Examples of symmetric primitives

D. J. Bernstein

	message len
Permutation	fixed
Compression function	fixed
Block cipher	fixed
Tweakable block cipher	fixed
Hash function	variable
MAC (without nonce)	variable
MAC (using nonce)	variable
Stream cipher	variable
Authenticated cipher	variable

tweak	key	encrypts	authenticates
no	no	—	—
yes	no	—	—
no	yes	yes	—
yes	yes	yes	—
no	no	—	—
no	yes	no	yes
yes	yes	no	yes
yes	yes	yes	no
yes	yes	yes	yes

1994 Wheeler–Needham "TEA, a tiny encryption algorithm":

```
void encrypt(uint32 *b,uint32 *k)
{
  uint32 x = b[0], y = b[1];
  uint32 r, c = 0;
  for (r = 0;r < 32;r += 1) {
    c += 0x9e3779b9;
    x += y+c ^ (y<<4)+k[0]
             ^ (y>>5)+k[1];
    y += x+c ^ (x<<4)+k[2]
             ^ (x>>5)+k[3];
  }
  b[0] = x; b[1] = y;
}
```

`uint32`: 32 bits $(b_0, b_1, \ldots, b_{31})$ representing the "unsigned" integer $b_0 + 2b_1 + \cdots + 2^{31} b_{31}$.

`+`: addition mod 2^{32}.

`c += d`: same as `c = c + d`.

`^`: xor; $\oplus$; addition of each bit separately mod 2. Lower precedence than `+` in C, so spacing is not misleading.

`<<4`: multiplication by 16, i.e., $(0, 0, 0, 0, b_0, b_1, \ldots, b_{27})$.

`>>5`: division by 32, i.e., $(b_5, b_6, \ldots, b_{31}, 0, 0, 0, 0, 0)$.

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Output: 64-bit **ciphertext** (final `b[0],b[1]`).

Can efficiently **encrypt**: (key, plaintext) $\mapsto$ ciphertext.

Can efficiently **decrypt**: (key, ciphertext) $\mapsto$ plaintext.

Wait, how can we decrypt?

```
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  uint32 r, c = 0;
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    c += 0x9e3779b9;
    x += y+c ^ (y<<4)+k[0]
             ^ (y>>5)+k[1];
    y += x+c ^ (x<<4)+k[2]
             ^ (x>>5)+k[3];
  }
  b[0] = x; b[1] = y;
}
```

Answer: Each step is invertible.

```
void decrypt(uint32 *b,uint32 *k)
{
  uint32 x = b[0], y = b[1];
  uint32 r, c = 32 * 0x9e3779b9;
  for (r = 0;r < 32;r += 1) {
    y -= x+c ^ (x<<4)+k[2]
             ^ (x>>5)+k[3];
    x -= y+c ^ (y<<4)+k[0]
             ^ (y>>5)+k[1];
    c -= 0x9e3779b9;
  }
  b[0] = x; b[1] = y;
}
```

Generalization, **Feistel network** (used in, e.g., "Lucifer" from 1973 Feistel–Coppersmith):

```
x += function1(y,k);
y += function2(x,k);
x += function3(y,k);
y += function4(x,k);
...
```

Decryption, inverting each step:

```
...
y -= function4(x,k);
x -= function3(y,k);
y -= function2(x,k);
x -= function1(y,k);
```

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TEA-CTR produces ciphertext
$c_0 = m_0 \oplus \text{TEA}_k(n, 0)$,
$c_1 = m_1 \oplus \text{TEA}_k(n, 1)$,
$c_2 = m_2 \oplus \text{TEA}_k(n, 2)$, ...
using 128-bit key k,
32-bit **nonce** n,
32-bit **block counter** $0, 1, 2, \ldots$.

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32-bit **nonce** n,
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CTR is a **mode of operation** that converts block cipher TEA into **stream cipher** TEA-CTR.

