A Time Leap Challenge for SAT-Solving

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Abstract

We compare the impact of hardware advancement and algorithm advancement for SATsolving over the last two decades. In particular, we compare 20-year-old SAT-solvers on new computer hardware with modern SAT-solvers on 20-year-old hardware. Our findings show that the progress on the algorithmic side has at least as much impact as the progress on the hardware side.

1 Introduction

The last decades have brought enormous technological progress and innovation. Two main factors that are undoubtedly key to this development are (i) *hardware advancement* and (ii) *algorithm advancement*. Moore's Law, the prediction made by Gordon Moore in 1965 [72], that the number of components per integrated circuit doubles every year, has shown to be astonishingly accurate for several decades. Given such an exponential improvement on the hardware side, one is tempted to overlook the progress on the algorithmic side.

This paper aims to compare the impact of hardware advancement and algorithm advancement based on a genuine problem, the propositional satisfiability problem (SAT). This problem is wellsuited for such a comparison since it is one of the first problems for which progress in solving has been measured regularly through competitions [54]. Also, a standardized instance format has been established very early. By focusing on this problem, the comparison allows us to fathom the SAT and CP community's contribution to the overall progress.

Of course, the advancements in hardware and algorithms cannot be separated entirely. Targeted algorithm engineering can use new hardware features [16, 22, 33, 56], and hardware development can be guided by the specific demands of modern algorithms. We are well aware that this can quickly end up in comparing apples and oranges. Nevertheless, we think that by carefully setting up the experiment and choosing hardware and algorithms, it still allows us to draw some conclusions on the individual components' impact.

We base the general setup of the comparison on a *Time Leap Challenge*, where virtual teams compete. Team SW uses new solvers on old hardware; Team HW uses old solvers on new hardware. The time between "old" and "new" spans about two decades. Which team can solve more instances? Depending on the outcome, one can compare the impact of hardware advancement and algorithm advancement. The idea for this time leap challenge for SAT-solvers was inspired by a thought experiment on algorithms in mixed-integer linear programming (MILP), suggested by Sebastian Stiller [91]. Furthermore, we received inspirations from work by Brixby [14, 15], who carried out experimental work comparing old and new solvers limited to one, at the time, modern computer in the area of mixed integer linear programming.

In the early 1990s, the dominant complete method for SAT-solving was the *DPLL Algorithm* (Davis-Putnam-Logemann-Loveland [26, 25]), which combines backtracking search with Boolean constraint propagation [99]. However, in the late 1990s, the *CDCL Solvers* (Conflict-Driven Clause Learning) took over. They extended the basic DPLL framework with new methods, including clause learning [85], lazy data structures like watched literals [73], backjumping [85, 73], and dynamic branching heuristics [73]; the combination of these methods resulted in a significant performance boost, often referred to as the "CDCL Revolution". Although the CDCL paradigm is still predominating today's SAT-solving, there have been several significant improvements made over the last two decades, including efficient preprocessing [27] and inprocessing [56], aggressive clause deletion [2], fast restarts [67], lightweight component caching [77], implication queue sorting [64], and new branching heuristics [66].

1.1 Experimental Setting

For our Time Leap Challenge, Team HW (old solvers on new hardware) is composed of the solvers Jerusat (2003), siege_v3 (2003), and Forklift (2003) running on a computer from 2019 with an Intel Xeon Silver 4112 CPU at 2.60GHz base frequency and 128GB RAM. Team SW (new solvers on old hardware) is composed of the solvers MapleSat19 (2019), CaDiCal (2019), and Glucose (2016) running on a computer from 1999 with a Pentium III processor at 467MHz frequency and 1.5GB RAM. An essential question for setting up the experiment was the choice of a suitable set of benchmark instances. On the one hand, the instances should not be too challenging so that they are not entirely out of reach for old solvers or old hardware; on the other hand, the instances should still be challenging enough to provide interesting results. We settled on the benchmark set set-asp-gauss [51] that provides a reasonably good compromise, as it contains a large variety of instances, tailors adapted instance hardness, is free of duplicates, reproducible, and publicly available. We used a timeout of 900 seconds, which is the default for SAT competitions. Right in the beginning, we state a clear disclaimer. While a theoretical challenge is easy to design, a practical comparison can rarely be comprehensive and complete. About 20 years of evolution increases the practical search space by orders. There are many possibilities to combine hardware, software, benchmarks, and solvers. Particularly, there might be solvers that are still available. but we missed during our research. Still, we provide a clear guideline on how we selected the teams and provide extensive details beyond. Our results are reproducible in the setting, and the conclusions provide a general idea. However, the ideas might not generalize to conclusions over other benchmark sets or solvers we might have missed. However, this is a usual situation in many experiments with combinatorial solving as there is no good theoretical understanding of the practical effects [76]. Still, we aimed to put the concept of a thought time leap challenge from literature in popular science into a practical scientific context.

