

# APPLYING SATISFIABILITY TO THE ANALYSIS OF CRYPTOGRAPHY

---

Aaron Tomb, Galois, Inc.

September 25, 2015

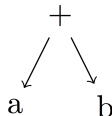
# WHY USE SAT FOR CRYPTOGRAPHY?

- 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-vectory things)
- We'll focus on primitives with type  $\{0, 1\}^n \rightarrow \{0, 1\}^m$

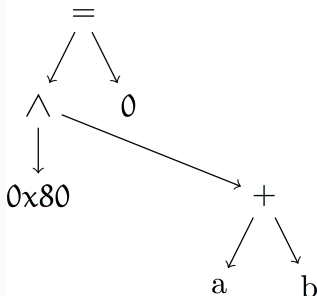
- A function from the ZUC stream cipher

```
uint8_t c = a + b;  
if (c & 0x80) {  
    c = (c & 0x7F) + 1;  
}  
return c;
```



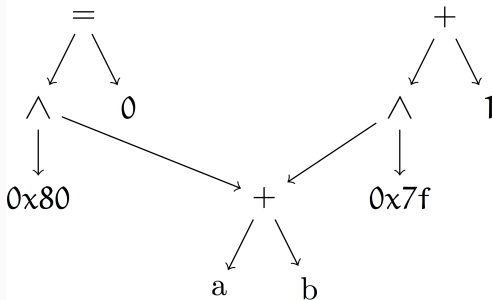
- A function from the ZUC stream cipher

```
uint8_t c = a + b;  
if (c & 0x80) {  
    c = (c & 0x7F) + 1;  
}  
return c;
```



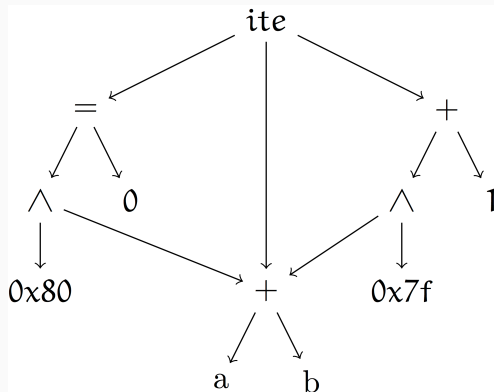
- A function from the ZUC stream cipher

```
uint8_t c = a + b;  
if (c & 0x80) {  
    c = (c & 0x7F) + 1;  
}  
return c;
```

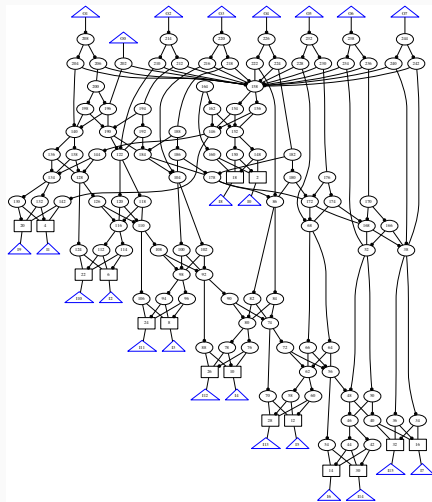


- A function from the ZUC stream cipher

```
uint8_t c = a + b;  
if (c & 0x80) {  
    c = (c & 0x7F) + 1;  
}  
return c;
```



# 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



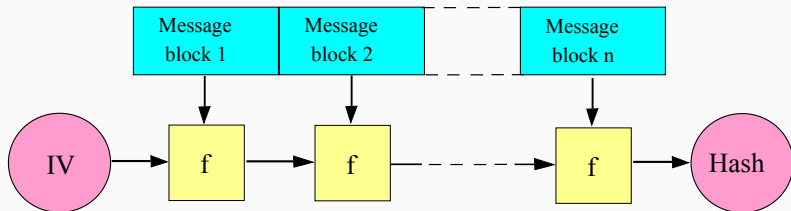
- Used to steal around \$6k of BitCoin
- Fixed in Android 4.4 (KitKat)
- Similar weaknesses existed in Debian, FreeBSD at times

