Inverting Step-reduced SHA-1 and MD5 by Parameterized SAT Solvers

Oleg Zaikin

ISDCT SB RAS, Russia

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Outline

1. Cryptographic hash functions MD5 and SHA-1
2. Intermediate inverse problems for MD5 and SHA-1
3. SAT encoding
4. Solving intermediate inverse problems by Kissat
5. Tuning Kissat
6. Inverting 24-step SHA-1 and 29-step MD5 by parameterized Kissat

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The first two properties are obligatory.

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- **Password verification**: they are not stored as clear text, their hashes are stored instead.
- **Proof-of-work**: a mining reward is unlocked after some partial hash inversions (e.g. in Bitcoin).

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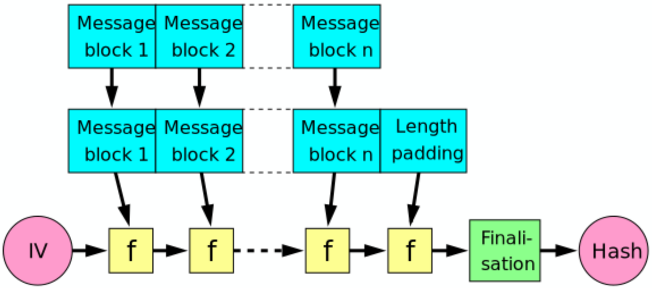

- Initialization vector (IV) has a fixed value.
- The compression function *f* takes the result so far, combines it with a message block, and produces an intermediate result.

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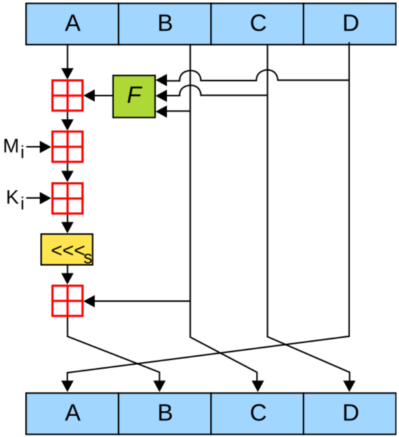

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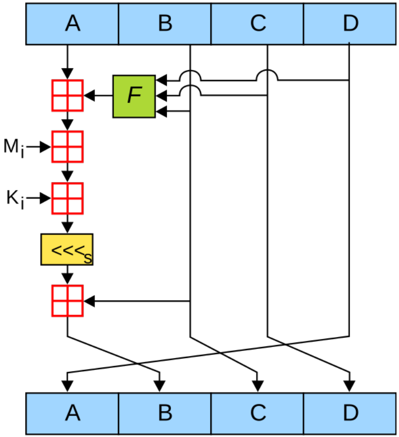

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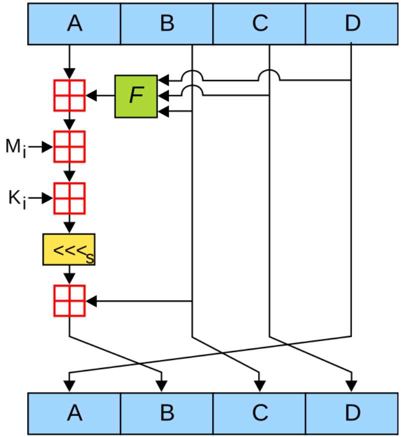
- 64 steps; each step all registers are updated.
- Before the 1st step A, B, C, D are IV, on the last step they are hash.



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- SHA-1 – a Merkle-Damgard-based cryptographic hash function proposed in 1995.