1.2 Results

Table 1 gives a summary of our results (we provide more details in Section 3). We see that both teams perform in a similar range with a slight advantage for Team SW.

1.3 Prior Work

This paper is an extended and updated version of a paper that appeared in the proceedings of the 26th International Conference on Principles and Practice of Constraint Programming (CP 2020) [32]. The present paper extends the preliminary work by additional experimental work, including solvers from the SAT heritage project launched in Summer 2020 [1]. Furthermore, in contrast to our previous work [32], we check whether the solvers output the correct decision [12]. We limit ourselves to a check, since the old solvers do not include techniques for proof checking

	Jerusat (2003)	siege_v3 (2003)	Forklift (2003)	Glucose (2016)	CaDiCal (2019)	MapleSat19 (2019)
old HW (1999)	38	43	43	Te	am SW 100	72
new HW (2019)	71	eam HW 96	105	188	184	187

Table 1: Summary of experimental results

unsatisfiable instances. Finally, we include the results of the solvers on a more recent CPU generation.

1.4 Related Work

Knuth [61] provides an overview of various aspects of SAT-solving, including commented implementations of algorithms from several epochs of SAT-solving. His implementations assemble a DPLL solver (SAT10), a DPLL look-ahead solver (SAT11), and a CDCL solver (SAT13), as well as a preprocessor (SAT12). Since all these solvers are implemented uniformly, without special implementation or hardware tricks, they provide an excellent comparison of the algorithmic advancement of solver techniques. We therefore included, for comparison, the results of Knuth's solvers on the same benchmark set and hardware platform as the time leap challenge. Mitchell [71] provides an overview of techniques, implementations, and algorithmic advances of the year 2005 and looking back for 15 years. He already mentioned that the success of SAT-solving is due to three factors: improved algorithms, improved implementation techniques, and increased machine capacity. However, Mitchell's work does not provide evaluations on any actual practical effects at the time. Kohlhase [63] recently published work on collecting and preserving the comparability of old theorem provers to preserve cultural artifacts and history in Artificial Intelligence. For an overview on the technique of CDCL-based solvers we refer the reader to introductory literature such as a chapter in the Handbook of Knowledge Representation [40], chapters on the history of modern SAT-solving [35], and CDCL-solvers [70] in the Handbook of Satisfiability [13]. Katebi, Sakallah, and Marques-Silva [60, 82] considered various techniques of modern SAT-solvers from an empirical viewpoint. They designed experiments to evaluate factors and the aggregation of different SAT-enhancements that contribute to today's practical success of modern solvers. Works on targeted algorithm engineering for SAT-solvers are extensive. Just to name a few examples, there is work on exploiting features such as optimizing memory footprints for the architecture [16], on implementing cache-aware [22], on using huge pages [33], on how to benefit from parallel solving [52] or employing inprocessing. Inprocessing particularly takes advantage of modern hardware as one can execute a lot more instructions on a modern CPU than accessing bytes on memory [42, 68]. Very recently, Audemard, Paulevé, and Simon [1] published a heritage system for SAT solvers. It allows for compiling, archiving, and running almost all released SAT solvers and is based on Docker, GitHub, and Zenodo. While they aim for archivability, our work provides an actual experiment incorporating soft- and hardware advances. We hope that their system allows for long term preservation and, if there is no major change in computer architecture, one can repeat our time leap challenge in another decade.

2 The Arena: Designing the Time Leap Challenge

To run a proper challenge, we design an arena by selecting from standard benchmark sets and several contestants out of a vast space of possibilities. We aim for the oldest reasonable hardware on which we can still run modern benchmark sets and solvers. In turn, this requires setting up a modern operating system on old hardware. To make it a time leap challenge, we are interested in solvers and hardware from similar generations, in other words in a preferably small time frame from which both originate. The physical effort restricts us to consider only two time frames in the following. We take modern hardware and solvers from 2019 and old hardware from around 2000 and solvers from 2001/2002. Following academic ideas by Stallman [90], we focus on benchmark sets and solvers that are publicly available. Throughout the experimental work, we follow standard guidelines for benchmarking [96]. In the course of this section, we elaborate on various technical and organizational obstacles. Setting up a time leap challenge is also somewhat of an archaeological challenge.

In theory, a variety of competitions have been organized in the past. The competition results give a broad picture of benchmark instances and solvers. Old hardware and operating systems should still be widely available. In practice, neither open source, nor version control systems, nor public platforms to host software projects such as SourceForge [98], bitbucket, github, or gitlab, were popular in the community around the millennium. Publicly funded data libraries such as Zenodo [75] were also established much later. While the culture of storing text in libraries dates back to Alexandria and the first librarian Zenodotus in 280 BC, searching for datasets and source codes from 20 years ago feels like digging through a burnt library. Enthusiasts maintained datasets and source codes from early competitions. Sometimes source codes were kept as a secret [39]. Some links redirect to grabbed domains, or people moved and with them, the webpages. Sometimes binaries show up from private collections or the Internet Archive [59]. However, it turned out that they do not run, as libraries on which they depend, do not run on modern Linux or Unix distributions.

