White-box cryptography

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29 December 2013
This is a survey talk, partially inspired by the ongoing research on white-box cryptographic designs at the University of Luxembourg (together with Alex Biryukov).

https://www.cryptolux.org
White-box cryptography, what is it?
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All versions are partly true.
Overview
1. Man at the end
   Standard model of adversary
   Man at the end
   Details of protection schemes
   Key hiding problem

2. White-Box cryptography
   White-box implementation
   Lookup table method
   White-boxing AES
   Cryptanalysis
   Market
   Weak and strong white-box implementations

3. New approaches
   WBC from scratch
   Weak white-box candidate
   Non-invertibility problem
   White-box cryptography from polynomials
We consider protection of large amounts of data: databases, digital media, scientific experiments, etc..
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Performance is important
Performance and security are typically addressed with symmetric cryptography, where secret components are shared by parties.

Confidentiality/privacy:
- Symmetric ciphers: AES-128/192/256 (key size in bits).
- Modes of operation to process large data: CTR (counter), CBC (chaining).

Integrity/authenticity:
- Hash functions: SHA-1, SHA-256, SHA-3 (Keccak) and Message Authentication Codes (HMAC).
- Authenticated encryption: OCB, GCM.
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All these designs withstood years of cryptanalysis, and their security is often backed up with security proofs and arguments.
Symmetric vs. public-key cryptography

Performance has some cost:

- RSA is believed to be secure, because it is related to the hardness of factoring;
- AES is believed to be secure, just because no one has broken it (and many tried).
Standard model of adversary
Standard cryptographic model (dates back to Kerchoffs):
  • Algorithm is open and available for public scrutiny;
  • Key is secret (hidden in hardware, remote computer, etc.).

Sometimes the latter assumption does not hold.
Man at the end: unorthodox model for cryptographic algorithms
An attacker downloads a DRM-protected song from a server to an authorized music player:

- Connection can be eavesdropped;
- The player code is accessible;
- Dynamic execution allows to view the entire cryptographic transformation.
- Keys are difficult to hide.
More applications:

- Distribution of digital cinema to theaters;
- Playing encrypted HD movies in authorized players (AACS for HD DVD);
- Direct streaming of protected media (DTCP).

Quite many protocols have been attacked. How?
Details
How digital cinema is protected:

- Movie is encrypted with AES (since it is fast);
- AES key is encrypted with the RSA key of the device;
- To reduce the server workload the AES key may repeat.
Where it can be attacked:

CSS (1999), AACS (2007), HDCP (2010) have been broken along these lines.
Quite often, it is possible to extract the entire code and use it for decryption (code lifting).

However, it is better to obtain keys directly:

- Easy to distribute;
- Easy to update;
- Not traceable;
- Sometimes the decoding procedure can not be isolated.
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Staying apart from code lifting, how can we hide these keys?
Hardware (various tamper-proof dongles, TPM):

- Significantly increases the attack cost;
- Also more expensive, less flexible, and vulnerable to side-channel attacks (timing and power analysis).
Hiding keys in software

**Obfuscation** – concealing program’s logic, purpose, or behaviour.

Issues with obfuscation:

- Does not target keys specifically.
- Existing techniques are vulnerable to static and dynamic analysis.
- Theoretical results are ambiguous: generic obfuscators do not exist [Barak et al. 2001], but simple functions (e.g., point functions) can be obfuscated.
- No theoretical method that just waits for optimization.
Let us elaborate more on obfuscation:

- If we cannot make provably unbreakable, we can try to make it seemingly unbreakable (cf. the security of AES).
- The “obfuscation path” was initially offered for the public-key cryptography, but eventually the mathematically hard problems have been chosen.
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• So how could we obfuscate keys?

• What sort of security would we want to get?
White-box cryptography
White-box implementation

WBC centers around white-box implementation:

1. Pure software implementation of a cipher (encryption or decryption routine) with embedded key;
2. Implementation is assumed available to an adversary;
3. Adversary gets little to no advantage over a black-box implementation, where only inputs and outputs are observed.

Similar to public-key cryptography (RSA). Why not using it?

• RSA-2048 encryption speed — 1000 CPU cycles per byte.
• AES-128 encryption speed — 0.7 CPU cycles per byte.

Impractical for large amount of data. So one more requirement:

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Apparently, our tools are limited...
Naive way to hide a key: put everything in a large lookup table.

However, conventional ciphers work with 128-bit blocks. A single table is clearly infeasible ($\approx 2^{128}$ size).
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\[
\text{plaintext} \quad P \\
\downarrow \\
\text{key} \quad K \\
\downarrow \\
E \\
\downarrow \\
\text{ciphertext} \quad C
\]

\[
\begin{array}{c|c}
\text{plaintext} & \text{ciphertext} \\
P_1 & C_1 \\
P_2 & C_2 \\
\ldots & \ldots
\end{array}
\]

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Smaller key-dependent tables?

- Implements any function in given domain;
- Memory-consuming (4 GB for 32-bit tables);
- Easily invertible.
White-box implementation of AES
First proposal

Chow, Eisen, Johnson, and van Oorschot, “White-Box Cryptography and an AES Implementation” (2002).

- Obfuscate AES implementation with embedded keys;
- Publish algorithm as a sequence of smaller table lookups.

Goal: make the key recovery difficult.

