

APPLYING SATISFIABILITY TO THE ANALYSIS OF CRYPTOGRAPHY

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WHY USE SAT FOR CRYPTOGRAPHY?

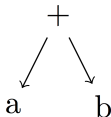
- Cryptographic algorithms are critical
 - Central to commerce, private communication, etc.
 - We want them to be correct
- Cryptography is hard
 - Rare expertise
 - Top experts have designed algorithms now known vulnerable
 - Design \rightarrow implementation can introduce other problems
- Key primitives used in cryptography amenable to SAT
 - Can be given denotational semantics in propositional logic
 - Many interesting problems surprisingly tractable

- Many primitives naturally made of bit vector operations
 - Block ciphers
 - Stream ciphers
 - Hash functions
 - Pseudo-random number generators (PRNGs)
- Public-key algorithms representable, but trickier
 - Lots of number theory, including multiplication
 - SMT can alleviate some of this (but tends to be slower on bit-vector things)
- We'll focus on primitives with type $\{0, 1\}^n \rightarrow \{0, 1\}^m$

- A function from the ZUC stream cipher

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uint8_t c = a + b;  
if (c & 0x80) {  
    c = (c & 0x7F) + 1;  
}  
return c;
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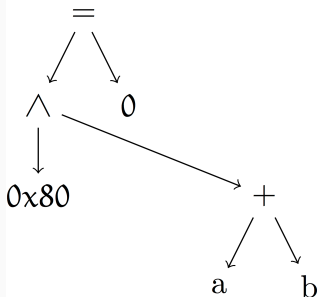
- Key technique:
symbolic execution
with path merging



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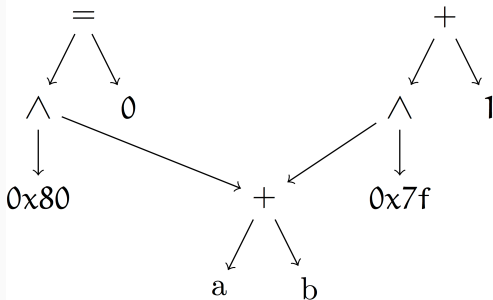
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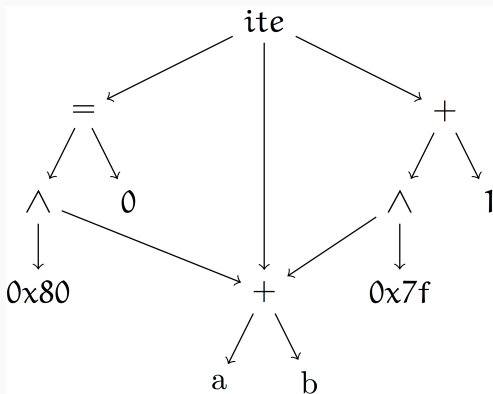
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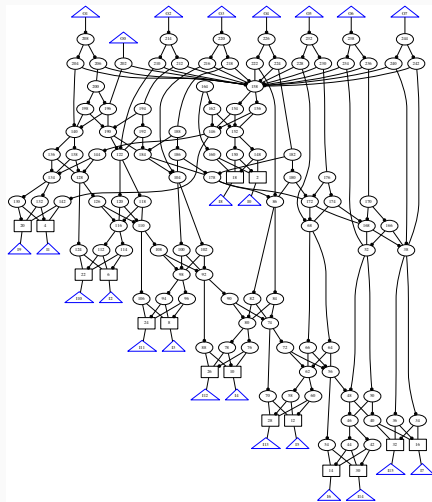
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TRANSLATING ALGORITHMS TO PROPOSITIONAL LOGIC (CONT.)



- Transalg (Russian Academy of Sciences) [8]
- C++ operator overloading (several) [4]
- Cryptol and the Software Analysis Workbench (SAW) (Galois)
 - Cryptol for describing algorithms concisely
 - SAW for proving properties about them
 - Both freely available!

- Each with a concise formula summarizing the SAT problem

$$\forall x. P \text{ or } \exists y. Q$$

- Cryptol specifications available online
- Analyzed using SAW + ABC
- Cryptol or SAW file names mentioned in slides (e.g. `file.saw`)

<https://github.com/galoisinc/sat2015-crypto>

`file.saw` → `examples/file.saw`

- Randomness is critical to cryptography
 - Keys must be unpredictable, or they're vulnerable
- Typical structure:
seed \rightarrow pseudo-random function \rightarrow pseudo-random value
- Seed often comes from “true” random source
- But it's critical not to lose entropy from this source!