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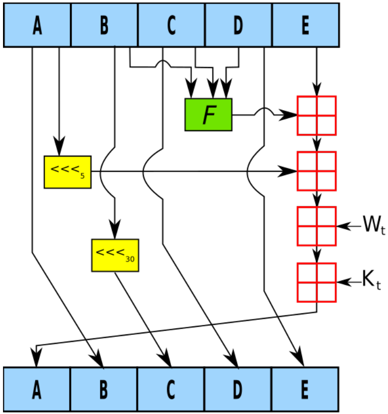
- Compared to MD5:
  1. 160-bit hash.
  2. 5 registers A, B, C, D, E.
  3. 80 steps; 4 rounds, 20 steps each.



One SHA-1 step[2]. F is a round function.

[2] https://en.wikipedia.org/wiki/SHA-1

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- MD5 and SHA-1 are still preimage resistant.
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- In 2012, the 28-step MD5 and 23-step SHA-1 were inverted (i.e. their preimages were found) via a SAT solver[3].
- **Goal: invert 29-step MD5 and 24-step SHA-1 via SAT.**

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The $(i+1)$-th step of MD5:

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\begin{aligned}
&temp \leftarrow Func(B, C, D) \boxplus A \boxplus K[i] \boxplus M[g] \\
&A \leftarrow D \\
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Idea: assign constant values to several bits in $M[g]$ in step $i+1$ thus forming a family of intermediate inverse problems between steps i and $i+1$.

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Intermediate inverse problems for MD5

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A weakened $(i + 1)$-th step of MD5:

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- The j-th intermediate MD5 function between i and $i + 1$, is called $(i\ j/32)$-step MD5.

- The main hardness lies in $M[g]$ as well.
- 31 intermediate inverse problems are formed in the same way as for MD5.

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- In the present study, the implementation is extended to maintain MD5.

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- To encode the j-th intermediate inverse problem between steps i and $i+1$:
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Table: Characteristics of CNFs.

Hash	Steps	Variables	Clauses	Literals
SHA-1	23	4 288	132 672	873 727
SHA-1	23 16/32	4 480	138 812	913 700
SHA-1	24	4 448	138 764	913 620

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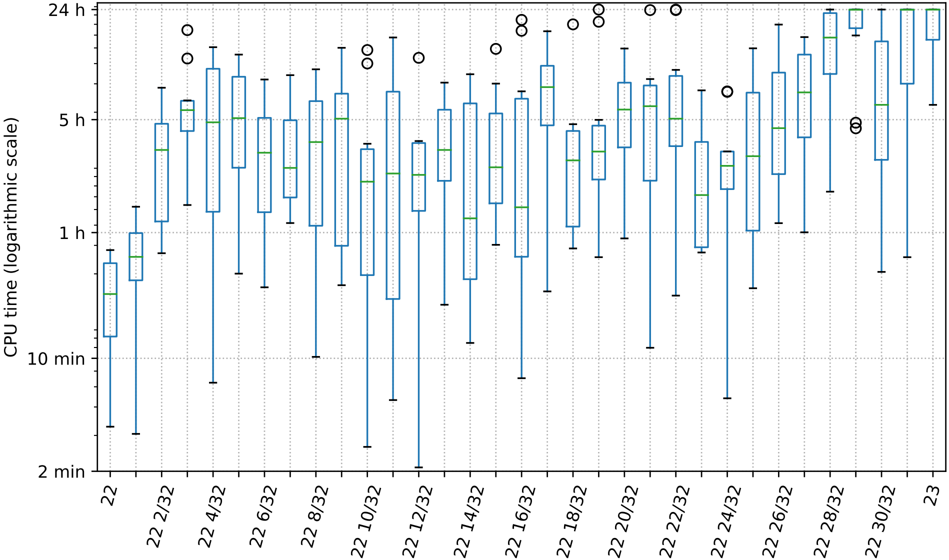
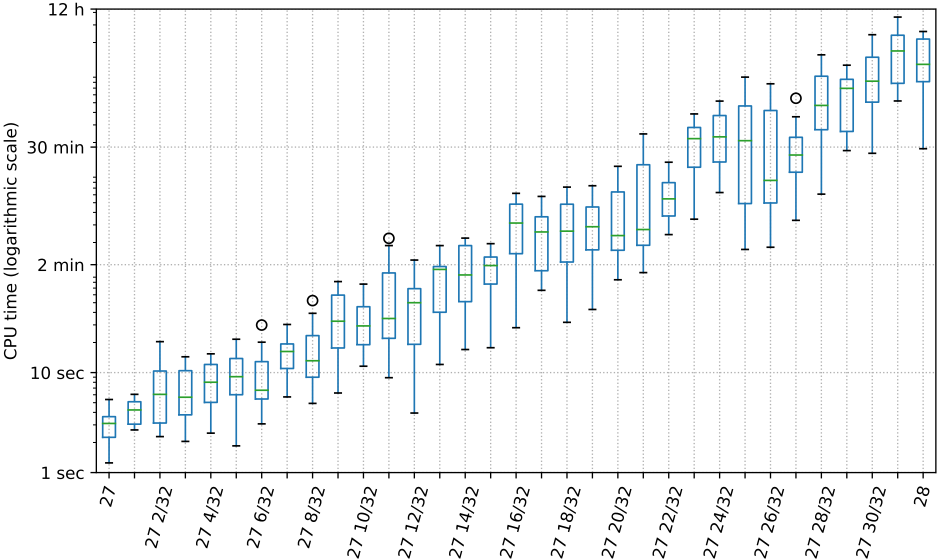
Boxplots for SHA-1



