Implementing SAT Algorithms in Software

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Abstract

The Boolean Satisfiability Problem is a fundamental part of Computer Science. First proven to be an NP-Complete problem by both Stephen Cook in 1971[1], and Leonid Levin in 1973[2]. Since then, many more NP-Complete problems have been identified, along with their respective uses in the real world outside of pure computer science. Due to this, there has been a growing need for solvers that can effectively and efficiently process these problems. In the last two decades alone, huge progress has been made to coincide with the advancements in technology. And more SAT solvers have appeared that can be deployed in industries where they are most needed.

This paper explores the basic concept behind SAT solvers, and how they can be implemented in software using modern programming languages and tools. The algorithm that will be implemented is one proposed by Donald Knuth in his book "The Art of Computer Programming". Knuth proposes many algorithms, ranging from the most basic backtracking based algorithm, to an advanced implementation of Walk-SAT[!]. We will explore the fundamentals of how to implement these algorithms, implement one of them, then test its performance against a suite of SAT problems.

The result of this paper will be a SAT solver implemented in C++, using the data structures and steps provided by Donald Knuth in his book "The Art of Computer Programming".

Contents

1   Introduction

Satisfiability has presented itself a huge area of research throughout the history of computer science. Being the first proved to be NP-Complete in 1971[1], it has been the go-to for complex computation. And using reduction techniques pioneered in the mid-twentieth century, many other types of complex problems can be converted into SAT and solved using the plethora of solvers freely available. In more recent years, SAT competitions have added an incentive to the development of more advanced solvers, such as Minisat, zChaff, and CaDiCaL. On top of these, parallel solvers have gained popularity and one such solver, called Plingaling, ranked very highly in the SAT Competition 2020. Showing how parallel solvers can be just as good as their counterparts, if not better.

Donald Knuth has taken particular interest in this topic with his recent chapter of "The Art of Computer Programming". He discusses how important SAT solvers are to both industry and research, as well as providing algorithms and sample problems to test them against.

This paper will be an exploration into the world of SAT solvers and how they can provide crucial services to both industry and research. As well as methods in which proposed SAT solver algorithms can be implemented into a robust piece of software. Due to the sheer size of literature and research in this field, it would be unrealistic to think it is possible to cover everything in a comprehensive way. Therefore, this paper focuses on the fundamentals of SAT and the significant research through the years since Cooks paper in 1971[1]. As well as the ideas presented by Donald Knuth for implementation in modern programming languages.

1.1   Motivation

The motivation behind this project stems from the ever growing need for more efficient and faster SAT solvers. But in order to begin researching in this field, one must know the basics and tried methods present today. This project will do just that, in both studying literature that has formed the basis of most of the field, and implementing a basic SAT solver.

One of the most common arguments for the research into SAT solving is its viability for both science and industry. This presents a convenient compatibility between the two. As industry requirements grow, so too does the need for research into better algorithms to satisfy those requirements. An example in which SAT solvers are a key part of industry include Electronic Design Automation (or EDA). We will explore these usages further as we progress and highlight the advantages of fast SAT solvers when applied to these industries.

Another common viability for SAT solvers includes their usage for most complex problems that can be reduced to SAT. Most problems in the real world can be cast as optimisation problems. This allows us to create a mathematical description of these problems, which in turn can present themselves for solving. The use of a solver in

this instance would produce results which would allow for cost-saving or general efficiency improvements.

1.2   Aims and Objectives

To preface this project we must present the aims and objectives that we wish to aim for. As explained above, we do not wish to push the boundaries of SAT solvers in this particular project. But instead want to explore the basics and expand on current research. Aiding us in this goal will be the series by Donald Knuth, "The Art of Computer Programming". Knuth has recently taken interest in the concept of satisfiability for "Fascicle 6: Satisfiability" , and presents a large amount of content for us to analyse. In this book, Knuth outlines multiple algorithms that could be used to implement multiple common SAT solvers[3]. These include:

- Algorithm B - Backtracking with watched literals.

- Algorithm D - DPLL.

- Algorithm C - CDCL.

- Algorithm L - DPLL with lookahead.

- Algorithm W - WalkSAT.

