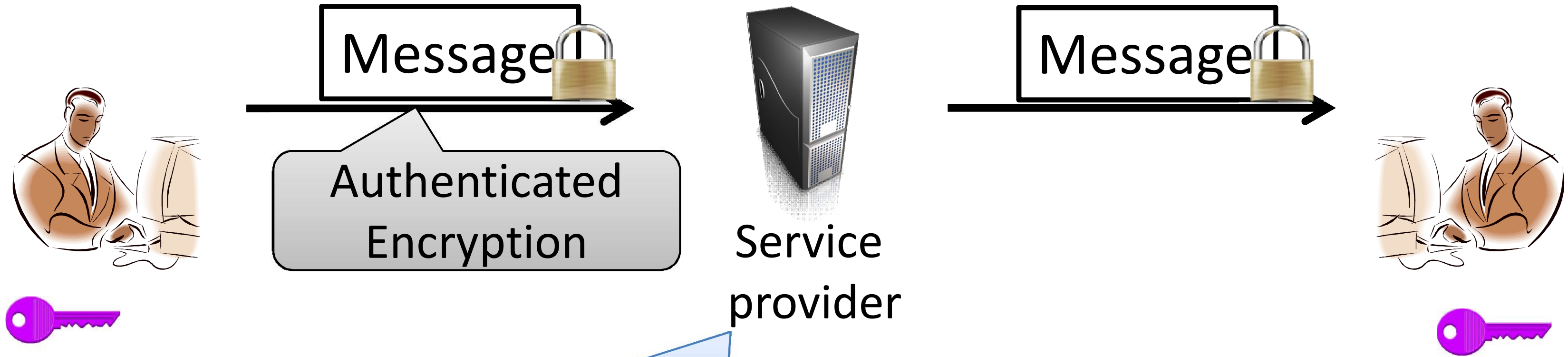
Fast Message Franking:
From Invisible Salamanders to Encryptment