- Bug in Android cryptographic PRNG discarded entropy
- Intended: 160 bits of entropy, from system PRNG to SHA-1



- Implemented: 64 bits of entropy survive



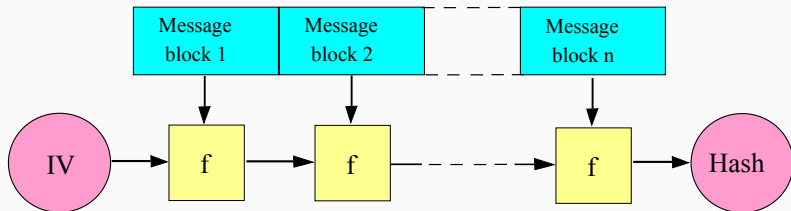
- Used to steal around \$6k of BitCoin
- Fixed in Android 4.4 (KitKat)
- Similar weaknesses existed in Debian, FreeBSD at times

INJECTIVITY OF PRNG SEEDING (CONT.)

$$\forall x, y. x \neq y \Rightarrow f(x) \neq f(y)$$

- Here, x and y come from system PRNG, f is code between system PRNG and SHA-1
- Easily provable with SAT solver [\[android-prng.saw\]](#)
 - Symbolic execution: Java code \rightarrow AIG
 - Annotation on system RNG variables, input to SHA-1
 - ABC can find collision (0.017s), prove fixed version (0.010s)
- Dörre and Klebanov used a different approach to prove the fixed code injective [1]
 - Information flow annotations on methods using a contract verification tool (KeY) and 95 manual proof steps

HASH FUNCTIONS



- Key property: hard to find two messages that have the same hash (a **collision**)
- Often built using Merkle–Damgård construction, iterating compression function
- Compression function f usually n iterations of simpler function g

$$\exists x, y. x \neq y \wedge f(x) = f(y)$$

- Discovering a collision
- Black box search in $O(2^{n/2})$

$$\exists x. f(x) = a \text{ (for some known value } a)$$

- Discovering message given hash value (inversion)
- Harder than finding a collision ($O(2^n)$)
- We want to know that it's **hard** to solve these problems

- Mironov and Zhang analyzed collisions in MD4, MD5, and SHA-0 [6]
 - Direct translation of MD4 $\rightarrow 2^{22}$ solutions in $< 1h$
 - Collision on full MD5 in around 100h
 - Reduced rounds much easier (25 in 38s with ABC) [MD5.saw]
 - Used differential path derived manually (more on this later)
 - Estimated around 3 million (2006-era) CPU hours for SHA-0
- No known collisions on SHA-1 from this, but it may be a matter of time
 - Algorithm (not SAT-based) to find collisions in 2^{63} operations

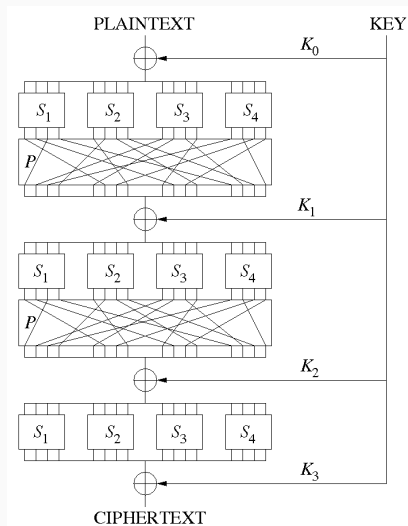
EVALUATING SHA-3 CANDIDATES

- Many candidate algorithms for the SHA-3 standard
- No preimages discoverable by SAT on full algorithms
- Homsirikamol et al. found preimages for fewer rounds [3]
 - Direct translation, with no manual cryptanalysis

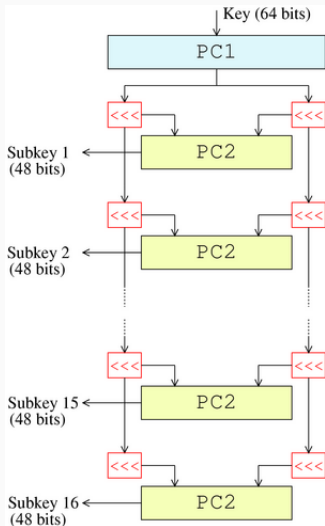
Algorithm	Rounds	Security margin	Code
SHA-1	21	74% (21/80)	SHA-0-1.saw (36s)
SHA-256	16	75% (16/64)	SHA265.saw (1.3s)
Keccak-256	2	92% (2/24)	N/A
BLAKE-256	1	93% (1/14)	Blake256.saw (17s)
Groestl-256	0.5	95% (0.5/10)	N/A
JH-256	2	96% (2/42)	N/A
Skein-512-256	1	99% (1/72)	N/A

