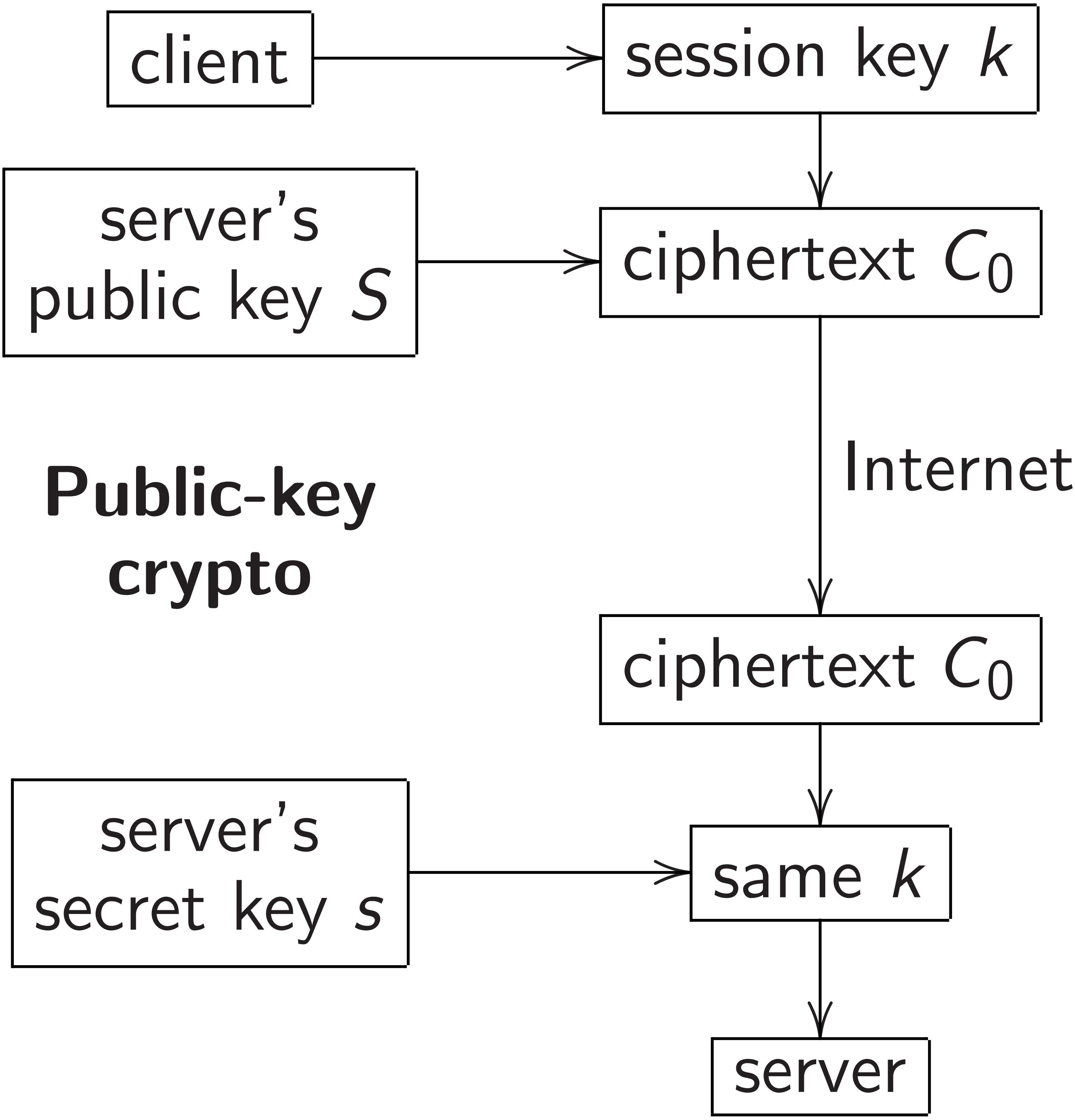
