(define-fun Y_b () BV4 (bvand (bvnot LEFT_Y) RIGHT_Y))
(define-fun Y_c () BV4 (bvand LEFT_Y (bvnot RIGHT_Y)))
(define-fun Y_d () BV4 (bvand LEFT_Y RIGHT_Y))


; Theory Diff
(define-fun LEFT_XY () BV4 (bvxor LEFT_X LEFT_Y))
(define-fun RIGHT_XY () BV4 (bvxor RIGHT_X RIGHT_Y))


; Actual
(define-fun a_XY () BV4 (bvand (bvnot LEFT_XY) (bvnot RIGHT_XY)))
(define-fun b_XY () BV4 (bvand (bvnot LEFT_XY) RIGHT_XY))
(define-fun c_XY () BV4 (bvand LEFT_XY (bvnot RIGHT_XY)))
(define-fun d_XY () BV4 (bvand LEFT_XY RIGHT_XY))


; Logic
(define-fun a2 () BV4
    (bvor (bvand X_a Y_a)
          (bvand X_b Y_b)
          (bvand X_c Y_c)
          (bvand X_d Y_d)
    )
)

(define-fun b2 () BV4
    (bvor (bvand X_a Y_b)
```

```
            (bvand X_b Y_a)
            (bvand X_c Y_d)
            (bvand X_d Y_c)
    )
)

(define-fun c2 () BV4
    (bvor (bvand X_a Y_c)
            (bvand X_c Y_a)
            (bvand X_b Y_d)
            (bvand X_d Y_b)
    )
)

(define-fun d2 () BV4
    (bvor (bvand X_a Y_d)
            (bvand X_d Y_a)
            (bvand X_b Y_c)
            (bvand X_c Y_b)
    )
)


; Assert mismatch
(assert (not (and
    (= a2 a_XY)
    (= b2 b_XY)
    (= c2 c_XY)
    (= d2 d_XY)
)))

(check-sat)
```

D.3 Rust Codebase

Listing D.6: main.rs

```
use std::error::Error;
use std::fs;
use std::ops::Range;
use std::path::PathBuf;
use std::time::Duration;
use clap::{Parser, Subcommand};
use plotters::prelude::RGBColor;
use crate::benchmark::runner::BenchmarkRunner;
use crate::data::data_retriever::DataRetriever;
use crate::graphing::graph_renderer::GraphRenderer;
use crate::sha::{MessageBlock, Sha, StartVector, Word};
use crate::smt_lib::smt_lib::generate_smtlib_files;
use crate::smt_lib::smt_retriever::{EncodingType, SmtRetriever};
use crate::structs::benchmark::{Benchmark, SmtSolver};
use crate::structs::collision_type::CollisionType;
use crate::structs::hash_function::HashFunction;

#[cfg(not(unix))]
compile_error!("This␣crate␣supports␣only␣Unix-like␣operating␣systems");

```

```rust
mod smt_lib;
mod sha;
mod verification;
mod structs;
mod graphing;
mod data;
mod benchmark;


#[derive(Parser, Debug)]
#[command(author, version, about, long_about = None)]
struct Cli {
  #[command(subcommand)]
  command: Commands,
}

#[derive(Subcommand, Debug)]
enum Commands {
  /// Generate SMTLIB 2.6 standard files
  Generate {
    /// Directory where smt2 files will be saved. Default `smt/`
    #[arg(short = 'S', long)]
    smt_dir: Option<PathBuf>,
  },

  /// Run an exhaustive benchmark over all solvers, hash functions, collision types and arguments
  Benchmark {
    /// Argument to select solver. Use multiple `--solver <SOLVER>` statements for multiple solvers
    #[arg(required = true, long)]
    solver: Vec<SmtSolver>,

    /// Argument to select hash function. Use separate `--hash-function <HASH_FUNCTION>` statements for multiple hash functions
    #[arg(required = true, long)]
    hash_function: Vec<HashFunction>,

    /// Argument to select collision type. Use separate `--collision-type <COLLISION_TYPE>` statements for multiple collision types
    #[arg(required = true, long)]
    collision_type: Vec<CollisionType>,

    /// Argument to set (non-inclusive) range of compression rounds. Input with `--round-range <MIN>..<MAX>`. Default 1..hash function max
    #[arg(long, value_parser = parse_range)]
    round_range: Option<Range<u8>>,

    /// Argument to set the solver argument sets (combinations of solver arguments).
    /// An arugment set can contain multiple arguments which will all be executed on the solver.
    /// To test each argument separately, set each solver argument as a separate --arg-set.
    /// Use separate `--arg-set "<ARG_SET>"` statements for multiple argument sets.
    /// Default <No Args>
    #[arg(long, allow_hyphen_values = true)]
    arg_set: Option<Vec<String>>,

    /// The number of required sequential failures to stop. Default 3
```

```
    #[arg(short, long)]
    stop_tolerance:  Option<u8>,

    /// Duration after which run is marked as timed out. Default 15 mins
    #[arg(short, long)]
    timeout_sec: Option<u64>,

    /// Path to directory containing SMT files. Default `smt/`
    #[arg(short = 'S', long)]
    smt_dir: Option<PathBuf>,

    /// Path to directory where result files will be saved to. `None` to disable output.
        Default `results/`
    #[arg(short, long)]
    result_dir: Option<PathBuf>,

    /// Should remaining benchmark runs continue despite error on one. Default false
    #[arg(short = 'C', visible_alias = "cof", long)]
    continue_on_fail: Option<bool>,

    /// Type of encoding to benchmark.
    /// Format `<encoding_type>:[simplified_maj_and_ch_functions]:[alternative_add]`,
    /// where simplified_maj_and_ch_functions and alternative_add are bool with default
        false.
    ///
    /// Valid examples: `bruteforce:true:true`, `dxor::true`, `base4:true`, `dsub`.
    /// Default bruteforce:false:false
    ///
    /// [encoding_type possible values: bruteforce, dxor, dsub, base4]
    #[arg(short = 'E', long)]
    encoding_type: Option<String>,

    /// Should the benchmark be marked as a rerun. Useful for flagging up anomalies.
        Default false
    #[arg(short = 'R', long)]
    is_rerun: Option<bool>,
  },

  /// Run the underlying sha2 function
  Sha2 {
    /// Message to hash
    #[arg(short, long)]
    msg: Option<String>,

    /// Message digest block to hash (pre-padded and pre-processed digest), separated
        word-by-word with spaces
    #[arg(short = 'M', visible_alias = "mb", long)]
    msg_block: Option<String>,

    /// Hash function
    hash_function: HashFunction,

    /// Number of compression rounds. Default hash function max
    #[arg(short, long)]
    rounds: Option<u8>,

    /// Starting vector for hash function, separated word-by-word with spaces. Default
        Initial Vector (IV)
    #[arg(long, visible_alias = "sv")]
```

```
    start_vector: Option<String>,
  },

  /// Load, verify and display result files
  Load {
    /// Path to a result file, or a directory. Default `results/`
    #[arg(short = 'R', long)]
    result_path: Option<PathBuf>,

    /// Should directory scan be recursive. Default true
    #[arg(short, long)]
    recursive: Option<bool>,
  },

  /// Render result graphs
  Graph {
    /// Directory where graphs will be saved. Default `graphs/`
    #[arg(long)]
    graph_dir: Option<PathBuf>,

    /// Directory where all benchmark results are stored. Default `results/`
    #[arg(long)]
    result_dir: Option<PathBuf>,
  }
}

fn main() -> Result<(), Box<dyn Error>> {
  let cli = Cli::parse();

  match &cli.command {
    Commands::Generate { smt_dir } => {
      let smt_dir = smt_dir.clone().unwrap_or(PathBuf::from("smt/"));
      generate_smtlib_files(
        SmtRetriever::new(smt_dir)?
      )?;
    },

    Commands::Benchmark {
      solver,
      hash_function: hash_functions,
      collision_type: collision_types,
      round_range,
      arg_set,
      stop_tolerance,
      timeout_sec,
      smt_dir,
      result_dir,
      continue_on_fail,
      encoding_type,
      is_rerun,
    } => {
      let round_range = round_range.clone().unwrap_or(1..80);
      let arg_set = arg_set.clone().unwrap_or(Vec::with_capacity(0));
      let stop_tolerance = (*stop_tolerance).unwrap_or(3);
      let timeout = Duration::from_secs((*timeout_sec).unwrap_or(15 * 60));
      let continue_on_fail = (*continue_on_fail).unwrap_or(false);
      let encoding_type: EncodingType = encoding_type.as_deref().map_or(
        EncodingType::BruteForce {
          simplified_maj_and_ch_functions: false,
```

```
            alternative_add: false,
        },
        |s| s.parse().expect("Failed to parse encoding type")
    );
    let smt_dir = smt_dir.clone().unwrap_or(PathBuf::from("smt/"));
    let is_rerun = is_rerun.unwrap_or(false);

    let save_dir = if result_dir
        .clone()
        .is_some_and(|path| path.to_str().unwrap().to_lowercase() == "none")
    {
        None
    } else if let Some(path) = result_dir.clone() {
        Some(path)
    } else {
        Some(PathBuf::from("results/"))
    };

    let runner = BenchmarkRunner::new(
        stop_tolerance,
        timeout,
        SmtRetriever::new(smt_dir)?,
        save_dir,
        continue_on_fail,
        encoding_type,
        is_rerun,
    );

    runner.run_benchmarks(
        solvers.clone(),
        hash_functions.clone(),
        collision_types.clone(),
        round_range,
        arg_set,
    )?;
}

Commands::Sha2 {
    msg,
    msg_block,
    hash_function,
    rounds,
    start_vector,
} => {
    let rounds = rounds.unwrap_or(hash_function.max_rounds());

    let start_vector = match start_vector {
        None => StartVector::IV,
        Some(start_vector) => {
            let mut words= Vec::with_capacity(8);
            for word in start_vector.split_whitespace() {
                words.push(Word::from_str_radix(word, 16, *hash_function)?);
            }

            StartVector::CV(<[Word; 8]>::try_from(words).unwrap())
        }
    };

    let result = if let Some(msg) = msg {
```

```
        Sha::from_string(
          msg,
          *hash_function,
          rounds,
          start_vector,
        )?.execute()?
      } else if let Some(msg_block) = msg_block {
        Sha::from_message_block(
          MessageBlock::from_str_radix(msg_block, 16, *hash_function)?,
          *hash_function,
          rounds,
          start_vector,
        )?.execute()?
      } else {
        return Err(Box::from("Either msg or msg_block must be provided"));
      };

      println!("{}", result.hash);
    },

    Commands::Load {
      result_path,
      recursive,
    } => {
      let result_path = result_path.clone().unwrap_or(PathBuf::from("results/"));
      let recursive = recursive.unwrap_or(true);

      let benchmarks_with_files = load_mapped(&result_path, recursive)?;
      let show_file_names = benchmarks_with_files.len() > 1;
      for (mut benchmark, file_path) in benchmarks_with_files {
        let file_name = file_path
          .file_name()
          .unwrap()
          .to_str()
          .ok_or("Failed to read file")?;

        if show_file_names {
          println!("{file_name}");
        }

        match benchmark.parse_output() {
          Ok(output) => match output {
            None => println!("UNSAT\n"),
            Some(colliding_pair) => println!("{}\n", colliding_pair),
          }
          Err(err) => println!("{err}"),
        }

        println!("---\n")
      }
    }

    Commands::Graph {
      graph_dir,
      result_dir,
    } => {
      let graph_dir = graph_dir.clone().unwrap_or(PathBuf::from("graphs/"));
      let result_dir = result_dir.clone().unwrap_or(PathBuf::from("results/"));

```

```
      let mut graph_renderer = GraphRenderer::new(
        graph_dir.clone(),
        (1024, 768),
        ("noto sans", 36),
        ("noto sans", 14),
        Box::from([
          RGBColor(166, 30, 77), // Maroon
          RGBColor(24, 100, 171), // Dark Blue
          RGBColor(8, 127, 91), // Green
          RGBColor(250, 176, 5), // Yellow
          RGBColor(156, 54, 181), // Purple
          RGBColor(12, 133, 153), // Cyan
          RGBColor(95, 61, 196), // Light Purple
          RGBColor(70, 210, 94), // Light Green
          RGBColor(116, 143, 252), // Light Blue
          RGBColor(0, 0, 0),
        ]),
        2,
        DataRetriever::new(result_dir.clone())?,
      )?;

      graph_renderer.generate_all_graphs()?;
    },
  }

  Ok(())
}

fn load_mapped(
  dir_location: &PathBuf,
  recursive: bool,
) -> Result<Vec<(Benchmark, PathBuf)>, Box<dyn Error>> {
  let mut map = Vec::new();

  if dir_location.is_file() {
    map.push((Benchmark::load(dir_location)?, dir_location.clone()));
    return Ok(map);
  }

  for dir_entry in fs::read_dir(dir_location)? {
    if let Ok(entry) = dir_entry {
      let metadata = entry.metadata()?;
      if recursive && metadata.is_dir() {
        map.extend(load_mapped(&entry.path(), true)?);
      } else if metadata.is_file() {
        map.push((Benchmark::load(&entry.path())?, entry.path()));
      }
    }
  }

  Ok(map)
}

fn parse_range(s: &str) -> Result<Range<u8>, String> {
  let (start, end) = s.split_once("..")
    .ok_or_else(|| format!("Invalid range format: '{}'", s))?;

  Ok(Range {
    start: start.parse().map_err(|e| format!("Start: {}", e))?,
```

```
    end: end.parse().map_err(|e| format!("End: {}", e))?
  })
}
```

Listing D.7: sha/structs.rs

```
use std::fmt::{Display, Formatter, LowerHex};
use std::num::ParseIntError;
use crate::structs::hash_function::HashFunction;
use crate::verification::bit_differential::BitDifferential;

#[derive(thiserror::Error, Debug, PartialEq, Clone)]
pub enum HashError {
  #[error("requested rounds {requested} exceeds maximum rounds {maximum} for hash
      function")]
  TooManyRounds {
    requested: u8,
    maximum: u8,
  },
  #[error("failed to convert bytes into valid word")]
  FailedToConvertBytes,
  #[error("attempted to {operation} on two different word sizes")]
  WordMismatch {
    operation: String,
  }
}

#[derive(Debug, Eq, PartialEq, Copy, Clone, serde::Serialize, serde::Deserialize)]
pub enum Word {
  W32(u32),
  W64(u64)
}

impl Display for Word {
  fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
    match self {
      Word::W32(w) => f.write_str(&format!("{w:08x}")),
      Word::W64(w) => f.write_str(&format!("{w:016x}"))
    }
  }
}

impl From<u32> for Word {
  fn from(value: u32) -> Self {
    Word::W32(value)
  }
}

impl From<u64> for Word {
  fn from(value: u64) -> Self {
    Word::W64(value)
  }
}

impl PartialEq<u32> for Word {
  fn eq(&self, other: &u32) -> bool {
    match self {
      Word::W32(s) => s == other,
      Word::W64(_) => false,
```

```
    }
  }

  fn ne(&self, other: &u32) -> bool {
    !self.eq(other)
  }
}

impl PartialEq<u64> for Word {
  fn eq(&self, other: &u64) -> bool {
    match self {
      Word::W32(_) => false,
      Word::W64(s) => s == other,
    }
  }

  fn ne(&self, other: &u64) -> bool {
    !self.eq(other)
  }
}

impl LowerHex for Word {
  fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
    match self {
      Word::W32(w) => f.write_str(&format!("{w:08x}")),
      Word::W64(w) => f.write_str(&format!("{w:016x}")),
    }?;

    Ok(())
  }
}

impl BitDifferential for Word {
  fn bit_diff(self, rhs: Self) -> String {
    use Word::*;
    match (self, rhs) {
      (W32(l), W32(r)) => l.bit_diff(r),
      (W64(l), W64(r)) => l.bit_diff(r),
      (_, _) => HashError::WordMismatch { operation: String::from("bit␣diff") }.to_string
          (),
    }
  }
}

impl Word {
  pub(super) fn ch(e: Self, f: Self, g: Self) -> Result<Self, HashError> {
    use Word::*;
    match (e, f, g) {
      (W32(e), W32(f), W32(g)) => Ok(W32((e & f) ^ (!e & g))),
      (W64(e), W64(f), W64(g)) => Ok(W64((e & f) ^ (!e & g))),
      (_, _, _) => Err(HashError::WordMismatch { operation: String::from("ch")}),
    }
  }

  pub(super) fn maj(a: Self, b: Self, c: Self) -> Result<Self, HashError> {
    use Word::*;
    match (a, b, c) {
      (W32(a), W32(b), W32(c)) => Ok(W32((a & b) ^ (a & c) ^ (b & c))),
      (W64(a), W64(b), W64(c)) => Ok(W64((a & b) ^ (a & c) ^ (b & c))),
```

```
      (_, _, _) => Err(HashError::WordMismatch { operation: String::from("maj")}),
    }
  }

  pub(super) fn sigma0(a: Self) -> Self {
    use Word::*;
    match a {
      W32(a) => W32(a.rotate_right(2) ^ a.rotate_right(13) ^ a.rotate_right(22)),
      W64(a) => W64(a.rotate_right(28) ^ a.rotate_right(34) ^ a.rotate_right(39)),
    }
  }

  pub(super) fn sigma1(e: Self) -> Self {
    use Word::*;
    match e {
      W32(e) => W32(e.rotate_right(6) ^ e.rotate_right(11) ^ e.rotate_right(25)),
      W64(e) => W64(e.rotate_right(14) ^ e.rotate_right(18) ^ e.rotate_right(41)),
    }
  }

  pub(super) fn gamma0(x: Self) -> Self {
    use Word::*;
    match x {
      W32(x) => W32(x.rotate_right(7) ^ x.rotate_right(18) ^ (x >> 3)),
      W64(x) => W64(x.rotate_right(1) ^ x.rotate_right(8) ^ (x >> 7)),
    }
  }

  pub(super) fn gamma1(x: Self) -> Self {
    use Word::*;
    match x {
      W32(x) => W32(x.rotate_right(17) ^ x.rotate_right(19) ^ (x >> 10)),
      W64(x) => W64(x.rotate_right(19) ^ x.rotate_right(61) ^ (x >> 6)),
    }
  }

  pub fn from_u32_vec(slice: Vec<u32>) -> Vec<Self> {
    slice.into_iter().map(|x| Word::W32(x)).collect()
  }

  pub fn from_u64_vec(slice: Vec<u64>) -> Vec<Self> {
    slice.into_iter().map(|x| Word::W64(x)).collect()
  }

  pub fn from_str_radix(
    src: &str,
    radix: u32,
    hash_function: HashFunction,
  ) -> Result<Word, ParseIntError> {
    use HashFunction::*;
    match hash_function {
      SHA224 | SHA256 => Ok(Word::W32(u32::from_str_radix(src, radix)?)),
      SHA512 => Ok(Word::W64(u64::from_str_radix(src, radix)?)),
    }
  }

  pub(super) fn wrapping_add(self, rhs: Word) -> Result<Self, HashError> {
    match (self, rhs) {
      (Word::W32(l), Word::W32(r)) => Ok(Word::W32(l.wrapping_add(r))),
```

```
      (Word::W64(l), Word::W64(r)) => Ok(Word::W64(l.wrapping_add(r))),
      (_, _) => Err(HashError::WordMismatch { operation: String::from("wrapping add")})
    }
  }

  pub(super) fn from_be_bytes(bytes: &[u8]) -> Result<Self, HashError> {
    match bytes.len() {
      4 => Ok(Word::W32(u32::from_be_bytes(bytes.try_into().unwrap()))),
      8 => Ok(Word::W64(u64::from_be_bytes(bytes.try_into().unwrap()))),
      _ => Err(HashError::FailedToConvertBytes),
    }
  }

  #[allow(dead_code)]
  pub fn to_be_bytes(self) -> Box<[u8]> {
    match self {
      Word::W32(w) => Box::from(w.to_be_bytes()),
      Word::W64(w) => Box::from(w.to_be_bytes()),
    }
  }
}

#[cfg(test)]
mod tests {
  use super::Word;

  #[test]
  fn test_word_ch() {
    use Word::*;

    let e = W32(20);
    let f = W32(40);
    let g = W32(60);

    assert_eq!(Word::ch(e, f, g), Ok(W32(40)));

    let e = W64(20);
    let f = W64(40);
    let g = W64(60);

    assert_eq!(Word::ch(e, f, g), Ok(W64(40)));
  }

  #[test]
  fn test_word_maj() {
    use Word::*;

    let a = W32(20);
    let b = W32(40);
    let c = W32(60);

    assert_eq!(Word::maj(a, b, c).unwrap(), W32(60));

    let a = W64(20);
    let b = W64(40);
    let c = W64(60);

    assert_eq!(Word::maj(a, b, c).unwrap(), W64(60));
  }
```

```
229
230   #[test]
231   fn test_word_sigma0() {
232     use Word::*;
233     assert_eq!(Word::sigma0(W32(1)), W32(1074267136));
234     assert_eq!(Word::sigma0(W64(1)), W64(69826772992));
235   }
236
237   #[test]
238   fn test_word_sigma1() {
239     use Word::*;
240     assert_eq!(Word::sigma1(W32(1)), W32(69206144));
241     assert_eq!(Word::sigma1(W64(1)), W64(1196268659408896));
242   }
243
244   #[test]
245   fn test_word_gamma0() {
246     use Word::*;
247     assert_eq!(Word::gamma0(W32(1)), W32(33570816));
248     assert_eq!(Word::gamma0(W64(1)), W64(9295429630892703744));
249   }
250
251   #[test]
252   fn test_word_gamma1() {
253     use Word::*;
254     assert_eq!(Word::gamma1(W32(1)), W32(40960));
255     assert_eq!(Word::gamma1(W64(1)), W64(35184372088840));
256   }
257
258   #[test]
259   fn test_word_from_be_bytes() {
260     use Word::*;
261
262     assert_eq!(Word::from_be_bytes(&8u32.to_be_bytes()).unwrap(), W32(8));
263     assert_eq!(Word::from_be_bytes(&8u64.to_be_bytes()).unwrap(), W64(8));
264   }
265
266   #[test]
267   fn test_word_wrapping_add() {
268     use Word::*;
269     assert_eq!(Word::wrapping_add(W32(1), W32(2)).unwrap(), W32(3));
270     assert_eq!(Word::wrapping_add(W64(1), W64(2)).unwrap(), W64(3));
271
272     assert_eq!(Word::wrapping_add(W32(u32::MAX), W32(2)).unwrap(), W32(1));
273     assert_eq!(Word::wrapping_add(W64(u64::MAX), W64(2)).unwrap(), W64(1));
274   }
275 }
```

Listing D.8: sha/sha.rs

```
1 use std::cmp::PartialEq;
2 use std::error::Error;
3 use std::fmt::{Debug, Display, Formatter};
4 use crate::sha::structs::{HashError, Word};
5 use crate::structs::hash_function::HashFunction;
6 use crate::structs::hash_result::HashResult;
7 use crate::structs::sha_state::ShaState;
8
9 macro_rules! impl_word_display {
```

```
    ($type:ty, $closure:expr) => {
        impl Display for $type {
            fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
                for (i, word) in $closure(self).iter().enumerate() {
                    if i > 0 {
                        write!(f, "␣")?;
                    }
                    write!(f, "{word}")?;
                }