## 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  $O(2^{n/2})$

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

- 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



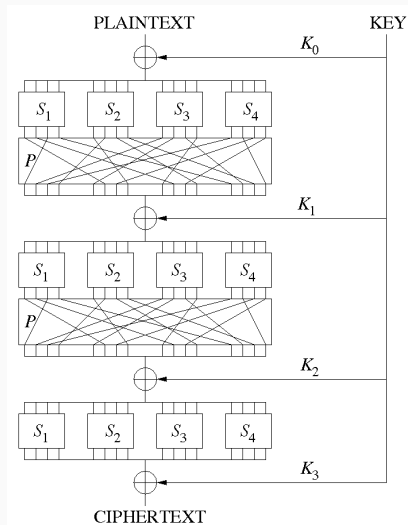
## EVALUATING SHA-3 CANDIDATES

- 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

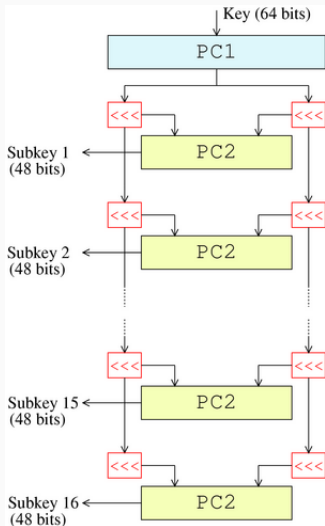
Algorithm	Rounds	Security margin	Code
SHA-1	21	74% (21/80)	SHA-0-1.saw (36s)
SHA-256	16	75% (16/64)	SHA265.saw (1.3s)
Keccak-256	2	92% (2/24)	N/A
BLAKE-256	1	93% (1/14)	Blake256.saw (17s)
Groestl-256	0.5	95% (0.5/10)	N/A
JH-256	2	96% (2/42)	N/A
Skein-512-256	1	99% (1/72)	N/A

# 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

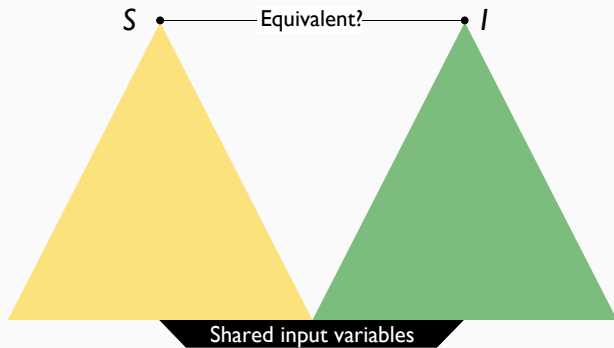
$$\forall m, k. D(E(m, k), k) = m$$

- 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]

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

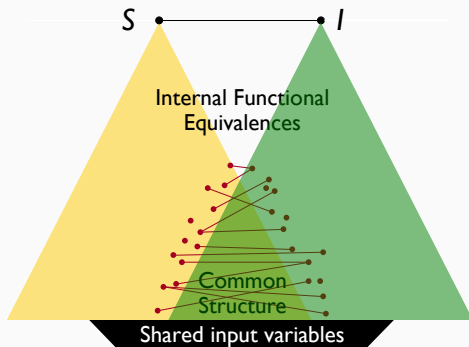
- Two functions give equivalent output for all inputs
- AIGs give distinct benefits over direct CNF creation
  - Intuitive construction
  - Sharing subterms reduces overall expression size
  - SAT sweeping helps identify candidate equivalences
    - Especially effective for cryptography
  - Use best 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