Yevgeniy Dodis, ***Paul Grubbs***,
Thomas Ristenpart, Joanne Woodage

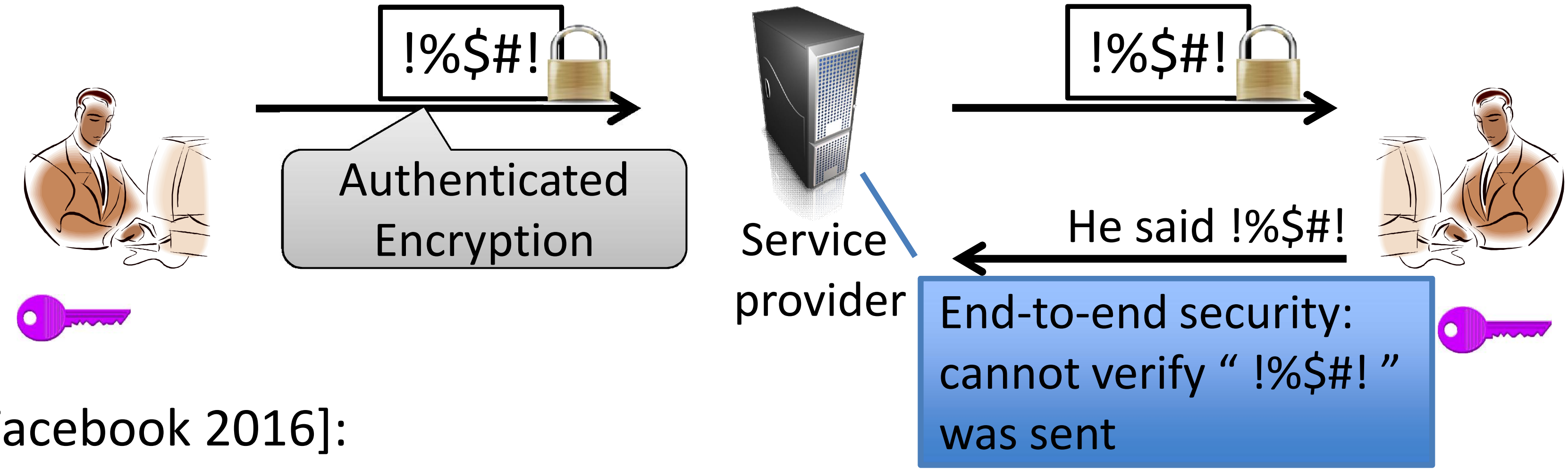
End-to-end encrypted messaging



End-to-end security:
Provider cannot read or modify messages

[Frosch et al. 2014]
[Cohn-Gordon et al. 2016]
[Cohn-Gordon, Cremers, Garratt 2016]
[Bellare et al. 2017]
[Jaeger and Stepanovs 2018]

Providers want to help users with abuse



[Facebook 2016]:

- Provide cryptographic proof of message contents when reporting abuse
- Called technique ***message franking***

Our contributions

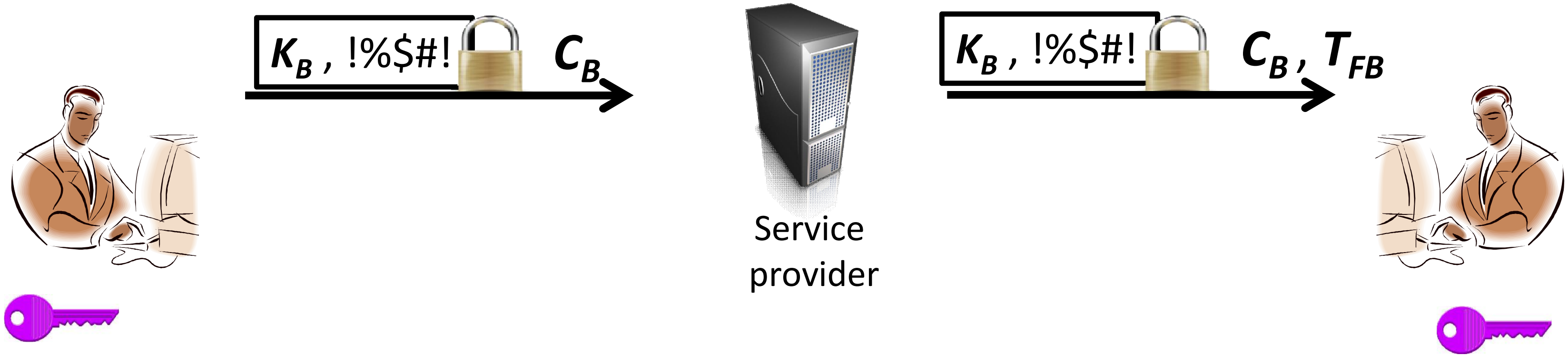
Show vulnerability in Facebook's scheme:
invisible salamanders

Lower bound on efficiency of ccAE

New symmetric-key primitive: ***encryptment.***
Hash-Function-Chaining (HFC):
single-pass encryptment construction