                Ok(())
            }
        }
    };
}

macro_rules! impl_from_word_array {
    ($array_type:ty, $array_size:expr, $for_type:ty, $constructor:expr) => {
        impl From<[$array_type; $array_size]> for $for_type {
            fn from(arr: [$array_type; $array_size]) -> Self {
                $constructor(arr.map(Word::from))
            }
        }
    };
}

#[derive(Debug, Eq, PartialEq, Copy, Clone, serde::Serialize, serde::Deserialize)]
pub enum StartVector {
  /// Initial Vector
  IV,
  /// Chaining Vector
  CV([Word; 8])
}

impl_from_word_array!(u32, 8, StartVector, StartVector::CV);
impl_from_word_array!(u64, 8, StartVector, StartVector::CV);

impl Display for StartVector {
  fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
    match self {
      StartVector::IV => write!(f, "IV␣Start␣Vector")?,
      StartVector::CV(vec) => {
        for (i, word) in vec.iter().enumerate() {
          if i > 0 {
            write!(f, "␣")?;
          }
          write!(f, "{word}")?;
        }
      }
    }

    Ok(())
  }
}

impl StartVector {
  /// Retrieves initial vector (IV), often referred to as H variables
  pub fn get_vector(self, hash_function: HashFunction) -> [Word; 8] {
    let vec = match (self, hash_function) {
```

```
      (StartVector::IV, HashFunction::SHA224) => Word::from_u32_vec(vec![
        0xc1059ed8, 0x367cd507, 0x3070dd17, 0xf70e5939,
        0xffc00b31, 0x68581511, 0x64f98fa7, 0xbefa4fa4,
      ]),
      (StartVector::IV, HashFunction::SHA256) => Word::from_u32_vec(vec![
        0x6a09e667, 0xbb67ae85, 0x3c6ef372, 0xa54ff53a,
        0x510e527f, 0x9b05688c, 0x1f83d9ab, 0x5be0cd19,
      ]),
      (StartVector::IV, HashFunction::SHA512) => Word::from_u64_vec(vec![
        0x6a09e667f3bcc908, 0xbb67ae8584caa73b, 0x3c6ef372fe94f82b, 0xa54ff53a5f1d36f1,
        0x510e527fade682d1, 0x9b05688c2b3e6c1f, 0x1f83d9abfb41bd6b, 0x5be0cd19137e2179,
      ]),
      (StartVector::CV(vec), _) => return vec,
    };

    vec.try_into().expect("Failed to convert initial vector; vector size mismatch!")
  }
}

#[derive(Copy, Clone, Debug)]
pub struct MessageBlock(pub [Word; 16]);

impl_word_display!(MessageBlock, |mb: &MessageBlock| mb.0);
impl_from_word_array!(u32, 16, MessageBlock, MessageBlock);
impl_from_word_array!(u64, 16, MessageBlock, MessageBlock);

impl MessageBlock {
  pub fn from_str_radix(
    src: &str,
    radix: u32,
    hash_function: HashFunction,
  ) -> Result<MessageBlock, Box<dyn Error>> {
    let mut words = Vec::with_capacity(16);
    for word_str in src.split_whitespace() {
      words.push(Word::from_str_radix(word_str, radix, hash_function)?);
    }

    if words.len() != 16 {
      return Err(Box::from(format!("Message digest should be 16 words in length, parsed
          {} instead", words.len())));
    }

    // Ensure all words are same size
    let base_discriminant = std::mem::discriminant(&words[0]);
    for word in words.iter() {
      if base_discriminant != std::mem::discriminant(word) {
        return Err(Box::from("Words length must be of the same size, parsed both u32 and
            u64"));
      }
    }

    Ok(MessageBlock(<[Word; 16]>::try_from(words).expect("Failed to word Vec convert to
        array")))
  }
}

#[derive(Clone, Debug, PartialEq, Eq)]
pub struct OutputHash(pub Box<[Word]>);
```

```rust
impl_word_display!(OutputHash, |oh: &OutputHash| oh.0.clone());

#[derive(Debug)]
pub struct Sha {
  /// Message blocks
  block: MessageBlock,
  /// Current state of sha function
  state: [Word; 8],
  /// Hash function to use
  hash_function: HashFunction,
  /// Number of compression rounds
  rounds: u8,
}

impl Sha {
  /// Construct an SHA digest from a string message.
  ///
  /// # Arguments
  ///
  /// * `message`: Message to hash
  /// * `hash_function`: Hash function to use
  /// * `rounds`: Number of compression rounds
  /// * `start_vector`: Vector to start with
  ///
  /// # Returns
  /// `Result<Sha<W>, HashError>`
  ///
  /// Returns SHA digest or HashError.
  ///
  /// # Examples
  ///
  /// ```
  /// let sha_digest = Sha::from_string("abc", SHA256, 64, IV);
  /// ```
  pub fn from_string(
    message: &str,
    hash_function: HashFunction,
    rounds: u8,
    start_vector: StartVector
  ) -> Result<Self, HashError> {
    hash_function.validate_rounds(rounds)?;

    let bytes = Self::pad_message(message.as_bytes(), hash_function);
    let block = Self::bytes_to_block(&bytes, hash_function)?;

    let state = start_vector.get_vector(hash_function);

    Ok(Sha {
      block,
      state,
      hash_function,
      rounds,
    })
  }

  /// Construct an SHA digest from a prepared padded message block.
  ///
  /// # Arguments
  ///
```

```rust
/// * `blocks`: Message blocks to hash
/// * `hash_function`: Hash function to use
/// * `rounds`: Number of compression rounds
/// * `start_vector`: Vector to start with
///
/// # Returns
/// `Result<Sha<W>, HashError>`
///
/// Returns SHA digest or HashError.
///
/// # Examples
///
/// ```
/// let message: [u32; 16] = [
///   0xc61d6de7, 0x755336e8, 0x5e61d618, 0x18036de6,
///   0xa79f2f1d, 0xf2b44c7b, 0x4c0ef36b, 0xa85d45cf,
///   0xf72b8c2f, 0x0def947c, 0xa0eab159, 0x8021370c,
///   0x4b0d8011, 0x7aad07f6, 0x33cd6902, 0x3bad5d64,
/// ];
///
/// let sha_digest = Sha::from_hash(message, SHA256, 64, IV);
/// ```
pub fn from_message_block(
  block: MessageBlock,
  hash_function: HashFunction,
  rounds: u8,
  start_vector: StartVector,
) -> Result<Self, HashError> {
  hash_function.validate_rounds(rounds)?;

  let state = start_vector.get_vector(hash_function);

  Ok(Sha {
    block,
    state,
    hash_function,
    rounds,
  })
}

/// Executes the hashing and compression algorithm.
///
/// # Returns
/// `HashResult<W>`
///
/// Returns HashResult of words.
///
/// # Examples
///
/// ```
/// let sha_digest = Sha::from_hash(message, SHA256, 64, IV)?;
///
/// let hash = sha_digest.execute();
/// ```
pub fn execute(mut self) -> Result<HashResult, HashError> {
  let k = self.hash_function.get_constant();
  let mut w = vec![self.hash_function.default_word(); k.len()];
  let mut states = Vec::<ShaState>::with_capacity(self.rounds as usize);

```

```
    // Initialization of first 16 words with current block
    w[..16].copy_from_slice(&self.block.0);

    // Message schedule expansion
    for i in 16..self.rounds as usize {
      w[i] = w[i-16]
        .wrapping_add(Word::gamma0(w[i-15]))?
        .wrapping_add(w[i-7])?
        .wrapping_add(Word::gamma1(w[i-2]))?;
    }

    // Initialize working variables
    let mut working_vars = self.state.clone();

    // Compression loop
    for i in 0..self.rounds as usize {
      let t1 = working_vars[7]
        .wrapping_add(Word::sigma1(working_vars[4]))?
        .wrapping_add(Word::ch(working_vars[4], working_vars[5], working_vars[6])?)?
        .wrapping_add(k[i])?
        .wrapping_add(w[i])?;

      let t2 = Word::sigma0(working_vars[0])
        .wrapping_add(Word::maj(working_vars[0], working_vars[1], working_vars[2])?)?;

      // Rotate working variables
      working_vars.rotate_right(1);
      working_vars[0] = t1.wrapping_add(t2)?;
      working_vars[4] = working_vars[4].wrapping_add(t1)?;

      states.push(ShaState {
        i: i as u8,
        w: w[i].clone(),
        a: working_vars[0],
        e: working_vars[4],
      });
    }

    // Update state
    for i in 0..8 {
      self.state[i] = self.state[i].wrapping_add(working_vars[i])?;
    }

    // Truncate
    let truncate_to_length = self.hash_function
      .truncate_to_length()
      .or(Some(self.state.len()))
      .unwrap();

    let hash = OutputHash(Box::from(&self.state[..truncate_to_length]));

    Ok(HashResult {
      hash,
      states,
    })
  }

  /// Pads the given message with SHA2 rules.
  /// Returns vector of padded message, with block size length of given hash function.
```

```
302   ///
303   /// # Arguments
304   ///
305   /// * `message`: Message to pad
306   /// * `hash_function`: Hash function to pad for
307   ///
308   /// # Returns
309   /// `Vec<u8, Global>`
310   ///
311   /// # Examples
312   ///
313   /// ```
314   /// let message = b"abc";
315   /// let padded_message = Self::pad_message(message, HashFunction::SHA256);
316   /// ```
317   fn pad_message(message: &[u8], hash_function: HashFunction) -> Vec<u8> {
318     // Example message "ABC" (3 char, 24b) for SHA 256
319     // | Original Message | Single 1 | Padding (0's)             | Length (64b)
          |
320     //
          |------------------|----------|---------------------------|----------------------|

321     // | 24b              |    1b    | 423b of zero-padding      | 64b representing "24"
          |
322
323     let block_size_bytes = hash_function.block_size().bytes();
324     let length_size_bytes = hash_function.length_size().bytes();
325
326     let mut padded = message.to_vec();
327     padded.push(0x80);  // '1' bit
328
329     // Calculate padding zeros
330     let needed = block_size_bytes - ((padded.len() + length_size_bytes) %
          block_size_bytes);
331     padded.extend(vec![0u8; needed]);
332
333     // Append original bit length
334     let bit_len = (message.len() as u128) * 8;
335     padded.extend(&bit_len.to_be_bytes()[16 - length_size_bytes..]);
336
337     padded
338   }
339
340   /// Converts padded byte message to blocks.
341   ///
342   /// # Arguments
343   ///
344   /// * `bytes`: padded byte message
345   ///
346   /// # Returns
347   /// `Result<[W; 16], HashError>` 16 blocks of words
348   fn bytes_to_block(bytes: &[u8], hash_function: HashFunction) -> Result<MessageBlock,
        HashError> {
349     let mut words = [hash_function.default_word(); 16];
350     let size = hash_function.word_size().bytes();
351
352     for (i, chunk) in bytes.chunks_exact(size).enumerate() {
353       words[i] = Word::from_be_bytes(chunk)?;
354     }
```

```
355
356       Ok(MessageBlock(words))
357     }
358   }
359
360   #[cfg(test)]
361   mod tests {
362     use super::HashFunction::{SHA224, SHA256, SHA512};
363     use super::StartVector::*;
364     use super::*;
365
366     const MESSAGE: &str = "abc";
367
368     #[test]
369     fn test_padding() {
370       // MESSAGE "abc" (3 char, 24b) for SHA 256
371       // | Original Message | Single 1 | Padding (0's)              | Length (64b)
          |
372       //
          |------------------|----------|----------------------------|----------------------|

373       // | 24b              |    1b    | 423b of zero-padding       | 64b representing "24"
          |
374
375       let expected = vec![
376         // Original message characters
377         97, 98, 99,
378         // Single 1 as Big Endian
379         128, // Binary 1000 0000
380         // Padding of 0s
381         0, 0, 0, 0, 0, 0, 0, 0,
382         0, 0, 0, 0, 0, 0, 0, 0,
383         0, 0, 0, 0, 0, 0, 0, 0,
384         0, 0, 0, 0, 0, 0, 0, 0,
385         0, 0, 0, 0, 0, 0, 0, 0,
386         0, 0, 0, 0, 0, 0, 0, 0,
387         0, 0, 0, 0, 0, 0, 0, 0,
388         0, 0, 0,
389         // Lenth of message in bits
390         24
391       ];
392
393       assert_eq!(Sha::pad_message(MESSAGE.as_bytes(), SHA256), expected);
394     }
395
396     #[test]
397     /// Using 64 rounds should match the standard SHA-224 for "abc".
398     fn test_sha224_correctness() {
399       let result = Sha::from_string(MESSAGE, SHA224, 64, IV)
400         .unwrap()
401         .execute()
402         .unwrap();
403
404       let expected: [u32; 7] = [
405         0x23097d22, 0x3405d822, 0x8642a477, 0xbda255b3,
406         0x2aadbce4, 0xbda0b3f7, 0xe36c9da7,
407       ];
408
409       assert_eq!(*result.hash.0, expected);
```

```
}

#[test]
/// Using 64 rounds should match the standard SHA-256 for "abc".
fn test_sha256_correctness() {
  let result = Sha::from_string(MESSAGE, SHA256, 64, IV)
    .unwrap()
    .execute()
    .unwrap();

  let expected: [u32; 8] = [
    0xba7816bf, 0x8f01cfea, 0x414140de, 0x5dae2223,
    0xb00361a3, 0x96177a9c, 0xb410ff61, 0xf20015ad,
  ];

  assert_eq!(*result.hash.0, expected);
}

#[test]
/// Using 80 rounds should match the standard SHA-512 for "abc".
fn test_sha512_correctness() {
  let result = Sha::from_string(MESSAGE, SHA512, 80, IV)
    .unwrap()
    .execute()
    .unwrap();

  let expected: [u64; 8] = [
    0xddaf35a193617aba, 0xcc417349ae204131, 0x12e6fa4e89a97ea2, 0x0a9eeee64b55d39a,
    0x2192992a274fc1a8, 0x36ba3c23a3feebbd, 0x454d4423643ce80e, 0x2a9ac94fa54ca49f,
  ];

  assert_eq!(*result.hash.0, expected);
}

#[test]
fn test_sha256_round_difference() {
  let result_32r = Sha::from_string(MESSAGE, SHA256, 32, IV)
    .unwrap()
    .execute()
    .unwrap();

  let result_64r = Sha::from_string(MESSAGE, SHA256, 64, IV)
    .unwrap()
    .execute()
    .unwrap();

  assert_ne!(result_32r, result_64r);
}

#[test]
fn test_sha512_round_difference() {
  let result_40r = Sha::from_string(MESSAGE, SHA512, 40, IV)
    .unwrap()
    .execute()
    .unwrap();

  let result_80r = Sha::from_string(MESSAGE, SHA512, 80, IV)
    .unwrap()
    .execute()
```

```
      .unwrap();

    assert_ne!(result_40r, result_80r);
  }

  #[test]
  /// Example in Li et al. (p.17, Table 5)
  fn test_single_cv_collision_sha256() {
    let cv = StartVector::from([
      0x02b19d5a, 0x88e1df04, 0x5ea3c7b7, 0xf2f7d1a4,
      0x86cb1b1f, 0xc8ee51a5, 0x1b4d0541, 0x651b92e7_u32,
    ]);

    let m: [u32; 16] = [
      0xc61d6de7, 0x755336e8, 0x5e61d618, 0x18036de6,
      0xa79f2f1d, 0xf2b44c7b, 0x4c0ef36b, 0xa85d45cf,
      0xf72b8c2f, 0x0def947c, 0xa0eab159, 0x8021370c,
      0x4b0d8011, 0x7aad07f6, 0x33cd6902, 0x3bad5d64,
    ].into();

    let m_prime: [u32; 16] = [
      0xc61d6de7, 0x755336e8, 0x5e61d618, 0x18036de6,
      0xa79f2f1d, 0xf2b44c7b, 0x4c0ef36b, 0xa85d45cf,
      0xe72b8c2f, 0x0fcf907c, 0xb0eab159, 0x81a1bfc1,
      0x4b098611, 0x7aad07f6, 0x33cd6902, 0x3bad5d64,
    ];

    let expected: [u32; 8] = [
      0x431cadcd, 0xce6893bb, 0xd6c9689a, 0x334854e8,
      0x3baae1ab, 0x038a195a, 0xccf54a19, 0x1c40606d,
    ];

    let result_m = Sha::from_message_block(m.into(), SHA256, 39, cv)
      .unwrap()
      .execute()
      .unwrap();

    let result_m_prime = Sha::from_message_block(m_prime.into(), SHA256, 39, cv)
      .unwrap()
      .execute()
      .unwrap();

    assert_eq!(*result_m.hash.0, expected);
    assert_eq!(*result_m.hash.0, *result_m_prime.hash.0);
  }

  #[test]
  /// Example in Li et al. (p.26, Table 9)
  fn test_single_cv_collision_sha512() {
    let m: [u64; 16] = [
      0x1f736d69a0368ef6, 0x7277e5081ad1c198, 0xe953a3cdc4cbe577, 0xbd05f6a203b2f75f,
      0xdd18b3e39f563fca, 0xcad0a5bb69049fcd, 0x4d0dd2a06e2efdc0, 0x86db19c26fc2e1cf,
      0x0184949e92cdd314, 0x82fb3c1420112000, 0xe4930d9b8295ab26, 0x5500d3a2f30a3402,
      0x26f0aa8790cb1813, 0xa9c09c5c5015bc0d, 0x53892c5a64e94edb, 0x8e60d500013a1932,
    ];

    let m_prime: [u64; 16] = [
      0x1f736d69a0368ef6, 0x7277e5081ad1c198, 0xe953a3cdc4cbe577, 0xbd05f6a203b2f75f,
      0xdd18b3e39f563fca, 0xcad0a5bb69049fcd, 0x4d0dd2a06e2efdc0, 0x86db19c26fc2e1cf,
```

```
      0x037a8f464c0bb995, 0x83033bd41e111fff, 0xe4930d9b8295ab26, 0x5500d3a2f30a3402,
      0x26f0aa8790cb1813, 0xa9809e5c4015bc45, 0x53892c5a64e94edb, 0x8e60d500013a1932,
    ];

    let expected: [u64; 8] = [
      0xdceb3d88adf54bd2, 0x966c4cb1ab0cf400, 0x01e701fdf10ab603, 0x796d6e5028a5e89a,
      0xf29a7517b216c09f, 0x46dbae73b1db8cce, 0x8ea44d45041010ea, 0x26a7a6b902f2632f,
    ];

    let result_m = Sha::from_message_block(m.into(), SHA512, 28, IV)
      .unwrap()
      .execute()
      .unwrap();

    let result_m_prime = Sha::from_message_block(m_prime.into(), SHA512, 28, IV)
      .unwrap()
      .execute()
      .unwrap();

    assert_eq!(*result_m.hash.0, expected);
    assert_eq!(*result_m.hash.0, *result_m_prime.hash.0);
  }

  #[test]
  /// Example in Li et al. (p.27, Table 10)
  fn test_dual_cv_collision_sha224() {
    let cv = StartVector::from([
      0x791c9c6b_u32, 0xbaa7f900, 0xf7c53298, 0x9073cbbd,
      0xc90690c5_u32, 0x5591553c, 0x43a5d984, 0xaf92402d,
    ]);

    let cv_prime = StartVector::from([
      0x791c9c6b_u32, 0xbaa7f900, 0xf7c53298, 0x9073cbbd,
      0xc90690c5_u32, 0x5591553c, 0x43a5d984, 0xbf92402d,
    ]);

    let m: [u32; 16] = [
      0xf41d61b4, 0xce033ba2, 0xdd1bc208, 0xa268189b,
      0xee6bda2c, 0x5ddbe94d, 0x9675bbd3, 0x32c1ba8a,
      0x7eba797d, 0x88b06a8f, 0x3bc3015c, 0xd36f38cc,
      0xcfcb88e0, 0x3c70f7f3, 0xfaa0c1fe, 0x35c62535,
    ];

    let m_prime: [u32; 16] = [
      0xe41d61b4, 0xce033ba2, 0xdd1bc208, 0xa268189b,
      0xee6bda2c, 0x5ddbe94d, 0x9675bbd3, 0x32c1ba8a,
      0x7eba797d, 0x98b06a8f, 0x39e3055c, 0xc36f38cc,
      0xce4b002d, 0x3c74f1f3, 0xfaa0c1fe, 0x35c62535,
    ];

    let expected: [u32; 7] = [
      0x9af50cac, 0xc165a72f, 0xb6f1c9f3, 0xef54bad9,
      0xaf0cfb1f, 0x57d357c9, 0xc6462616,
    ];

    let result_m = Sha::from_message_block(m.into(), SHA224, 40, cv)
      .unwrap()
      .execute()
      .unwrap();
```

```
587
588     let result_m_prime = Sha::from_message_block(m_prime.into(), SHA224, 40, cv_prime)
589       .unwrap()
590       .execute()
591       .unwrap();
592
593     assert_eq!(*result_m.hash.0, expected);
594     assert_eq!(*result_m.hash.0, *result_m_prime.hash.0);
595   }
596
597   #[test]
598   fn test_too_many_rounds() {
599     let result = Sha::from_string(MESSAGE, SHA224, 65, IV);
600     assert!(matches!(result, Err(HashError::TooManyRounds { .. })));
601
602     let result = Sha::from_string(MESSAGE, SHA256, 65, IV);
603     assert!(matches!(result, Err(HashError::TooManyRounds { .. })));
604
605     let result = Sha::from_string(MESSAGE, SHA512, 81, IV);
606     assert!(matches!(result, Err(HashError::TooManyRounds { .. })));
607   }
608 }
```

Listing D.9: sha/mod.rs

```
1 mod sha;
2 mod structs;
3
4 #[allow(unused_imports)] pub use sha::{Sha, StartVector, MessageBlock, OutputHash};
5 #[allow(unused_imports)] pub use structs::{Word, HashError};
```

Listing D.10: benchmark/mod.rs

```
1 pub mod runner;
```

Listing D.11: benchmark/runner.rs

```
1  use std::error::Error;
2  use std::io::{BufReader, Read};
3  use std::ops::Range;
4  use std::os::unix::prelude::CommandExt;
5  use std::path::PathBuf;
6  use std::process::{Command, ExitStatus, Stdio};
7  use std::time::{Duration, Instant};
8  use chrono::Local;
9  use nix::sys::signal::{killpg, Signal};
10 use nix::unistd::Pid;
11 use wait_timeout::ChildExt;
12 use crate::smt_lib::smt_retriever::{EncodingType, SmtRetriever};
13 use crate::structs::benchmark::{Benchmark, BenchmarkResult, SmtSolver, SolverArg};
14 use crate::structs::collision_type::CollisionType;
15 use crate::structs::hash_function::HashFunction;
16
17 #[derive(thiserror::Error, Debug, PartialEq, Clone)]
18 pub enum BenchmarkError {
19   #[error("solver {solver} was not found on the host system")]
20   SolverNotFound {
21     solver: String,
22   },
```