Below we report and explain details of the selection process.

Instance Format Johnson and Trick suggested a uniform input format description in 1993, which is still used as the standard for SAT input instances [57]. The standardized input format and backward compatibility substantially simplified our selection process.

2.1 Selecting a Suitable Benchmark Set

Our focus on selecting a benchmark set is to consider a larger benchmark set, say of a cardinality ranging from 100 to 300. We are interested in a safe and stable choice of instances since benchmarks run a wide variety of experiments with preferably more than 10 solvers resulting in months of running time. Hence, we push to a reasonable state-of-the-art benchmark setting. We prefer instances that (i) are publicly available, (ii) contain a good selection of domains, including an industrial background, random, and combinatorial instances, and (iii) highlight differences for modern solvers. We summarize runtime and number of solved instances during our instance selection process in Table 2. For an initial selection, we ran instances only with the solver Glucose [4], which showed robust performance on many earlier experimental works that we carried out.

Available Instances The first available benchmark instances *DIMACS-2* date back to 1992 and the 2nd DIMACS Challenge 1992–1993 on NP-hard problems, which also considered SAT as a problem [95]. The 241 instances are still well maintained and downloadable [94]. Note that the 1st SAT competition already took place in 1992 [19]. However, the instances are not publicly available. Over time researchers collected benchmarks such as *SATLIB* [49], which count more than 50,000 instances in total. The instances are still available on an old webpage by the collector [49]. A subset of these instances was also used for the SAT Competition 2002. However,

benchmark	solver	#	ТО	ERR	t[h]	avg[s]
DIMACS2	Glucose	225	15	1	0.34	5.46
SATLIB	Glucose	43892	15	6399	4.45	0.36
set-asp-gauss	Glucose	189	11	0	4.50	85.71

Table 2: Runtime of a modern solver and modern hardware on selected benchmark sets. # refers to the number of solved instances, TO refers to the number of instances on which the solver timed out, ERR refers to the number of instances on which the solver found an input error, t[h] refers to the total running time on the solved instances in hours, avg[s] refers to the average running time of an instance.

those instances are not available from the SAT Competition website due to an abandoned domain. Instances from one of the annual SAT competitions from 2002 to 2019 [44] follow stricter rules, and detailed reports are available [55]. There are plenty of tracks, thousands of instances, and many of the more modern instances are enormous in size. A popular benchmark set with various instances from SAT competitions until 2013 and various fields is the benchmark set *set-asp-gauss* [51]. The set is a composition of representative benchmarks from a variety of sources. It has been widely used as a robust selection for tuning solvers in the past and was obtained by classifying the practical hardness of the instances from the SAT Competition 2009 and SAT Challenge 2012 and then selecting instances by sampling with the Gaussian probability distribution [51].

Initial Evaluations In order to gather initial insights, we ran all available solvers on our cluster. The hardware for the benchmark selection process consisted of a cluster of RHEL 7.7 Linux machines equipped with two Intel Xeon E5-2680v3 CPUs of 12 physical cores each running at 2.50GHz, which we enforced by performance governors. The machines are equipped with 64GB main memory of which 60.5GB are freely available to programs. We compare wall clock time and number of timeouts. However, we avoid IO access on the CPU solvers whenever possible, i.e., we load instances into the RAM before we start solving. We run four solvers on one node at most, set a timeout of 900 seconds, and limit available RAM to 8GB per instance and solver. We summarize our initial evaluation of the early benchmark sets in Table 2. The DIMACS-2 instances turned out to be very easy for modern solvers. For example, the solver Glucose solved almost all instances within less than one second, only five large instances (par32-X.cnf) of a parity learning problem remained unsolved within 900 seconds. The SATLIB instances are more challenging but still fairly easy for modern solvers. The SAT Competition 2002–2019 instances provide a broad selection. Since the results are still publicly available, we refrained from rerunning these sets. The runtime results on the benchmark set set-asp-gauss revealed that modern solvers can solve many instances. However, the instances are still challenging as the overall runtimes are reasonably long. Old solvers are still able to solve plenty of instances on modern hardware. The benchmark set consists of 200 instances in total.

Decision After running the instances, we picked one existing benchmark set. Since the set DIMACS-2 contains almost only easy instances, we rejected the set right away. While the SATLIB instances contain mainly easy instances, they are not very challenging for modern solvers. Further, the contained benchmarks have a strong bias towards handcrafted and random instances. The SAT 2002–2019 instances contain very interesting sets. However, some of the more modern instances are very large, and we figured that it is impossible to transfer and run the instances on old hardware. After reviewing the initial results and sampling memory requirements from earlier SAT competitions, we decided to use the benchmark set *set-asp-gauss* [51], which provides a reasonably good compromise. It contains a large variety of instances, tailors

adapted instance hardness, is free of duplicates, reproducible, and publicly available.