Generic, fast transform:
encryptment + compression function=ccAE

Facebook's message franking protocol



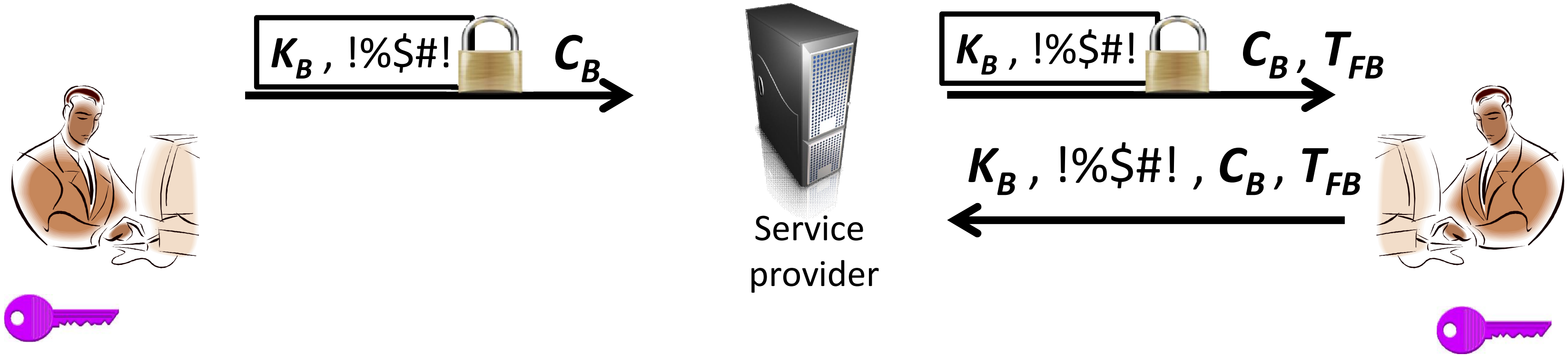
Sender ***cryptographically commits*** to message: $C_B = HMAC(K_B, M)$

Encrypt-then-HMAC message along with K_B (called the opening)

Provider signs C_B using HMAC to generate tag T_{FB} (fast because C_B short)

Receiver decrypts, retrieves K_B, and verifies C_B

Facebook’s message franking protocol



To report abuse, send message as well as K_B , C_B , T_{FB}

Provider can verify C_B , T_{FB} , convinced that message was “ !%$#! ”

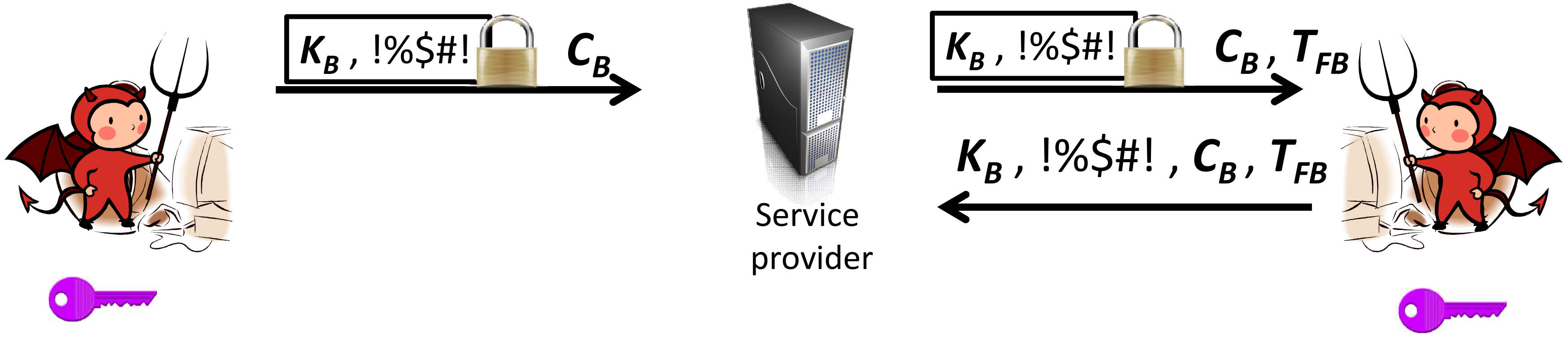
Attachments (images, videos) handled differently

Is Facebook’s approach secure?