Boxplots for MD5



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- **Idea: to invert $i + 1$ steps, tune Kissat on intermediate inverse problems between steps i and $i + 1$.**

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- (1+1)-EA (Evolutionary Algorithm) was chosen for tuning because of its simplicity.
  1. Consider n parameters.
  2. New set of values: the value of each parameter is changed with probability $1/n$.
  3. Any value can be assigned, but with high probability it will be the closest to the current one.

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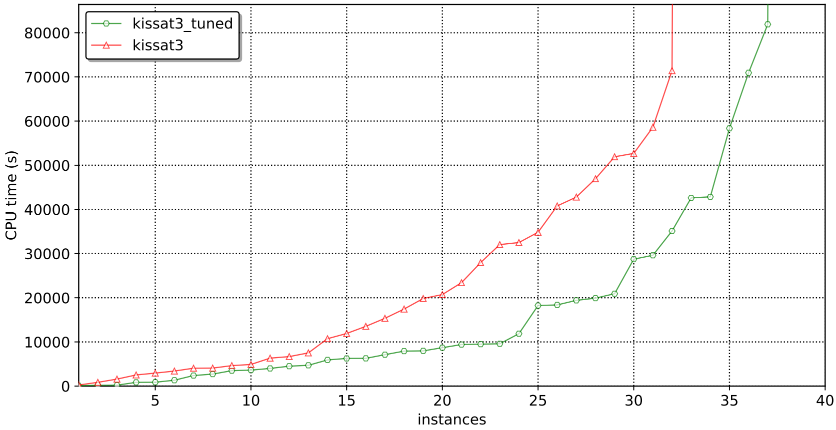
- The total runtime on them is **1 hour 58 minutes** on 1 CPU core.
- 3 seeds for tuning, each on 16-core CPU during 24 hours.
- The best set of parameters' values: **22 minutes** in total (5 times faster).

Table: The best KISSAT's configuration found for SHA-1.

Parameter	Default value	Found value
backbonerounds	100	10
definitionticks	1 000 000	100
eliminatebound	16	32
eliminateclslim	100	10
emafast	33	10
minimizedepth	1 000	100
restartmargin	10	20
stable	1	2
sweepfliprounds	1	5
sweepmaxclauses	4 096	2 147 483 647
sweepvars	128	64
vivifytier1	3	2

Tuning Kissat for SHA-1



Comparison of the default KISSAT with its tuned version on intermediate inverse problems for steps 22-24 of SHA-1, 1-hash.