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Usual strategy:
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TEA-XCBC-MAC computes
$a_0 = \text{TEA}_j(c_0)$,
$a_1 = \text{TEA}_j(c_1 \oplus a_0)$,
$a_2 = \text{TEA}_j(c_2 \oplus a_1)$, $\ldots$,
$a_{\ell-1} = \text{TEA}_j(c_{\ell-1} \oplus a_{\ell-2})$,
$a_\ell = \text{TEA}_j(i \oplus c_\ell \oplus a_{\ell-1})$
using 128-bit key j, 64-bit key i.
Authenticator is a_ℓ: i.e., transmit $(c_0, c_1, \ldots, c_\ell, a_\ell)$.

Specifying TEA-CTR-XCBC-MAC **authenticated cipher**:

320-bit key (k, j, i).

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message is sequence of
at most 2^{32} 64-bit blocks.
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Specify how nonce is chosen:
message number. (Stateless
alternative: uniform random.)

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Another useless extreme:
"Any structure is an attack."
Hard to define clearly.
Everything seems "attackable".

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target security definition,
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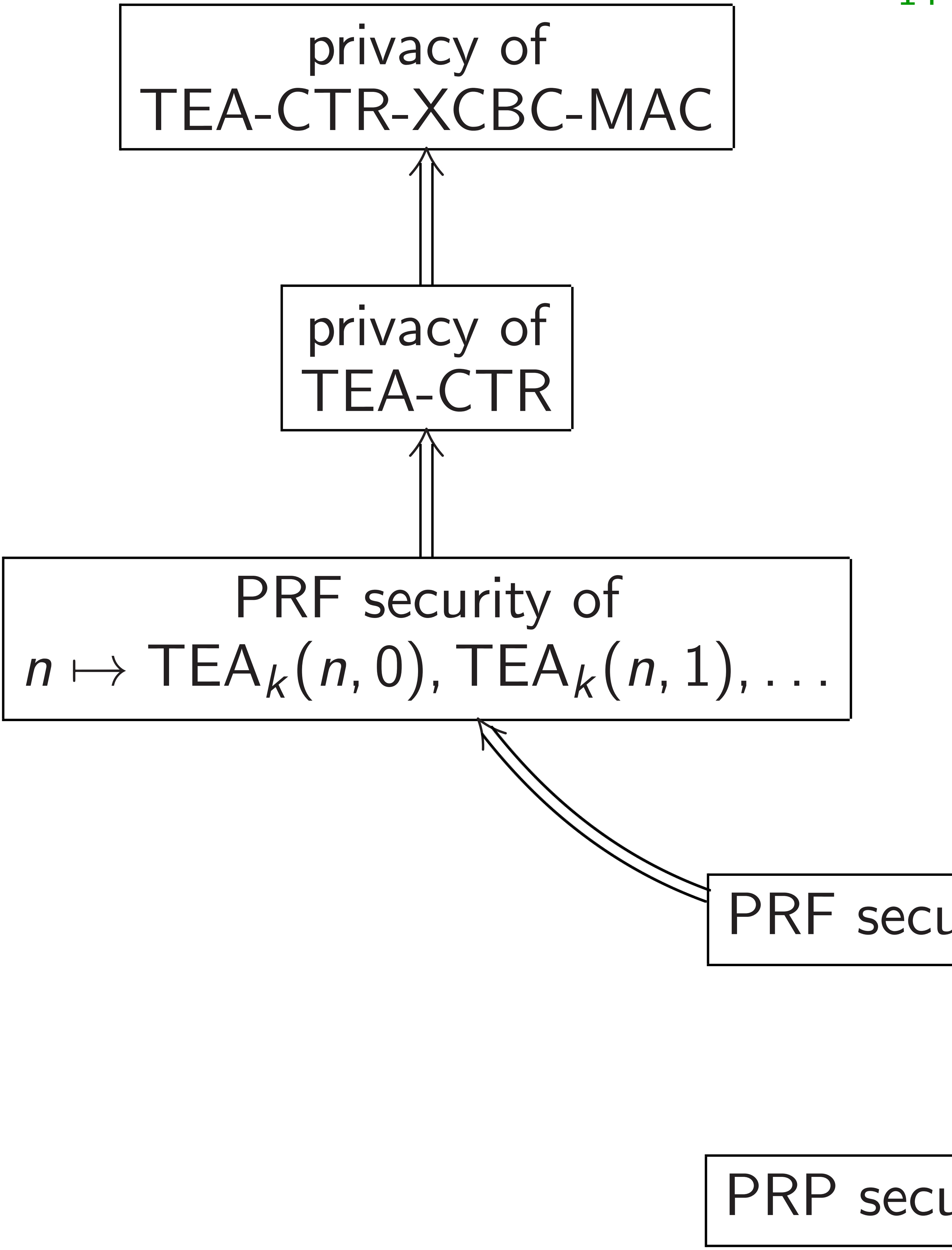
i.e. Prove that any PRF attack against $n \mapsto \text{TEA}_k(n, 0), \text{TEA}_k(n, 1), \ldots$ implies PRF attack against $b \mapsto \text{TEA}_k(b)$.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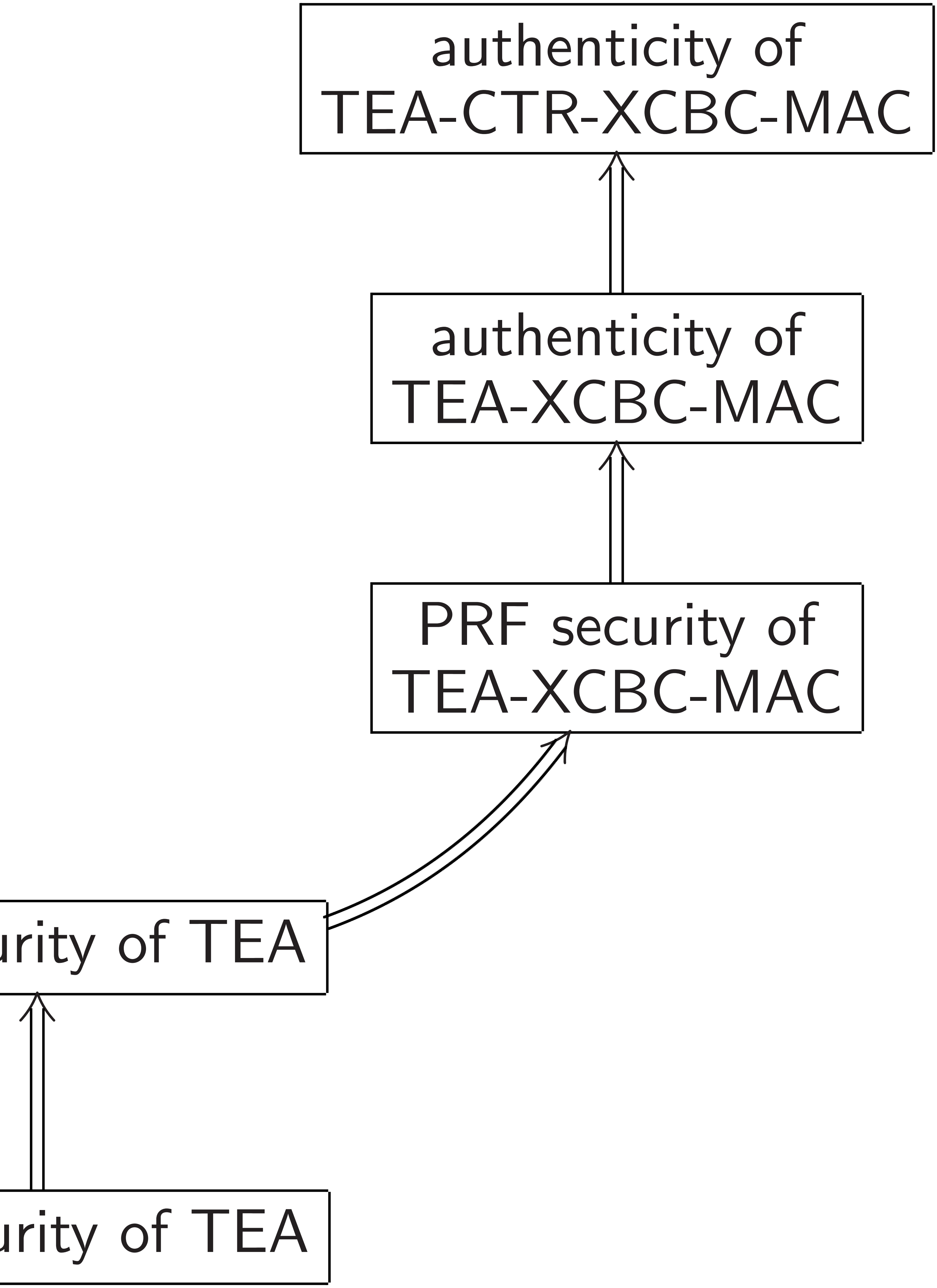
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5. **Is TEA PRP-secure?**