```rust
}

pub struct BenchmarkRunner {
  stop_tolerance: u8,
  timeout: Duration,
  smt_retriever: SmtRetriever,
  benchmark_save_dir: Option<PathBuf>,
  continue_on_failure: bool,
  encoding_type: EncodingType,
  is_rerun: bool,
}

impl BenchmarkRunner {
  pub fn new(
    stop_tolerance: u8,
    timeout: Duration,
    smt_retriever: SmtRetriever,
    benchmark_save_dir: Option<PathBuf>,
    continue_on_failure: bool,
    encoding_type: EncodingType,
    is_rerun: bool,
  ) -> Self {
    BenchmarkRunner {
      stop_tolerance,
      timeout,
      smt_retriever,
      benchmark_save_dir,
      continue_on_failure,
      encoding_type,
      is_rerun,
    }
  }

  pub fn run_benchmarks(
    &self,
    solvers: Vec<SmtSolver>,
    hash_functions: Vec<HashFunction>,
    collision_types: Vec<CollisionType>,
    round_range: Range<u8>,
    arguments: Vec<SolverArg>,
  ) -> Result<(), Box<dyn Error>> {
    for solver in solvers {
      for hash_function in &hash_functions {
        for collision_type in &collision_types {
          let mut sequential_fails = 0;
          if arguments.len() == 0 {
            self.invoke(
              solver,
              hash_function,
              collision_type,
              round_range.clone(),
              None,
              &mut sequential_fails,
            )?;
          } else {
            for arg in arguments.clone() {
              self.invoke(
                solver,
                hash_function,
```

```
                collision_type,
                round_range.clone(),
                Some(arg),
                &mut sequential_fails,
              )?;
            }
          }
        }
      }

      Ok(())
  }

  fn invoke(
    &self,
    solver: SmtSolver,
    hash_function: &HashFunction,
    collision_type: &CollisionType,
    round_range: Range<u8>,
    arg: Option<SolverArg>,
    sequential_fails: &mut u8,
  ) -> Result<(), Box<dyn Error>> {
    // Ensure range max does not exceed hash function max rounds.
    let hash_max = hash_function.max_rounds();
    let min = round_range.clone().min().unwrap_or(1).max(1);
    let max = round_range.clone().max().unwrap_or(hash_max).min(hash_max) + 1;

    for rounds in min..max {
      let smt_path = self.smt_retriever.get_file(
        *hash_function,
        *collision_type,
        rounds,
        self.encoding_type.clone(),
      );

      let mut result = self.run_solver_with_benchmark(
        *hash_function,
        rounds,
        *collision_type,
        solver,
        self.is_rerun,
        self.encoding_type.clone(),
        smt_path,
        arg.clone(),
      );

      if let Err(err) = self.handle_result(&mut result, sequential_fails) {
        if !self.continue_on_failure {
          return Err(err);
        }

        continue;
      }

      if self.stop_tolerance != 0 && self.stop_tolerance == *sequential_fails {
        println!("Failed␣{}␣in␣a␣row!\n", sequential_fails);
        break;
      }
```

```
    }

    Ok(())
  }

  fn handle_result(
    &self,
    result: &mut Result<Benchmark, Box<dyn Error>>,
    sequential_fails: &mut u8,
  ) -> Result<(), Box<dyn Error>> {
    match result {
      Ok(benchmark) => {
        if let Some(path) = &self.benchmark_save_dir {
          benchmark
            .save(path)
            .expect("Failed to save benchmark!");
        }

        match benchmark.result {
          BenchmarkResult::SMTError => {
            println!("Received SMT Error: {:?}\n", benchmark.console_output);
            *sequential_fails += 1;
          }
          BenchmarkResult::Sat | BenchmarkResult::Unsat => {
            match benchmark.parse_output()? {
              None => println!("UNSAT\n"),
              Some(colliding_pair) => println!("{}\n", colliding_pair),
            }

            *sequential_fails = 0;
          }
          _ => {
            println!("{}\n", benchmark.result);
            *sequential_fails += 1;
          }
        }
        Ok(())
      }
      Err(err) => {
        println!("{}\n", err);
        if !self.continue_on_failure {
          Err(Box::from("Aborting benchmarks!"))
        } else {
          println!("Continuing!\n\n");
          Ok(())
        }
      }
    }
  }

  fn run_solver_with_benchmark(
    &self,
    hash_function: HashFunction,
    rounds: u8,
    collision_type: CollisionType,
    solver: SmtSolver,
    is_rerun: bool,
    encoding: EncodingType,
    smt_file: PathBuf,
```

```
    arguments: Option<SolverArg>,
) -> Result<Benchmark, Box<dyn Error>> {
    if !check_command_present(&solver.command())? {
        return Err(Box::from(BenchmarkError::SolverNotFound { solver: solver.command() }));
    }

    let mut full_args: Vec<SolverArg> = vec![
        "-v".into(),
        solver.command(),
    ];

    let mut split_args: Vec<String> = vec![];
    let mut has_args = false;
    if let Some(args) = &arguments {
        split_args.extend(args.split("␣").map(String::from));
        has_args = true;
    }

    let file_path = smt_file.to_str().ok_or("Failed␣to␣get␣smt␣file␣path")?;
    full_args.extend(split_args);
    full_args.push(file_path.into());

    let date_time = Local::now().to_utc();
    let start_time = Instant::now();
    let mut child = Command::new("time")
        .args(full_args)
        .process_group(0)
        .stdout(Stdio::piped())
        .stderr(Stdio::piped())
        .spawn()?;

    let pid = child.id();
    let arg_str = if let Some(args) = &arguments {
        if args.len() > 0 {
            &format!("␣{args}")
        } else { "" }
    } else { "" };

    println!("{rounds}␣rounds;␣{hash_function}␣{collision_type}␣collision;␣{solver}{
        arg_str};␣SMT␣solver␣PID:␣{pid}\nFile:␣{file_path}");

    // Await process exit
    let status = child.wait_timeout(self.timeout)?;
    let execution_time = start_time.elapsed();

    // Read output
    let (cout, cerr) = match status {
        None => {
            killpg(Pid::from_raw(pid as i32), Signal::SIGKILL)?;
            child.wait()?;
            (String::new(), String::new())
        },
        Some(_) => {
            let cout = if let Some(stdout) = child.stdout.take() {
                let mut cout = String::new();
                BufReader::new(stdout).read_to_string(&mut cout)?;
                cout
            } else { String::new() };

```

```
        let cerr = if let Some(stderr) = child.stderr.take() {
          let mut cerr = String::new();
          BufReader::new(stderr).read_to_string(&mut cerr)?;
          cerr
        } else { String::new() };

        (cout, cerr)
      }
    };

    // Extract memory information
    let mut bytes_rss = 0;
    if let Some(line) = cerr
      .lines()
      .find(|line| line.contains("Maximum␣resident␣set␣size")) {
      if let Some(val_str) = line.split(':').nth(1) {
        if let Ok(value) = val_str.trim().parse::<u64>() {
          // Convert kB to bytes
          bytes_rss = value * 1024;
        }
      }
    }

    let is_baseline = !has_args && self.timeout == Duration::from_secs(900);

    Ok(Benchmark {
      date_time,
      solver,
      arguments,
      hash_function,
      rounds,
      collision_type,
      execution_time,
      memory_bytes: bytes_rss,
      result: Self::categorize_status(status, &cout)?,
      console_output: (cout, cerr),
      is_valid: None,
      is_baseline,
      is_rerun,
      encoding,
      stop_tolerance: self.stop_tolerance,
      timeout: self.timeout,
    })
  }

  fn categorize_status(exit_status: Option<ExitStatus>, cout: &String) -> Result<
      BenchmarkResult, Box<dyn Error>> {
    use Signal::*;
    use BenchmarkResult::*;

    Ok(match exit_status {
      None => CPUOut,
      Some(status) => {
        let code = status.code().ok_or("Failed␣to␣retrieve␣status␣code!")?;
        let outcome = cout
          .lines()
          .next()
          .unwrap_or("unknown")
          .to_lowercase();
```

```
316
317         if outcome.contains("unsat") {
318           Unsat
319         } else if outcome.contains("sat") {
320           Sat
321         } else {
322           let signal = Signal::try_from(code)?;
323
324           match signal {
325             SIGABRT | SIGKILL | SIGSEGV => MemOut,
326             SIGALRM | SIGTERM | SIGXCPU => CPUOut,
327             SIGHUP | SIGILL | SIGSYS => SMTError,
328             _ => Unknown,
329           }
330         }
331       }
332     })
333   }
334 }
335
336 fn check_command_present(command: &str) -> Result<bool, Box<dyn Error>> {
337   let output = Command::new("sh")
338     .arg("-c")
339     .arg(format!("command␣-v␣{}", command))
340     .output()?;
341
342   Ok(output.status.success())
343 }
```

Listing D.12: data/mod.rs

```
1 // mod result_store;
2 pub mod data_retriever;
```

Listing D.13: data/data_retriever.rs

```
1  use std::collections::BTreeMap;
2  use std::error::Error;
3  use std::fs;
4  use std::path::PathBuf;
5  use crate::smt_lib::smt_retriever::EncodingType;
6  use crate::smt_lib::smt_retriever::EncodingType::BruteForce;
7  use crate::structs::benchmark::{Benchmark, SmtSolver, SolverArg};
8  use crate::structs::collision_type::CollisionType;
9  use crate::structs::hash_function::HashFunction;
10
11
12 pub struct DataRetriever {
13   data_dir: PathBuf,
14   all_results: Option<Vec<Benchmark>>,
15 }
16
17 impl DataRetriever {
18   pub fn new(data_dir: PathBuf) -> Result<Self, Box<dyn Error>> {
19     if !data_dir.exists() {
20       fs::create_dir_all(data_dir.clone())?;
21     }
22
23     Ok(DataRetriever {
```

```
      data_dir,
      all_results: None,
    })
  }

  #[allow(dead_code)]
  pub fn default() -> Result<Self, Box<dyn Error>> {
    DataRetriever::new(PathBuf::from("results/"))
  }

  fn cache_all(&mut self) -> Result<(), Box<dyn Error>> {
    let benchmarks: Vec<_> = Benchmark::load_all(&self.data_dir, true)?
      .into_iter()
      .filter(|b| b.is_valid != Some(false))
      .collect();

    if !benchmarks.is_empty() {
      self.all_results = Some(benchmarks);
    }

    Ok(())
  }

  pub fn retrieve_all_baselines(
    &mut self,
    hash_function: HashFunction,
    collision_type: CollisionType,
    prefer_test_reruns: bool,
  ) -> Result<Vec<Benchmark>, Box<dyn Error>> {
    if self.all_results.is_none() {
      self.cache_all()?;
    }

    let mut baselines = Vec::new();
    let mut reruns = Vec::new();
    for b in self.all_results.clone().unwrap() {
      if b.is_baseline
        && b.hash_function == hash_function
        && b.collision_type == collision_type
        && b.arguments.is_none()
      {
        if b.is_rerun {
          reruns.push(b);
        } else {
          baselines.push(b);
        }
      }
    }

    if prefer_test_reruns {
      substitute_reruns(&mut baselines, reruns);
    }

    Ok(baselines)
  }

  pub fn retrieve_all_baselines_with_encoding(
    &mut self,
    hash_function: HashFunction,
```

```
    collision_type: CollisionType,
    encoding_type: EncodingType,
    prefer_test_reruns: bool,
  ) -> Result<Vec<Benchmark>, Box<dyn Error>> {
    if self.all_results.is_none() {
      self.cache_all()?;
    }

    let mut baselines = Vec::new();
    let mut reruns = Vec::new();
    for b in self.all_results.clone().unwrap() {
      if b.is_baseline
        && b.hash_function == hash_function
        && b.collision_type == collision_type
        && b.arguments.is_none()
        && b.encoding == encoding_type
      {
        if b.is_rerun {
          reruns.push(b);
        } else {
          baselines.push(b);
        }
      }
    }

    if prefer_test_reruns {
      substitute_reruns(&mut baselines, reruns);
    }

    Ok(baselines)
  }

  pub fn retrieve_baseline(
    &mut self,
    solver: SmtSolver,
    hash_function: HashFunction,
    collision_type: CollisionType,
    encoding_type: EncodingType,
    prefer_test_reruns: bool,
  ) -> Result<Vec<Benchmark>, Box<dyn Error>> {
    let all_baselines = self.retrieve_all_baselines(
      hash_function,
      collision_type,
      prefer_test_reruns
    )?;

    Ok(
      all_baselines
        .into_iter()
        .filter(|b| b.solver == solver)
        .filter(|b| b.encoding == encoding_type)
        .collect()
    )
  }

  pub fn retrieve_with_args(
    &mut self,
    solver: SmtSolver,
    hash_function: HashFunction,
```

```
    collision_type: CollisionType,
    prefer_test_reruns: bool,
    arg_identifier: &str,
  ) -> Result<BTreeMap<SolverArg, Vec<Benchmark>>, Box<dyn Error>> {
    if self.all_results.is_none() {
      self.cache_all()?;
    }

    fn has_similar_arg(benchmark: &Benchmark, identifier: &str) -> bool {
      benchmark.arguments.iter().any(|arg| arg.contains(identifier))
    }

    let mut baselines = Vec::new();
    let mut reruns = Vec::new();
    for b in self.all_results.clone().unwrap() {
      if b.solver == solver
        && b.hash_function == hash_function
        && b.collision_type == collision_type
        && has_similar_arg(&b, arg_identifier)
      {
        if b.is_rerun {
          reruns.push(b);
        } else {
          baselines.push(b);
        }
      }
    }

    if prefer_test_reruns {
      substitute_reruns(&mut baselines, reruns);
    }

    let mut map = BTreeMap::new();
    for benchmark in baselines {
      let key = benchmark.arguments.clone().unwrap_or("".into());
      map.entry(key)
        .or_insert_with(Vec::new)
        .push(benchmark);
    }

    Ok(map)
  }

  pub fn retrieve_non_bruteforce_encodings(
    &mut self,
    solver: SmtSolver,
    hash_function: HashFunction,
    collision_type: CollisionType,
    prefer_test_reruns: bool,
  ) -> Result<BTreeMap<EncodingType, Vec<Benchmark>>, Box<dyn Error>> {
    if self.all_results.is_none() {
      self.cache_all()?;
    }

    let mut baselines = Vec::new();
    let mut reruns = Vec::new();
    for b in self.all_results.clone().unwrap() {
      if b.solver == solver
        && b.hash_function == hash_function
```

```
        && b.collision_type == collision_type
        && !matches!(b.encoding, BruteForce {..})
      {
        if b.is_rerun {
          reruns.push(b);
        } else {
          baselines.push(b);
        }
      }
    }

    if prefer_test_reruns {
      substitute_reruns(&mut baselines, reruns);
    }

    let mut map = BTreeMap::new();
    for benchmark in baselines {
      let key = benchmark.encoding.clone();
      map.entry(key)
        .or_insert_with(Vec::new)
        .push(benchmark);
    }

    Ok(map)
  }
}

fn substitute_reruns(
  baselines: &mut Vec<Benchmark>,
  reruns: Vec<Benchmark>,
) {
  for rerun in reruns.into_iter() {
    for baseline in baselines.iter_mut() {
      if baseline.rounds == rerun.rounds
        && baseline.collision_type == rerun.collision_type
        && baseline.hash_function == rerun.hash_function
        && baseline.solver == rerun.solver
      {
        *baseline = rerun;
        break;
      }
    }
  }
}
```

Listing D.14: graphing/mod.rs

```
pub mod graph_renderer;
pub mod graphs;
mod utils;
mod components;
```

Listing D.15: graphing/utils.rs

```
use std::ops::{Add, Range};
use num_traits::One;
use crate::structs::benchmark::Benchmark;


```

```rust
/// Utility method to retrieve the range of a given data set for any numerical data.
///
/// # Arguments
///
/// * `data`: Data to retrieve range for.
/// * `retr`: Retriever lambda to define which field and how to map it.
///
/// # Returns
/// `Option<Range<T>>`
///
/// Returns `None` if length 0 data provided, otherwise provides a range of the retrieved data type.
// Potential bug/oversight with plotters.rs?
// Range<u8> and Range<u16> don't implement plotters::prelude::Ranged as expected?
pub(super) fn get_range<T: Copy + PartialOrd>(
  data: &Vec<Benchmark>,
  retr: &dyn Fn(&Benchmark) -> T,
) -> Option<Range<T>> {
  let mut it = data.into_iter();
  let first = retr(it.next()?);
  let (min, max) = it.fold((first, first), |(min_agg, max_agg), b| {
    let v = retr(b);
    (
      if v < min_agg { v } else { min_agg },
      if v > max_agg { v } else { max_agg }
    )
  });

  Some(min..max)
}

/// Splits a data set to multiple segments.
/// This is useful when there is a gap in the data which is meant to be rendered as disjoint.
///
/// # Arguments
///
/// * `data`: Data to split.
///
/// # Returns
/// Vec<Vec<(XT, YT), Global>, Global>
///
/// A set of continious cartesian data.
pub(super) fn split_data<XT, YT>(
  data: Vec<(XT, YT)>
) -> Vec<Vec<(XT, YT)>>
where
  XT: Clone + Copy + Add<Output = XT> + PartialOrd + One + 'static,
  YT: Clone + 'static,
{
  if data.is_empty() {
    return vec![];
  }

  let mut segments = Vec::new();
  let mut current_segment = Vec::new();
  current_segment.push(data[0].clone());

  for window in data.windows(2) {
```

```
    let (x1, _) = window[0];
    let (x2, _) = window[1];

    if x2 > x1 + XT::one() {
      segments.push(current_segment);
      current_segment = Vec::new();
    }

    current_segment.push(window[1].clone());
  }

  if !current_segment.is_empty() {
    segments.push(current_segment);
  }

  segments
}
```

Listing D.16: graphing/graphs.rs

```
use std::collections::BTreeMap;
use std::error::Error;
use std::ops::Range;
use std::path::PathBuf;
use num_traits::Float;
use plotters::prelude::*;
use crate::graphing::graph_renderer::{GraphRenderer, GraphRendererError};
use crate::graphing::graph_renderer::GraphRendererError::{FailedToGenerate, MissingData};
use crate::graphing::utils::get_range;
use crate::smt_lib::smt_retriever::EncodingType;
use crate::structs::benchmark::{Benchmark, BenchmarkResult, SmtSolver};


/// Implementation of graph types
impl GraphRenderer {
  /// Create graph describing the relation of time and memory for a given run.
  ///
  /// # Arguments
  ///
  /// * `data`: Single run benchmark data.
  ///
  /// # Returns
  /// `Result<PathBuf, Box<dyn Error>>`
  ///
  /// Returns path of saved graph file, or error.
  fn create_time_and_memory_chart(
    &self,
    data: Vec<Benchmark>,
  ) -> Result<PathBuf, Box<dyn Error>> {
    if data.len() == 0 {
      println!("{}", MissingData { graph_name: "Time & Memory", dataset_name: "data" });
    }

    let solver_name = data[0].solver.to_string().to_lowercase();
    let file_name = format!(
      "detailed_{}_{}_{}.svg",
      solver_name,
      data[0].hash_function,
      data[0].collision_type,
```

```
    );
    let path = self.output_dir.join(file_name);

    let data: Vec<_> = data
      .into_iter()
      .filter(|b| b.result == BenchmarkResult::Sat || b.result == BenchmarkResult::Unsat)
      .collect();

    let mut sorted_data = data;
    sorted_data.sort_by_key(|b| b.rounds);

    // Define ranges
    let x_range = get_range(&sorted_data.clone(), &|b| b.rounds as u32)
      .ok_or(GraphRendererError::GetRangeFailed { variable: "x_range"})?;
    let y_range_mem = get_range(&sorted_data.clone(), &|b| b.memory_bytes as f64 /
        1048576.0)
      .ok_or(GraphRendererError::GetRangeFailed { variable: "y_range_mem"})?;
    let y_range_time = get_range(&sorted_data.clone(), &|b| b.execution_time.as_secs_f64
        ())
      .ok_or(GraphRendererError::GetRangeFailed { variable: "y_range_time"})?;

    let path_clone_bind = path.clone();
    let root = SVGBackend::new(&path_clone_bind, self.output_size)
      .into_drawing_area();
    root.fill(&WHITE)?;

    let title = format!("{solver_name} Memory & Time vs Rounds");
    let mut chart = ChartBuilder::on(&root)
      .x_label_area_size(45)
      .y_label_area_size(60)
      .right_y_label_area_size(60)
      .margin(5)
      .caption(title, self.title_style)
      .build_cartesian_2d(x_range.clone(), y_range_time.log_scale().base(2.0))? // Time
      .set_secondary_coord(x_range, y_range_mem); // Memory

    // Draw axis
    self.set_x_axis_as_rounds(&mut chart)?;
    self.set_y_axis(
      &mut chart,
      "Time (s)",
      Some(self.color_palette[0].to_rgba()),
      Some(&|y: &f64| format!("2^{}", y.log2())),
    )?;
    self.set_secondary_y_axis(
      &mut chart,
      "Memory (MiB)",
      Some(self.color_palette[1].to_rgba()),
      None,
    )?;

    // Draw primary data
    let time_data: Vec<_> = sorted_data
      .clone()
      .into_iter()
      .map(|b| (b.rounds as u32, b.execution_time.as_secs_f64()))
      .collect();

    self.draw_series(
```

```
      &mut chart,
      time_data,
      true,
      true,
      "Time",
      Some(self.color_palette[0].to_rgba())
    )?;

    // Draw secondary data
    let memory_data: Vec<_> = sorted_data
      .clone()
      .into_iter()
      .map(|b| (b.rounds as u32, b.memory_bytes as f64 / 1048576.0))
      .collect();

    self.draw_secondary_series(
      &mut chart,
      memory_data,
      true,
      true,
      "Memory",
      Some(self.color_palette[1].to_rgba())
    )?;

    self.draw_legend(&mut chart)?;

    // Write to PathBuf
    root.present()?;
    Ok(path)
  }

  /// Create graph where one solver run is a baseline, and the remaining data is compared
      against it.
  ///
  /// # Arguments
  ///
  /// * `baseline`: Single run benchmark data, used as a baseline.
  /// * `data`: Vector of benchmark runs, used as deviation.
  /// * `argument_name`: String outputted to the title.
  /// * `buffer`: Should the graph be buffered on each end?
  /// * `enforce`: Should minimums and a max range be respected?
  ///
  /// # Returns
  /// `Result<PathBuf, Box<dyn Error>>`
  ///
  /// Returns path of saved graph file, or error.
  fn create_baseline_graph<L>(
    &self,
    baseline_data: Vec<Benchmark>,
    data: BTreeMap<L, Vec<Benchmark>>,
    title_str: &str,
    buffer: bool,
    enforce: bool,
    draw_background: bool,
  ) -> Result<PathBuf, Box<dyn Error>>
  where
    L: Clone + Ord + Into<String>,
  {
    if baseline_data.len() == 0 {
```

```
    return Err(MissingData { graph_name: "baseline", dataset_name: "baseline" }.into())
        ;
}

if data.len() == 0 {
  println!("{}", MissingData { graph_name: "baseline", dataset_name: "data" });
}

// Define x range
let x_range = get_range(&baseline_data, &|b| b.rounds as u32)
  .ok_or(GraphRendererError::GetRangeFailed { variable: "x_range" })?;

// Trim data
let mut trimmed_data: BTreeMap<L, Vec<Benchmark>> = BTreeMap::new();
for (encoding, mut benchmarks) in data.clone().into_iter() {
  if benchmarks.len() > x_range.end as usize {
    benchmarks.retain(|b| b.rounds <= x_range.end as u8);
  }

  trimmed_data.insert(encoding, benchmarks);
}

let title = format!(
  "{}␣{}␣{}:␣{}",
  baseline_data[0].solver,
  baseline_data[0].hash_function,
  baseline_data[0].collision_type,
  title_str,
);

let file_name = format!(
  "{}_{}.svg",
  baseline_data[0].solver.to_string().to_lowercase(),
  title_str.to_lowercase().replace("␣", "_"),
);

let path = self.output_dir.join(file_name);

let mut baseline_data = baseline_data;
baseline_data.sort_by_key(|b| b.rounds);

let mut baseline = BTreeMap::new();
for b in &baseline_data {
  baseline.insert(b.rounds as u32, b.execution_time.as_secs_f64());
}