2.2 Selecting Solvers

In the following section, we describe the selection process of SAT-solvers for our challenge. To foster reproducibility and favor open-source, we focus on publicly available solvers (binary or source code). Note that modern SAT-solving also includes various parallel algorithms. Due to the unavailability of wide parallel computation on old hardware, we restrict ourselves to sequential solvers. Further, we consider only solvers that are, vaguely speaking, descendants of the DPLL [26, 25] algorithm, i.e., CDCL. These solvers are often referred to as solvers implementing complete and systematic search. However, restarts and deletion might affect completeness under certain conditions in practice [70]. To our knowledge, CDCL-based solvers with various additional techniques on top, which even extend the underlying proof system, are still the most prevailing paradigm for SAT-solvers. However, today, some solvers use strong proof techniques such as the division rule in cutting planes [30, 38] or Gaussian Elimination [87, 88].

Researching for Solvers The 1st SAT Competition [19] and 2nd DIMACS Challenge [95] took place around 1992. However, no online resources on detailed solvers or source codes are available. The earliest public collection of solvers, which is still available online, is the SATLIB Solver Collection [50]. The collection contains implementations on DPLL-based implementations as well as stochastic local search solvers. DPLL-based Implementations in the collection are Grasp [85], NTAB [24], POSIT [36], various versions of REL_SAT [7, 58], which are also available on github [6], two versions of SATO [100], and four versions of Satz [65]. Further, we asked colleagues for the source code of old solvers and received an even older version of Grasp from 1996 [69]. The era of CDCL solvers started in 2001 [73]. There, successful solvers such as BerkMin [39], siege [81], and zChaff [37] materialized. Siege [81] is publicly available with binaries in three versions from 2003 to 2004. We contacted colleagues on the source code of siege, but the author retired, and the sources seem to be lost. For zChaff [37] even the source code is publicly available in four versions from 2001 to 2007. Binaries of BerkMin showed up in a backup of experiments on SAT-solvers from earlier works. We contacted the authors on source codes but received no answer. Audemard, Paulevé, and Simon [1] very recently started the SAT Heritage project, which provides software heritage [23] for the SAT community. The SAT Heritage project contains binaries or source codes for solvers starting from the early SAT competitions in 2002.¹Among the binaries, we also found a working binary of BerkMin and its successor Forklift from 2003. A famous solver in the SAT-solvers line is MiniSat, which is available online in various versions [29, 28, 89]. The development of MiniSat started around 2003 [28] intending to create a compact, readable, and efficient solver for the community. The earliest version online is from 2005, and the most known and very popular version 2.2 from 2008. Another popular SAT-solver is Glucose [3], which was developed to aggressively remove clauses that are not helpful during clause learning of the CDCL procedure. This results in an incomplete algorithm as keeping learnt clauses is essential for completeness. We consider the version Glucose syrup 4.2.1 [4]. A very popular, successful and recent solver is Lingeling [10], which won several SAT competitions and the prize on the most innovative solver [5] in 2015. Two medalists of the SAT 2019 Race were CaDiCaL 1.0.3 [11] and a descendant of the solver MapleSAT [66], namely MapleLCMDistChronoBTDL-v3 (MapleSat19) [62]. We would like to point the reader at swMATH [21], an information service for mathematical software that allows for researching solvers and publications in which a solver is referenced. Indeed, swMATH can be quite helpful when the solver name is known.

¹Note that we did not run the solver within SAT Heritage, but extracted relevant solvers. Audemard, Paulevé, and Simon provide an easy option on that account. After installing Docker and then SAT Heritage by running pip install -U satex, one can simply extract the solver with the command satex extract berkmin561:2003 myfolder.

Testing the Solvers To benchmark a solver, we first need to compile it or run the binary with a modern operating system as there is otherwise no chance to get the solvers running on modern hardware. First, we considered all solvers from the SATLIB collection. We were able to compile and successfully run the solvers Grasp, Relsat, Satz, and SATO. However, we had to modify the source codes and build files so that they would compile with a modern compiler due to harder interpretations of language standards in modern compilers. Since the solvers were originally designed for 32bit Linux, we compiled the solvers on 32bit Linux and used them late on 64bit Linux by compatibility layers. While we were also successful in compiling solvers on 64bit systems, the 64bit binary would often solve fewer instances on the 64bit system or result in many segfaults. We suspect compatibility issues as either the developers of the old solvers could not expect certain datatypes on a future architecture or implemented sloppy memory management. All versions of the solver **siege**, which were available as a binary, still ran on a modern Linux using the 32bit compatibility mode. We were successful in building all versions of the solver zChaff; both on a 32bit as well as 64bit architecture. Unfortunately, the solver BerkMin does not run on modern or fairly recent Linux distribution. It turns out that the binary was compiled with an old gcc and linked to an old version of the glibc, which we discovered in an old Red Hat Enterprise Linux, but we were unable to integrate it into a modern Linux distribution. We found that all modern solvers were well maintained and still compiled on 32 and 64bit Linux distributions as well as a 64bit version of NetBSD.