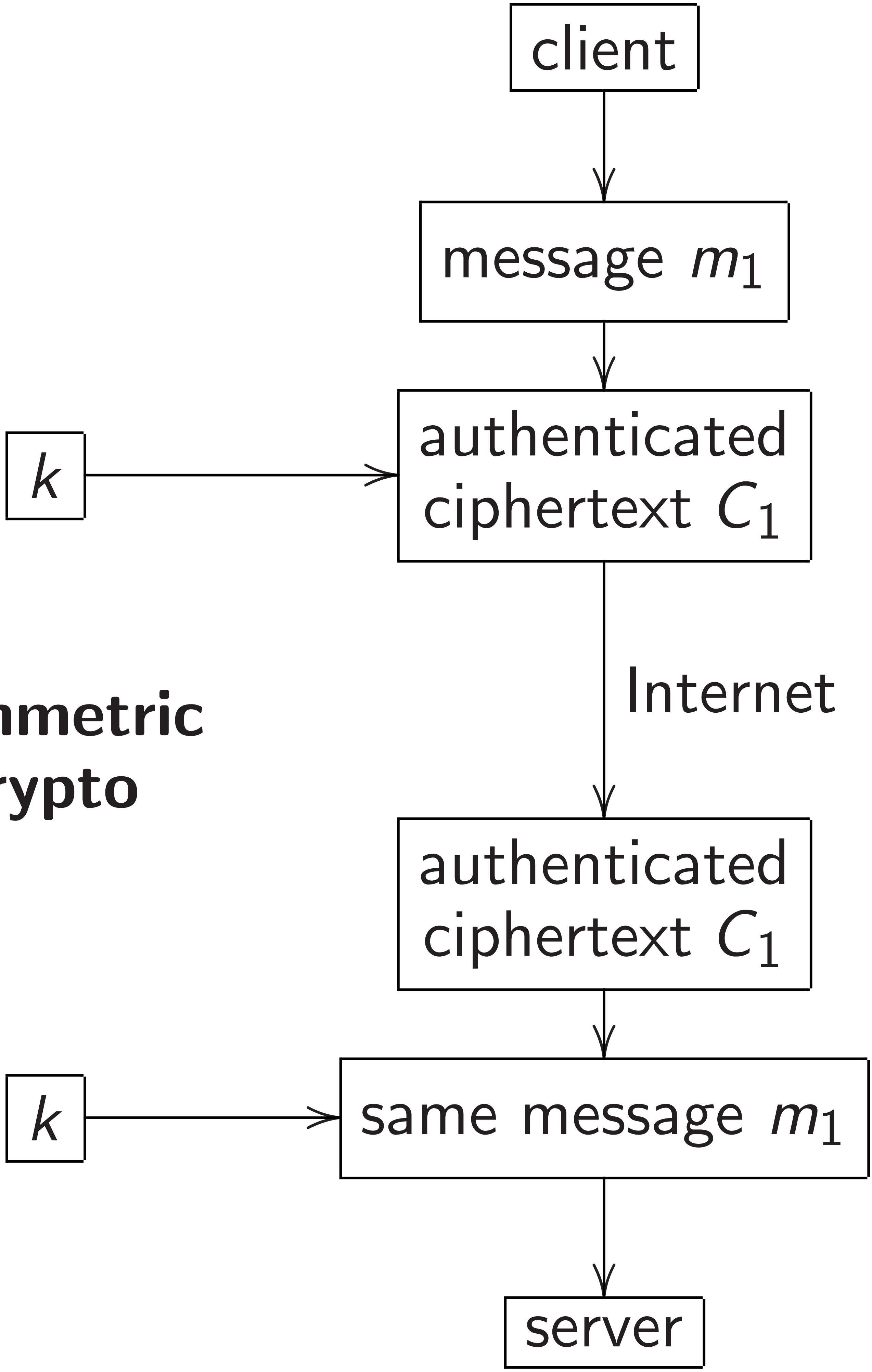
Symmetric crypto, part 2