// Convert generic to str

// Get range & calculate deviation from baseline
let mut deviation_range: Range<f64> = f64::MAX..f64::MIN;
let mut deviation_data: BTreeMap<String, Vec<(u32, f64)>> = BTreeMap::new();
for (label, run) in trimmed_data.clone() {
  let mut data = vec![];
  for b in run {
    let dev_percent = if let Some(&base_time) = baseline.get(&(b.rounds as u32)) {
      let dev_time = b.execution_time.as_secs_f64();
      let dev_percent = ((dev_time / base_time) - 1.0) * 100.0;

      if deviation_range.start > dev_percent {
```

```
            deviation_range.start = dev_percent;
          }

          if deviation_range.end < dev_percent {
            deviation_range.end = dev_percent;
          }

          dev_percent
        } else {
          f64::neg_infinity()
        };

        data.push((b.rounds as u32, dev_percent))
      }

      data.sort_by_key(|b| b.0);
      deviation_data.insert(label.into(), data);
    }

    if buffer {
      deviation_range.start = deviation_range.start - 5.0;
      deviation_range.end = deviation_range.end + 5.0;
    }

    // Truncate max range & enforce a minimum
    if enforce {
      deviation_range.end = deviation_range.end.min(100.0);
      deviation_range.start = deviation_range.start.min(-5.0);
    }

    // Define y range
    let y_range = deviation_range;

    let path_clone_bind = path.clone();
    let root = SVGBackend::new(&path_clone_bind, self.output_size)
      .into_drawing_area();
    root.fill(&WHITE)?;

    let mut chart = ChartBuilder::on(&root)
      .x_label_area_size(45)
      .y_label_area_size(60)
      .margin(5)
      .caption(title, self.title_style)
      .build_cartesian_2d(x_range.clone(), y_range.clone())?;

    // Draw background
    if draw_background {
      chart
        .draw_series(std::iter::once(
          Rectangle::new(
            [(x_range.start, -2.0), (x_range.end, y_range.start)],
            RGBAColor(182, 255, 182, 0.4).filled(),
          )
        ))?;

      chart
        .draw_series(std::iter::once(
          Rectangle::new(
            [(x_range.start, 2.0), (x_range.end, -2.0)],
```

```
            RGBAColor(182, 182, 182, 0.2).filled(),
          )
        ))?;

      chart
        .draw_series(std::iter::once(
          Rectangle::new(
            [(x_range.start, 2.0), (x_range.end, y_range.end)],
            RGBAColor(255, 182, 182, 0.4).filled(),
          )
        ))?;
    }

    // Draw axis
    self.set_x_axis_as_rounds(&mut chart)?;
    self.set_y_axis(
      &mut chart,
      "Time␣(%dev)",
      None,
      Some(&|v| format!("{:+.0}%", v)),
    )?;

    // Draw deviation data
    for (i, (label, run)) in deviation_data.into_iter().enumerate() {
      if run.len() <= 0 {
        continue;
      }

      self.draw_series(
        &mut chart,
        run.clone(),
        true,
        true,
        &label,
        Some(self.color_palette[i].to_rgba()),
      )?
    }

    // Draw baseline data
    self.draw_series(
      &mut chart,
      baseline.keys().map(|&x| (x, 0.0)).collect(),
      true,
      true,
      "Baseline",
      Some(RGBAColor(0, 0, 0, 0.3)),
    )?;

    self.draw_legend(&mut chart)?;

    // Write to PathBuf
    root.present()?;
    Ok(path)
  }

  /// Create graph comparing solvers.
  ///
  /// # Arguments
  ///
```

```rust
/// * `data`: All runs combined.
///
/// # Returns
/// `Result<PathBuf, Box<dyn Error>>`
///
/// Returns path of saved graph file, or error.
fn solver_comparison(
  &self,
  data: Vec<Benchmark>,
) -> Result<PathBuf, Box<dyn Error>> {
  if data.is_empty() {
    return Err(MissingData { graph_name: "comparison", dataset_name: "data" }.into());
  }

  let title = format!(
    "{} {} Solver Comparison",
    data[0].hash_function,
    data[0].collision_type,
  );

  let file_name = format!(
    "solver_comparison_{}_{}.svg",
    data[0].hash_function,
    data[0].collision_type,
  );

  let path = self.output_dir.join(file_name);

  let mut sorted_data = data.clone();
  sorted_data.sort_by_key(|b| b.rounds);

  // Define ranges
  let x_range = get_range(&data, &|b| b.rounds as u32)
    .ok_or(GraphRendererError::GetRangeFailed { variable: "x_range"})?;
  let y_range = get_range(&data, &|b| b.execution_time.as_secs_f64())
    .ok_or(GraphRendererError::GetRangeFailed { variable: "y_range"})?;

  let path_clone_bind = path.clone();
  let root = SVGBackend::new(&path_clone_bind, self.output_size)
    .into_drawing_area();
  root.fill(&WHITE)?;

  let mut chart = ChartBuilder::on(&root)
    .x_label_area_size(45)
    .y_label_area_size(60)
    .margin(5)
    .caption(title, self.title_style)
    .build_cartesian_2d(x_range, y_range.log_scale().base(2.0))?;

  // Draw axis
  self.set_x_axis_as_rounds(&mut chart)?;
  self.set_y_axis(
    &mut chart,
    "Time (s)",
    None,
    Some(&|y: &f64| format!("2^{}", y.log2())),
  )?;

  // Draw data
```

```
    let mut split_data = BTreeMap::new();
    for b in sorted_data {
      split_data
        .entry(b.solver)
        .or_insert_with(Vec::new)
        .push((b.rounds as u32, b.execution_time.as_secs_f64()));
    }

    for (i, (solver, data)) in split_data.into_iter().enumerate() {
      self.draw_series(
        &mut chart,
        data,
        true,
        true,
        &solver.to_string(),
        Some(self.color_palette[i].to_rgba())
      )?;
    }

    // TODO: Add shapes for result types!
    // TODO: Do secondary legend with the result types
    self.draw_legend(&mut chart)?;

    Ok(path)
  }

  /// Collection function to generate all graphs.
  pub fn generate_all_graphs(&mut self) -> Result<(), Box<dyn Error>> {
    use crate::structs::hash_function::HashFunction::*;
    use crate::structs::collision_type::CollisionType::*;
    use crate::smt_lib::smt_retriever::EncodingType::*;


    // Generate all solver comparisons for each HashFunction and CollisionType
    for hash_function in [SHA224, SHA256, SHA512] {
      for collision_type in [Standard, SemiFreeStart, FreeStart] {
        let baselines = self.data_retriever.retrieve_all_baselines_with_encoding(
          hash_function,
          collision_type,
          BruteForce {
            simplified_maj_and_ch_functions: false,
            alternative_add: false,
          },
          false,
        )?;

        if baselines.is_empty() {
          println!(
            "WARNING:␣{}",
            FailedToGenerate {
              hash_function,
              collision_type,
              err: &MissingData {
                graph_name: "Time␣&␣Memory",
                dataset_name: "Bitwuzla",
              }.to_string(),
            },
          );
          continue;
```

```
        }
        self.solver_comparison(baselines)?;
      }
    }


    // Generate Bitwuzla detail chart
    let bitwuzla_baseline_with_anomalies = self.data_retriever.retrieve_baseline(
      SmtSolver::Bitwuzla,
      SHA256,
      Standard,
      BruteForce {
        simplified_maj_and_ch_functions: false,
        alternative_add: false
      },
      true,
    )?;
    self.create_time_and_memory_chart(bitwuzla_baseline_with_anomalies.clone())?;


    // Generate Bitwuzla argument Graphs
    let arg_categories = BTreeMap::from([
      ("Abstraction", "-abstraction"),
      ("Preprocessing", "-pp-"),
      ("Propagation", "-prop"),
      ("Rewrite␣Level", "-rwl"),
      ("SAT␣Solver", "--sat-solver"),
      ("Solver␣Engine", "--bv-solver"),
    ]);

    let bitwuzla_baseline: Vec<_> = self.data_retriever.retrieve_baseline(
      SmtSolver::Bitwuzla,
      SHA256,
      Standard,
      BruteForce {
        simplified_maj_and_ch_functions: false,
        alternative_add: false
      },
      false,
    )?
      .into_iter()
      .filter(|b| b.result != BenchmarkResult::CPUOut)
      .collect()
      ;

    for (category, identifier) in arg_categories {
      let deviation_data = self.data_retriever.retrieve_with_args(
        SmtSolver::Bitwuzla,
        SHA256,
        Standard,
        false,
        identifier,
      )?;

      let deviation_data = deviation_data
        .into_iter()
        .map(|(a, runs)|{
          let runs = runs.into_iter()
            .filter(|b| b.result != BenchmarkResult::CPUOut)
```

```
            .collect();
          (a, runs)
        })
        .collect();

    self.create_baseline_graph(
      bitwuzla_baseline.clone(),
      deviation_data,
      &format!("{category} Args"),
      true,
      true,
      true,
    )?;
  }


  // Generate Bitwuzla encoding graphs
  let encoding_data = self.data_retriever.retrieve_non_bruteforce_encodings(
    SmtSolver::Bitwuzla,
    SHA256,
    Standard,
    false,
  )?;

  // DXOR
  let dxor_encoding_data: BTreeMap<_, _> = encoding_data
    .clone()
    .into_iter()
    .filter(|(e, _)| matches!(e, DeltaXOR { .. }))
    .collect();

  self.create_baseline_graph(
    bitwuzla_baseline.clone(),
    dxor_encoding_data,
    "Delta XOR Encoding Comparison",
    true,
    true,
    true,
  )?;

  // DSUB
  let dsub_encoding_data: BTreeMap<_, _> = encoding_data
    .clone()
    .into_iter()
    .filter(|(e, _)| matches!(e, DeltaSub { .. }))
    .collect();

  self.create_baseline_graph(
    bitwuzla_baseline.clone(),
    dsub_encoding_data,
    "Delta Sub Encoding Comparison",
    true,
    true,
    true,
  )?;

  // Pure encoding comparison graph
  let mut all_encodings: BTreeMap<EncodingType, Vec<Benchmark>> = BTreeMap::new();

```

```
    // Retrieve remaining results
    let bruteforce_simpl = self.data_retriever.retrieve_baseline(
      SmtSolver::Bitwuzla,
      SHA256,
      Standard,
      BruteForce {
        simplified_maj_and_ch_functions: true,
        alternative_add: false,
      },
      false
    ).expect("Failed to retrieve bruteforce simplified baseline");

    let bruteforce_alt_add = self.data_retriever.retrieve_baseline(
      SmtSolver::Bitwuzla,
      SHA256,
      Standard,
      BruteForce {
        simplified_maj_and_ch_functions: false,
        alternative_add: true,
      },
      false
    ).expect("Failed to retrieve bruteforce alt add baseline");

    let bruteforce_alt_add_simpl = self.data_retriever.retrieve_baseline(
      SmtSolver::Bitwuzla,
      SHA256,
      Standard,
      BruteForce {
        simplified_maj_and_ch_functions: true,
        alternative_add: true,
      },
      false
    ).expect("Failed to retrieve bruteforce alt add simplified baseline");

    // Insert baselines
    all_encodings.insert(BruteForce {
      simplified_maj_and_ch_functions: true,
      alternative_add: false,
    }, bruteforce_simpl);
    all_encodings.insert(BruteForce {
      simplified_maj_and_ch_functions: false,
      alternative_add: true,
    }, bruteforce_alt_add);
    all_encodings.insert(BruteForce {
      simplified_maj_and_ch_functions: true,
      alternative_add: true,
    }, bruteforce_alt_add_simpl);

    self.create_baseline_graph(
      bitwuzla_baseline.clone(),
      all_encodings,
      "Bruteforce Encoding Comparison",
      true,
      true,
      true,
    )?;

    Ok(())
  }
```

```
}
```

Listing D.17: graphing/graph_renderer.rs

```rust
use std::error::Error;
use std::fs;
use std::path::PathBuf;
use plotters::prelude::RGBColor;
use crate::data::data_retriever::DataRetriever;
use crate::structs::collision_type::CollisionType;
use crate::structs::hash_function::HashFunction;


pub struct GraphRenderer {
  pub(super) output_dir: PathBuf,
  pub(super) output_size: (u32, u32),
  pub(super) title_style: (&'static str, u32),
  pub(super) text_style: (&'static str, u32),
  pub(super) color_palette: Box<[RGBColor]>,
  pub(super) line_thickness: u32,
  pub(super) data_retriever: DataRetriever,
}

impl GraphRenderer {
  pub fn new(
    output_dir: PathBuf,
    output_size: (u32, u32),
    title_style: (&'static str, u32),
    text_style: (&'static str, u32),
    color_palette: Box<[RGBColor]>,
    line_thickness: u32,
    data_retriever: DataRetriever,
  ) -> Result<Self, Box<dyn Error>> {
    if !output_dir.exists() {
      fs::create_dir_all(output_dir.clone())?;
    }

    Ok(GraphRenderer {
      output_dir,
      output_size,
      title_style,
      text_style,
      color_palette,
      line_thickness,
      data_retriever,
    })
  }

  #[allow(dead_code)]
  pub fn default() -> Result<Self, Box<dyn Error>> {
    Ok(GraphRenderer {
      output_dir: PathBuf::from("graphs/"),
      output_size: (1024, 768),
      title_style: ("noto sans", 36),
      text_style: ("noto sans", 14),
      color_palette: Box::from([
        RGBColor(166, 30, 77), // Maroon
        RGBColor(24, 100, 171), // Dark Blue
        RGBColor(8, 127, 91), // Green
```

```
        RGBColor(250, 176, 5), // Yellow
        RGBColor(156, 54, 181), // Purple
        RGBColor(12, 133, 153), // Cyan
        RGBColor(95, 61, 196), // Light Purple
        RGBColor(70, 210, 94), // Light Green
        RGBColor(116, 143, 252), // Light Blue
        RGBColor(0, 0, 0), // Black
      ]),
      line_thickness: 2,
      data_retriever: DataRetriever::default()?,
    })
  }
}

#[derive(thiserror::Error, Debug, PartialEq, Clone)]
pub enum GraphRendererError<'a> {
  #[error("failed to get range for {variable}")]
  GetRangeFailed {
    variable: &'a str,
  },
  #[error("failed to generate chart {hash_function} {collision_type}: {err}")]
  FailedToGenerate {
    hash_function: HashFunction,
    collision_type: CollisionType,
    err: &'a str,
  },
  #[error("{graph_name} graph generation - {dataset_name} data cannot be empty!")]
  MissingData {
    graph_name: &'a str,
    dataset_name: &'a str,
  },
}
```

Listing D.18: graphing/components.rs

```
use std::error::Error;
use std::ops::Add;
use num_traits::One;
use plotters::chart::DualCoordChartContext;
use plotters::coord::ranged1d::ValueFormatter;
use plotters::prelude::*;
use crate::graphing::graph_renderer::GraphRenderer;
use crate::graphing::utils::split_data;

/// Generalized components for reuse in graphs.
impl GraphRenderer {
  /// Set the X-Axis to Compression Rounds
  ///
  /// # Arguments
  ///
  /// * `chart`: The chart to add axis to.
  ///
  /// # Returns
  /// `Result<(), Box<dyn Error>>`
  pub(super) fn set_x_axis_as_rounds<'a, DB, X, Y, XT, YT>(
    &self,
    chart: &mut ChartContext<'a, DB, Cartesian2d<X, Y>>,
  ) -> Result<(), Box<dyn Error>>
  where
```

```
    DB: DrawingBackend + 'a,
    DB::ErrorType: 'static,
    X: Ranged<ValueType = XT> + ValueFormatter<XT>,
    Y: Ranged<ValueType = YT> + ValueFormatter<YT>,
{
    chart
        .configure_mesh()
        .disable_mesh()
        .disable_y_axis()
        .x_desc("Compression␣Rounds")
        .label_style(self.text_style.with_color(&BLACK))
        .draw()?;
    Ok(())
}

/// Set the primary (left side) Y-Axis to the given label and color.
/// For secondary (right side) Y-Axis see [Self::set_secondary_y_axis].
///
/// # Arguments
///
/// * `chart`: The chart to add axis to.
/// * `label`: Axis label.
/// * `color`: Color of axis labels, or black by default.
/// * `formatter`: Formatter of Y-Axis, that takes Y-Axis type and returns String.
///
/// # Returns
/// `Result<(), Box<dyn Error>>`
pub(super) fn set_y_axis<'a, DB, X, Y, XT, YT>(
    &self,
    chart: &mut ChartContext<'a, DB, Cartesian2d<X, Y>>,
    label: &str,
    color: Option<RGBAColor>,
    formatter: Option<&dyn Fn(&YT) -> String>,
) -> Result<(), Box<dyn Error>>
where
    DB: DrawingBackend + 'a,
    DB::ErrorType: 'static,
    X: Ranged<ValueType = XT> + ValueFormatter<XT>,
    Y: Ranged<ValueType = YT> + ValueFormatter<YT>,
    YT: 'a,
{
    let color = color.unwrap_or(BLACK.to_rgba());
    let mut builder = chart.configure_mesh();

    if let Some(formatter) = formatter {
        builder.y_label_formatter(formatter);
    }

    builder
        .disable_mesh()
        .disable_x_axis()
        .y_desc(label)
        .label_style(self.text_style.with_color(color))
        .draw()?;
    Ok(())
}

/// Set the secondary (right side) Y-Axis to the given label and color.
/// For primary (left side) Y-Axis see [Self::set_y_axis].
```

```rust
  ///
  /// # Arguments
  ///
  /// * `chart`: The chart to add axis to.
  /// * `label`: Axis label.
  /// * `color`: Color of axis labels, or black by default.
  /// * `formatter`: Formatter of Y-Axis, that takes Y-Axis type and returns String.
  ///
  /// # Returns
  /// `Result<(), Box<dyn Error>>`
  pub(super) fn set_secondary_y_axis<'a, DB, X, Y1, Y2, XT, YT1, YT2>(
    &self,
    chart: &mut DualCoordChartContext<'a, DB, Cartesian2d<X, Y1>, Cartesian2d<X, Y2>>,
    label: &str,
    color: Option<RGBAColor>,
    formatter: Option<&dyn Fn(&YT2) -> String>,
  ) -> Result<(), Box<dyn Error>>
  where
    DB: DrawingBackend + 'a,
    DB::ErrorType: 'static,
    X: Ranged<ValueType = XT> + ValueFormatter<XT>,
    Y1: Ranged<ValueType = YT1> + ValueFormatter<YT1>,
    Y2: Ranged<ValueType = YT2> + ValueFormatter<YT2>,
  {
    let color = color.unwrap_or(BLACK.to_rgba());
    let mut builder = chart.configure_secondary_axes();

    if let Some(formatter) = formatter {
      builder.y_label_formatter(formatter);
    }

    builder
      .y_desc(label)
      .label_style(self.text_style.with_color(color))
      .draw()?;
    Ok(())
  }

  /// Draw a line series of provided data on the primary Y-Axis.
  /// For drawing on the secondary Y-Axis see [Self::draw_secondary_series].
  ///
  /// # Arguments
  ///
  /// * `chart`: The chart to draw on.
  /// * `data`: The data to draw.
  /// * `with_points`: Should circle points be made for each data plot?
  /// * `discontinue_line`: Should the line be continious/discontinue if part of the data is missing?
  /// * `label`: Legend label for the charted data.
  /// * `color`: Color of drawn line, or black by default.
  ///
  /// # Returns
  /// `Result<(), Box<dyn Error>>`
  pub(super) fn draw_series<'a, DB, X, Y, XT, YT>(
    &self,
    chart: &mut ChartContext<'a, DB, Cartesian2d<X, Y>>,
    data: Vec<(XT, YT)>,
    with_points: bool,
    discontinue_line: bool,
```

```
    label: &str,
    color: Option<RGBAColor>,
) -> Result<(), Box<dyn Error>>
where
    DB: DrawingBackend + 'a,
    DB::ErrorType: 'static,
    X: Ranged<ValueType = XT> + ValueFormatter<XT>,
    Y: Ranged<ValueType = YT> + ValueFormatter<YT>,
    XT: Clone + Copy + Add<Output = XT> + PartialOrd + 'static + One,
    YT: Clone + 'static,
{
    let color = color.unwrap_or(BLACK.to_rgba());

    // Split into data contigious data segments
    let data = if discontinue_line {
        split_data(data)
    } else {
        vec![data]
    };

    // Render
    let mut was_legend_defined = false;
    for split in data {
        let series = chart
            .draw_series(LineSeries::new(
                split.clone(),
                ShapeStyle {
                    color: color.to_rgba(),
                    filled: false,
                    stroke_width: self.line_thickness,
                }
            ))?;

        // Define only once
        if !was_legend_defined {
            was_legend_defined = true;
            series
                .label(label)
                .legend(move |(x, y)| PathElement::new(vec![(x, y), (x + 20, y)], color));
        }

        if with_points {
            chart.draw_series(PointSeries::of_element(
                split,
                3,
                color,
                &|c, s, st| Circle::new(c, s, st.filled()),
            ))?;
        }
    }

    Ok(())
}

/// Draw a line series of provided data on the secondary Y-Axis.
/// For drawing on the primary Y-Axis see [Self::draw_series].
///
/// # Arguments
///
```

```rust
/// * `chart`: The chart to draw on.
/// * `data`: The data to draw.
/// * `with_points`: Should circle points be made for each data plot?
/// * `discontinue_line`: Should the line be continious/discontinue if part of the data is missing?
/// * `label`: Legend label for the charted data.
/// * `color`: Color of drawn line, or black by default.
///
/// # Returns
/// `Result<(), Box<dyn Error>>`
pub(super) fn draw_secondary_series<'a, DB, X, Y1, Y2, XT, YT1, YT2>(
  &self,
  chart: &mut DualCoordChartContext<'a, DB, Cartesian2d<X, Y1>, Cartesian2d<X, Y2>>,
  data: Vec<(XT, YT2)>,
  with_points: bool,
  discontinue_line: bool,
  label: &str,
  color: Option<RGBAColor>,
) -> Result<(), Box<dyn Error>>
where
  DB: DrawingBackend + 'a,
  DB::ErrorType: 'static,
  X: Ranged<ValueType = XT> + ValueFormatter<XT>,
  Y1: Ranged<ValueType = YT1> + ValueFormatter<YT1>,
  Y2: Ranged<ValueType = YT2> + ValueFormatter<YT2>,
  XT: Clone + Copy + Add<Output = XT> + PartialOrd + 'static + One,
  YT1: Clone + 'static,
  YT2: Clone + 'static,
{
  let color = color.unwrap_or(BLACK.to_rgba());

  // Split into data contigious data segments
  let data = if discontinue_line {
    split_data(data)
  } else {
    vec![data]
  };

  // Render
  let mut was_legend_defined = false;
  for split in data {
    let series = chart
      .draw_secondary_series(LineSeries::new(
        split.clone(),
        ShapeStyle {
          color: color.to_rgba(),
          filled: false,
          stroke_width: self.line_thickness,
        }
      ))?;