One round of AES:

- Four 32-bit blocks:
  - AddRoundKey (simple XOR);
  - SubBytes (bytewise nonlinear);
  - MixColumns (linear).
- ShiftRows (byte permutation).
White-boxing AES round

Simplistic view of white-box encoding:

- Add secret, random, mutually compensative transformations $P$ and $Q$;
- Replace every 32-bit block with a lookup table;
- Store everything in memory.
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Actual proposal used smaller and weaker tables.
Cryptanalysis
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Consider multiple inputs \( I_1, I_2, \ldots, I_k \) and the evolution of differences between them: \( I_a \oplus I_b \).

- Suppose \( P(I_a \oplus I_b) \) is non-zero in only one S-box;
- Such input pairs form a linear space;
- The output differences form a matrix of low rank.
Consider multiple inputs $I_1, I_2, \ldots, I_k$ and the evolution of differences between them: $I_a \oplus I_b$.

We retrieve $P$ and $Q$ up to linear equivalence, and then just guess the key bytewise.

With other optimizations, the entire key can be extracted from tables in $2^{30}$ simple operations (seconds on a PC).
Here we have only one nonlinear layer. Even 3 nonlinear layers are not enough [Biryukov-Shamir’01].
Why table-based approach fails for AES? Recall the structure:

- Small tables contain too little key material;
- Hiding entire key would require enormously large tables.
Other proposals

White-box implementation of AES (2002):

- Attack on the first variant [Billet’04];
- Improved variants [Bringer’06, Karroumi’11];
- Attacks on improved variants [DeMulder’10, ’12, ’13].

All attacks have practical complexity.

White-box implementation of DES (2002):

- Attacks on “naked variant” (fault attack [Jacob’02], statistical attack [Link’05]);
- Improved variant;
- Attacks on improved variant [Goubin’07, Wyseur’07].
So is everything broken?
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Principally, yes
Still, many proprietary solutions available at the market:

- SafeNet Sentinel;
- Irdeto Cloakware Security Kernel;
- Arxan TransformIT;
- whiteCryption MCFACT;
- Microsemi’s Whiteboxcrypto.

They probably combine academic proposals with ad-hoc obfuscation techniques.
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No public attacks.
We have talked about key recovery only. What about other security goals?
What security should we expect from a white-box implementation?

**Weak WBC**

**Key-recovery security:** an adversary can not extract the key from the code.

- Chronologically first definition;
- Apparently easier to achieve;

**Strong WBC**

**Plaintext-recovery security:** an adversary can not invert the cipher, i.e. decrypt given the encryption routine.

- More sound definition;
- Applies also in the case of code lifting;
- Almost identical to public-key cryptography (may replace it).
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New approaches to WBC
Problems with existing ciphers:

- Not designed with white-box implementations in mind;
- Even key-recovery security is difficult to achieve.

What if we make a white-box suitable cipher from scratch?
Let’s start with key-recovery security (weak WBC).
It is apparently easy to hide a key in a small table.
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$32 \times t$-bit block cipher with 128-bit key:

- 20 rounds;
- Round: subkey injection + 32-bit S-box (taken from AES) + linear transformation;
- Each key byte is used 5 times.
- Make a lookup table for all $2^{32}$ inputs and given key.
- Mix the tables linearly if wideblock-cipher is needed.

Security margin larger than in AES...

but trivially invertible.
How to make the construction non-invertible without a key?

Lookup table problems:

- Lookup tables allow inputs up to 32 bits only;
- Any network of lookup tables are usually trivially invertible (search in the table);
- We do not know how to do otherwise (open problem!).
Can we use functions (one-way permutations) that are difficult to invert?
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- If it is easy to invert with a key, we face a **trapdoor permutation**.

Known candidates such as RSA $x \rightarrow x^3 \pmod{N}$ are believed secure for $N$ of thousand bits long only. Still open problem for smaller $N$ and reasonable performance.
Non-invertibility from functions

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are believed secure for \( N \) of thousand bits long only.
• Still open problem for smaller \( N \) and reasonable performance.
How about other algebraic constructions?

We know that inverting a random degree-2 vector-polynomial is hard

\[(x_1, x_2, \ldots, x_n) \rightarrow (x_1x_2 + x_3x_7 + \cdots + x_8x_n + x_{n-3}, \ldots)\].

The problem is that we can not make it random enough to hide a trapdoor there.
Public-key cryptography with polynomials:

\[ b = T \circ a \circ S, \]  

(1)

where \( S \) and \( T \) are key-dependent and secret, and \( a \) is a public invertible polynomial of degree 2.

- Degree-2 polynomials of 128 boolean variables are compact enough (less than 1 MByte), and there is no generic inversion algorithm.
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- However, virtually all variants of this scheme have been broken because of properties of \( a \): only a few families of invertible polynomials are available (even without trapdoors).
Some work in progress:

\[ b = U \circ a_2 \circ T \circ a_1 \circ S \]

- Two nonlinear layers;
- Nonlinear transformations are expanding and more random-looking;
- Noise \((a_3)\) added to defeat generic decomposition algorithms.
Summary
• White-box cryptography aims to obfuscate encryption or decryption routines with embedded keys to make the key extraction or inversion impossible;
• It is quite similar to public-key cryptography and generic obfuscation;
• All academic proposals are weak;
• Many proprietary solutions available with unknown basis and security level;
• Good solutions may not exist.
Questions?