D. J. Bernstein



Symmetric crypto



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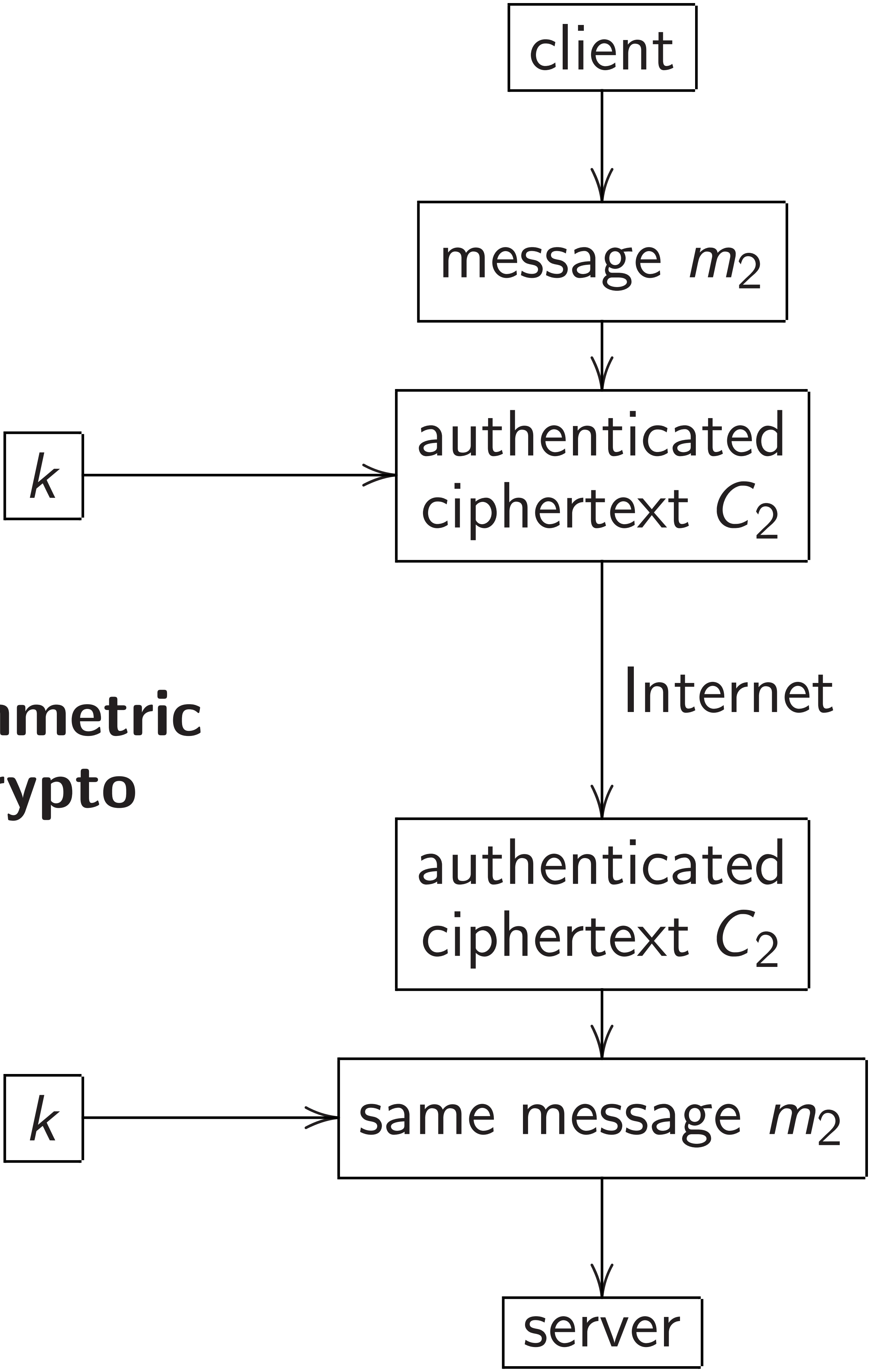