We shall be analysing one of these algorithms and presenting the data structures needed and methods of implementation using C++. Once our implementation is complete, and testing has proved the solver to be working as intended, we will record the performance metrics in a scientific manner to ensure accuracy. These metrics will then be compared to other FOSS solvers that are well tested and commonly used. This will give us a benchmark as to how increasing complexity of the algorithm and program can achieve greater performance. As well as how the programming language chosen can effect the overall performance.

We can easily turn these actions into functional and non-functional requirements. Doing so will allow us to test against the requirements stated and compare the expected result to the actual result. This format matches a more "software engineering" approach, which is desired for this project.

1.2.1   FREQ1

The resulting software should be able to process an input CNF formula in the semi-standard DIMACS format.

1.2.2   FREQ2

The resulting software should be able to evaluate the satisfiability of a simple formula from FREQ1, and return the result when found. Simple refers to a formula which most

SAT solvers would be able to process in a short amount of time. Result refers to the decision returned from the solver that concludes as "SATISFIABLE" or "UNSATISFIABLE".

1.2.3   Non-Functional Requirements

These requirements differ from functional requirements as they are not crucial to the project's success. These are simply goals that, if time allows, can be implemented for further data.

1.2.4   NFREQ1

The resulting software should be able to process a complex formula within a reasonable amount of time. Reasonable refers to the length of time it takes to return a result when compared to other SAT solvers, i.e. 300 seconds to return "SATISFIABLE".

1.3   Methodology

This project is not being shared amongst a large team of engineers. This allows us to choose from a plethora of software methodologies that would typically not be considered. The usual norm is to commit to the AGILE methodology no matter the project. But for us we do not need the potentially cumbersome nature that can come from AGILE. We also need to consider the idea of rapid prototyping and development. For this reason, we have chosen to use the traditional Waterfall methodology. It gives us the general structure for the project, and fits well with our rigid requirements.

2   Background

Before we get into the implementation and software, it is always good to have a solid understanding of the topic at hand. SAT in particular is quite a deep topic, it is easy to spend a long time researching into all the intricacies[!]. For this paper, we will just be concentrating on the general concepts and ideas behind 3SAT problems.

- Maybe include some complex problem sets here?

2.1   SAT Fundamentals

2.2   3SAT

2.3   SAT From Other Problems

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2.4   Complete vs. Incomplete

When we talk about SAT solvers, they can be sorted into two categories; complete and incomplete. Complete solvers are

2.5   Modern SAT

Modern SAT solvers typically fall into two categories: *Conflict Driven Clause Learning* and local search based. Out of the two, CDCL solvers are the most commonly used. Local-search based solvers are usually not used as they are often not considered *complete*. Alongside this, they are usually slower than modern CDCL solvers. Outside of these two reasons, there are situations where local-search can be used on specific problems.

2.5.1   CDCL Solvers

Conflict Driven Clause Learning solvers are themselves an evolution of the original *Davis-Putnam-Logemann-Loveland* algorithm. A CDCL solver is normally both complete and sound. The difference between a traditional DPLL solver and a CDCL solver is the inclusion of *non-chronological backtracking*, or *backjumping*. This feature allows

the solver to determine at what point a variable assignment was made, and jump back multiple nodes to avoid running into the same conflict multple times.

The way in which we can implement this *backjumping* is by analysing the current conflict, often called *conflict clause.* This finds the earliest variable assignment that has lead to the conflict and jumps back to it. This conflict clause is then added to the problem to revisiting nodes within the search space that have already been visited.

3   Related Work

Moving on from the background of SAT, we can look into existing solutions that are freely available. As of 2020, there are plenty of FOSS programs that can be used to solve large sets of problems. This is in part due to the regularity of the SAT competitions that encourage people to build groundbreaking solvers.

3.1   Minisat

A popular and early solver that has won many competitions[!] is Minisat. Written in C++ and boasting just a mere few hundred lines of code, Minisat has been proven to be an effective tool for medium sized problem sets. First written in 2003 by Niklas Een[!] and Niklas Sorensson[!], its primary goal was to help developers and researchers get into the field of SAT solving by providing a simple interface and minimal codebase.