    // Define only once
    if !was_legend_defined {
      was_legend_defined = true;
      series
        .label(label)
        .legend(move |(x, y)| PathElement::new(vec![(x, y), (x + 20, y)], color));
    }

```

```
      if with_points {
        chart.draw_secondary_series(PointSeries::of_element(
          split,
          3,
          color,
          &|c, s, st| Circle::new(c, s, st.filled()),
        ))?;
      }
    }

    Ok(())
  }

  /// Draw a legend in the bottom right corner.
  ///
  /// # Arguments
  ///
  /// * `chart`: The chart to draw on.
  ///
  /// # Returns
  /// `Result<(), Box<dyn Error>>`
  pub(super) fn draw_legend<'a, DB, CT>(
    &self,
    chart: &mut ChartContext<'a, DB, CT>,
  ) -> Result<(), Box<dyn Error>>
  where
    DB: DrawingBackend + 'a,
    DB::ErrorType: 'static,
    CT: CoordTranslate + 'a,
  {
    chart
      .configure_series_labels()
      .label_font(self.text_style.with_color(BLACK))
      .background_style(RGBAColor(200, 200, 200, 0.8))
      .position(SeriesLabelPosition::LowerRight)
      .draw()?;
    Ok(())
  }
}
```

Listing D.19: verification/mod.rs

```
mod verification;
pub mod bit_differential;
pub(crate) mod verify_hash;
pub mod colliding_pair;
```

Listing D.20: verification/verification.rs

```
#[cfg(test)]
mod tests {
  use crate::sha::{Sha, StartVector};
  use crate::sha::StartVector::IV;
  use crate::structs::hash_function::HashFunction::*;
  use crate::verification::bit_differential::BitDifferential;

  #[test]
  /// Example in Li et al. (p.17, Table 4)
  fn test_sha256_state_collision_table() {
```

```
    let cv = StartVector::from([
      0x02b19d5a_u32, 0x88e1df04, 0x5ea3c7b7, 0xf2f7d1a4,
      0x86cb1b1f_u32, 0xc8ee51a5, 0x1b4d0541, 0x651b92e7,
    ]);

    let m: [u32; 16] = [
      0xc61d6de7, 0x755336e8, 0x5e61d618, 0x18036de6,
      0xa79f2f1d, 0xf2b44c7b, 0x4c0ef36b, 0xa85d45cf,
      0xf72b8c2f, 0x0def947c, 0xa0eab159, 0x8021370c,
      0x4b0d8011, 0x7aad07f6, 0x33cd6902, 0x3bad5d64,
    ];

    let m_prime: [u32; 16] = [
      0xc61d6de7, 0x755336e8, 0x5e61d618, 0x18036de6,
      0xa79f2f1d, 0xf2b44c7b, 0x4c0ef36b, 0xa85d45cf,
      0xe72b8c2f, 0x0fcf907c, 0xb0eab159, 0x81a1bfc1,
      0x4b098611, 0x7aad07f6, 0x33cd6902, 0x3bad5d64,
    ];

    let expected: [u32; 8] = [
      0x431cadcd, 0xce6893bb, 0xd6c9689a, 0x334854e8,
      0x3baae1ab, 0x038a195a, 0xccf54a19, 0x1c40606d,
    ];

    let result_m = Sha::from_message_block(m.into(), SHA256, 39, cv)
      .unwrap()
      .execute()
      .unwrap();

    let result_m_prime = Sha::from_message_block(m_prime.into(), SHA256, 39, cv)
      .unwrap()
      .execute()
      .unwrap();

    println!("{}", result_m.states.bit_diff(result_m_prime.states));

    assert_eq!(*result_m.hash.0, expected);
    assert_eq!(*result_m.hash.0, *result_m_prime.hash.0);
  }

  #[test]
  /// Example in Li et al. (p.25, Table 8)
  fn test_sha512_state_collision_table() {
    let m: [u64; 16] = [
      0x1f736d69a0368ef6, 0x7277e5081ad1c198, 0xe953a3cdc4cbe577, 0xbd05f6a203b2f75f,
      0xdd18b3e39f563fca, 0xcad0a5bb69049fcd, 0x4d0dd2a06e2efdc0, 0x86db19c26fc2e1cf,
      0x0184949e92cdd314, 0x82fb3c1420112000, 0xe4930d9b8295ab26, 0x5500d3a2f30a3402,
      0x26f0aa8790cb1813, 0xa9c09c5c5015bc0d, 0x53892c5a64e94edb, 0x8e60d500013a1932,
    ];

    let m_prime: [u64; 16] = [
      0x1f736d69a0368ef6, 0x7277e5081ad1c198, 0xe953a3cdc4cbe577, 0xbd05f6a203b2f75f,
      0xdd18b3e39f563fca, 0xcad0a5bb69049fcd, 0x4d0dd2a06e2efdc0, 0x86db19c26fc2e1cf,
      0x037a8f464c0bb995, 0x83033bd41e111fff, 0xe4930d9b8295ab26, 0x5500d3a2f30a3402,
      0x26f0aa8790cb1813, 0xa9809e5c4015bc45, 0x53892c5a64e94edb, 0x8e60d500013a1932,
    ];

    let expected: [u64; 8] = [
      0xdceb3d88adf54bd2, 0x966c4cb1ab0cf400, 0x01e701fdf10ab603, 0x796d6e5028a5e89a,
```

```
      0xf29a7517b216c09f, 0x46dbae73b1db8cce, 0x8ea44d45041010ea, 0x26a7a6b902f2632f,
    ];

    let result_m = Sha::from_message_block(m.into(), SHA512, 28, IV)
      .unwrap()
      .execute()
      .unwrap();

    let result_m_prime = Sha::from_message_block(m_prime.into(), SHA512, 28, IV)
      .unwrap()
      .execute()
      .unwrap();

    println!("{}", result_m.states.bit_diff(result_m_prime.states));

    assert_eq!(*result_m.hash.0, expected);
    assert_eq!(*result_m.hash.0, *result_m_prime.hash.0);
  }

  #[test]
  /// Example in Li et al. (p.27, Table 10)
  fn test_sha224_state_collision_table() {
    let cv = StartVector::from([
      0x791c9c6b_u32, 0xbaa7f900, 0xf7c53298, 0x9073cbbd,
      0xc90690c5_u32, 0x5591553c, 0x43a5d984, 0xaf92402d,
    ]);

    let cv_prime = StartVector::from([
      0x791c9c6b_u32, 0xbaa7f900, 0xf7c53298, 0x9073cbbd,
      0xc90690c5_u32, 0x5591553c, 0x43a5d984, 0xbf92402d,
    ]);

    let m: [u32; 16] = [
      0xf41d61b4, 0xce033ba2, 0xdd1bc208, 0xa268189b,
      0xee6bda2c, 0x5ddbe94d, 0x9675bbd3, 0x32c1ba8a,
      0x7eba797d, 0x88b06a8f, 0x3bc3015c, 0xd36f38cc,
      0xcfcb88e0, 0x3c70f7f3, 0xfaa0c1fe, 0x35c62535,
    ];

    let m_prime: [u32; 16] = [
      0xe41d61b4, 0xce033ba2, 0xdd1bc208, 0xa268189b,
      0xee6bda2c, 0x5ddbe94d, 0x9675bbd3, 0x32c1ba8a,
      0x7eba797d, 0x98b06a8f, 0x39e3055c, 0xc36f38cc,
      0xce4b002d, 0x3c74f1f3, 0xfaa0c1fe, 0x35c62535,
    ];

    let expected: [u32; 7] = [
      0x9af50cac, 0xc165a72f, 0xb6f1c9f3, 0xef54bad9,
      0xaf0cfb1f, 0x57d357c9, 0xc6462616,
    ];

    let result_m = Sha::from_message_block(m.into(), SHA224, 40, cv)
      .unwrap()
      .execute()
      .unwrap();

    let result_m_prime = Sha::from_message_block(m_prime.into(), SHA224, 40, cv_prime)
      .unwrap()
      .execute()
```

```
      .unwrap();

    println!("{}", result_m.states.bit_diff(result_m_prime.states));

    assert_eq!(*result_m.hash.0, expected);
    assert_eq!(*result_m.hash.0, *result_m_prime.hash.0);
  }
}
```

Listing D.21: verification/verify_hash.rs

```
use crate::sha::HashError;
use crate::structs::hash_function::HashFunction;

pub trait VerifyHash {
  fn verify(&self, hash_function: HashFunction, rounds: u8) -> Result<bool, HashError>;
}
```

Listing D.22: verification/colliding_pair.rs

```
use std::fmt::{Display, Formatter};
use crate::sha::{HashError, MessageBlock, OutputHash, Sha, StartVector};
use crate::structs::hash_function::HashFunction;
use crate::structs::hash_result::HashResult;
use crate::structs::sha_state::ShaState;
use crate::verification::bit_differential::BitDifferential;
use crate::verification::verify_hash::VerifyHash;

#[derive(Debug)]
pub struct MessageData {
  pub m: MessageBlock,
  pub cv: StartVector,
  pub states: Vec<ShaState>,
  pub expected_hash: OutputHash,
}

impl MessageData {
  fn run_sha(
    &self,
    hash_function: HashFunction,
    rounds: u8
  ) -> Result<HashResult, HashError> {
    Sha::from_message_block(
      self.m,
      hash_function,
      rounds,
      self.cv,
    )?.execute()
  }
}

impl VerifyHash for MessageData {
  fn verify(
    &self,
    hash_function: HashFunction,
    rounds: u8,
  ) -> Result<bool, HashError> {
    let hash_result = self.run_sha(hash_function, rounds)?;
    Ok(hash_result.hash == self.expected_hash)
```

```
  }
}

#[derive(Debug)]
pub struct CollidingPair {
  pub m0: MessageData,
  pub m1: MessageData,
  pub hash_function: HashFunction,
  pub rounds: u8,
}

impl CollidingPair {
  pub fn verify(&self) -> Result<bool, HashError> {
    let is_m0_hash_same = self.m0.verify(self.hash_function, self.rounds)?;
    let is_m1_hash_same = self.m0.verify(self.hash_function, self.rounds)?;

    Ok(is_m0_hash_same && is_m1_hash_same)
  }
}

impl Display for CollidingPair {
  fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
    let is_m0_hash_same = self.m0.verify(self.hash_function, self.rounds).unwrap_or(false
        );
    let is_m1_hash_same = self.m1.verify(self.hash_function, self.rounds).unwrap_or(false
        );

    let mut mismatch_info = String::new();
    if !is_m0_hash_same {
      match self.m0.run_sha(self.hash_function, self.rounds) {
        Ok(result) => mismatch_info += &format!("\nActual␣Hash:␣{}", result.hash),
        Err(_) => mismatch_info += "\nUnable␣to␣retrieve␣actual␣hash␣for␣M!",
      }
    }

    if !is_m1_hash_same {
      match self.m1.run_sha(self.hash_function, self.rounds) {
        Ok(result) => mismatch_info += &format!("\nActual␣Hash':␣{}", result.hash),
        Err(_) => mismatch_info += "\nUnable␣to␣retrieve␣actual␣hash␣for␣M'!",
      }
    }

    if mismatch_info.len() > 0 {
      mismatch_info += "\n";
    }

    let hash_message = format!(
      "Hash␣:␣{}␣(Valid?␣{})\nHash':␣{}␣(Valid?␣{})\n{}",
      self.m0.expected_hash,
      is_m0_hash_same,
      self.m1.expected_hash,
      is_m1_hash_same,
      mismatch_info,
    );

    write!(f, "CV␣␣␣:␣{}\n", self.m0.cv)?;
    write!(f, "CV'␣␣:␣{}\n", self.m1.cv)?;
    write!(f, "M␣␣␣␣:␣{}\n", self.m0.m)?;
    write!(f, "M'␣␣␣:␣{}\n", self.m1.m)?;
```

```
    write!(f, "{hash_message}\n\n")?;
    write!(f, "{}", self.m0.states.clone().bit_diff(self.m1.states.clone()))?;
    Ok(())
  }
}
```

Listing D.23: verification/bit_differential.rs

```
#[derive(Debug, Eq, PartialEq)]
enum DiffType {
  INCREASE,
  DECREASE,
  EQUAL,
  FALSE,
  TRUE,
}

impl DiffType {
  fn represent(&self) -> char {
    match self {
      DiffType::INCREASE => 'n',
      DiffType::DECREASE => 'u',
      DiffType::EQUAL => '=',
      DiffType::FALSE => '0',
      DiffType::TRUE => '1',
    }
  }
}

pub trait BitDifferential {
  fn bit_diff(self, other: Self) -> String;
}

macro_rules! impl_bit_differential_for {
    ($($t:ty),*) => {
        $(
            impl BitDifferential for $t {
                fn bit_diff(self, other: Self) -> String {
          let size = size_of::<Self>() * 8;
          let mut s: String = String::with_capacity(size);

          for i in (0..size).rev() {
            let bit_self = (self >> i) & 1 == 1;
            let bit_other = (other >> i) & 1 == 1;

            let representation = match (bit_self, bit_other) {
              (false, true) => DiffType::INCREASE,
              (true, false) => DiffType::DECREASE,
              _ if bit_self == bit_other => DiffType::EQUAL,
              (false, false) => DiffType::FALSE,
              (true, true) => DiffType::TRUE,
            }.represent();

            s.push(representation);
          }

          s
        }
            }
```

```
        )*
    }
}

impl_bit_differential_for!(u8, u16,u32, u64, u128);

impl<T: BitDifferential + Copy, const N: usize> BitDifferential for [T; N] {
  fn bit_diff(self, other: Self) -> String {
    self.into_iter()
      .zip(other)
      .map(|(s, o)| s.bit_diff(o))
      .collect::<String>()
  }
}

impl<T: BitDifferential + Copy> BitDifferential for &[T] {
  fn bit_diff(self, other: Self) -> String {
    self.into_iter()
      .zip(other)
      .map(|(s, o)| s.bit_diff(*o))
      .collect::<String>()
  }
}

#[cfg(test)]
mod test {
  use super::BitDifferential;

  #[test]
  fn test_differential_same() {
    let a = 5u8;
    let b = 5u8;

    assert_eq!(a.bit_diff(b), "========");
  }

  #[test]
  fn test_differential_different() {
    let a = 123u8;
    let b = 5u8;

    assert_eq!(a.bit_diff(b), "=uuuunu=");
  }

  #[test]
  fn test_differential_slice() {
    let a = [2u8; 2];
    let b = [1, 3];
    assert_eq!(a.bit_diff(b), "======un=======n");
  }

  #[test]
  fn test_differential_boxed_slice() {
    let a = Box::<[u8]>::from([2; 2]);
    let b = Box::<[u8]>::from([1, 3]);
    assert_eq!(a.bit_diff(&b), "======un=======n");
  }
}
```

Listing D.24: structs/mod.rs

```rust
pub mod collision_type;
pub mod hash_result;
pub mod sha_state;
pub mod size;
pub mod hash_function;
pub mod benchmark;
```

Listing D.25: structs/size.rs

```rust
/// Representation of a size, retrievable as bits or bytes.
/// Useful for distinguishing between bits and bytes in code.
pub struct Size(usize);

#[allow(dead_code)]
impl Size {
  /// Construct a size from a given number of bits.
  ///
  /// # Arguments
  ///
  /// `bits`: Number of bits to represent
  ///
  /// # Returns
  /// `Size`
  ///
  /// # Examples
  ///
  /// ```
  /// let size = Bits::from_bits(8);
  /// ```
  pub fn from_bits(bits: usize) -> Self {
    Size(bits)
  }

  /// Construct a size from a given number of bytes.
  ///
  /// # Arguments
  ///
  /// `bytes`: Number of bytes to represent
  ///
  /// # Returns
  /// `Size`
  ///
  /// # Examples
  ///
  /// ```
  /// let size = Bits::from_bytes(2);
  /// ```
  pub fn from_bytes(bytes: usize) -> Self {
    Size(bytes * 8)
  }

  /// Retreive the number of bits.
  ///
  /// # Returns
  /// `usize`
  ///
  /// # Examples
  ///
```

```rust
  /// ```
  /// let size = Bits::from_bytes(2);
  /// println!("{}", size.bits()); // Outputs 16
  /// ```
  pub fn bits(&self) -> usize {
    self.0
  }

  /// Retreive the number of bytes.\
  /// The value will always be padded to the nearest full byte.
  ///
  /// # Returns
  /// `usize`
  ///
  /// # Examples
  ///
  /// ```
  /// let size = Size::from_bits(8);
  /// println!("{}", size.bytes()); // Outputs 1
  /// ```
  ///
  /// ```
  /// let size = Size::from_bits(12);
  /// println!("{}", size.bytes()); // Outputs 2
  /// ```
  pub fn bytes(&self) -> usize {
    (self.0 + 7) / 8
  }
}

#[cfg(test)]
mod tests {
  use super::Size;

  #[test]
  fn test_from_bits() {
    assert!(matches!(Size::from_bits(8), Size(8)));
    assert!(matches!(Size::from_bits(12), Size(12)));
  }

  #[test]
  fn test_from_bytes() {
    assert!(matches!(Size::from_bytes(1), Size(8)));
    assert!(matches!(Size::from_bytes(2), Size(16)));
  }

  #[test]
  fn test_bits() {
    assert_eq!(Size(8).bits(), 8);
  }

  #[test]
  fn test_bytes() {
    assert_eq!(Size(8).bytes(), 1);
  }

  #[test]
  fn test_non_full_bytes() {
    assert_eq!(Size(11).bytes(), 2);
```

```
  }
}
```

Due to tex errors related to invalid UTF-8 byte sequence, the Δ and $_i$ symbols have been substituted with `d` and `i`.

Listing D.26: structs/sha_state.rs

```rust
use crate::sha::Word;
use crate::verification::bit_differential::BitDifferential;

#[derive(Copy, Clone, Debug, PartialEq)]
pub struct ShaState {
  pub i: u8,
  pub w: Word,
  pub a: Word,
  pub e: Word,
}

impl BitDifferential for ShaState {
  fn bit_diff(self, other: Self) -> String {
    let a_delta = self.a.bit_diff(other.a);
    let e_delta = self.e.bit_diff(other.e);
    let w_delta = self.w.bit_diff(other.w);

    format!("{a_delta} | {e_delta} | {w_delta}")
  }
}

impl BitDifferential for Vec<ShaState> {
  fn bit_diff(self, other: Self) -> String {
    let mut output = String::new();
    let padding = if let Some(state) = self.get(0) {
      match state.w {
        Word::W32(_) => 32,
        Word::W64(_) => 64,
      }
    } else { return output };

    // Append heading
    output += &format!(
      " i | {:^padding$} | {:^padding$} | {:^padding$}\n",
      "dAi", "dEi", "dWi"
    );

    // Append differential for each compression round
    for i in 0..self.len() {
      let diff = self[i].clone().bit_diff(other[i].clone());
      output += &format!("{i:2} | {diff}\n");
    }

    output.shrink_to_fit();
    output
  }
}
```

Listing D.27: structs/hash_result.rs

```rust
use crate::sha::OutputHash;
```

```rust
use crate::structs::sha_state::ShaState;

#[derive(Debug, PartialEq, Clone)]
pub struct HashResult {
  pub hash: OutputHash,
  pub states: Vec<ShaState>,
}
```

Listing D.28: structs/hash_function.rs

```rust
use std::fmt::{Display, Formatter};
use crate::sha::{HashError, Word};
use crate::structs::size::Size;

#[derive(Debug, Clone, Copy, Eq, PartialEq, serde::Serialize, serde::Deserialize, clap::
    ValueEnum)]
pub enum HashFunction {
  SHA224,
  SHA256,
  SHA512,
}

impl Display for HashFunction {
  fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
    match self {
      HashFunction::SHA224 => f.write_str("SHA224"),
      HashFunction::SHA256 => f.write_str("SHA256"),
      HashFunction::SHA512 => f.write_str("SHA512"),
    }
  }
}

impl HashFunction {
  pub fn max_rounds(&self) -> u8 {
    use HashFunction::*;
    match self {
      SHA224 | SHA256 => 64,
      SHA512 => 80,
    }
  }

  pub fn length_size(&self) -> Size {
    use HashFunction::*;
    match self {
      SHA224 | SHA256 => Size::from_bits(64),
      SHA512 => Size::from_bits(128),
    }
  }

  pub fn block_size(&self) -> Size {
    use HashFunction::*;
    match self {
      SHA224 | SHA256 => Size::from_bits(512),
      SHA512 => Size::from_bits(1024),
    }
  }

  pub fn default_word(&self) -> Word {
    use HashFunction::*;
```

```
    match self {
      SHA224 | SHA256 => Word::W32(0),
      SHA512 => Word::W64(0),
    }
  }

  pub fn word_size(&self) -> Size {
    use HashFunction::*;
    match self {
      SHA224 | SHA256 => Size::from_bits(32),
      SHA512 => Size::from_bits(64),
    }
  }

  pub fn truncate_to_length(&self) -> Option<usize> {
    use HashFunction::*;
    match self {
      SHA224 => Some(7),
      _ => None,
    }
  }

  /// Validates number of compression rounds.
  /// Returns error if rounds exceed max_rounds of given hash function.
  ///
  /// # Arguments
  ///
  /// * `rounds`: Number of compression rounds
  /// * `hash_function`: Hash function to validate against
  ///
  /// # Returns
  /// `Result<(), HashError>`
  pub fn validate_rounds(&self, rounds: u8) -> Result<(), HashError> {
    let max_rounds = self.max_rounds();
    if rounds > max_rounds {
      return Err(HashError::TooManyRounds {
        requested: rounds,
        maximum: max_rounds,
      });
    }

    Ok(())
  }

  /// Retrieves constant K
  pub fn get_constant(&self) -> Vec<Word> {
    use HashFunction::*;
    match self {
      SHA224 | SHA256 => Word::from_u32_vec(vec![
        0x428a2f98, 0x71374491, 0xb5c0fbcf, 0xe9b5dba5,
        0x3956c25b, 0x59f111f1, 0x923f82a4, 0xab1c5ed5,
        0xd807aa98, 0x12835b01, 0x243185be, 0x550c7dc3,
        0x72be5d74, 0x80deb1fe, 0x9bdc06a7, 0xc19bf174,
        0xe49b69c1, 0xefbe4786, 0x0fc19dc6, 0x240ca1cc,
        0x2de92c6f, 0x4a7484aa, 0x5cb0a9dc, 0x76f988da,
        0x983e5152, 0xa831c66d, 0xb00327c8, 0xbf597fc7,
        0xc6e00bf3, 0xd5a79147, 0x06ca6351, 0x14292967,
        0x27b70a85, 0x2e1b2138, 0x4d2c6dfc, 0x53380d13,
        0x650a7354, 0x766a0abb, 0x81c2c92e, 0x92722c85,
```