Correctness The first SAT competitions revealed that many early SAT solvers were buggy, produced segfaults, and outputted wrong results [86, Sec. 2.1.2]. Since then, solver correctness has been addressed by intensive testing, including fuzzing [18], and extending the solvers by systems that allow for formal verification of the results of unsatisfiable instances by using resolution. Proof logging [46, 97, 43] moved modern SAT solving far beyond high-performance tools for combinatorial solving. Proof logging and verification enabled SAT solvers in mathematical applications [48, 45, 17]. To incorporate these advancements and make the results between old solvers comparable, we exclude solvers that produce a significant number of erroneous results; for more details, see below. Armin Biere is currently working on providing bugfixes on various early SAT solvers [12]. While we checked results and base our experiment on the original sources, we believe that it would still be interesting to repeat the experiment when the improved solvers are publicly available.

Final Teams To have a comparison on theoretical advances in SAT-solving between DPLL and CDCL from an abstract perspective and out of the hand of a programmer, we picked the implementations by Donald Knuth [61]. The implementations represent particular periods, more precisely, DPLL solver (SAT10), a DPLL look-ahead solver (SAT11), and a CDCL solver (SAT13), as well as a preprocessor (SAT12). We still tested the old solvers Relsat, Satz, and SATO, which resulted in less than 20 solved instances on our modern hardware for the best solver among them (SATO). Since it is theoretically well-known that CDCL can be significantly faster than DPLL [78, 76], we already have the solvers by Knuth. There has already been work on the technological advances of various techniques between techniques in DPLL and CDCL solvers; we focus on the more modern CDCL solvers for both teams. Then, we have several solvers available for Team HW from the researched origins and the newly available SAT Heritage project. We focus on the solvers that output results for a considerable number of instances. We excluded solver Grasp, which already implements conflict learning, but unfortunately has a bug in the parser yielding unpredictable behavior. One of the earliest well-known solvers, zChaff (2001), also produces a total of 9 wrong outputs. Similar, the solver compsat (2002) outputs 17 wrong results and bmsat (2003) 8 wrong results. We excluded solver BerkMin561, as its successor Forklift performed much better. Since the solver Jerusat produced only one wrong instance on a system from 2013, we decided to include this solver still. Hence, there are three solvers left for a team of solvers from about 20 years ago (Team HW), namely, Forklift (2003), siege

(2003), and Jerusat (2003). We preferred to include version 3 of the solver siege (2003) as it solved about 12 instances more than version 1 (2001) on our modern reference hardware. We discarded MiniSat as the youngest of the older solvers. We picked CaDiCaL 1.0.3 [11] and MapleLCMDistChronoBTDL-v3 (MapleSat19) [62] for Team SW (new solvers on old hardware) due to their good performance in the SAT 2019 Race. MapleSat19 won the SAT 2019 Race, and CaDiCal scored second place. Since the slightly older solver Glucose syrup 4.2.1 [4] solved about ten instances more than the solver Lingeling 7d5db72 [10] on our modern reference hardware, we decided to pick Glucose for our Team SW.

2.3 Selecting the Environment: Operating System and Compiler

Since we are interested in comparing the teams "new solvers on old hardware" and "old solvers on new hardware", we think that it is only fair to also include advancements in kernel architecture, compilers, and operating systems for new solvers. Anyway, it is impossible to obtain ancient Linux or Unix distributions due to missing source code mirrors. It is not possible to run such Linux or Unix distributions on modern hardware because of the lack of modern chipset drivers in ancient kernels. Due to long term support of hardware, we decided to favor Debian 10 codename buster (July 2019) [20] and try NetBSD 9 (Feb. 2020) [93] as operating systems. We ran the experiments on Linux kernel version 4.19.0-8-686-pae. We use gcc 8.3.0 on Debian and NetBSD. Our modern hardware at university was equipped with Linux Mint 19 codename Tara, kernel version 4.15.0-91, and gcc compiler version 7.5.0-3.

2.4 Selecting the Hardware

To have a wide variety of hardware, we started to gather old hardware from friends and colleagues. We collected ten systems over different generations, namely systems containing a Pentium II (1998), a Pentium III (1999), an Ultra Sparc IIe (2001), a Pentium IV (2002), a Pentium IV Prescott (2004), a Core2 Duo (2007), an i5 Nehalem (2009), a Xeon Haswell (2013), a Xeon Skylake (2017), an i7 Icelake (2019), and an AMD Rome (2020). A colleague prepared a SPARCstation II (1995) and SPARCstation Voyager (1995) for us.