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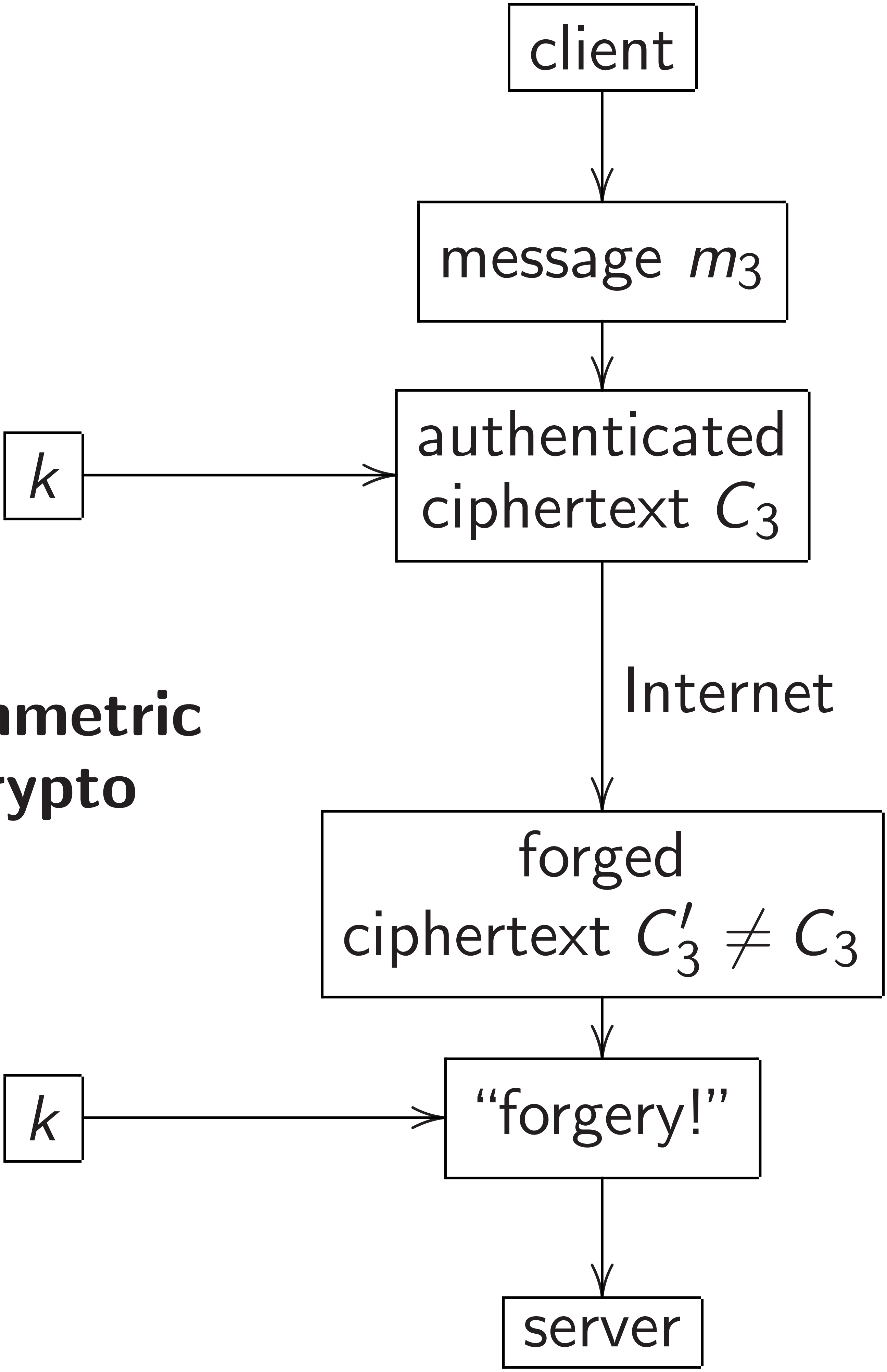

Symmetric crypto: main objectives

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Attacker can't forge ciphertexts.