[**G**LR17]: without attachments, yes

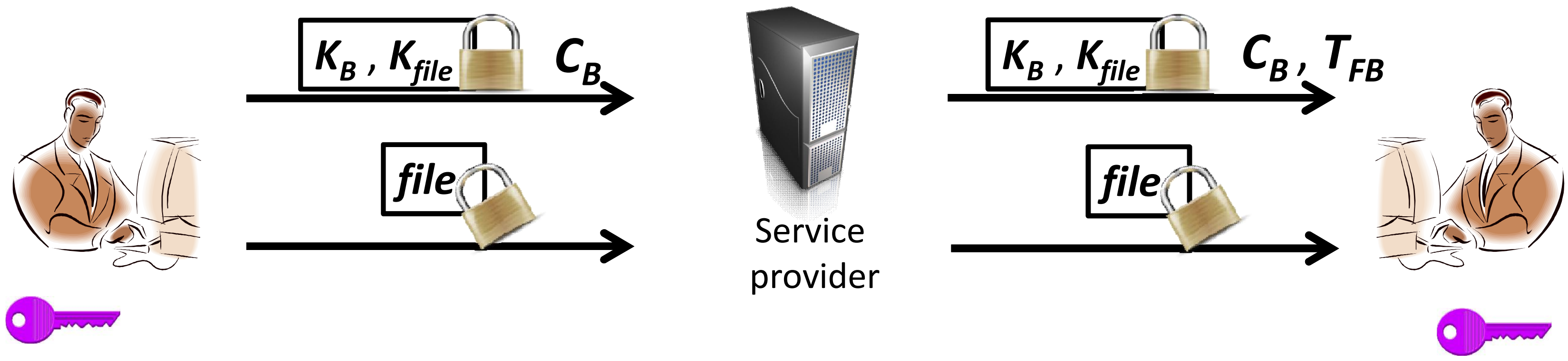
This work: with attachments, ***no!***

Security goals for message franking



1) ***Receiver binding***: receiver can't open a message not sent
2) ***Sender binding***: can't send a message that can't be reported
3) End-to-end confidentiality/authenticity for messages not reported

Facebook's *attachment* franking protocol



Sender ***cryptographically commits*** to attachment encryption key:

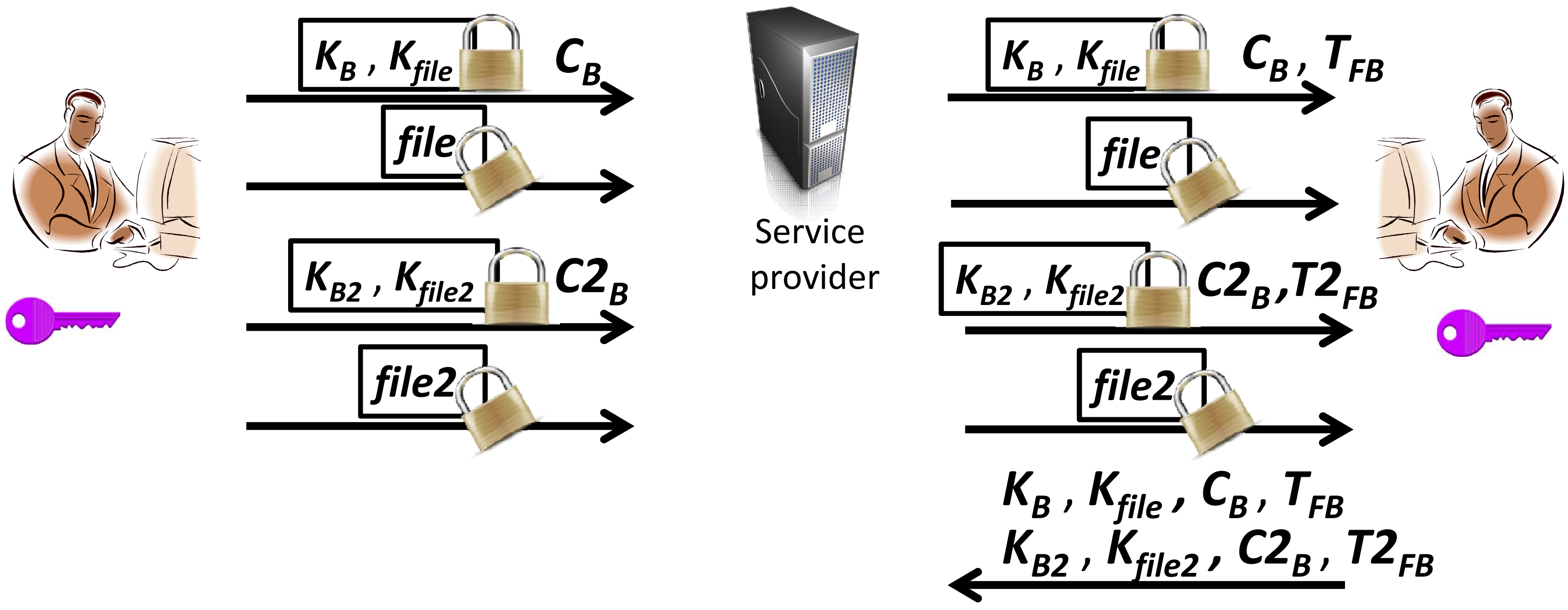
$$C_B = HMAC(K_B, K_{file})$$

Encrypt-then-HMAC file encryption key K_{file} along with K_B

AES-GCM encrypt attachment: ***AES-GCM(K_{file} , file)***

Receiver decrypts as before to get K_{file} and then decrypts attachment

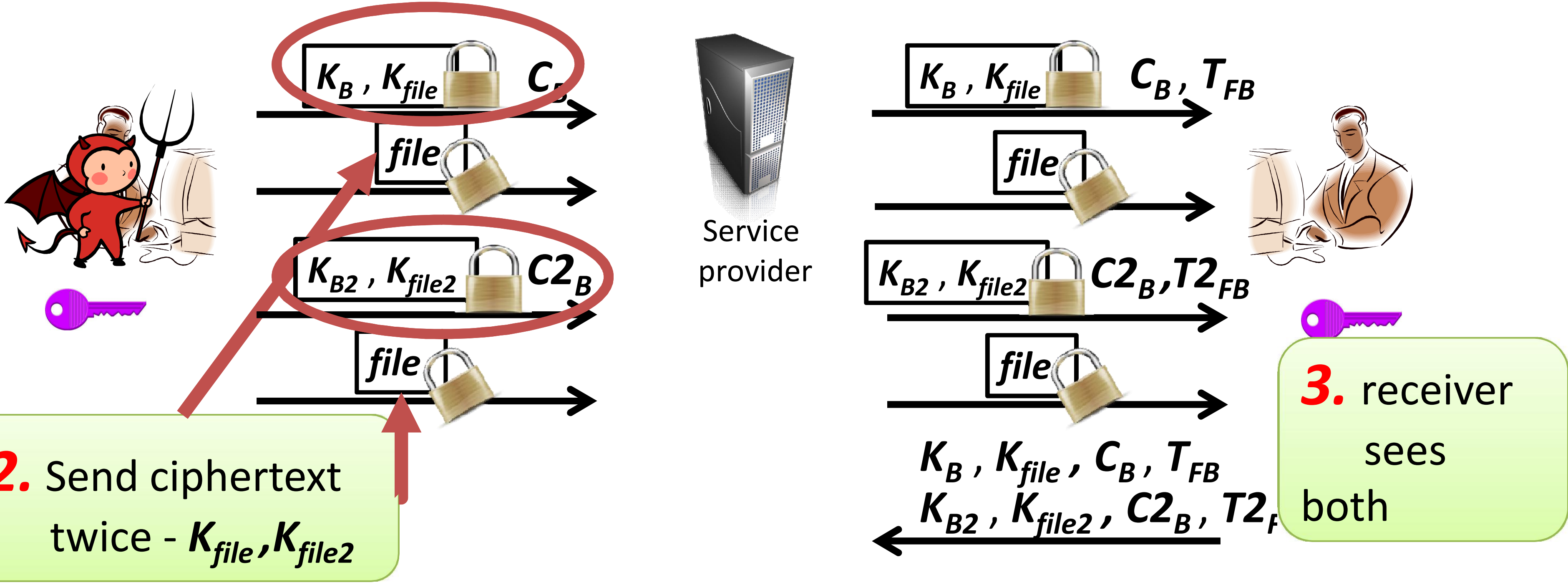
Facebook's *attachment* franking protocol