```
        0xa2bfe8a1, 0xa81a664b, 0xc24b8b70, 0xc76c51a3,
        0xd192e819, 0xd6990624, 0xf40e3585, 0x106aa070,
        0x19a4c116, 0x1e376c08, 0x2748774c, 0x34b0bcb5,
        0x391c0cb3, 0x4ed8aa4a, 0x5b9cca4f, 0x682e6ff3,
        0x748f82ee, 0x78a5636f, 0x84c87814, 0x8cc70208,
        0x90befffa, 0xa4506ceb, 0xbef9a3f7, 0xc67178f2,
      ]),
      SHA512 => Word::from_u64_vec(vec![
        0x428a2f98d728ae22, 0x7137449123ef65cd, 0xb5c0fbcfec4d3b2f, 0xe9b5dba58189dbbc,
        0x3956c25bf348b538, 0x59f111f1b605d019, 0x923f82a4af194f9b, 0xab1c5ed5da6d8118,
        0xd807aa98a3030242, 0x12835b0145706fbe, 0x243185be4ee4b28c, 0x550c7dc3d5ffb4e2,
        0x72be5d74f27b896f, 0x80deb1fe3b1696b1, 0x9bdc06a725c71235, 0xc19bf174cf692694,
        0xe49b69c19ef14ad2, 0xefbe4786384f25e3, 0x0fc19dc68b8cd5b5, 0x240ca1cc77ac9c65,
        0x2de92c6f592b0275, 0x4a7484aa6ea6e483, 0x5cb0a9dcbd41fbd4, 0x76f988da831153b5,
        0x983e5152ee66dfab, 0xa831c66d2db43210, 0xb00327c898fb213f, 0xbf597fc7beef0ee4,
        0xc6e00bf33da88fc2, 0xd5a79147930aa725, 0x06ca6351e003826f, 0x142929670a0e6e70,
        0x27b70a8546d22ffc, 0x2e1b21385c26c926, 0x4d2c6dfc5ac42aed, 0x53380d139d95b3df,
        0x650a73548baf63de, 0x766a0abb3c77b2a8, 0x81c2c92e47edaee6, 0x92722c851482353b,
        0xa2bfe8a14cf10364, 0xa81a664bbc423001, 0xc24b8b70d0f89791, 0xc76c51a30654be30,
        0xd192e819d6ef5218, 0xd69906245565a910, 0xf40e35855771202a, 0x106aa07032bbd1b8,
        0x19a4c116b8d2d0c8, 0x1e376c085141ab53, 0x2748774cdf8eeb99, 0x34b0bcb5e19b48a8,
        0x391c0cb3c5c95a63, 0x4ed8aa4ae3418acb, 0x5b9cca4f7763e373, 0x682e6ff3d6b2b8a3,
        0x748f82ee5defb2fc, 0x78a5636f43172f60, 0x84c87814a1f0ab72, 0x8cc702081a6439ec,
        0x90befffa23631e28, 0xa4506cebde82bde9, 0xbef9a3f7b2c67915, 0xc67178f2e372532b,
        0xca273eceea26619c, 0xd186b8c721c0c207, 0xeada7dd6cde0eb1e, 0xf57d4f7fee6ed178,
        0x06f067aa72176fba, 0x0a637dc5a2c898a6, 0x113f9804bef90dae, 0x1b710b35131c471b,
        0x28db77f523047d84, 0x32caab7b40c72493, 0x3c9ebe0a15c9bebc, 0x431d67c49c100d4c,
        0x4cc5d4becb3e42b6, 0x597f299cfc657e2a, 0x5fcb6fab3ad6faec, 0x6c44198c4a475817,
      ]),
    }
  }
}
```

Listing D.29: structs/collision_type.rs

```
use std::fmt::{Display, Formatter};

#[derive(Debug, Eq, PartialEq, Copy, Clone, serde::Serialize, serde::Deserialize, clap::
    ValueEnum)]
pub enum CollisionType {
  /// Use the fixed iv for both m0 and m1, where m0 != m1
  #[value(name = "std")]
  Standard,
  /// Use a shared cv for both m0 and m1, where m0 != m1
  #[value(name = "sfs")]
  SemiFreeStart,
  /// Use cv0 for m0, cv1 for m1, where cv0 != cv1 and m0 ?= m1
  #[value(name = "fs")]
  FreeStart,
}

impl Display for CollisionType {
  fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
    match self {
      CollisionType::Standard => f.write_str("STD"),
      CollisionType::SemiFreeStart => f.write_str("SFS"),
      CollisionType::FreeStart => f.write_str("FS"),
    }
  }
```

```
}
```

Listing D.30: structs/benchmark.rs

```
use std::collections::BTreeMap;
use std::error::Error;
use std::fmt::{Display, Formatter};
use std::fs;
use std::fs::File;
use std::io::Write;
use std::path::{Path, PathBuf};
use std::time::Duration;
use chrono::{DateTime, Utc};
use regex::Regex;
use serde::{Deserialize, Serialize};
use crate::sha::{MessageBlock, OutputHash, StartVector, Word};
use crate::smt_lib::smt_retriever::EncodingType;
use crate::structs::collision_type::CollisionType;
use crate::structs::hash_function::HashFunction;
use crate::structs::sha_state::ShaState;
use crate::verification::colliding_pair::{CollidingPair, MessageData};


#[derive(Copy, Clone, Debug, Serialize, Deserialize, Eq, PartialEq, Hash, Ord, PartialOrd
    , clap::ValueEnum)]
pub enum SmtSolver {
  Z3,
  CVC5,
  Yices2,
  Bitwuzla,
  Boolector,
  // STP, // STP Does not support SMTLIB 2.6!
  Colibri2,
  MathSAT,
}

// TODO: TO TEST:
// Z3:
// core.minimize (bool) minimize computed core (default: false)
//    bce (bool) eliminate blocked clauses (default: false)
//    ate (bool) asymmetric tautology elimination (default: true)
//    abce (bool) eliminate blocked clauses using asymmetric literals (default: false)
//     acce (bool) eliminate covered clauses using asymmetric added literals (default:
    false)
//     anf (bool) enable ANF based simplification in-processing (default: false)
//    binspr (bool) enable SPR inferences of binary propagation redundant clauses. This
    inprocessing step eliminates models (default: false)
//    cce (bool) eliminate covered clauses (default: false)
//    cut (bool) enable AIG based simplification in-processing (default: false)
//    threads (unsigned int) number of parallel threads to use (default: 1)
//    cancel_backup_file (symbol) file to save partial search state if search is canceled
     (default: )
//    enable_sls (bool) enable SLS tuning during weighted maxsat (default: false)
//    enable (bool) enable parallel solver by default on selected tactics (for QF_BV) (
    default: false)
//    check_lemmas (bool) check lemmas on the fly using an independent nlsat solver (
    default: false)
//    blast_distinct (bool) expand a distinct predicate into a quadratic number of
    disequalities (default: false)
```

```
//    blast_eq_value (bool) blast (some) Bit-vector equalities into bits (default: false)
//    bv_extract_prop (bool) attempt to partially propagate extraction inwards (default:
    false)
//    bv_not_simpl (bool) apply simplifications for bvnot (default: false)
//    bv_sort_ac (bool) sort the arguments of all AC operators (default: false)
//    elim_and (bool) conjunctions are rewritten using negation and disjunctions (default
    : false)
//[module] sls, description: Experimental Stochastic Local Search Solver (for QFBV only).
//

// CVC5:
//  --arith-rewrite-equalities
//                          turns on the preprocessing rewrite turning equalities
//                          into a conjunction of inequalities [*]
//   --arith-static-learning
//                          do arithmetic static learning for ite terms based on
//                          bounds when static learning is enabled [*]
//   --dio-solver           turns on Linear Diophantine Equation solver (Griggio,
//                          JSAT 2012) (EXPERTS only) [*]
//  --dio-decomps          let skolem variables for integer divisibility
//                          constraints leak from the dio solver (EXPERTS only) [*]
//  --new-prop             use the new row propagation system (EXPERTS only) [*]
//  --nl-cov               whether to use the cylindrical algebraic coverings
//                          solver for non-linear arithmetic [*]
//  --use-approx           attempt to use an approximate solver (EXPERTS only) [*]
//  --use-fcsimplex        use focusing and converging simplex (FMCAD 2013
//                          submission) (EXPERTS only) [*]
//   --use-soi              use sum of infeasibility simplex (FMCAD 2013
//                          submission) (EXPERTS only) [*]
//  --plugin-share-skolems true if we permit sharing theory lemmas and SAT clauses
//                          with skolems (EXPERTS only) [*]
//  --bitblast=MODE        choose bitblasting mode, see --bitblast=help
//  --bool-to-bv=MODE      convert booleans to bit-vectors of size 1 at various
//                          levels of aggressiveness, see --bool-to-bv=help
//  --bv-assert-input      assert input assertions on user-level 0 instead of
//                          assuming them in the bit-vector SAT solver (EXPERTS
//                          only) [*]
//  --bv-eager-eval        perform eager context-dependent evaluation for
//                          applications of bv kinds in the equality engine [*]
//  --bv-eq-engine         enable equality engine when possible in bitvector
//                          theory (EXPERTS only) [*]
//   --bv-gauss-elim        simplify formula via Gaussian Elimination if applicable
//                          (EXPERTS only) [*]
//   --bv-propagate         use bit-vector propagation in the bit-blaster (EXPERTS
//                          only) [*]
//   --bv-rw-extend-eq      enable additional rewrites over zero/sign extend over
//                          equalities with constants (useful on
//                          BV/2017-Preiner-scholl-smt08) (EXPERTS only) [*]
//   --bv-sat-solver=MODE   choose which sat solver to use, see
//                          --bv-sat-solver=help
//   --bv-solver=MODE       choose bit-vector solver, see --bv-solver=help
//  --minisat-simplification=MODE
//                          Simplifications to be performed by Minisat. (EXPERTS
//                          only)

// - Different arguments for each solver
// - Different kernels (https://askubuntu.com/a/126671)
// - Different memory timings
// - CPU Core Clock difference
```

```
// - Run to run variance

// TODO: Yices2
// TODO: Boolector

impl Display for SmtSolver {
  fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
    use SmtSolver::*;

    write!(f, "{}", match self {
      Z3 => "Z3",
      CVC5 => "CVC5",
      Yices2 => "Yices",
      Bitwuzla => "Bitwuzla",
      Boolector => "Boolector",
      // STP => "STP",
      Colibri2 => "Colibri2",
      MathSAT => "MathSAT",
    })
  }
}

impl SmtSolver {
  pub fn command(&self) -> String {
    use SmtSolver::*;

    match self {
      Z3 => "z3",
      CVC5 => "cvc5",
      Yices2 => "yices-smt2",
      Bitwuzla => "bitwuzla",
      Boolector => "boolector",
      // STP => "stp",
      Colibri2 => "./solvers/colibri2",
      MathSAT => "./solvers/mathsat",
    }.into()
  }
}

pub type SolverArg = String;

#[derive(Debug, Serialize, Deserialize, Eq, PartialEq, Clone)]
pub enum BenchmarkResult {
  Sat,
  Unsat,
  MemOut,
  CPUOut,
  Aborted,
  SMTError,
  Unknown,
}

impl Display for BenchmarkResult {
  fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
    write!(f, "{}", match self {
      BenchmarkResult::Sat => "SAT",
      BenchmarkResult::Unsat => "UNSAT",
      BenchmarkResult::MemOut => "OUT␣OF␣MEMORY",
      BenchmarkResult::CPUOut => "OUT␣OF␣CPU␣TIME",
```

```
      BenchmarkResult::Aborted => "ABORTED",
      BenchmarkResult::SMTError => "SMT␣ERROR",
      BenchmarkResult::Unknown => "UNKNOWN",
    })
  }
}

#[derive(Clone, Copy)]
enum SmtOutputFormat {
  Boolean,
  Hex,
  Decimal,
}

impl SmtOutputFormat {
  fn output_string(self) -> String {
    match self {
      SmtOutputFormat::Boolean => "#b([01]*)",
      SmtOutputFormat::Hex => "#x([0-9a-fA-F]*)",
      SmtOutputFormat::Decimal => "([0-9]*)",
    }.to_string()
  }

  fn get_base_size(
    self,
    capture: &str,
    hash_function: HashFunction
  ) -> Result<Word, Box<dyn Error>> {
    let radix_size = match self {
      SmtOutputFormat::Boolean => 2,
      SmtOutputFormat::Hex => 16,
      SmtOutputFormat::Decimal => 10,
    };

    Ok(Word::from_str_radix(capture, radix_size, hash_function)?)
  }
}

#[derive(Debug, PartialEq, Clone)]
pub struct MutableShaState {
  pub i: u8,
  pub w: Option<Word>,
  pub a: Option<Word>,
  pub e: Option<Word>,
}

impl Default for MutableShaState {
  fn default() -> Self {
    MutableShaState {
      i: 0,
      w: None,
      a: None,
      e: None,
    }
  }
}

impl MutableShaState {
  fn to_immutable(self) -> Option<ShaState> {
```

```
    Some(ShaState {
      i: self.i,
      w: self.w?,
      a: self.a?,
      e: self.e?,
    })
  }

  fn update_state_variable(&mut self, variable: char, value: Word) {
    match variable {
      'a' => self.a = Some(value),
      'e' => self.e = Some(value),
      'w' => self.w = Some(value),
      _ => {},
    }
  }
}

#[derive(Debug, Clone, Serialize, Deserialize, Eq, PartialEq)]
pub struct Benchmark {
  pub date_time: DateTime<Utc>,
  pub solver: SmtSolver,
  pub arguments: Option<SolverArg>,
  pub hash_function: HashFunction,
  pub rounds: u8,
  pub collision_type: CollisionType,
  pub execution_time: Duration,
  pub memory_bytes: u64,
  pub result: BenchmarkResult,
  pub console_output: (String, String),
  pub is_valid: Option<bool>,
  pub is_baseline: bool,
  pub is_rerun: bool,
  pub encoding: EncodingType,
  pub stop_tolerance: u8,
  pub timeout: Duration,
}

impl Benchmark {
  pub fn save(&self, path: &Path) -> Result<PathBuf, Box<dyn Error>> {
    if !path.exists() {
      fs::create_dir_all(path)?;
    }

    let path = path.join(
      format!("{}_{}_{}_{}_{}.json",
          self.hash_function,
          self.collision_type,
          self.solver,
          self.rounds,
          self.date_time,
      )
    );

    let mut file = File::options()
      .create_new(true)
      .write(true)
      .open(path.clone())?;

```

```
    let json = serde_json::to_string(&self)?;
    file.write_all(json.as_bytes())?;

    Ok(path)
  }

  pub fn load(file: &Path) -> Result<Self, Box<dyn Error>> {
    let contents = fs::read(file)?;
    let benchmark: Self = serde_json::from_slice(&contents)?;
    Ok(benchmark)
  }

  pub fn load_all(dir_location: &Path, recursively: bool) -> Result<Vec<Self>, Box<dyn
      Error>> {
    let mut benchmarks = vec![];

    if dir_location.is_file() {
      benchmarks.push(Self::load(dir_location)?);
      return Ok(benchmarks);
    }

    for dir_entry in fs::read_dir(dir_location)? {
      if let Ok(entry) = dir_entry {
        let metadata = entry.metadata()?;
        if recursively && metadata.is_dir() {
          benchmarks.extend(Self::load_all(&entry.path(), recursively)?)
        } else if metadata.is_file() {
          benchmarks.push(Self::load(&entry.path())?);
        }
      }
    }

    Ok(benchmarks)
  }

  pub fn parse_output(&mut self) -> Result<Option<CollidingPair>, Box<dyn Error>> {
    if self.result != BenchmarkResult::Sat {
      return Ok(None);
    }

    let output_format = self.get_output_format()?;
    let number_format = output_format.output_string();
    let re = Regex::new(
      &format!(
        r"\((?:m([01])_|)(delta_[aew]|[a-hw]|hash)([0-9]+)␣(?:\(_␣bv{number_format}␣
            (?:32|64)\)|{number_format})\)",
      )
    )?;

    let (smt_output, _) = self.console_output.clone();
    let default_word = self.hash_function.default_word();

    let mut hash = Box::new([None; 8]);
    let mut start_blocks = [[default_word; 16]; 2];
    let mut start_vectors = [[default_word; 8]; 2];
    let mut states = [BTreeMap::new(), BTreeMap::new()];

    for capture in re.captures_iter(&smt_output) {
      let msg= capture.get(1);
```

```
      let var = &capture[2];
      let round: usize = capture[3].parse()?;

      let val = match (capture.get(4), capture.get(5)) {
        (Some(val), _) => val,
        (_, Some(val)) => val,
        (None, None) => {
          return Err(Box::from("Failed to retrieve value"));
        }
      };
      let val = output_format.get_base_size(val.into(), self.hash_function)?;

      let is_differential = var.contains("delta");

      match msg {
        Some(msg) => {
          self.parse_update_for_msg(
            msg.as_str().parse()?,
            var,
            round,
            val,
            &mut hash,
            &mut start_blocks,
            &mut start_vectors,
            &mut states,
            is_differential,
          )?;
        }
        None => {
          self.parse_update_for_msg(
            0,
            var,
            round,
            val,
            &mut hash,
            &mut start_blocks,
            &mut start_vectors,
            &mut states,
            is_differential,
          )?;
          self.parse_update_for_msg(
            1,
            var,
            round,
            val,
            &mut hash,
            &mut start_blocks,
            &mut start_vectors,
            &mut states,
            is_differential,
          )?;
        }
      }
    }

    // Trim hash
    let output_size = self.hash_function.truncate_to_length().unwrap_or(8);
    let mut trimmed_hash = Vec::with_capacity(output_size);
    for (i, word) in hash.into_iter().enumerate() {
```

```
      if let Some(word) = word {
        trimmed_hash.push(word);
      } else if i == output_size {
        break;
      }
    }

    // Process messages
    let mut messages = vec![];
    for (i, message_states) in states.into_iter().enumerate() {
      let mut states = vec![];
      for (_, mut state) in message_states {
        if self.rounds == 0 {
          state.w = Some(self.hash_function.default_word());
        }

        states.push(
          state
            .to_immutable()
            .ok_or("Failed to retrieve all message states")?
        );
      }

      messages.push(MessageData {
        m: MessageBlock(start_blocks[i]),
        cv: StartVector::CV(start_vectors[i]),
        states,
        expected_hash: OutputHash(Box::from(trimmed_hash.clone())),
      });
    }

    let [m0, m1] = messages.try_into().unwrap();
    let colliding_pair = CollidingPair {
      m0,
      m1,
      hash_function: self.hash_function,
      rounds: self.rounds,
    };

    // Verify benchmark
    self.is_valid = Some(colliding_pair.verify()?);

    Ok(Some(colliding_pair))
  }

  fn parse_update_for_msg(
    &self,
    msg: usize,
    var: &str,
    round: usize,
    val: Word,
    hash: &mut Box<[Option<Word>; 8]>,
    start_blocks: &mut [[Word; 16]; 2],
    start_vectors: &mut [[Word; 8]; 2],
    states: &mut [BTreeMap<usize, MutableShaState>; 2],
    differential: bool,
  ) -> Result<(), Box<dyn Error>> {
    // Special handling if differential
    let (var, val) = if differential {
```

```
      let var = var.split("_").collect::<Vec<_>>()[1];
      let val = if msg == 0 {
        val
      } else {
        self.hash_function.default_word()
      };

      (var, val)
    } else { (var, val) };

    // Parse
    if var == "hash" {
      hash[round] = Some(val);
    } else {
      let var_char: char = var.parse()?;

      // Parse H constants (CV/IV)
      if !differential && round == 0 && var_char != 'w' {
        let i = (var_char as u8) - ('a' as u8);
        start_vectors[msg][i as usize] = val;
      }

      // Parse start blocks
      if !differential && var_char == 'w' && round < 16 {
        start_blocks[msg][round] = val;
      }

      // Upsert updated state
      states[msg].entry(round).and_modify(|state| {
        state.update_state_variable(var_char, val);
      }).or_insert_with(|| {
        let mut state = MutableShaState::default();
        state.i = round as u8;
        state.update_state_variable(var_char, val);
        state
      });
    }
    Ok(())
  }

  fn get_output_format(&self) -> Result<SmtOutputFormat, Box<dyn Error>> {
    let (smt_output, _) = self.console_output.clone();
    if smt_output.contains("#b") {
      Ok(SmtOutputFormat::Boolean)
    } else if smt_output.contains("#x") {
      Ok(SmtOutputFormat::Hex)
    } else {
      Ok(SmtOutputFormat::Decimal)
    }
  }
}
```

Listing D.31: smt_lib/mod.rs

```
pub mod smt_lib;
pub mod smt_retriever;
mod utilities;
pub(super) mod encodings;
```

Listing D.32: smt_lib/smt_lib.rs

```rust
use std::error::Error;
use std::fs::File;
use std::io::Write;
use std::path::PathBuf;
use crate::sha::{HashError};
use crate::smt_lib::smt_retriever::{EncodingType, SmtRetriever};
use crate::structs::collision_type::CollisionType;
use crate::structs::hash_function::HashFunction;

pub struct SmtBuilder {
  /// Sha defined in SMTLIB2 format
  pub(super) smt: String,
  /// Hash function to use
  pub(super) hash_function: HashFunction,
  /// Number of compression rounds
  pub(super) rounds: u8,
  /// The target collision type
  pub(super) collision_type: CollisionType,
  /// The target encoding type
  pub(super) encoding: EncodingType,
}

impl SmtBuilder {
  fn new(
    hash_function: HashFunction,
    rounds: u8,
    collision_type: CollisionType,
    encoding: EncodingType
  ) -> Result<Self, HashError> {
    hash_function.validate_rounds(rounds)?;

    Ok(SmtBuilder {
      smt: String::new(),
      hash_function,
      rounds,
      collision_type,
      encoding,
    })
  }

  fn to_file(self, file_path: PathBuf) -> Result<File, std::io::Error> {
    let mut file = File::create(file_path)?;

    file.write(self.smt.as_bytes())?;

    Ok(file)
  }

  fn write_encoding(&mut self)  -> Result<(), Box<dyn Error>> {
    use EncodingType::*;

    match self.encoding {
      BruteForce { .. } => self.brute_force_encoding()?,
      DeltaXOR { .. } => self.dxor_encoding()?,
      DeltaSub { .. } => self.dsub_encoding()?,
      Base4 { .. } => self.base4_encoding()?,
    };

```

```
    Ok(())
  }
}

pub fn generate_smtlib_files(
  smt_retriever: SmtRetriever,
) -> Result<(), Box<dyn Error>> {
  use HashFunction::*;
  use CollisionType::*;

  for hash_function in [SHA224, SHA256, SHA512] {
    for collision_type in [Standard, SemiFreeStart, FreeStart] {
      for encoding in EncodingType::get_all_permutations() {
        for rounds in 1..=hash_function.max_rounds() {
          let mut builder = SmtBuilder::new(
            hash_function,
            rounds,
            collision_type,
            encoding,
          )?;

          builder.write_encoding()?;

          let file_path = smt_retriever.get_file(
            hash_function,
            collision_type,
            rounds,
            encoding,
          );

          builder.to_file(file_path)?;
        }
      }
    }
  }

  Ok(())
}
```

Listing D.33: smt_lib/smt_retriever.rs

```
use std::error::Error;
use std::fmt::{Display, Formatter};
use std::fs;
use std::path::PathBuf;
use std::str::FromStr;
use serde::{Deserialize, Serialize};
use crate::smt_lib::smt_retriever::EncodingType::{BruteForce, DeltaSub, DeltaXOR, Base4};
use crate::structs::collision_type::CollisionType;
use crate::structs::hash_function::HashFunction;

#[derive(Debug, Copy, Clone, Serialize, Deserialize, Eq, PartialEq, PartialOrd, Ord)]
pub enum EncodingType {
  BruteForce {
    simplified_maj_and_ch_functions: bool,
    alternative_add: bool,
  },
  DeltaXOR {
    simplified_maj_and_ch_functions: bool,
```