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We *conjecture* security after enough failed attack efforts. "All of these attacks fail and we don't have better attack ideas."

XORTEA: a bad cipher

```
void encrypt(uint32 *b,uint32 *k)
{
  uint32 x = b[0], y = b[1];
  uint32 r, c = 0;
  for (r = 0;r < 32;r += 1) {
    c += 0x9e3779b9;
    x ^= y^c ^ (y<<4)^k[0]
             ^ (y>>5)^k[1];
    y ^= x^c ^ (x<<4)^k[2]
             ^ (x>>5)^k[3];
  }
  b[0] = x; b[1] = y;
}
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e.g. First output bit is
$1 \oplus k_0 \oplus k_1 \oplus k_3 \oplus k_{10} \oplus k_{11} \oplus k_{12} \oplus k_{20} \oplus k_{21} \oplus k_{30} \oplus k_{32} \oplus k_{33} \oplus k_{35} \oplus k_{42} \oplus k_{43} \oplus k_{44} \oplus k_{52} \oplus k_{53} \oplus k_{62} \oplus k_{64} \oplus k_{67} \oplus k_{69} \oplus k_{76} \oplus k_{85} \oplus k_{94} \oplus k_{96} \oplus k_{99} \oplus k_{101} \oplus k_{108} \oplus k_{117} \oplus k_{126} \oplus b_1 \oplus b_3 \oplus b_{10} \oplus b_{12} \oplus b_{21} \oplus b_{30} \oplus b_{32} \oplus b_{33} \oplus b_{35} \oplus b_{37} \oplus b_{39} \oplus b_{42} \oplus b_{43} \oplus b_{44} \oplus b_{47} \oplus b_{52} \oplus b_{53} \oplus b_{57} \oplus b_{62}$.

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Very fast attack:
if $b_4 = b_1 \oplus b_2 \oplus b_3$ then
$\text{XORTEA}_k(b_1) \oplus \text{XORTEA}_k(b_2) =$
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This breaks PRP (and PRF): uniform random permutation (or function) F almost never has $F(b_1) \oplus F(b_2) = F(b_3) \oplus F(b_4)$.

LEFTEA: another bad cipher

```
void encrypt(uint32 *b,uint32 *k)
{
  uint32 x = b[0], y = b[1];
  uint32 r, c = 0;
  for (r = 0;r < 32;r += 1) {
    c += 0x9e3779b9;
    x += y+c ^ (y<<4)+k[0]
             ^ (y<<5)+k[1];
    y += x+c ^ (x<<4)+k[2]
             ^ (x<<5)+k[3];
  }
  b[0] = x; b[1] = y;
}
```

Addition is not $\mathbf{F}_2$-linear,
but addition mod 2 is $\mathbf{F}_2$-linear.

First output bit is
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How TEA avoids this problem:
>>5 **diffuses** nonlinear changes
from high bits to low bits.

(Diffusion from low bits to high
bits: <<4; carries in addition.)

TEA4: another bad cipher

```
void encrypt(uint32 *b,uint32 *k)
{
  uint32 x = b[0], y = b[1];
  uint32 r, c = 0;
  for (r = 0;r < 4;r += 1) {
    c += 0x9e3779b9;
    x += y+c ^ (y<<4)+k[0]
             ^ (y>>5)+k[1];
    y += x+c ^ (x<<4)+k[2]
             ^ (x>>5)+k[3];
  }
  b[0] = x; b[1] = y;
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Trace x, y differences through steps in computation.

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$r = 1$: multiples of $2^{21}, 2^{16}$.