BLOCK CIPHERS

- Given a key, a block cipher is a pseudo-random permutation
 - Therefore, invertible (for a fixed key)
- Often built as a substitution-permutation network
 - Will return to S-boxes



KEY EXPANSION



- Symmetric encryption often involves a single shared key
 - Block ciphers typically need one key per round
 - Stream ciphers need one “key” per message block
- So we need to **expand** the initial key in an unpredictable way
- Should preserve size of key space

$$\forall x, y. x \neq y \Rightarrow f(x) \neq f(y)$$

- Provable injectivity of SIMON, Salsa20 key expansion
 - Around 10-20s with ABC [\[simon.saw\]](#) [\[Salsa20.saw\]](#)
- Provable injectivity of AES key expansion
 - A little under a minute with ABC [\[AES.saw\]](#)
- ZUC, a stream cipher for GSM, had a vulnerability
 - Key expansion not injective in ZUC 1.4 (0.5s) [\[zuc.saw\]](#)
 - Provably fixed in ZUC 1.5 (0.6s) [\[zuc.saw\]](#)
 - Originally shown with custom search procedure taking 3m [9]
- **Not injective** for DES!
 - Known to have weak keys
 - Can show quickly with ABC (0.08s) [\[DES.saw\]](#)

$$\exists m. E(m, k) = c \text{ for known } k \text{ and } c$$

- Decrypting using encryption code
- This actually works!
 - Relatively efficient for DES (0.2s), 3DES (0.8s) [DES.saw] [3DES.saw]
 - More modern ciphers slower:
 - AES (1.5m) [AES.saw]
 - SIMON (3.6m) [simon.saw]
 - Speck (20s) [speck.saw]
- Can also run the encryption directly:
 - $\exists c. E(m, k) = c$ for known m and k
 - Usually takes 1/5 to 1/2 the time of decryption
 - Not really useful, but illustrates the flexibility of SAT

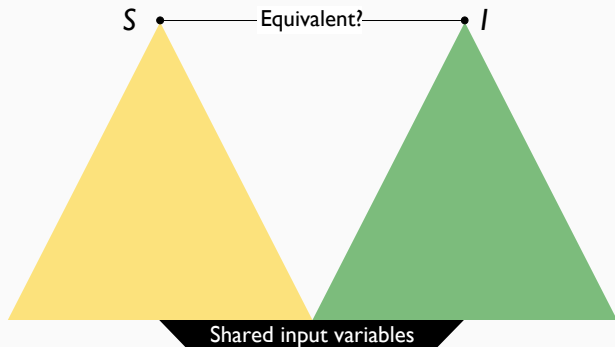
$$\forall m, k. D(E(m, k), k) = m$$

- For a block cipher with encryption function E , decryption D
- Feasible to show for many ciphers
 - DES (4s) [DES.saw]
 - 3DES (8s) [3DES.saw]
 - SIMON (6.2m) [simon.saw]
 - Speck (2.7m) [speck.saw]
- Hard to show for AES (at least with encodings and solvers we've tried) [AES.saw]

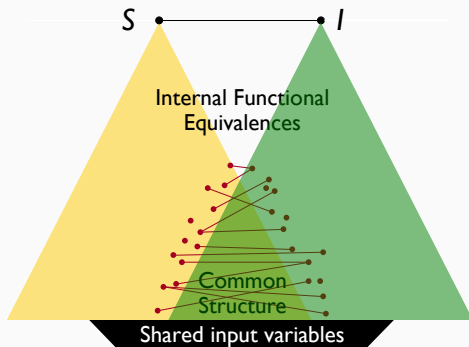
$$\forall x. f(x) = g(x)$$

- Two functions give equivalent output for all inputs
- AIGs give distinct benefits over direct CNF creation
 - Intuitive construction
 - Sharing subterms reduces overall expression size
 - SAT sweeping helps identify candidate equivalences
 - Especially effective for cryptography
 - Use best available SAT solver for final phase
- Works on many core cryptographic primitives, including AES (on a single block) (~6.4m) [AES-eq.saw]