Technical Restrictions The selection of a benchmark set and operating systems restricted the space of possibilities on the potential old hardware. Preferably, we are interested in the oldest possible hardware and the youngest possible hardware. In more detail, modern Linux distributions, such as Debian 10, still support all x86-based (IA-32) i686 processors, including various AMD, Intel, and VIA processors. However, the i686 architectures limits experiments to Pentium II processors (1997) or later [53]. BSD distributions, such as NetBSD 9, still support the Sparc64 architecture, which in theory allows for running systems with processors SPARC64 (1995) and UltraSPARC IIe (1999). We were able to run NetBSD 9 on a system with the latter CPU namely, the Sun Netra X1, from about 2000/2001. Since we only had access to Linux or Solaris binaries for some solvers, and we were unable to set Debian 10 or Solaris onto the Netra system in decent time due to a required setup via serial LOM interface and network boot, we discarded the Sun system from our final hardware selection. It is well known that modern operating systems and SAT-solvers are very memory-demanding [33] resulting in a requirement of having at least 1GB of total RAM inside the system. Since the L2 cache controllers of the Pentium II only allow the use of 512MB of RAM and we could not access a system with a Pentium Pro processor, our oldest possible system (1999) was a Pentium III processor running at 467MHz equipped with 1.5GB RAM. Hence, we picked this system to run the solvers of Team SW. While the most modern Intel CPU architecture we had access to was an i7 Icelake (2019), we decided to prefer the system running a Xeon Skylake due to the availability of ECC-RAM and the much larger caches, which are usually beneficial for SAT-solving. Still, the modern system with the

Xeon Skylate was bought in 2019 for dedicated benchmarking, while the i7 was just a small-formfactor barebone desktop computer for which we feared that high permanent load over months might significantly degenerate performance due to overheating. Also, we benchmarked solvers on systems equipped with AMD Rome CPUs (2020). The behavior was mostly similar, with a few instances solved less. Still, we refrained from using the system for systematic experimental work to favor reproducibility and due to limited available resources. In more detail, the AMD Rome systems consist of 2 CPUs each having a price of about 7.000 EUR, which makes such systems not widely available and limits access for many researchers. Furthermore, the system is part of a TOP500 cluster [34], requiring detailed billing of system usage measured by CPU hours. Since SAT solvers are highly memory intensive, one often favors employing the memory caches lines well. We observed a different number of solved instances when used 8 or 32 cores. One might take the number of available memory channels to be very conservative. In our case, each CPU consists of 128 logical cores (64 physical cores) but only 16 memory channels. However, this results in high overbilling of cluster resources, usually counted by reserved logical cores. At the same time, the Rome CPU has a base-frequency of only 2.0GHz where one would expect slower solving times. However, the system has a faster cacheline and much larger L1, L2, and L3 caches. This might result in faster solving or yield unexpected results as some solvers are sophistically engineered for memory cachelines [33]. In order to favor reproducibility, we decided on a standard and widely used system. Thus, Team HW's system contained two Intel Xeon Silver 4112 CPUs (Skylake architecture) of 2.60GHz base-frequency equipped with 128GB RAM. We ran the experiments at the base-frequency. Since the Netra X1 from 2000 was equipped with 2GB and the NetBSD allowed to still run all source code based solvers, even the very modern ones, the Sun system serves as a point of reference.

2.5 The Final Stage: Experimental Setting and Limitations

We compare wall clock time and the number of timeouts. However, we avoid IO access on the CPU solvers whenever possible, i.e., we load instances into the RAM if a network file system is involved and store uncompressed instances. We set a timeout of 900 seconds and limited available RAM to 512MB per instance and solver. We also tested for some solvers with resident set size restricted to 1GB RAM and observed only a minimal difference. Since Intel hardware around 2002 rarely had more than 512MB RAM available, we went for the 512MB setup. We follow standard guidelines for benchmarking [96]. We set and enforce resource limits by the tool runsolver [79]. We are aware that runsolver suffers from sampling-based issues. Measuring resources results in immediately expired information, and enforcing limits might not affect if the used RSS (resident set size) exceeds the intended maximum limit only in sudden resource spikes [8, 9]. We have no strong indicators that this is the case in our setting and hence still favor runsolver over a significantly more complex system setup using cgroups. We force performance governors to the respective base-frequency for modern CPUs [83], disable hyperthreading, and enforce the process that handles the solver invocation to run on at most the number of cores that equals the number of memory channels. We explicitly enable transparent huge pages systems with modern CPUs and large caches, which is also the default with SAT competitions that run on StarExec [92]. Note that the Pentium 3 system has non-ECC memory, which might cause memory errors and affect results [84].