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Uniform random function F:
$F(x + 2^{31}, y)$ and $F(x, y)$ have
same first bit with probability $1/2$.

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Uniform random function F:

$F(x + 2^{31}, y)$ and $F(x, y)$ have

same first bit with probability $1/2$.

PRF advantage $1/2$.

Two pairs (x, y): advantage $3/4$.

More sophisticated attacks: trace *probabilities* of differences; probabilities of linear equations; probabilities of higher-order differences $C(x+\delta+\epsilon)-C(x+\delta)-C(x+\epsilon)+C(x)$; etc. Use algebra+statistics to exploit non-randomness in probabilities.

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Very far from full TEA.

Hard question in cipher design:
How many "rounds" are
really needed for security?

REPTEA: another bad cipher

```
void encrypt(uint32 *b,uint32 *k)
{
  uint32 x = b[0], y = b[1];
  uint32 r, c = 0x9e3779b9;
  for (r = 0;r < 1000;r += 1) {
    x += y+c ^ (y<<4)+k[0]
             ^ (y>>5)+k[1];
    y += x+c ^ (x<<4)+k[2]
             ^ (x>>5)+k[3];
  }
  b[0] = x; b[1] = y;
}
```

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where I_k does x+=...;y+=....

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Good chance that some b in list
also has $a = I_k(b)$ in list. Then
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For each (b, a) from list:
Try solving equations $a = I_k(b)$,
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to figure out k. (More equations: try re-encrypting these outputs.)

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This is a **slide attack.**
TEA avoids this by varying c.