To report abuse, receiver opens K_{file} and other recent messages

Facebook checks openings & decrypts all unique AES-GCM ciphertexts to add them to abuse report

Our attack exploits AES-GCM



1. Craft special ***AES-GCM*** ciphertext:

- Decrypts under K_{file} to innocuous image
- Decrypts under K_{file2} to abuse image

4. Only the innocuous image appears in report! (Violates sender binding)

Our attack exploits AES-GCM

Craft special ***AES-GCM*** ciphertext:

1) Decrypts under K_{file} to innocuous image
2) Decrypts under K_{file2} to abuse image

But isn't ***AES-GCM*** a secure authenticated encryption scheme?

Yes, but ... this type of attack is not standard

attacker gets to choose K_{file} and K_{file2}

GCM uses a universal-hash-based MAC

not collision resistant (CR)

Our attack violates ***robustness***: can find ciphertext that decrypts under two keys

(First robustness attack against real system)

[Abdalla, Bellare, Neven 2010] [Farshim et al. 2013] [Farshim et al. 2017]

Abusive JPEG seen by receiver,
but not in abuse report

Innocuous BMP
in abuse report

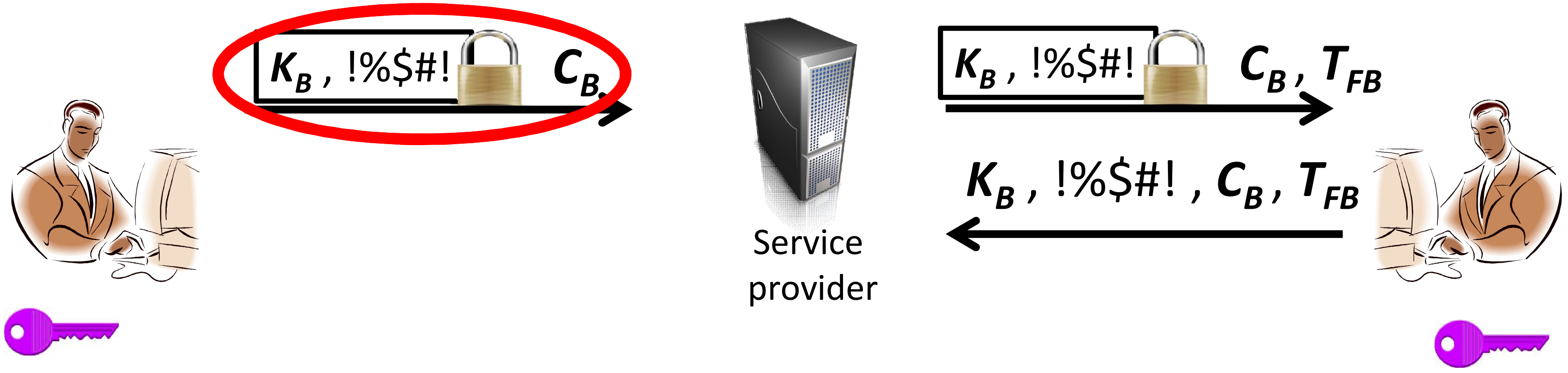
Disclosed to Facebook

Thanks to Jon Millican for answering questions!