```
    alternative_add: bool,
  },
  DeltaSub {
    simplified_maj_and_ch_functions: bool,
    alternative_add: bool,
  },
  Base4 {
    simplified_maj_and_ch_functions: bool,
    alternative_add: bool,
  },
}

impl Into<String> for EncodingType {
  fn into(self) -> String {
    let mut encoding_str = match self {
      BruteForce { .. } => "bruteforce",
      DeltaXOR { .. } => "delta-xor",
      DeltaSub { .. } => "delta-sub",
      Base4 { .. } => "base-4",
    }.to_string();

    if self.alternative_add() {
      encoding_str.push_str("␣bitwise␣add");
    }

    if self.simplified_maj_and_ch_functions() {
      encoding_str.push_str("␣simplified␣MAJ␣&␣CH␣fn");
    }

    encoding_str
  }
}

impl EncodingType {
  pub fn get_diff(&self) -> Result<&str, Box<dyn Error>> {
    use EncodingType::*;
    match self {
      DeltaXOR { .. } => Ok("bvxor"),
      DeltaSub { .. } => Ok("bvsub"),
      _ => Err(Box::from("get_diff␣not␣supported␣for␣encoding␣type")),
    }
  }

  pub fn simplified_maj_and_ch_functions(&self) -> bool {
    use EncodingType::*;
    *match self {
      BruteForce { simplified_maj_and_ch_functions, .. } =>
          simplified_maj_and_ch_functions,
      DeltaXOR { simplified_maj_and_ch_functions, .. } => simplified_maj_and_ch_functions
          ,
      DeltaSub { simplified_maj_and_ch_functions, .. } => simplified_maj_and_ch_functions
          ,
      Base4 { simplified_maj_and_ch_functions, .. } => simplified_maj_and_ch_functions,
    }
  }

  pub fn alternative_add(&self) -> bool {
    use EncodingType::*;
    *match self {
```

```
      BruteForce { alternative_add, .. } => alternative_add,
      DeltaXOR { alternative_add, .. } => alternative_add,
      DeltaSub { alternative_add, .. } => alternative_add,
      Base4 { alternative_add, .. } => alternative_add,
    }
  }

  pub fn get_all_permutations() -> Vec<Self> {
    let mut vec = Vec::with_capacity(4 * 3);

    for simplified_maj_and_ch_functions in [false, true] {
      for alternative_add in [false, true] {
        vec.push(BruteForce {
          simplified_maj_and_ch_functions,
          alternative_add,
        });
        vec.push(DeltaXOR {
          simplified_maj_and_ch_functions,
          alternative_add,
        });
        vec.push(DeltaSub {
          simplified_maj_and_ch_functions,
          alternative_add,
        });
        // TODO: Uncomment once implemented
        // vec.push(Base4 {
        //  simplified_maj_and_ch_functions,
        //  alternative_add,
        // });
      }
    }

    vec
  }
}

fn parse_bool(s: &str) -> bool {
  match s.to_lowercase().as_str() {
    "true" | "1" | "yes" | "y" => true,
    _ => false,
  }
}

impl FromStr for EncodingType {
  type Err = String;

  fn from_str(s: &str) -> Result<Self, Self::Err> {
    use EncodingType::*;

    let parts: Vec<_> = s.splitn(3, ":").collect();
    let encoding_type_str = parts[0].trim();

    let simplified_maj_and_ch_functions = parts
      .get(1)
      .map_or(false, |&s| parse_bool(s));

    let alternative_add = parts
      .get(2)
      .map_or(false, |&s| parse_bool(s));
```

```
134
135     match encoding_type_str {
136       "bruteforce" => {
137         Ok(BruteForce {
138           simplified_maj_and_ch_functions,
139           alternative_add,
140         })
141       },
142       "dxor" => {
143         Ok(DeltaXOR {
144           simplified_maj_and_ch_functions,
145           alternative_add,
146         })
147       },
148       "dsub" => {
149         Ok(DeltaSub {
150           simplified_maj_and_ch_functions,
151           alternative_add,
152         })
153       },
154       "base4" => {
155         Ok(Base4 {
156           simplified_maj_and_ch_functions,
157           alternative_add,
158         })
159       },
160       _ => Err(format!("Unknown encoding type: {}", encoding_type_str)),
161     }
162   }
163 }
164
165 impl Display for EncodingType {
166   fn fmt(&self, f: &mut Formatter<'_>) -> std::fmt::Result {
167     use EncodingType::*;
168
169     let (et_name, simplified_maj_and_ch_functions, alternative_add) = match self {
170       BruteForce { simplified_maj_and_ch_functions, alternative_add } =>
171         ("", *simplified_maj_and_ch_functions, *alternative_add),
172       DeltaXOR { simplified_maj_and_ch_functions, alternative_add } =>
173         ("DXOR", *simplified_maj_and_ch_functions, *alternative_add),
174       DeltaSub { simplified_maj_and_ch_functions, alternative_add } =>
175         ("DSUB", *simplified_maj_and_ch_functions, *alternative_add),
176       Base4 { simplified_maj_and_ch_functions, alternative_add } =>
177         ("BASE4", *simplified_maj_and_ch_functions, *alternative_add),
178     };
179
180     let mut s = String::from(et_name);
181
182     if simplified_maj_and_ch_functions {
183       if !s.is_empty() {
184         s.push('_');
185       }
186
187       s += "SIMP";
188     }
189
190     if alternative_add {
191       if !s.is_empty() {
192         s.push('_');
```

```
      }

      s += "ALTADD";
    }

    write!(f, "{s}")
  }
}

pub struct SmtRetriever {
  smt_dir: PathBuf,
}

impl SmtRetriever {
  pub fn new(smt_dir: PathBuf) -> Result<Self, Box<dyn Error>> {
    if !smt_dir.exists() {
      fs::create_dir_all(smt_dir.clone())?;
    }

    Ok(SmtRetriever {
      smt_dir,
    })
  }

  #[allow(dead_code)]
  pub fn default() -> Result<Self, Box<dyn Error>> {
    SmtRetriever::new(PathBuf::from("smt/"))
  }

  pub fn get_file(
    &self,
    hash_function: HashFunction,
    collision_type: CollisionType,
    rounds: u8,
    encoding_type: EncodingType,
  ) -> PathBuf {
    let mut base = format!("{hash_function}_{collision_type}_{rounds}");
    if encoding_type.to_string().len() > 0 {
      base += &format!("_{encoding_type}");
    }

    self.smt_dir.join(base + ".smt2")
  }
}
```

Listing D.34: smt_lib/utilities.rs

```
use crate::sha::Word;
use crate::structs::collision_type::CollisionType;
use crate::structs::hash_function::HashFunction;

pub(super) fn smt_hex(val: Word, hash_function: &HashFunction) -> String {
  let size = hash_function.word_size().bytes() * 2;
  format!("#x{:0size$x}", val)
}

pub(super) fn get_previous_var(var: char) -> char {
  if var == 'a' {
    'h'
```

```
  } else {
    char::from_u32(var as u32 - 1).unwrap()
  }
}

pub(super) fn msg_prefix(
  message: u8,
  i: u64,
  collision_type: CollisionType,
) -> String {
  // SemiFreeStart has separate parameters for the 0th iteration
  if i == 0 && collision_type != CollisionType::FreeStart {
    "".to_string()
  } else {
    format!("m{message}_")
  }
}
```

Listing D.35: smt_lib/encodings/mod.rs

```
mod brute_force;
mod generic_shared;
mod dxor;
mod dsub;
mod differential_shared;
mod base4;
mod bitwise_adder;
```

Listing D.36: smt_lib/encodings/generic_shared.rs

```
use std::error::Error;
use crate::sha::StartVector;
use crate::smt_lib::smt_lib::SmtBuilder;
use crate::smt_lib::utilities::{get_previous_var, msg_prefix, smt_hex};
use crate::structs::collision_type::CollisionType;


impl SmtBuilder {
  pub(super)  fn title(&mut self, title: &str) {
    let break_like = if self.smt.len() != 0 {"\n\n"} else {""};
    self.smt += format!("{break_like};; {title}\n").as_str();
  }

  pub(super) fn comment(&mut self, comment: &str) {
    self.smt += format!("; {comment}\n").as_str();
  }

  pub(super) fn break_line(&mut self) {
    self.smt += "\n";
  }

  pub(super) fn set_logic(&mut self) {
    self.smt += "(set-option :produce-models true)\n(set-logic QF_BV)\n";
  }

  pub(super) fn define_word_type(&mut self) {
    let bit_size = self.hash_function.word_size().bits();
    self.smt += &format!("(define-sort Word () (_ BitVec {bit_size}))\n");
  }
```

```rust

pub(super) fn define_functions(&mut self) -> Result<(), Box<dyn Error>> {
  let word_size = self.hash_function.word_size().bits();
  let simplified = self.encoding.simplified_maj_and_ch_functions();

  // MAJ & CH simplification
  let ch = if simplified {
    "(define-fun ch ((e Word) (f Word) (g Word)) Word\n\t(bvor (bvand e f) (bvand (
        bvnot e) g))\n)"
  } else {
    "(define-fun ch ((e Word) (f Word) (g Word)) Word\n\t(bvxor (bvand e f) (bvand (
        bvnot e) g))\n)"
  };

  let maj = if simplified {
    "(define-fun maj ((a Word) (b Word) (c Word)) Word\n\t(bvor (bvand a b) (bvand a c)
        (bvand b c))\n)"
  } else {
    "(define-fun maj ((a Word) (b Word) (c Word)) Word\n\t(bvxor (bvand a b) (bvand a c
        ) (bvand b c))\n)"
  };

  if self.encoding.alternative_add() {
    self.comment("Append bitwise adder and helpers if necessary");
    self.smt += &self.define_bitwise_add();
    self.break_line();
  }

  // ALT ADD
  let t1_add = self.add(vec!["h", "(sigma1 e)", "(ch e f g)", "k", "w"])?;
  let t2_add = self.add(vec!["(sigma0 a)", "(maj a b c)"])?;
  let expand_message_add = self.add(vec!["a", "(gamma0 b)", "c", "(gamma1 d)"])?;

  let sigma0 = "(define-fun sigma0 ((a Word)) Word\n\t(bvxor ((_ rotate_right 2) a) ((_
      rotate_right 13) a) ((_ rotate_right 22) a))\n)";
  let sigma1 = "(define-fun sigma1 ((e Word)) Word\n\t(bvxor ((_ rotate_right 6) e) ((_
      rotate_right 11) e) ((_ rotate_right 25) e))\n)";
  let gamma0 = format!("(define-fun gamma0 ((x Word)) Word\n\t(bvxor ((_ rotate_right
      7) x) ((_ rotate_right 18) x) (bvlshr x (_ bv3 {word_size}))))\n)");
  let gamma1 = format!("(define-fun gamma1 ((x Word)) Word\n\t(bvxor ((_ rotate_right
      17) x) ((_ rotate_right 19) x) (bvlshr x (_ bv10 {word_size}))))\n)");
  let t1 = format!("(define-fun t1 ((h Word) (e Word) (f Word) (g Word) (k Word) (w
      Word)) Word\n\t{t1_add}\n)");
  let t2 = format!("(define-fun t2 ((a Word) (b Word) (c Word)) Word\n\t{t2_add}\n)");
  let expand_message = format!("(define-fun expandMessage ((a Word) (b Word) (c Word) (
      d Word)) Word\n\t{expand_message_add}\n)");

  self.smt += &format!("{ch}\n{maj}\n{sigma0}\n{sigma1}\n{gamma0}\n{gamma1}\n{t1}\n{t2
      }\n{expand_message}");
  Ok(())
}

pub(super) fn define_constants(&mut self) {
  if self.rounds == 0 {
    self.comment("K constants irrelevant for 0 rounds");
    return;
  }

  self.comment("Define K constants");
```

```
    let k = self.hash_function.get_constant();

    // Only k[i] constants required, where i is number of compression rounds
    // Therefore, we only take the number of rounds required

    let mut s = String::new();
    for (i, val) in k.iter().take(self.rounds as usize).enumerate() {
      s += &format!("(define-fun k{i} () Word {})\n", smt_hex(*val, &self.hash_function))
    };

    self.smt += &s;
  }

  pub(super) fn define_expansion_for_message(&mut self, message: u8) {
    self.comment(&format!("MESSAGE {message}"));
    let msg = format!("m{message}_w");

    // Only w[i] required, where i is number of compression rounds
    // Therefore, we only take the number of rounds required, and initialize the first 16
        as 0.

    self.comment("Initial state");
    let mut s = String::new();
    for i in 0..self.rounds.min(16) {
      if i < self.rounds.min(16) {
        s += &format!("(declare-fun {msg}{i} () Word)\n");
      } else {
        s += &format!(
          "(define-fun {msg}{i} () Word {}) ; Irrelevant for {} rounds\n",
          smt_hex(self.hash_function.default_word(), &self.hash_function),
          self.rounds,
        );
      }
    }
    self.smt += &s;

    if self.rounds <= 16 {
      self.comment(&format!("Message expansion irrelevant for {} rounds", self.rounds));
    } else {
      self.break_line();
      self.comment("Message expansion");
      for i in 16..self.rounds {
        self.smt += &format!(
          "(define-fun {msg}{i} () Word (expandMessage {msg}{} {msg}{} {msg}{} {msg}{}))\
              n",
          i - 16, i - 15, i - 7, i - 2
        )
      }
    }
  }

  pub(super) fn define_compression_for_message(&mut self, message: u8) -> Result<(), Box<
      dyn Error>> {
    self.comment(&format!("MESSAGE {message}"));

    let mut s = String::new();
    for i in 1..=self.rounds {
      let prev = i - 1;
      let msg = &msg_prefix(message, prev.into(), self.collision_type);
```

```
134
135       s.push_str(&format!("(define-fun␣m{message}_t1_{i}␣()␣Word␣(t1␣{msg}h{prev}␣{msg}e{
              prev}␣{msg}f{prev}␣{msg}g{prev}␣k{prev}␣m{message}_w{prev}))\n\
136 ␣␣␣␣␣␣␣␣(define-fun␣m{message}_t2_{i}␣()␣Word␣(t2␣{msg}a{prev}␣{msg}b{prev}␣{msg}c{prev})
    )\n"));
137
138       for var in 'a'..='h' {
139         if var == 'a' {
140           let a_add = self.add(vec![
141             &format!("m{message}_t1_{i}"),
142             &format!("m{message}_t2_{i}"),
143           ])?;
144
145           s.push_str(&format!("(define-fun␣m{message}_{var}{i}␣()␣Word␣{a_add})\n"))
146         } else if var == 'e' {
147           let e_add = self.add(vec![
148             &format!("{msg}d{prev}"),
149             &format!("m{message}_t1_{i}"),
150           ])?;
151
152           s.push_str(&format!("(define-fun␣m{message}_{var}{i}␣()␣Word␣{e_add})\n"))
153         } else {
154           let prev_var = get_previous_var(var);
155           s.push_str(&format!("(define-fun␣m{message}_{var}{i}␣()␣Word␣{msg}{prev_var}{
                prev})\n"))
156         }
157       }
158     }
159
160     self.smt += &s;
161     Ok(())
162   }
163
164   pub(super) fn define_initial_vector(&mut self) {
165     self.comment("Define␣H␣constants␣(IV/CV)");
166     use crate::structs::collision_type::CollisionType::*;
167
168     let iv_vec = StartVector::IV.get_vector(self.hash_function);
169     let mut s = String::new();
170     for (i, var) in ('a'..='h').enumerate() {
171       s += &match self.collision_type {
172         Standard => format!("(define-fun␣{var}0␣()␣Word␣{})\n", smt_hex(iv_vec[i], &self.
              hash_function)),
173         SemiFreeStart => format!("(declare-fun␣{var}0␣()␣Word)\n"),
174         FreeStart => format!("(declare-fun␣m0_{var}0␣()␣Word)\n(declare-fun␣m1_{var}0␣()␣
              Word)\n"),
175       }
176     }
177
178     self.smt += &s;
179   }
180
181   pub(super) fn final_state_update(&mut self) -> Result<(), Box<dyn Error>> {
182     self.comment("Final␣state␣update");
183
184     let final_size = self.hash_function.truncate_to_length().unwrap_or(8);
185     for (i, var) in ('a'..='h').take(final_size).enumerate() {
186       for m in 0..2 {
187         let msg_round0 = msg_prefix(m, 0, self.collision_type);
```

```
188         let msg = msg_prefix(m, self.rounds.into(), self.collision_type);
189
190         let state_update_add = self.add(vec![
191           &format!("{msg_round0}{var}0"),
192           &format!("{msg}{var}{round}", round = self.rounds)
193         ])?;
194
195         self.smt += &format!("(define-fun m{m}_hash{i} () Word {state_update_add})\n");
196       }
197     }
198     Ok(())
199   }
200
201   pub(super) fn check_sat(&mut self) {
202     self.title("GO!");
203     self.smt += "(check-sat)\n";
204   }
205
206   pub(super) fn get_full_model(&mut self) {
207     self.title("GET OUTPUT");
208
209     self.comment("H Constants (IV/CV)");
210     let mut h = String::new();
211     for var in 'a'..='h' {
212       if self.collision_type == CollisionType::FreeStart {
213         h += &format!("m0_{var}0 m1_{var}0 ");
214       } else {
215         h += &format!("{var}0 ");
216       }
217     }
218     self.smt += &format!("(get-value ({}))\n", h.trim());
219     self.break_line();
220
221     self.comment("Output hash");
222     let final_size = self.hash_function.truncate_to_length().unwrap_or(8);
223     let mut hash = String::new();
224     for i in 0..final_size {
225       hash += &format!("m0_hash{i} ");
226     }
227     self.smt += &format!("(get-value ({}))\n", hash.trim());
228
229     if self.rounds == 0 {
230       return;
231     }
232
233     self.break_line();
234     self.comment("Output round A/E/W state changes");
235     let mut s = String::new();
236     for i in 0..self.rounds {
237       for var in ['a', 'e', 'w'] {
238         if i == 0 && self.collision_type != CollisionType::FreeStart && var != 'w' {
239           s += &format!("{var}{i} ");
240         } else {
241           for m in 0..2 {
242             s += &format!("m{m}_{var}{i} ");
243           }
244         }
245       }
246     }
```

```
    self.smt += &format!("(get-value␣({}))\n", s.trim());
  }
}
```

Listing D.37: smt_lib/encodings/differential_shared.rs

```
use std::error::Error;
use crate::smt_lib::smt_lib::SmtBuilder;
use crate::structs::collision_type::CollisionType;


impl SmtBuilder {
  pub(super) fn define_calculated_differential_initial_vector(
    &mut self
  ) -> Result<(), Box<dyn Error>> {
    let encoding = self.encoding.clone();
    let diff = encoding.get_diff()?;
    self.comment("Initial␣Vector␣difference");

    let word_size = self.hash_function.word_size().bits();
    for var in 'a'..='h' {
      if self.collision_type == CollisionType::FreeStart {
        self.smt += &format!("(define-fun␣delta_{var}0␣()␣Word␣({diff}␣m0_{var}0␣m1_{var
            }0))\n");
      } else {
        self.smt += &format!("(define-fun␣delta_{var}0␣()␣Word␣#b{})\n", "0".repeat(
            word_size));
      }
    }

    Ok(())
  }

  pub(super) fn define_differential_words(&mut self) -> Result<(), Box<dyn Error>> {
    let encoding = self.encoding.clone();
    let diff = encoding.get_diff()?;

    self.define_expansion_for_message(0);
    self.break_line();
    self.define_expansion_for_message(1);
    self.break_line();

    self.comment("Message␣Differential␣(W)");
    for i in 0..self.rounds.min(16) {
      self.smt += &format!("(define-fun␣delta_w{i}␣()␣Word␣({diff}␣m0_w{i}␣m1_w{i}))\n");
    }

    if self.rounds <= 16 {
      self.comment(&format!("Message␣expansion␣differentials␣irrelevant␣for␣{}␣rounds",
          self.rounds));
    } else {
      self.break_line();
      self.comment("Message␣Expansion␣Assertions");
      for i in 16..self.rounds {
        self.smt += &format!(
          "(define-fun␣delta_w{i}␣()␣Word␣(expandMessage␣delta_w{}␣delta_w{}␣delta_w{}␣
              delta_w{}))",
          i - 16, i - 15, i - 7, i - 2
        );
```

```
      }
    }

    Ok(())
  }

  pub(super) fn define_differential_for_working_variables(
    &mut self
  ) -> Result<(), Box<dyn Error>> {
    let encoding = self.encoding.clone();
    let diff = encoding.get_diff()?;
    self.comment("Variable Differential");

    for i in 1..=self.rounds {
      for var in 'a'..='h' {
        self.smt += &format!(
          "(define-fun delta_{var}{i} () Word ({diff} m0_{var}{i} m1_{var}{i}))\n"
        );
      }
    }

    Ok(())
  }

  pub(super) fn define_differential_final_state(&mut self) -> Result<(), Box<dyn Error>>
      {
    let encoding = self.encoding.clone();
    let diff = encoding.get_diff()?;
    self.comment("Final state difference");

    let final_size = self.hash_function.truncate_to_length().unwrap_or(8);
    for i in 0..final_size {
      self.smt += &format!("(define-fun delta_hash{i} () Word ({diff} m0_hash{i} m1_hash{
          i}))\n");
    }

    Ok(())
  }

  pub(super) fn assert_initial_vector_different(&mut self) {
    self.comment("Assert starting vector different");

    let word_size = self.hash_function.word_size().bits();
    let mut s = String::new();
    for var in 'a'..='h' {
      s += &format!("\t(distinct delta_{var}0 #b{})\n", "0".repeat(word_size));
    }

    self.smt += &format!("(assert (or\n{s}))\n");
  }

  pub(super) fn assert_message_difference(&mut self) {
    self.comment("Assert messages not the same");
    let word_size = self.hash_function.word_size().bits();

    let mut s = String::new();
    for i in 0..self.rounds.min(16) {
      s += &format!("\t(distinct delta_w{i} #b{})\n", "0".repeat(word_size));
    }
```

```
107
108     if self.rounds == 1 {
109       self.smt += &format!("(assert\n{s})\n");
110     } else if self.rounds > 1 {
111       self.smt += &format!("(assert␣(or\n{s}))\n");
112     }
113   }
114
115   pub(super) fn assert_hash_difference_equal(&mut self) {
116     self.comment("Assert␣difference␣in␣output␣hash␣is␣none");
117
118     let word_size = self.hash_function.word_size().bits();
119     let final_size = self.hash_function.truncate_to_length().unwrap_or(8);
120     let mut s = String::new();
121     for i in 0..final_size {
122       s += &format!("\t(=␣delta_hash{i}␣#b{})\n", "0".repeat(word_size));
123     }
124
125     self.smt += format!("(assert␣(and\n{s}))\n").as_str();
126   }
127 }
```

Listing D.38: smt_lib/encodings/dsub.rs

```
1  use std::error::Error;
2  use crate::smt_lib::smt_lib::SmtBuilder;
3  use crate::structs::collision_type::CollisionType;
4
5
6  impl SmtBuilder {
7    pub fn dsub_encoding(&mut self) -> Result<(), Box<dyn Error>>  {
8      self.title("SETUP");
9      self.set_logic();
10
11     self.title("TYPE");
12     self.define_word_type();
13
14     self.title("FUNCTIONS");
15     self.define_functions()?;
16
17     self.title("CONSTANTS");
18     self.define_constants();
19     self.break_line();
20     self.define_initial_vector();
21     self.define_calculated_differential_initial_vector()?;
22
23     self.title("MESSAGE␣EXPANSION");
24     self.define_differential_words()?;
25
26     self.title("MESSAGE␣COMPRESSION");
27     self.define_compression_for_message(0)?;
28     self.break_line();
29     self.define_compression_for_message(1)?;
30     self.break_line();
31     self.define_differential_for_working_variables()?;
32
33     self.break_line();
34     self.final_state_update()?;
35     self.break_line();
```