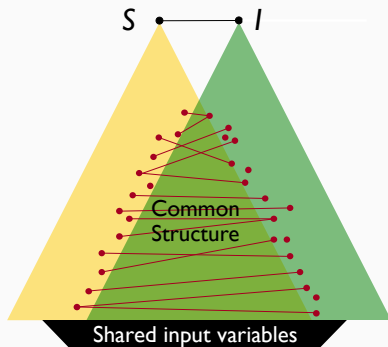
EQUIVALENCE CHECKING ILLUSTRATED

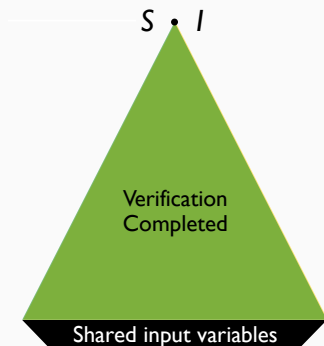


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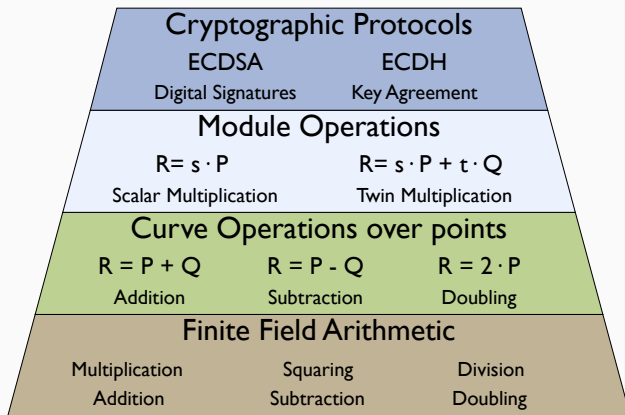


EQUIVALENCE CHECKING ILLUSTRATED





COMPOSITIONAL EQUIVALENCE CHECKING: MOTIVATION

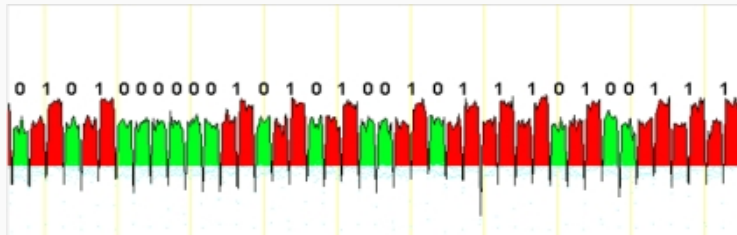


- Key tool: uninterpreted functions
- Symbolic execution turns imperative code into functional code
 - So procedure calls can be uninterpreted functions
 - If we know all inputs and outputs
- Used for checking equivalence between Cryptol and Java ECDSA implementations
 - Takes around 5 minutes to run
 - Takes ~1500 lines of script (mostly I/O mapping, rewrite rules)
 - ABC for leaves, rewriting + Z3 for higher layers

- Attack on symmetric block ciphers
- Known plaintext attack: assumes attacker has some set of (m, c) pairs
- Basic idea: can we approximate the encryption function by a linear function?
 - Where *linear* here means made up entirely of XOR operations
- Any time the encryption function agrees with a linear function too often, this can ease cryptanalysis
- Can use #SAT to count how often it behaves linearly

- Like linear cryptanalysis, known plaintext attack on symmetric block ciphers
- Analysis of how differences in input affect differences in output
- Disproportional effects can be exploitable
- A **differential characteristic** is a set of differences as they traverse a path through the algorithm
- Can use #SAT to calculate the distributions of differential characteristics

- SIMON is a lightweight block cipher published recently
- Kölbl *et al.* used SAT for linear and differential cryptanalysis of SIMON [5] [\[simon-diff.saw\]](#)
- Using #SAT to calculate differential characteristic distributions
- Not direct analysis of code, but of manually-derived simplification
- Serves as an additional tool for cryptanalysis, not push-button
- Suggests slightly different parameters possibly preferable to published numbers



- Traditional side channel analysis
 - Observe specific part of last round of block cipher
 - Combine with pre-calculated formulas to recover key
- Caveat: only works if you can observe the right signals