3 The Trophies

Table 3 gives an overview on the number of solved instances for each solver and the two hardware generations. Figure 1 illustrates the runtime of the selected solvers and hardware as a CDF-like plot. Our results and gathered source codes are all publicly available [31]. Note that we report only on the two Intel-based hardware generations in this table. The results on the Ultra Sparc IIe

group	Solver	Year/Generation	HW99	HW19
	MapleSat19	2019	≽ 72	187
	CaDiCal	2019	ğ 100	184
	Glucose	2016	Å 105	188
	vbest		124	198
	sum		277	559
	avg (%)		46	93
	Forklift	2003	43	≥ 105
	siege_v3	2003	43	g 96
	Jerusat	2003	38	${ m \ddot{\tiny E}}$ 71
	vbest		53	134
	sum		124	272
	$\operatorname{avg}(\%)$		21	45
	SAT13+12	CDCL+P	36	111
	SAT13	CDCL	30	98
uth	SAT11+12	LH+P	16	23
Km	SAT11	LH	16	19
	SAT10+12	DPLL+P	12	12
	SAT10	DPLL	6	6
Other Solvers	Lingeling	2019	67	178
	Lingeling-aqw-27d9fd4	2013	85	186
	Lingeling-276	2011	80	177
	MiniSat	2008	83	173
	siege_v4	2004	50	116
	siege_v1	2003	34	85
	Compsat	2003	47	92
	BerkMin561	2003	36	88
	zChaff(32)	2001	40	62
	sato	2000	17	19
	satz	1998	7	9

Table 3: Overview of the number of solved instances for the various solvers on our old and new hardware. HW99 represents the number of solved instances on the old hardware. HW19 represents the number of solved instances on the new hardware. vbest represents best virtual solvers, which are virtual solvers that we obtain by taking all instances that have been solved by the solvers considered in the group listed above.



Figure 1: Total runtime and cumulated solved instances for each considered solver. The dashed line indicates the total number of instances in our benchmark set. The maximum possible total runtime for each solver would be 180.000s (we observed a maximum of 140.000s). However, we limited the x-axis to 40.000s as (when ignoring timeouts) each solver successfully solved all its solvable instances within a total runtime of less than 40.000s. Each line illustrates a solver and the maximum number of instances it successfully solved if allowed to run for x seconds. The last data point represents, if shown, the total runtime of a solver. The x-axis refers to the total runtime. The y-axis depicts the maximum number of instances solved within this runtime. **vbest** refers to the best virtual solver, i.e., we take the union over the solved instances for each team and consider the minimum for each instance. In the legend, [X] refers to the number of X solved instances. HW19 refers to the new hardware, and HW99 refers to the old hardware. SAT19 refers to a modern solver on modern hardware, which one can consider as a potential baseline.

system look very similar, usually, a few more instances were solved. Detailed data can be found in the supplemental material.

3.1 Results

Before we start discussing the results, we would like to point out that we report fewer solved instances here than in the preliminary version (cf. [31]). In the present work, we enforce the CPU governors to the base frequency, which is lower than the maximum turbo frequency (as used in the preliminary work). Using the CPU at its maximum possible frequency requires a sophisticated system setup ensuring that the frequency is reproducible and the same for all solvers at all times. Setting the maximum possible frequency is not enough as the CPU might not run at its maximum turbo frequency and automatically throttle down due to thermal restrictions. A setup running at the maximum possible frequency requires observing the active CPU frequency constantly and checking whether it agrees with the maximum turbo frequency. In order to favor reproducibility, we opted against running the systems at their maximum frequency. When we consider the number of solved instances on the hardware from 2019, MapleSat19 solves 195 instances. Recall that Team HW consists of the old solvers on modern hardware. They solve 105 instances (Forklift), 96 instances (siege_v3), and 71 instances (Jerusat). On average, they solve about 91 instances (45.5% of the instances) at a standard deviation of about 18. However, the virtual best solver (vbest) for Team HW solves 134 instances, i.e., about 67% of the instances. The virtual best solver is the virtual solver that we obtain from taking the union over the solved instances by all three solvers and keeping the instance with the best solved runtime. The Team SW consists of the new solvers on old hardware. They solve 72 instances (MapleSat19), 100 instances (CaDiCal), and 105 instances (Glucose). On average, they solved about 92 instances (46.0 % of the instances) with a standard deviation of 18. Their virtual best solver (vbest) solves 124 instances, i.e., about 62.0% of the instances. When considering the solvers MapleSat19, CaDiCal, and Glucose on modern hardware, they solve 186 instances on average with a very low standard deviation of 2 instances. When considering the results on the solvers Forklift, siege_v3, and Jerusat) on old hardware, they solve on average about 41 instances (21.5% of the instances) at a standard deviation of about 3.