3.2   CryptoMiniSat

As the name suggests, this solver builds upon the foundations laid by Minisat to create an all in one solution to multiple problems. CryptoMiniSat implements most of the useful features from Minisat 2.0 core, along with PrecoSat and Glucose to try to make a one-stop solution. CryptoMiniSat is still in active development, hosting their code on GitHub for open collaboration.

This solver capitalises on modern techniques of using appropriate solvers for sections of a problem. By combining multiple solving algorithms

4   Design

- Summary of what we would want from a design.

- Include the algorithm from Donald Knuth (algorithm D).

- Discuss the data structures that we will need to implement based off of DK's ideas.

4.1   Algorithm D - Satisfiability by Cyclic DPLL

The key to all the most successful SAT solvers are the algorithms. The first SAT solver to be implemented for a computer used the DPLL algorithm[!]. As we previously established, the DPLL algorithm is considered one of the firsts and produced good results for the time. As of 2020, there have been a plethora of improvements to the original DPLL algorithm that has allowed it to keep up with the increasing complexity of problems available. The general pseudocode for the original DPLL algorithm can be written as such:

```
Algorithm DPLL
    Input: A set of clauses C
    Output: A truth value

Function DPLL(C)
    if C is a consistent set of literals then
        return true;
    if C contains an empty clause then
        return false;
    for every unit clause {L} in C do
        C ← unit-propagate(L, C);
    for every literal L that occurs pure in C do
        C ← pure-literal-assign(L, C);
    L ← choose-literal(C);
    return DPLL(C AND {L}) or DPLL(C AND {not(L)});
```

For our project, the algorithm that we will be interested in is a general DPLL algorithm. As previously discussed, this is just one of a few algorithms given from Donald Knuth. Although it is relatively simple, it is a good way to explore the basic idea of software SAT solvers. Forming a foundation for possible further improvements, much like those explained in algorithm L. Donald Knuth describes the algorithm in a series of steps, also outlining the data structures that we need to implement it as he has described. The following is the algorithm steps that are detailed by Knuth in his book:

1. Set $m_0 \leftarrow d \leftarrow h \leftarrow t \leftarrow 0$, and do the following for $k = n, n - 1, ..., 1$: Set $x_k \leftarrow -1$ (denoting an unset value); if $W_{2k} \neq 0$ or $W_{2k+1} \neq 0$, set NEXT(k) $\leftarrow h, h \leftarrow k$, and if $t = 0$ also set $t \leftarrow k$. Finally, if $t \neq 0$, complete the active ring by setting NEXT(t)$\leftarrow h$.

2. Terminate if $t = 0$ (all clauses are satisfied). Otherwise set $k \leftarrow t$.

This algorithm uses both unit

4.2   Algorithm L - Cyclic DPLL with Lookahead

This algorithms extends our initial version of Algorithm D by adding look-ahead procedures.

This algorithm will form the basis of our program and each step will be translated to appropriate code. This algorithm relies on the 'active ring' data structure that Knuth mentions previous to the algorithm. This active ring is key in the operations of the algorithm as we need to have a method of easily deleting and restoring variables in clauses. For C++, it is convienient for us to use the `std::vector` type when creating the data structure.

5   Implementation

The following will be an in-depth look at the steps we need to consider when implementing our project. Following the design, this section details the general input and output of the program. As well as the processing that forms the core of the solver. We will also outline the data structures that are to be implemented and how they will be integrated with the algorithm to culminate in a working SAT solver.

We will also be glazing over the tool-chain and related items that are to be used to create the solver. This includes the language and the compiler that will be used. As well as the editor and reasoning behind these choices.