- Example: hardware implementation
 - Encode entire algorithm (as implemented) as a boolean circuit
 - Observe any internal values possible
 - Constrain internal variables accordingly
 - Try to solve for key (or other aspects of state)
- More information than just inputs or outputs
- Can use **any internal variable** in the algorithm
- Hamming weights plus a handful of (m, c) pairs enough to recover AES key [7]

- S-boxes intended to unpredictably substitute bits
 - Ideally indistinguishable from a random function
 - But in practice representable as a short program using only linear operations
- Generating optimal S-boxes:
 - Or any function on a small domain
 - $\exists p. \llbracket p \rrbracket(x_0) = y_0 \wedge \dots \wedge \llbracket p \rrbracket(x_n) = y_n$
- Fuhs *et al.* found a 23-instruction AES S-box program [2]
 - Less than a minute with MiniSat
 - Proving unsatisfiability of 22 instructions took 106 hours (CryptoMiniSat)

- General synthesis:
 - $\exists p. \forall x. \llbracket p \rrbracket(x) = f(x)$
- Generating efficient implementations:
 - $\min p. \forall x. \llbracket p \rrbracket(x) = f(x)$
- Generally, a hard problem
 - But QBF solvers are getting powerful
 - Many papers in SMT community about this problem recently

- Cryptographic protocol analysis
- Diffusion analysis
- Differential fault analysis
- Constructing new encryption schemes
- What's next?

- Some problems are difficult with current solvers, but potentially tractable
 - AES equivalence in CNF (tractable using SAT sweeping!)
 - AES consistency
 - Good benchmarks for solver improvement!
- Some problems that are intrinsically difficult (we hope)
 - Multiplication difficulty seems related to hardness of factoring
 - Finding a hash collisions had better be hard
 - Finding k given m, c should be hard, too
- Synthesis is currently hard
 - But provers are getting better at this (QBF and $\exists\forall$ -SMT)
- Very similar problems can be different in difficulty
 - Reversing AES vs. finding k from m, c

- Cryptol is a DSL for cryptographic code
 - Allows expression of algorithms at a high-level of abstraction
 - Built-in connection to SMT solvers
 - BSD-licensed
 - <http://cryptol.net>
- The Software Analysis Workbench (SAW) allows analysis of implementations
 - Symbolic execution of Cryptol, C, Java
 - Bindings to SMT and SAT solvers, including ABC
 - Freely available (with source) for non-commercial use
 - <http://saw.galois.com>
- All the examples from this talk are available
 - <https://github.com/galoisinc/sat2015-crypto>

- Cryptography and SAT go very nicely together
 - Easily representable as propositional formulas
 - AIGs are super handy! (not just for hardware)
- More use of SAT during algorithm development will make our crypto stronger
 - And it's happening: see SHA-3, Trivium, SIMON, etc.
- Nice source of hard benchmark problems for solvers

<https://github.com/galoisinc/sat2015-crypto>

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- [1] Felix Dörre and Vladimir Klebanov. **Pseudo-random number generator verification - a case study.** In *7th Working Conference on Verified Software: Theories, Tools, and Experiments*, 2015.
- [2] Carsten Fuhs and Peter Schneider-Kamp. **Optimizing the AES S-Box using SAT.** In Geoff Sutcliffe, Stephan Schulz, and Eugenia Ternovska, editors, *IWIL 2010. The 8th International Workshop on the Implementation of Logics*, volume 2 of *EasyChair Proceedings in Computing*, pages 64–70. EasyChair, 2010.

- [3] Ekawat Homsirikamol, Paweł Morawiecki, Marcin Rogawski, and Marian Srebrny. **Security margin evaluation of SHA-3 contest finalists through SAT-based attacks.** In Agostino Cortesi, Nabendu Chaki, Khalid Saeed, and Sławomir Wieruchoń, editors, *Computer Information Systems and Industrial Management*, volume 7564 of *Lecture Notes in Computer Science*, pages 56–67. Springer Berlin Heidelberg, 2012.
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- [6] Ilya Mironov and Lintao Zhang. **Applications of SAT solvers to cryptanalysis of hash functions.** In Armin Biere and CarlaP. Gomes, editors, *Theory and Applications of Satisfiability Testing - SAT 2006*, volume 4121 of *Lecture Notes in Computer Science*, pages 102–115. Springer Berlin Heidelberg, 2006.

- [7] M.S.E. Mohamed, S. Bulygin, M. Zohner, A. Heuser, M. Walter, and J. Buchmann. **Improved algebraic side-channel attack on AES**, June 2012.
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