```
    self.define_differential_final_state()?;

    self.title("ASSERTIONS");
    if self.collision_type == CollisionType::FreeStart {
      self.assert_initial_vector_different();
    } else {
      self.assert_message_difference();
    }
    self.break_line();

    self.assert_hash_difference_equal();

    self.check_sat();
    self.get_full_model();

    Ok(())
  }
}
```

Listing D.39: smt_lib/encodings/dxor.rs

```
use std::error::Error;
use crate::smt_lib::smt_lib::SmtBuilder;
use crate::structs::collision_type::CollisionType;


impl SmtBuilder {
  pub fn dxor_encoding(&mut self) -> Result<(), Box<dyn Error>> {
    self.title("SETUP");
    self.set_logic();

    self.title("TYPE");
    self.define_word_type();

    self.title("FUNCTIONS");
    self.define_functions()?;

    self.title("CONSTANTS");
    self.define_constants();
    self.break_line();
    self.define_initial_vector();
    self.define_calculated_differential_initial_vector()?;

    self.title("MESSAGE␣EXPANSION");
    self.define_differential_words()?;

    self.title("MESSAGE␣COMPRESSION");
    self.define_compression_for_message(0)?;
    self.break_line();
    self.define_compression_for_message(1)?;
    self.break_line();
    self.define_differential_for_working_variables()?;

    self.break_line();
    self.final_state_update()?;
    self.break_line();
    self.define_differential_final_state()?;

    self.title("ASSERTIONS");
```

```
    if self.collision_type == CollisionType::FreeStart {
      self.assert_initial_vector_different();
    } else {
      self.assert_message_difference();
    }
    self.break_line();

    self.assert_hash_difference_equal();

    self.check_sat();
    self.get_full_model();

    Ok(())
  }
}
```

Listing D.40: smt_lib/encodings/brute_force.rs

```
use std::error::Error;
use crate::smt_lib::smt_lib::SmtBuilder;
use crate::structs::collision_type::CollisionType;


impl SmtBuilder {
  fn assert_initial_vector_not_same(&mut self) {
    self.comment("Assert starting vectors (CV) not the same");

    let mut s = String::new();
    for var in 'a'..='h' {
      s += &format!("\t(distinct m0_{var}0 m1_{var}0)\n")
    }

    self.smt += &format!("(assert (or\n{s}))\n");
  }

  fn assert_messages_not_same(&mut self) {
    self.comment("Assert messages not the same");

    let mut s = String::new();
    for i in 0..self.rounds.min(16) {
      s += &format!("\t(distinct m0_w{i} m1_w{i})\n");
    }

    if self.rounds == 1 {
      self.smt += &format!("(assert\n{s})\n");
    } else if self.rounds > 1 {
      self.smt += &format!("(assert (or\n{s}))\n");
    }
  }

  fn assert_hash_same(&mut self) {
    self.comment("Assert output hash is the same");

    let final_size = self.hash_function.truncate_to_length().unwrap_or(8);
    let mut s = String::new();
    for i in 0..final_size {
      s += &format!("\t(= m0_hash{i} m1_hash{i})\n");
    }

```

```
    self.smt += format!("(assert␣(and\n{s}))\n").as_str();
  }

  pub fn brute_force_encoding(&mut self) -> Result<(), Box<dyn Error>>{
    self.title("SETUP");
    self.set_logic();

    self.title("TYPE");
    self.define_word_type();

    self.title("FUNCTIONS");
    self.define_functions()?;

    self.title("CONSTANTS");
    self.define_constants();
    self.break_line();
    self.define_initial_vector();

    self.title("MESSAGE␣EXPANSION");
    self.define_expansion_for_message(0);
    self.break_line();
    self.define_expansion_for_message(1);

    self.title("MESSAGE␣COMPRESSION");
    self.define_compression_for_message(0)?;
    self.break_line();
    self.define_compression_for_message(1)?;
    self.break_line();
    self.final_state_update()?;

    self.title("ASSERTIONS");
    if self.collision_type == CollisionType::FreeStart {
      self.assert_initial_vector_not_same();
    } else {
      self.assert_messages_not_same();
    }
    self.break_line();

    self.assert_hash_same();

    self.check_sat();
    self.get_full_model();
    Ok(())
  }
}
```

Listing D.41: smt_lib/encodings/base4.rs

```
use std::error::Error;
use crate::smt_lib::smt_lib::SmtBuilder;
use crate::structs::collision_type::CollisionType;

#[allow(unreachable_code)]
#[allow(dead_code)]
impl SmtBuilder {
  fn define_base4_differential_constants(&mut self) {
    self.comment("Define␣K␣constant␣differential");

    let word_size = self.hash_function.word_size().bits();
```

```
    for i in 0..self.rounds {
      self.smt += &format!(
        "(define-fun␣delta_k{i}_A␣()␣Word␣#b{})\n",
        "0".repeat(word_size)
      );
      self.smt += &format!(
        "(define-fun␣delta_k{i}_B␣()␣Word␣#b{})\n",
        "0".repeat(word_size)
      );
      self.smt += &format!(
        "(define-fun␣delta_k{i}_C␣()␣Word␣#b{})\n",
        "0".repeat(word_size)
      );
      self.smt += &format!(
        "(define-fun␣delta_k{i}_D␣()␣Word␣#b{})\n",
        "0".repeat(word_size)
      );
      self.smt += &format!(
        "(define-fun␣delta_k{i}_E␣()␣Word␣#b{})\n",
        "0".repeat(word_size)
      );
      self.smt += &format!(
        "(define-fun␣delta_k{i}_F␣()␣Word␣#b{})\n",
        "0".repeat(word_size)
      );
      self.smt += &format!(
        "(define-fun␣delta_k{i}_G␣()␣Word␣#b{})\n",
        "0".repeat(word_size)
      );
    }
  }

  fn define_base4_differential_initial_vector(&mut self) {
    self.comment("Define␣H␣constant␣differential␣(IV/CV)");

    let word_size = self.hash_function.word_size().bits();
    for var in 'a'..='h' {
      if self.collision_type == CollisionType::Standard {
        self.smt += &format!(
          "(define-fun␣delta_{var}0␣()␣Word␣#b{})\n",
          "0".repeat(word_size));
      } else {
        self.smt += &format!("(declare-fun␣delta_{var}0␣()␣Word)\n");
      }
    }
  }

  // fn define_base4_differential_compression(&mut self) {
  //   for i in 1..=self.rounds {
  //     let prev = i - 1;
  //
  //     self.smt += &format!("(define-fun delta_t1_{i} () Word (t1 delta_h{prev} delta_e{
      prev} delta_f{prev} delta_g{prev} delta_k{prev} delta_w{prev}))\n\
  //       (define-fun delta_t2_{i} () Word (t2 delta_a{prev} delta_b{prev} delta_c{prev})
      )\n");
  //
  //     for var in 'a'..='h' {
  //       if var == 'a' {
  //         self.smt += &format!("(define-fun delta_{var}{i} () Word (bvadd delta_t1_{i}
```

```
    delta_t2_{i}))\n");
//      } else if var == 'e' {
//        self.smt += &format!("(define-fun delta_{var}{i} () Word (bvadd delta_d{prev}
     delta_t1_{i}))\n");
//      } else {
//        let prev_var = get_previous_var(var);
//        self.smt += &format!("(define-fun delta_{var}{i} () Word delta_{prev_var}{
    prev})\n");
//      }
//    }
//  }
// }
//
// fn define_base4_differential_hash_state(&mut self) {
//  self.comment("Final state difference");
//
//  let max_round = self.rounds;
//  let final_size = self.hash_function.truncate_to_length().unwrap_or(8);
//  for (i, var) in ('a'..='h').take(final_size).enumerate() {
//    self.smt += &format!("(define-fun delta_hash{i} () Word (bvadd delta_{var}0
    delta_{var}{max_round}))\n");
//  }
// }
//
// fn get_base4_full_model_differential(&mut self) {
//  self.title("GET OUTPUT");
//
//  self.comment("Input message");
//  let mut message = String::new();
//  for i in 0..=self.rounds.min(7) {
//    message += &format!("m0_w{i} m1_w{i} ");
//  }
//  self.smt += &format!("(get-value ({}))\n", message.trim());
//
//  if self.rounds == 0 {
//    return;
//  }
//
//  self.break_line();
//  self.comment("Output round A/E/W state changes");
//  let mut s = String::new();
//  for i in 0..self.rounds {
//    for var in ['a', 'e', 'w'] {
//      if i == 0 && self.collision_type != CollisionType::FreeStart && var != 'w' {
//        s += &format!("delta_{var}{i} ");
//      } else {
//        s += &format!("delta_{var}{i} ");
//      }
//    }
//  }
//  self.smt += &format!("(get-value ({}))\n", s.trim());
// }

pub fn base4_encoding(&mut self) -> Result<(), Box<dyn Error>> {
  todo!(); //TODO: Implement
  self.title("SETUP");
  self.set_logic();

  self.title("TYPE");
```

```
    self.define_word_type();

    self.title("FUNCTIONS");
    self.define_functions()?;

    self.title("CONSTANTS");
    self.define_base4_differential_constants();
    self.break_line();
    self.define_base4_differential_initial_vector();

    self.title("MESSAGE␣EXPANSION");
    // self.define_differential_words();

    self.title("MESSAGE␣COMPRESSION");
    // self.define_base4_differential_compression();

    // self.break_line();
    // self.define_base4_differential_hash_state();

    self.title("ASSERTIONS");
    // if self.collision_type == CollisionType::FreeStart {
    //  self.assert_initial_vector_different();
    // } else {
    //  self.assert_message_difference();
    // }
    // self.break_line();

    // self.assert_hash_difference_equal();

    self.check_sat();
    self.get_full_model();

    Ok(())
  }
}
```

Listing D.42: smt_lib/encodings/bitwise_adder.rs

```
use std::error::Error;
use crate::smt_lib::smt_lib::SmtBuilder;


fn bvadd(exprs: Vec<&str>) -> String {
  let mut s = String::from("(bvadd");
  for expr in exprs {
    s.push_str(&format!("␣{expr}"))
  }
  s.push(')');
  s
}

fn bitwise_add(exprs: Vec<&str>) -> String {
  if exprs.len() > 6 {
    unimplemented!("Bitwise␣add␣only␣implemented␣up␣to␣6␣expressions.")
  }

  let mut s = String::from(format!("(bitadd-{}␣", exprs.len()));

  for (i, expr) in exprs.iter().enumerate() {
```

```
    if i != 0 {
      s.push(' ');
    }
    s.push_str(expr);
  }
  s.push(')');
  s
}

impl SmtBuilder {
  pub(super) fn define_bitwise_add(&self) -> String {
    String::from("(define-fun␣bitadd-2␣((a␣(_␣BitVec␣32))␣(b␣(_␣BitVec␣32)))␣(_␣BitVec␣32)
␣␣␣␣(let␣(
␣␣␣␣␣␣(p0␣(bvxor␣a␣b))
␣␣␣␣␣␣(g0␣(bvand␣a␣b))
␣␣␣␣)
␣␣␣␣(
␣␣␣␣␣␣let␣(
␣␣␣␣␣␣␣␣(g1␣(bvor␣g0␣(bvand␣p0␣(bvshl␣g0␣#x00000001))))
␣␣␣␣␣␣␣␣(p1␣(bvand␣p0␣(bvshl␣p0␣#x00000001)))
␣␣␣␣␣␣)
␣␣␣␣␣␣(
␣␣␣␣␣␣␣␣let␣(
␣␣␣␣␣␣␣␣␣␣(g2␣(bvor␣g1␣(bvand␣p1␣(bvshl␣g1␣#x00000002))))
␣␣␣␣␣␣␣␣␣␣(p2␣(bvand␣p1␣(bvshl␣p1␣#x00000002)))
␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣(
␣␣␣␣␣␣␣␣␣␣let␣(
␣␣␣␣␣␣␣␣␣␣␣␣(g3␣(bvor␣g2␣(bvand␣p2␣(bvshl␣g2␣#x00000004))))
␣␣␣␣␣␣␣␣␣␣␣␣(p3␣(bvand␣p2␣(bvshl␣p2␣#x00000004)))
␣␣␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣␣␣(
␣␣␣␣␣␣␣␣␣␣␣␣let␣(
␣␣␣␣␣␣␣␣␣␣␣␣␣␣(g4␣(bvor␣g3␣(bvand␣p3␣(bvshl␣g3␣#x00000008))))
␣␣␣␣␣␣␣␣␣␣␣␣␣␣(p4␣(bvand␣p3␣(bvshl␣p3␣#x00000008)))
␣␣␣␣␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣␣␣␣␣(
␣␣␣␣␣␣␣␣␣␣␣␣␣␣let␣(
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣(g5␣(bvor␣g4␣(bvand␣p4␣(bvshl␣g4␣#x00000010))))
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣(p5␣(bvand␣p4␣(bvshl␣p4␣#x00000010)))
␣␣␣␣␣␣␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣␣␣␣␣␣␣(
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣let␣(
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣(g6␣(bvor␣g5␣(bvand␣p5␣(bvshl␣g5␣#x00000020))))
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣(p6␣(bvand␣p5␣(bvshl␣p5␣#x00000020)))
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣(
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣bvxor␣p0␣(bvshl␣g6␣#x00000001)
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣␣␣)
␣␣␣␣␣␣)
␣␣␣␣))
␣␣)

␣␣;␣Adder␣Helpers␣using␣some␣Walace␣Tree␣reduction␣principles
```

```
␣␣(define-fun␣bitadd-3␣((a␣(_␣BitVec␣32))␣(b␣(_␣BitVec␣32))␣(c␣(_␣BitVec␣32)))␣(_␣BitVec␣
    32)
␣␣␣␣(let␣(
␣␣␣␣␣␣␣(sum␣(bvxor␣a␣b␣c))
␣␣␣␣␣␣␣(carry␣(bvshl␣(bvor␣(bvand␣a␣b)␣(bvand␣a␣c)␣(bvand␣b␣c))␣#x00000001))
␣␣␣␣)
␣␣␣␣(
␣␣␣␣␣␣␣bitadd-2␣sum␣carry
␣␣␣␣))
␣␣)
␣␣(define-fun␣bitadd-4␣((a␣(_␣BitVec␣32))␣(b␣(_␣BitVec␣32))␣(c␣(_␣BitVec␣32))␣(d␣(_␣
    BitVec␣32)))␣(_␣BitVec␣32)
␣␣␣␣(let␣(
␣␣␣␣␣␣␣(sum␣(bvxor␣a␣b␣c))
␣␣␣␣␣␣␣(carry␣(bvshl␣(bvor␣(bvand␣a␣b)␣(bvand␣a␣c)␣(bvand␣b␣c))␣#x00000001))
␣␣␣␣)
␣␣␣␣(
␣␣␣␣␣␣␣bitadd-3␣sum␣carry␣d
␣␣␣␣))
␣␣)
␣␣(define-fun␣bitadd-5␣((a␣(_␣BitVec␣32))␣(b␣(_␣BitVec␣32))␣(c␣(_␣BitVec␣32))␣(d␣(_␣
    BitVec␣32))␣(e␣(_␣BitVec␣32)))␣(_␣BitVec␣32)
␣␣␣␣(let␣(
␣␣␣␣␣␣␣(sum1␣(bvxor␣a␣b␣c))
␣␣␣␣␣␣␣(carry1␣(bvshl␣(bvor␣(bvand␣a␣b)␣(bvand␣a␣c)␣(bvand␣b␣c))␣#x00000001))
␣␣␣␣␣␣␣(sum2␣(bvxor␣d␣e))
␣␣␣␣␣␣␣(carry2␣(bvshl␣(bvand␣d␣e)␣#x00000001))
␣␣␣␣)
␣␣␣␣(
␣␣␣␣␣␣␣bitadd-4␣sum1␣carry1␣sum2␣carry2
␣␣␣␣))
␣␣)
␣␣(define-fun␣bitadd-6␣((a␣(_␣BitVec␣32))␣(b␣(_␣BitVec␣32))␣(c␣(_␣BitVec␣32))␣(d␣(_␣
    BitVec␣32))␣(e␣(_␣BitVec␣32))␣(f␣(_␣BitVec␣32)))␣(_␣BitVec␣32)
␣␣␣␣(let␣(
␣␣␣␣␣␣␣(sum1␣(bvxor␣a␣b␣c))
␣␣␣␣␣␣␣(carry1␣(bvshl␣(bvor␣(bvand␣a␣b)␣(bvand␣a␣c)␣(bvand␣b␣c))␣#x00000001))
␣␣␣␣␣␣␣(sum2␣(bvxor␣d␣e␣f))
␣␣␣␣␣␣␣(carry2␣(bvshl␣(bvor␣(bvand␣d␣e)␣(bvand␣d␣f)␣(bvand␣e␣f))␣#x00000001))
␣␣␣␣)
␣␣␣␣(
␣␣␣␣␣␣␣bitadd-4␣sum1␣carry1␣sum2␣carry2
␣␣␣␣))
␣␣)")
  }

  pub(super) fn add(
    &self,
    exprs: Vec<&str>,
  ) -> Result<String, Box<dyn Error>> {
    if exprs.len() < 2 {
      return Err(Box::from("Add␣requires␣at␣least␣2␣expressions!"));
    }

    if self.encoding.alternative_add() {
      Ok(bitwise_add(exprs))
    } else {
      Ok(bvadd(exprs))
    }
```

```
135     }
136 }
```

Appendix E

Screenshots of Product Running

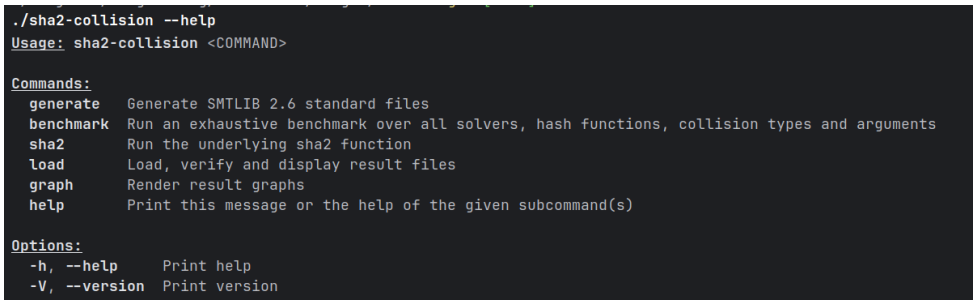


Figure E.1: Help output of main command.

Figure E.2: Help output of `benchmark` subcommand.

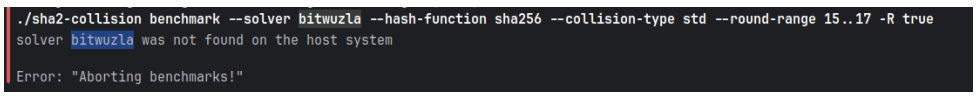


Figure E.3: An example output of constraint error, representing an error showing that the user has not installed the solver for the benchmark to run.

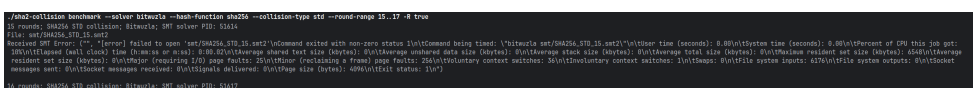


Figure E.4: An example output of a failed collision due to an SMT error. The error states that the smt2 file does not exist, as thrown by the solver, along with metadata, console output and additional context information.

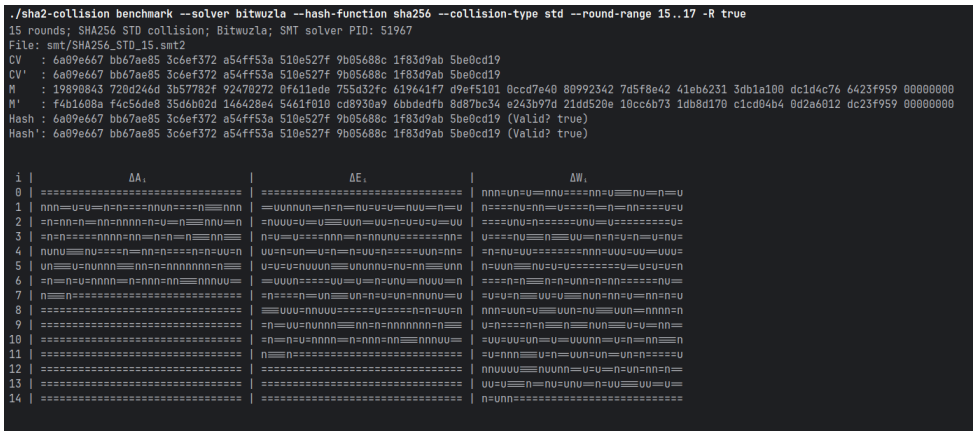


Figure E.5: An example output of a found collision.

Appendix F

Test Results

The supplied software package consists of 30 unit tests, predominantly designed to affirm the accuracy of the internal sha implementation against established standards.

Listing F.1: `cargo test` Results Output

```
running 30 tests
test sha::sha::tests::test_padding ... ok
test sha::sha::tests::test_dual_cv_collision_sha224 ... ok
test sha::sha::tests::test_sha224_correctness ... ok
test sha::sha::tests::test_sha256_correctness ... ok
test sha::sha::tests::test_sha256_round_difference ... ok
test sha::sha::tests::test_sha512_correctness ... ok
test sha::sha::tests::test_sha512_round_difference ... ok
test sha::sha::tests::test_single_cv_collision_sha256 ... ok
test sha::sha::tests::test_single_cv_collision_sha512 ... ok
test sha::sha::tests::test_too_many_rounds ... ok
test sha::structs::tests::test_word_ch ... ok
test sha::structs::tests::test_word_from_be_bytes ... ok
test sha::structs::tests::test_word_gamma0 ... ok
test sha::structs::tests::test_word_gamma1 ... ok
test sha::structs::tests::test_word_maj ... ok
test sha::structs::tests::test_word_sigma0 ... ok
test sha::structs::tests::test_word_sigma1 ... ok
test sha::structs::tests::test_word_wrapping_add ... ok
test structs::size::tests::test_bits ... ok
test structs::size::tests::test_bytes ... ok
test structs::size::tests::test_from_bits ... ok
test structs::size::tests::test_from_bytes ... ok
test structs::size::tests::test_non_full_bytes ... ok
test verification::bit_differential::test::test_differential_boxed_slice ... ok
test verification::bit_differential::test::test_differential_different ... ok
test verification::bit_differential::test::test_differential_same ... ok
test verification::bit_differential::test::test_differential_slice ... ok
test verification::verification::tests::test_sha256_state_collision_table ... ok
test verification::verification::tests::test_sha224_state_collision_table ... ok
test verification::verification::tests::test_sha512_state_collision_table ... ok

test result: ok. 30 passed; 0 failed; 0 ignored; 0 measured; 0 filtered out; finished in
    0.00s
```

Appendix G

Software Installation Guide

A comprehensive guide is available in the `README.md` file of the source code, accessible both on GitHub and via the submission.