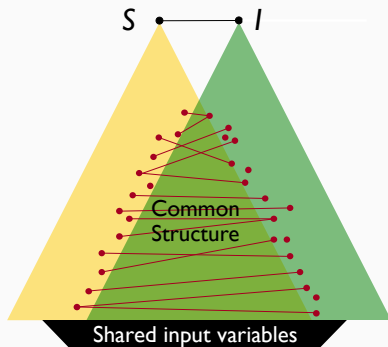


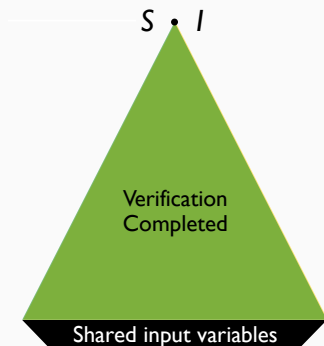


# EQUIVALENCE CHECKING ILLUSTRATED

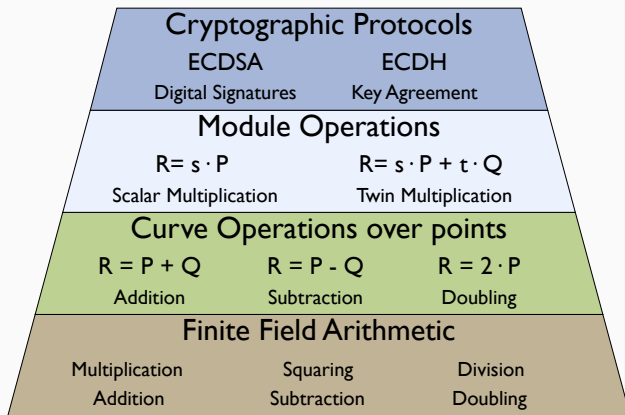


# EQUIVALENCE CHECKING ILLUSTRATED





# COMPOSITIONAL EQUIVALENCE CHECKING: MOTIVATION



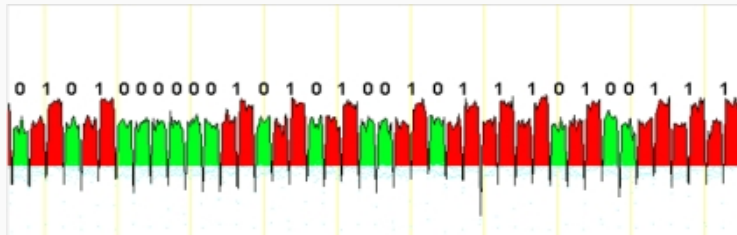
- Key tool: uninterpreted functions
- Symbolic execution turns imperative code into functional code
  - So procedure calls can be uninterpreted functions
  - If we know all inputs and outputs
- Used for checking equivalence between Cryptol and Java ECDSA implementations
  - Takes around 5 minutes to 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>



- [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.
- [4] Dejan Jovanović and Predrag Janičić. **Logical analysis of hash functions.** In Bernhard Gramlich, editor, *Frontiers of Combining Systems*, volume 3717 of *Lecture Notes in Computer Science*, pages 200–215. Springer Berlin Heidelberg, 2005.

- [5] Stefan Kölbl, Gregor Leander, and Tyge Tiessen. **Observations on the SIMON block cipher family.** In Rosario Gennaro and Matthew Robshaw, editors, *Advances in Cryptology – CRYPTO 2015*, volume 9215 of *Lecture Notes in Computer Science*, pages 161–185. Springer Berlin Heidelberg, 2015.
- [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.
- [8] Ilya Otpuschennikov, Alexander Semenov, and Stepan Kochemazov. **Transalg: a tool for translating procedural descriptions of discrete functions to SAT (tool paper)**, 2014.
- [9] Hongjun Wu, Tao Huang, PhuongHa Nguyen, Huaxiong Wang, and San Ling. **Differential attacks against stream cipher ZUC**. In Xiaoyun Wang and Kazue Sako, editors, *Advances in Cryptology – ASIACRYPT 2012*, volume 7658 of *Lecture Notes in Computer Science*, pages 262–277. Springer Berlin Heidelberg, 2012.