They fixed by changing report generation logic

Awarded us a bug bounty

Recall Facebook's message franking



Commitment + authenticated encryption (AE):

[**G**LR] proved secure as ccAE

Didn't use for attachments because too slow

- Signal uses ***AES-CBC*** then ***HMAC*** for AE
- Total of 3 passes (***HMAC-Encrypt-HMAC***)

Can we make faster ccAE schemes?

How do we build faster ccAE?

Ideally: ~1 blockcipher call per msg block.

Can any secure scheme achieve this?

No!

<u>Thm.</u> Secure ccAE => CR hashing.

Leverage prior impossibility results for CR hashing from fixed-key blockciphers

[Black, Cochran, Shrimpton 2005]
[Rogaway, Steinberger 2008]

No similar ccAE scheme can be secure!

Scheme	ccAE?	# passes
AES-GCM	No	1
OCB	No	1
Encrypt-then-HMAC (distinct keys)	No	2
Encrypt-then-HMAC (one key)	Yes	2
Facebook HMAC-Encrypt-HMAC	Yes	3

How do we build faster ccAE?

Step 1

New primitive: ***encryptment***
"one-time" ccAE

Hash-Function-Chaining (HFC) scheme

+

Step 2

Simple transforms from encryptment to ccAE

Encryptment-to-ccAE transform from compression function

ccAE in one SHA-256 call

Encryptment: syntax, semantics, security

Should be short: e.g. 256 bits

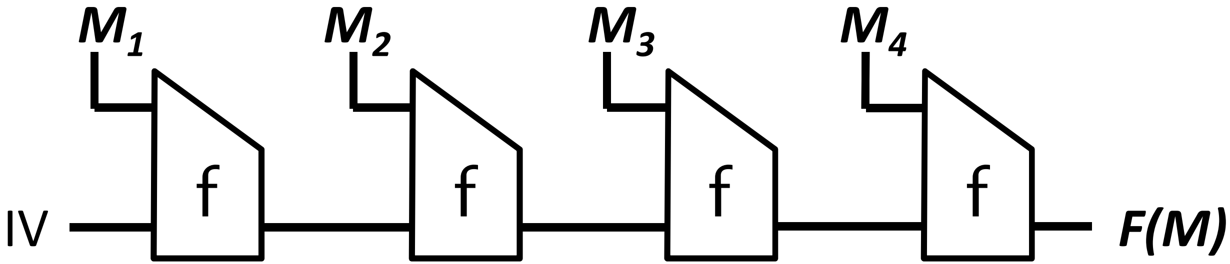
$EC(K, M) = C_1, C_B$	**encrypts** and **commits** to M
$DO(K, C_1, C_B) = M/\perp$	**decrypts** (C_1, C_B) and **opens** to M
$EVer(M, K, C_B) = 0/1$	**verifies** commitment C_B of M

1. ***Confidentiality:*** can't distinguish ciphertexts from random bits
2. ***Second-ciphertext unforgeability:*** can't forge ciphertexts in particular way
3. ***Receiver binding:*** can't generate K,M pairs that verify for same C_B
4. ***Sender binding:*** can't decrypt ciphertext that doesn't verify properly

The hash-function chaining (HFC) scheme

Recall Merkle-Damgard style hash functions (e.g., SHA-256) built in two steps:

1) Specify a compression function f: $\{0,1\}^n \times \{0,1\}^d \rightarrow \{0,1\}^n$
2) Iterate f to hash long message (after some suitable padding)