3.2 Discussion of the Results

3.2.1 Comparing the Teams

The solver Glucose, which is a very stable solver from 2016, solves the highest number of instances on the new hardware. We are not surprised that neither Team SW nor Team HW or their virtual best solver gets anywhere close to this result. In view of Table 3 and Figure 1, there are plenty of ways to compare the two teams. One can carry out (i) an individual comparison by the best (vbest), worst, or average solver, or even consider the individual solvers in direct comparison to each other, but one could also (ii) consider the virtual best solver for each team. If we choose Method (i) and individually compare the solvers, Team SW clearly wins for the measure best, worst, or average solver. We can also do one-by-one comparison and compare the solvers from each team individually with the solvers from the other team. Then, we take the number of solved instances for each solver X from Team SW against each solver Y from Team HW, and we give X a point if it solves more instances than Y or give a point to Y in the opposite case. Then, Glucose obtains 2 points (because it solves more instances than siege_v3 and Jerusat); CaDiCal obtains 2 points, and MapleSat19 obtains 0 points, which totals 4 points for Team SW. In comparison, Team HW receives 2 points for Forklift, 1 point for siege_v3, and 0 points for Jerusat, which totals 3 points. Hence, Team SW also wins. Nevertheless, if we consider the virtual best solvers, Team HW performs better than Team SW.

3.2.2 Notable Observations

We found it surprising that the winner from the 2019 SAT Race (MapleSat19/HW99) solves fewer instances than two solvers from Team SW (Forklift/HW19, siege_v3/HW19) of Team HW. This seems surprising to us, and we currently do not have a good explanation of why MapleSat19 solves so few instances on the old hardware, namely 28 instances less than CaDiCal and 33 instances less than Glucose. One might suspect that MapleSat19 runs out of memory as it stores hashes even for learnt clauses that have been deleted. However, we did not observe this on our instances. We observed a similar behavior with the latest implementation of Lingeling but not with CaDiCal, which also implements inprocessing techniques. Hence, we suspect that the advanced data structures in the solvers supporting large caches, the learning and restarting policy, and strong tuning towards modern hardware might be contributing factors.

We found it interesting that the old solvers Forklift, siege_v3, and Jerusat still solve a considerable number of instances on the new hardware. In particular, the solver Forklift and siege_v3 seem to benefit substantially from the new hardware, while Jerusat gains only a small benefit from the new hardware. Since siege_v3 already implements cache-aware algorithms that

might highly benefit from fast and large memory cachelines, the behavior is not entirely surprising [80]. In contrast, solvers that use pre-CDCL techniques such as Knuth's SAT10 solver, sato, and satz could not benefit from new hardware. When we consider Knuth's implementations, it is particularly remarkable that only solvers with modern techniques (CDCL) benefit from new hardware.

3.3 Summary

When reviewing the results, we believe that our test-setting revealed that both Team SW and HW perform in a similar range. If we compare individually, Team SW wins, which is also well visible in the CDF-like plot in Figure 1. However, if we consider virtual best solvers, Team HW performs equally well. This leaves us with the conclusion that the last decades have brought enormous technological progress and innovation for SAT-solving. The two main factors, (i) *hardware advancement* and (ii) *algorithm advancement*, both have a considerable influence. Results on the solvers by Donald Knuth, which represent different epochs of SAT solving, illustrate quite well that solvers benefit only from modern hardware after advanced algorithmic techniques (CDCL) have been integrated. Still, modern SAT solvers advanced far beyond efficient solving. Proof logging and automated proof verification allow for employing modern SAT solvers even to establish mathematical proofs [47].

4 Conclusion

We compare the impact of hardware and algorithm advancement on a genuine problem, namely the propositional satisfiability problem (SAT). We describe the decisions and challenges from a thought experiment to an actual experiment between old solvers and new solvers on new and old hardware with a time difference of about two decades. Our experiment's outcome confirms that modern algorithms have a strong influence on the solvers' performance, even when they run on old hardware. Nonetheless, solving significantly profits from technological advancement in hardware development. There is no clear winner between Team SW (new solvers on old hardware) vs. Team HW (old solvers on new hardware) in our time leap challenge. Overall, both teams perform in a similar range with a slight advantage for Team SW (new solvers on old hardware), which leads us to conclude that both hardware and software advances in science and industry have a mutual influence on modern solving. Hence, algorithm advancements are at least as important for the field of SAT-solving as hardware advancement. Further, algorithm engineering becomes of more importance.

During our research, we noticed that long term reproducibility highly depends on available source code or static binaries with few dependencies. Further, it turned out to be helpful if the setup of a solver requires few additional system tools and few dependencies on external libraries. The dependencies within the operating system and source codes usually were not the problem as architectural dependencies would forbid to run the solvers. From our archaeological investigations, we suggest avoiding any external system for the setup for future long term experiments, i.e., tight dependencies on kernel versions or software containers, such as Docker. Still, one uniform shared system for the entire community, such as the SAT Heritage project, might prove helpful [1] if implemented by competition organizers. Further, we think that public data libraries would help understand long term advancements, not just source code repositories of private companies or university webpages.

One could post an open call and repeat the experiment with any solver. However, we believe that this would probably challenge developers of modern solvers to optimize their implementation for old hardware, which would result in a distorted picture for old solvers. Hence, we do not primarily intend to repeat the experiments in the near future [74]. We hope that our work stimulates research for others to set up a time leap challenge in their fields, such as stochastic SAT-solvers, CSP-solvers, MaxSAT-solvers, and ILP-solvers.

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