5.1   Input

The input of the program will be a CNF formula presented in the DIMACS file format. This file format is the standard for the SAT competitions and allows for simple parsing of the problem. The format consists of few elements to ensure the problem is presented cleanly, the first of which being comments. Comments can be marked using the character 'c' followed by a single whitespace character:

```
c This is a comment line
```

Lines prefixed with this will be treated as a comment and thus will not be parsed as part of the problem. After the comments is a line telling the SAT solver about the problem it is about to ingest, denoted using the character 'p' followed by a single whitespace character.

```
p cnf 255 829
```

This line will include the type of problem, followed by the number of clauses then variables. Following the problem description line is the actual formula. This is presented by either a positive or negative integer, terminated with a '0'.

```
15 16 17 18 19 20 21 0
```

Each line corresponds to a clause formatted in the defined problem type. And each integer represents a unique variable. Using this format we can create consistent

problem files which our solver will be able to ingest and process easily. An example of a problem formatted in this format is presented below:

```
c pigeonhole 2 1
c label:unsatisfiable
c label:easy
p cnf 2 3
1 0
2 0
-1 -2 0
```

This input will be read line by line by the solvers parser, recording the key information that it needs. After successful parsing we can move on to the processing of this problem.

5.2   Processing

The processing section of the program pipeline is the most important here. This is where our algorithm will iterate through each variable and set them to either true or false. The way in which our program will go about this depends on the algorithm that we have chosen. In this instance we will explain how the cyclic DPLL algorithm presented by Donald Knuth will do this.

5.2.1   Initial Steps

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5.2.2   Unit Propagation

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5.2.3   Backtracking

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5.2.4   Watched Literals

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5.3   Output

The output of our program is just as important as the input. After all, we want to know how the solver has gotten to the solution it has ended at. Much like the input, we will be following a semi-standard format that is outlined at each SAT competition. Using this format will allow us to be consistent with how most SAT solvers output their solutions.

The format of the output is somewhat similar to the DIMACS format. In that each line is prefixed with a single character denoting its purpose, followed by a single whitespace character. The main difference here being that there is no particular order in which the lines must appear. There are three distinct types of lines in this format:

- 'c ': Denotes a comment line in which the program can output any auxilliary information.

- 's ': Denotes the line where the solution is presented. This must be either 'satisfiable', 'unsatisfiable', or 'unknown'. Only one instance of this line is allowed.

- 'v ': Denotes the values of the solution if one is found.

The resulting output should combine all three of these types to create a comprehensive result to the user. This includes the model that the solver has settled on if the solution is satisfiable. This will allow for the checking of the answer to ensure its correctness.

5.4   Data Structures

- Discuss why we're going to have to implement specific data types.

- Provide examples on the types of structures to be used.

5.5   Tool-chain

The following is a quick overview of the tool-chain that will be used for this project. As these aren't the meat of what the project is about, we shall only spend a short time glazing over the available solutions and those we picked.

5.5.1   Compiler & Libraries

There are multiple compilers available for C++ dependant on the platform. Generally for each of the three most common platforms (Windows, Linux, and MacOS) there are reliable and well tested compiler suites available. The GNU Compiler Collection, or GCC, is considered one of the standard compiler suites for C and C++. GCC has implementations for each of the aforementioned platforms via ports. The Windows implementation in particular is included in a few software development environments that are freely available; MinGW, MSYS2, and Cygwin.

As for Linux, the GCC suite can be installed natively typically using the preferred distro's package manager. For this project the code will be compiled on a Debian based system using the GCC suite. Linux provides a simpler method of developing using C / C++ and streamlines the time from development to testing. Alongside this, the included GDB debugger allows for a simple and lightweight debugging solution. We will also be making use of bash scripts to invoke the software and provide flags to control options, something that can be a little more challenging on a Windows machine.

No development will be carried out on a Macintosh as we simply do not have access to one. Typically these types of software are compiled and run using a Linux system, and thus it would make the most sense to follow the given norm.

5.5.2   Editor & Environment

There are a huge swathe of IDE's and editors available for use and as for which one to use, there isn't a definitive answer. We thought that it would be best to just stick with what we know best, and for this instance that would be Visual Studio Code. Although other IDE's are available that can take a lot of the work out of managing a project. It is not really necessary to use one here. This project will not contain a huge amount of code or files, and general debugging and profiling does not need to be done using bloated IDE's. Visual Studio Code contains a massive inventory of extensions available to give an experience just as rich as an IDE, but without the cumbersome

nature of one. As for this project we only need a single extension to get the required development environment:

- C / C++

It is also important to mention any other environment software aside from the previously mentioned. We are going to be using the `'time'` command to accurately measure the time metrics of the software from start to completion. This command is available through bash and is invoked at the same time as the program itself. An example of the method in which it can be invoked is as follows:

```
$ TIMEFMT=$'\nreal\t%E\nuser\t%U\nsys\t%S'
```

Figure 1: Command to achieve desired output format

We need to run this command first in order to achieve the desired format. This is only necessary as we are using the Z-Shell, but the command itself still works the same as traditional Bash. Using the time command we can effectively measure the time that it takes from invocation to completion in a consistent format. This is a simple alternative to implementing a time measuring system into the SAT solver, which could potentially make it less performant. An example of the usage of the time command is shown below:

```
$ time make bin/dpll
```

This command will invoke the 'make' binary to compile our program, called dpll. The output of this command will include both the output of the make command, as well as the time it took formatted to our previous rules:

```
real: 4.70s
user: 2.42s
 sys: 0.45s
```

5.6   Pseudocode & Code

- Investigate general pseudocode of generic DPLL algorithm (Wiki).
- Create some pseudocode from algorithm.
- Create some actual code to show?

6   Testing

As with all software, one of the most important parts of the development lifecycle is testing. For this project we must ensure that it not only works without fault, but also returns the correct results that we are looking for. In order to test our software we shall generate a plethora of testing criteria to test against. Each of these criteria will have an expected outcome. We will then compare the expected outcome to the actual outcome and record whether they are identical. Although this is a simple technique, it is hard to apply automated testing to our program as it is so niche.

As for ensuring the program returns correct results, the best way that we will be able to check is to use well known and reputable solvers to generate results and compare the two. This can also be added to the testing criteria and formatted in a table if preferred. The following will be the details of the testing strategy alongside the results.

6.1   Software Testing

There are a vast array of testing tools freely available to use for most software projects. These have been created from the need for automated testing due to programs changing rapidly. In this case, we do not need to deploy any advanced testing techniques or tools. As we have quite rigid requirements and a small codebase, keeping track of changes is somewhat trivial. Much like discussed in the initial sections of this paper, this is similar to the reasoning behind our choice of methodology. Therefore, let us create a simple suite of manual testing criteria.

6.2   Checking For Correct Solutions

Progressing from the program testing, we must also ensure the solver is returning correct results. This can also lead us to any bugs that may be present within the program. Using common SAT problems presented in the DIMACS format we can compare the results from our program to results from another solver. For statistical reasons we should ensure that each problem set is ran at least 10 times on each solver. To further back up the testing results we could run the same problems against a third solver. This would allow for comparison between each solver as a fall-back.

The first solver we will be using to ensure correctness is *Minisat*. This solver is one of the most tried and tested solvers freely available to use. And comes with plenty of features to allow each test set to be completed quickly. *Minisat* comes with a well documented interface that we can use to easily build and run our test sets.

The fall-back solver we will be using is *CryptoMiniSat*. This solver is still in active development and encorporates some of the most advanced features for a FOSS solver. Compared to *Minisat*, this solver is significantly more complex. It should give us safe results that we can use to ensure no descrepencies between our solver and *Minisat*.

Using the two mentioned solvers we can compare their results against our own. This is worth doing to make sure there are as little bugs as possible. The results for our testing are displayed below.

6.3   Monitoring Initial Performance Metrics

6.3.1   UNIX Time Command

There are multiple ways in which we could measure the performance of the solver. One easy way is measuring the CPU time that the solver takes to give a solution to the problem it is given. This is the reason we will be testing using the standard UNIX 'time' command. This command outputs three metrics; real, user, and system. Real corresponds to the 'wall clock' time that the program took. This refers to the actual time it took from invocation to completion whilst the CPU handles other processes. The 'user' time corresponds to the time the CPU spent on the program in User mode. Calls made in Kernel mode will not be reflected in this time. The 'sys' time corresponds to the time the CPU spent in Kernel mode when executing the program. These three metrics give us a good idea as to what the CPU spends the most time on when executing our program.