- The Cube-and-Conquer method was applied: a given formula is split via lookahead into a family of simpler subformulas, which are solved by a CDCL solver[7].

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- The lookahead solver march_cu split the inverse problem for 24-step SHA-1 into 166 subformulas.

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- The lookahead solver march_cu split the inverse problem for 24-step SHA-1 into 166 subformulas.
- The tuned Kissat was run on the subformulas on a supercomputer (166 CPU cores). A preimage was found in 23 hours.

Table: A preimage of 160 1s produced by 24-step SHA-1.

0xa6c5c463	0x182655e0	0x2c5ba5f0	0xe0028033
0x8c3779b1	0x98635880	0xc5b822e	0x297efce7
0x59987038	0xd764eca9	0x7ed9801d	0xdde4f1e0
0x524e678	0xa8ce47dc	0xa813fd76	0x8b58e09f

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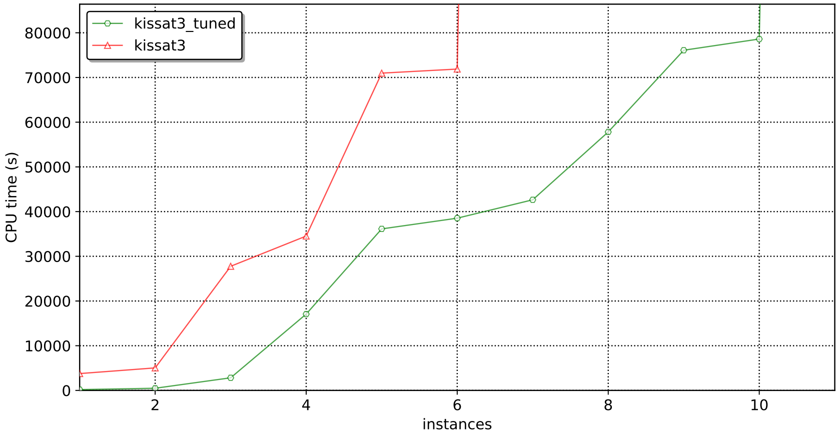
- The best set of parameters' values: **4 minutes** in total (3 times faster).

Table: The best KISSAT's configuration found for MD5.

Parameter	Default value	Found value
chronolevels	100	1 000
decay	50	32
definitionticks	1 000 000	100
eliminatebound	16	2
eliminateocclim	2 000	1 000
emaslow	100 000	75 000
minimizedepth	1 000	100
restartmargin	10	20
shrink	3	0
stable	1	2
substituterounds	2	32
subsumeclslim	1 000	10 000
sweepmaxclauses	4 096	2 048



Comparison of the default KISSAT with its tuned version on intermediate inverse problems for steps 28-29 of MD5, 1-hash.

- The lookahead solver march_cu split the inverse problem for 29-step MD5 into 74 470 subformulas.

Inverting 29-step MD5

- The lookahead solver march_cu split the inverse problem for 29-step MD5 into 74 470 subformulas.
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- The tuned Kissat was run on the subformulas on a supercomputer (540 CPU cores).
- A preimage was found in 37 hours.

Table: A preimage of 128 1s produced by 29-step MD5-1.

0xe1051a9e	0x48120773	0x996a5457	0xaaa1d815
0x37d8149c	0x5f999c05	0x182ba14b	0xdfff1673
0xc5db0a2f	0x44430b2a	0xa269f5a2	0x69781b85
0x2b7f0939	0xc1ff3c22	0xc55e990f	0x96ba3fb8

Conclusions

1. A new type of intermediate inverse problems for cryptographic hash functions was proposed.
2. A CDCL solver was tuned on intermediate inverse problems for MD5 and SHA-1.
3. 29-step MD5 and 24-step SHA-1 were inverted for the first time via the tuned solver.
4. In the future, SHA-256 will be studied.

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Thank you for your attention! Questions?