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Can define further objectives.
Example: If crypto is too slow, attacker can flood server's CPU.
Real client messages are lost.
This damages **availability**.

Easy encryption mechanism:
Assume 30-digit messages.
Assume client, server know
secret 30-digit numbers
t_1 to use for message 1;
t_2 to use for message 2;
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$C_1 = (m_1 + t_1) \bmod 10^{30}$;
$C_2 = (m_2 + t_2) \bmod 10^{30}$;
$C_3 = (m_3 + t_3) \bmod 10^{30}$; etc.
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This protects confidentiality.

AES-GCM, ChaCha20-Poly1305 work this way, scaled up to groups larger than $\mathbf{Z}/10^{30}$.

Last time: For each message
compute **authenticator**
using another secret number.

Sender attaches authenticator
to message before sending it.
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This would be the whole picture *if* client, server started with enough secret random numbers.

AES expands 256-bit secret k into $F(k, 1), F(k, 2), F(k, 3), \ldots$ simulating many independent secrets $r, s_1, t_1, \ldots$.

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Warning: "pseudorandom" has many other meanings.

PRF ("pseudorandom function"):
Attacker can't distinguish
$F(k,1), F(k,2), F(k,3), \ldots$ from
independent uniform random
blocks, given access to a server
that returns $F(k,i)$ given i.
Server is called an **oracle**.

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If block size is big then
PRP $\Rightarrow$ PRF $\Rightarrow$ PRG.

Small block sizes are dangerous.
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AES block size: 128 bits.
PRF attack chance $\approx q^2/2^{129}$ if AES is used for q blocks.
Is this safe? How big is q?

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ChaCha20 block size: 512 bits.

Can prove confidentiality and integrity of AES-GCM and ChaCha20-Poly1305 *assuming* AES and ChaCha20 are PRFs.

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Generalization: Prove security of $M(F)$ assuming cipher F is a PRF. M is a **mode of use** of F.

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Good modes: CTR ("counter mode"), CBC, OFB, many more.

Bad modes: ECB, many more.

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Generalization: Prove security of $M(F)$ assuming cipher F is a PRF. M is a **mode of use** of F.

Good modes: CTR ("counter mode"), CBC, OFB, many more.

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Mode that claimed proof but was recently broken: OCB2. Have to check proofs carefully!

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Remaining slides today:

- Simple example of block cipher. Seems to be a good cipher, except block size is too small.
- Variants of this block cipher that look similar but can be quickly broken.

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., $(b_5, b_6, \ldots, b_{31}, 0, 0, 0, 0, 0)$.

Functionality

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Input: 128-bit key (namely `k[0]`,`k[1]`,`k[2]`,`k[3]`); 64-bit **plaintext** (`b[0]`,`b[1]`).

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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?

```
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;
}
```

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);
```

TEA again for comparison

```
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;
}
```

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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But output bits are linear functions of input bits!

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e.g. First output bit is
$1 \oplus k_0 \oplus k_1 \oplus k_3 \oplus k_{10} \oplus k_{11} \oplus k_{12} \oplus k_{20} \oplus k_{21} \oplus k_{30} \oplus k_{32} \oplus k_{33} \oplus k_{35} \oplus k_{42} \oplus k_{43} \oplus k_{44} \oplus k_{52} \oplus k_{53} \oplus k_{62} \oplus k_{64} \oplus k_{67} \oplus k_{69} \oplus k_{76} \oplus k_{85} \oplus k_{94} \oplus k_{96} \oplus k_{99} \oplus k_{101} \oplus k_{108} \oplus k_{117} \oplus k_{126} \oplus b_1 \oplus b_3 \oplus b_{10} \oplus b_{12} \oplus b_{21} \oplus b_{30} \oplus b_{32} \oplus b_{33} \oplus b_{35} \oplus b_{37} \oplus b_{39} \oplus b_{42} \oplus b_{43} \oplus b_{44} \oplus b_{47} \oplus b_{52} \oplus b_{53} \oplus b_{57} \oplus b_{62}$.

There is a matrix M
with coefficients in $\mathbf{F}_2$
such that, for all (k, b),
$\text{XORTEA}_k(b) = (1, k, b)M$.

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Very fast attack:
if $b_4 = b_1 \oplus b_2 \oplus b_3$ then
$\text{XORTEA}_k(b_1) \oplus \text{XORTEA}_k(b_2) =$
$\text{XORTEA}_k(b_3) \oplus \text{XORTEA}_k(b_4)$.

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$\text{XORTEA}_k(b_3) \oplus \text{XORTEA}_k(b_4)$.

This breaks PRP (and PRF):
uniform random permutation
(or function) F almost never has
$F(b_1) \oplus F(b_2) = F(b_3) \oplus F(b_4)$.

TEA again for comparison