6.3.2   Memory Usage

Another method in which we can measure the performance of our solver is by keeping track of the memory that is used. Although this may not seem like a performance related metric, it can tell us about potential memory leaks which can in turn effect the general performance of the system. Aside from this, it is important to keep track of the memory usage as a method of judging the solver itself. Higher memory usage can indicate how many branches the solver is heading into before coming to its solution. Typically more complex solvers that contain multiple algorithms, to solve individual parts of the problem, can take up much less memory than a simpler one. The reason we add more complexity is to ensure that the solver knows when it should stop trying to branch in a particular direction. Less branching means we save a bit more memory and can sift through the problem much quicker.

7   Results

- Discuss what we found from our testing

8   Evaluation

- Discuss our findings statistically.

- Discuss how implemented code could be improved (summarise).

- Talk about the methodology we used.

- Talk about the risks encountered, and the time frame in which we carried this out.

- Discuss the things that could potentially be improved if we did the project again.

- Discuss the pandemic.

9   Future Work

- Explore performance implications of algorithm.

- Talk about DK's performance predictions from TAOCP.

- Talk about how we could potentially improve the performance of our solver.

- Maybe talk about things like parallelism?

9.1   Algorithm Performance

There are multiple improvements that are suggested by Donald Knuth to speed up the initial DPLL algorithm based solver. The first of which is already listed as one of his alternative algorithms. Algorithm L uses the lookahead concept to substantially speed up the standard DPLL algorithm. This concept

9.2   Pre-processing

One simple method that could greatly assist our solver is using a pre-processor. This will take the problem set and analyse it, and return a much simplified problem. This concept is applied accross modern solvers already, and is considered a vital part of the SAT solving system.

9.3   Parallel Solving

A more interesting concept is to capitalise on modern processor architectures, and the cheap availability of multi-core CPU's. It is commonplace to find consumer CPU's with at least 4 cores and hyper-threading. By taking advantage of this we can try to divide up the problem set and apply a solver to each smaller instance running on an individual thread. As usual with parallelism, this would not necessarily lead to a linear performance increase. It would require some research and engineering to determine the best way forward in order to achieve the desired results.

9.4 SIMD

Another interesting technique that could be applied to SAT solving is the use of SIMD instructions for data level parallelism. It has been shown in other applications that utilising SIMD instructions can quickly lead to almost linear performance improvements corresponding to each bit width of data processed. The most common SIMD instruction set is *SSE* (Streaming SIMD Extensions). Introduced in 1999 by Intel, it is now commonplace is all modern consumer x86 processors.

10   Challenges

As with any project there will always be some challenges faced that skew the planned timeline. The following details the problems that specifically effected this project and what could potentially be done to avoid facing these in the future.

10.1   Late Start

One of the first challenges that had effected this project was the late start. This was in part due to both personal obligations that could not be avoided. As well as in part due to the Coronavirus pandemic. Although this did not effect the overall project progressing, it did push the establised timeframe beyond what had been originally planned.

10.2   Coronavirus

The second major issues encountered was something completely out of our control. The Coronavirus pandemic of 2020 provided a massive slew of issues for all academia. Specifically for this project it meant the general plan for the project, as well as the time plan, were both interrupted. The general lockdown for the United Kingdom resulted in confinement to the home. The availability of face-to-face meetings proved to be unfavourable, and potential disruptions in the home delayed planned work.

10.3   Maths Heavy Topic

Another major issue encountered for this project was the lack of initial mathematical background. This topic is a rather maths heavy topic, with complex algorithms that can confuse most people who do not have strong mathematical skills. This lead to this project being delayed in certain phases where more time had to be spent to understand the maths involved.

10.4   C++ Learning Curve

The final major issue that was encountered in this project is the depth of knowledge required in the chosen programming language. Both C and C++ have a heavy learning curve associated with advanced usage. Like previously stated, this lead to some project phases being delayed due to the challenges of implementing theoretical concepts into program code.

11   Conclusion

- Just make a short summary of every single thing that was typed out above!

- Don't forget to basically copy and paste this to the abstract.

References

[1] S. Cook, "The complexity of theorem proving procedures," *Proceedings of the third annual ACM symposium on Theory of Computing*, pp. 151–158, 1971.

[2] L. Levin, "Universal search problems," *Problems of Information Transmission*, pp. 115–116, 1973.

[3] D. Knuth, *The Art of Computer Programming.* 2015.