What about original TEA?

```
void encrypt(uint32 *b,uint32 *k)
{
  uint32 x = b[0], y = b[1];
  uint32 r, c = 0;
  for (r = 0;r < 32;r += 1) {
    c += 0x9e3779b9;
    x += y+c ^ (y<<4)+k[0]
             ^ (y>>5)+k[1];
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  }
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```

Related keys: e.g.,

$\text{TEA}_{k'}(b) = \text{TEA}_k(b)$

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Is this an attack?

PRP attack goal: distinguish TEA_k, for one secret key k, from uniform random permutation.

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Related keys $\Rightarrow$ g succeeds with
chance 2^{-126}. Still very small.

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No evidence in literature that this helps brute-force attack, or otherwise affects PRP security. No challenge to security analysis of TEA-CTR-XCBC-MAC.

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But advertised as "related-key cryptanalysis" and claimed to justify recommendations for designers regarding key scheduling.

Some ways to learn more
about cipher attacks,
hash-function attacks, etc.:

Take upcoming course
"Selected areas in cryptology".
Includes symmetric attacks.

Read attack papers,
especially from FSE conference.
Try to break ciphers yourself:
e.g., find attacks on FEAL.
Reasonable starting point:
2000 Schneier "Self-study course
in block-cipher cryptanalysis".

Some cipher history

1973, and again in 1974:
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1976: NSA meets Diffie and Hellman to discuss criticism. Claims "somewhere over $400,000,000" to break a DES key; "I don't think you can tell any Congressman what's going to be secure 25 years from now."

1977: DES is standardized.

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1999: NIST selects five AES finalists: MARS, RC6, Rijndael, Serpent, Twofish.

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2013–now: CAESAR competition.

Main operations in AES:
add round key to block;
apply **substitution box**
$x \mapsto x^{254}$ in $\mathbf{F}_{256}$
to each byte in block;
linearly mix bits across block.

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So why isn't AES-256 the end
of the symmetric-crypto story?

The latest news and insights from Google on security and safety on the Internet

Speeding up and strengthening HTTPS connections for Chrome on Android

April 24, 2014

Posted by Elie Bursztein, Anti-Abuse Research Lead

Earlier this year, we deployed a new TLS cipher suite in Chrome that operates three times faster than AES-GCM on devices that don’t have AES hardware acceleration, including most Android phones, wearable devices such as Google Glass and older computers. This improves user experience, reducing latency and saving battery life by cutting down the amount of time spent encrypting and decrypting data.

To make this happen, Adam Langley, Wan-Teh Chang, Ben Laurie and I began implementing new algorithms -- ChaCha 20 for symmetric encryption and Poly1305

Date: 2018-08-06 22:32:51
Message-ID: 20180806223300.11389
[Download message RAW]

From: Eric Biggers <ebiggers@google.co

Hi all,

(Please note that this patchset is a tr
it to be merged quite yet!)

It was officially decided to *not* allo
encryption [1]. We've been working to
storage encryption to entry-level Andro
"Android Go" devices sold in developing
these devices still ship with no encryp
have to use older CPUs like ARM Cortex-
Cryptography Extensions, making AES-XTS

As we explained in detail earlier, e.g
challenging problem due to the lack of
the very strict performance requiremen
suitable for practical use in dm-crypt
Speck, in this day and age the choice
has a large political element, restric

Therefore, we (well, Paul Crowley did
encryption mode, HPolyC. In essence,
ChaCha stream cipher for disk encrypti
paper here: https://eprint.iacr.org/20

1-1-ebiggers () kernel ! org

m>

rue RFC, i.e. we're not ready for

ow Android devices to use Speck
find an alternative way to bring
oid devices like the inexpensive
g countries. Unfortunately, often
ption, since for cost reasons they
-A7; and these CPUs lack the ARMv8
S much too slow.

. in [2], this is a very
encryption algorithms that meet
ts, while still being secure and
and fscrypt. And as we saw with
of cryptographic primitives also
ting the options even further.

the real work) designed a new
HPolyC makes it secure to use the
on. HPolyC is specified by our
18/720.pdf ("HPolyC:

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AES software ecosystem is complicated and dangerous. Fast software implementations of AES S-box often leak secrets through timing.

Picture is worse for high-security authenticated ciphers. 128-bit block size limits PRF security. Workarounds are hard to audit.

ChaCha creates safe systems
with much less work than AES.

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More examples of how symmetric primitives have been improving speed, simplicity, security:

PRESENT is better than DES.

Skinny is better than Simon and Speck.

Keccak, BLAKE2, Ascon are better than MD5, SHA-0, SHA-1, SHA-256, SHA-512.

Next slides: reference software from 2017 Bernstein–Kölbl–Lucks–Massolino–Mendel–Nawaz–Schneider–Schwabe–Standaert–Todo–Viguier for “Gimli: a cross-platform permutation”.

Gimli permutes $\{0,1\}^{384}$.

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"Wait, where's the key?"

Even–Mansour SPRP mode:
$E_k(m) = k \oplus \text{Gimli}(k \oplus m)$.

Salsa/ChaCha PRF mode:
$S_k(m) = (k, m) \oplus \text{Gimli}(k, m)$.

Or: $(k, 0) \oplus \text{Gimli}(k, m)$.

```
void gimli(uint32 *b)
{
  int r,c;
  uint32 x,y,z;

  for (r = 24;r > 0;--r) {
    for (c = 0;c < 4;++c) {
      x = rotate(b[  c], 24);
      y = rotate(b[4+c],  9);
      z =             b[8+c];
      b[8+c]=x^(z<<1)^((y&z)<<2);
      b[4+c]=y^x      ^((x|z)<<1);
      b[  c]=z^y      ^((x&y)<<3);
    }
```

```
    if ((r & 3) == 0) {
      x=b[0]; b[0]=b[1]; b[1]=x;
      x=b[2]; b[2]=b[3]; b[3]=x;
    }

    if ((r & 3) == 2) {
      x=b[0]; b[0]=b[2]; b[2]=x;
      x=b[1]; b[1]=b[3]; b[3]=x;
    }

    if ((r & 3) == 0)
      b[0] ^= (0x9e377900 | r);
  }
}
```

No additions. Nonlinear carries are replaced by shifts of `&`, `|`. (Idea stolen from NORX cipher.)

Big rotations diffuse changes quickly across bit positions.

`x`, `y`, `z` interaction diffuses changes quickly through columns $(0, 4, 8; 1, 5, 9; 2, 6, 10; 3, 7, 11)$.

Other swaps diffuse changes through rows. Deliberately limited swaps per round $\Rightarrow$ faster rounds on a wide range of platforms.