```
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;
}
```

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];
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  }
  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
$1 \oplus k_0 \oplus k_{32} \oplus k_{64} \oplus k_{96} \oplus b_{32}$.

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How TEA avoids this problem:
>>5 **diffuses** nonlinear changes
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How TEA avoids this problem:
>>5 **diffuses** nonlinear changes
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(Diffusion from low bits to high
bits: <<4; carries in addition.)

TEA again for comparison

```
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;
}
```

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;
}
```

Fast attack:

$\text{TEA4}_k(x + 2^{31}, y)$ and

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Trace x, y differences

through steps in computation.

$r = 0$: multiples of $2^{31}, 2^{26}$.

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

$r = 2$: multiples of $2^{11}, 2^{6}$.

$r = 3$: multiples of $2^{1}, 2^{0}$.

Fast attack:

$\mathrm{TEA4}_k(x+2^{31},y)$ and

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Trace x,y differences

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

$r=2$: multiples of $2^{11},2^{6}$.

$r=3$: multiples of $2^{1},2^{0}$.

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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$r = 3$: multiples of $2^{1}, 2^{0}$.

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.

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Very far from full TEA.

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

TEA again for comparison

```
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;
}
```

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;
}
```

$\text{REPTEA}_k(b) = I_k^{1000}(b)$

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

$\text{REPTEA}_k(b) = I_k^{1000}(b)$
where I_k does `x+=...;y+=...`.

Try list of 2^{32} inputs b.
Collect outputs $\text{REPTEA}_k(b)$.

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

Try list of 2^{32} inputs b.
Collect outputs $\text{REPTEA}_k(b)$.
Good chance that some b in list also has $a = I_k(b)$ in list. Then $\text{REPTEA}_k(a) = I_k(\text{REPTEA}_k(b))$.

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

Try list of 2^{32} inputs b.
Collect outputs $\text{REPTEA}_k(b)$.
Good chance that some b in list also has $a = I_k(b)$ in list. Then $\text{REPTEA}_k(a)=I_k(\text{REPTEA}_k(b))$.

For each (b, a) from list:
Try solving equations $a = I_k(b)$, $\text{REPTEA}_k(a)=I_k(\text{REPTEA}_k(b))$ to figure out k. (More equations: try re-encrypting these outputs.)

$\text{REPTEA}_k(b) = I_k^{1000}(b)$
where I_k does `x+=...;y+=...`.

Try list of 2^{32} inputs b.
Collect outputs $\text{REPTEA}_k(b)$.
Good chance that some b in list also has $a = I_k(b)$ in list. Then $\text{REPTEA}_k(a)=I_k(\text{REPTEA}_k(b))$.

For each (b, a) from list:
Try solving equations $a = I_k(b)$, $\text{REPTEA}_k(a)=I_k(\text{REPTEA}_k(b))$ to figure out k. (More equations: try re-encrypting these outputs.)

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

Related keys: e.g.,

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

where $(k'[0], k'[1], k'[2], k'[3]) =$

$(k[0] + 2^{31}, k[1] + 2^{31}, k[2], k[3])$.

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

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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".