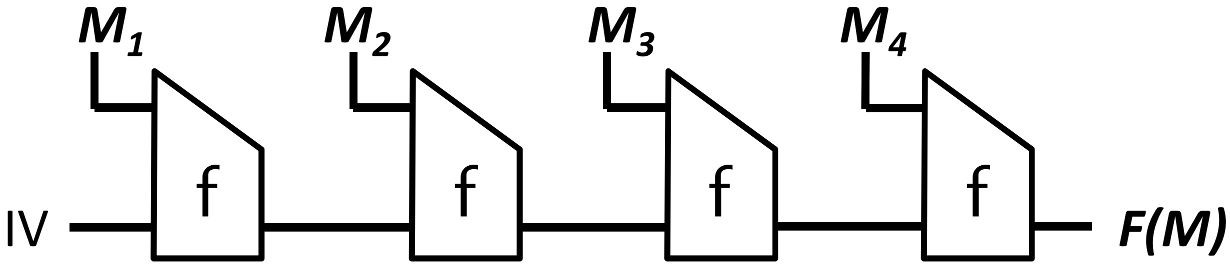


Constant bit string called initialization vector

The hash-function chaining (HFC) scheme

The HFC scheme **EC**(K, M):

1) Prepend message with a block of zeros, XOR key into each block
2) Use chaining variables as encryption pad to compute $\mathbf{C_1}$
3) MD output is the binding tag $\mathbf{C_B}$



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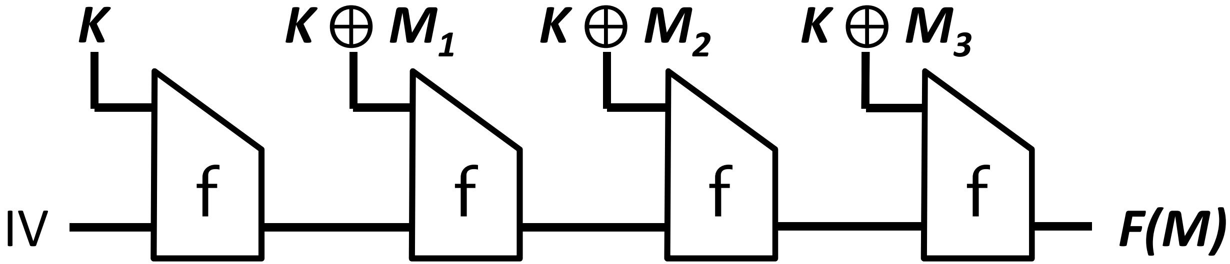

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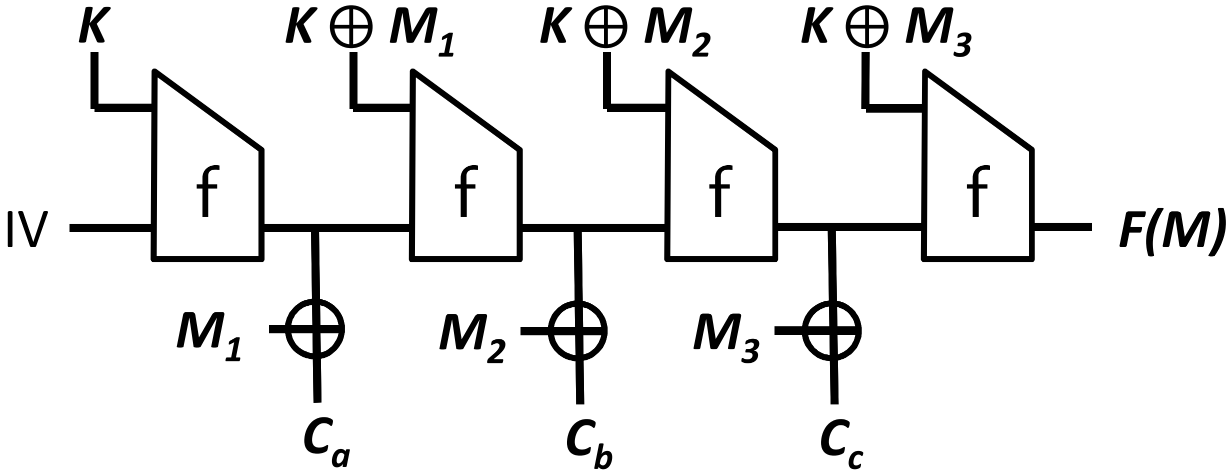

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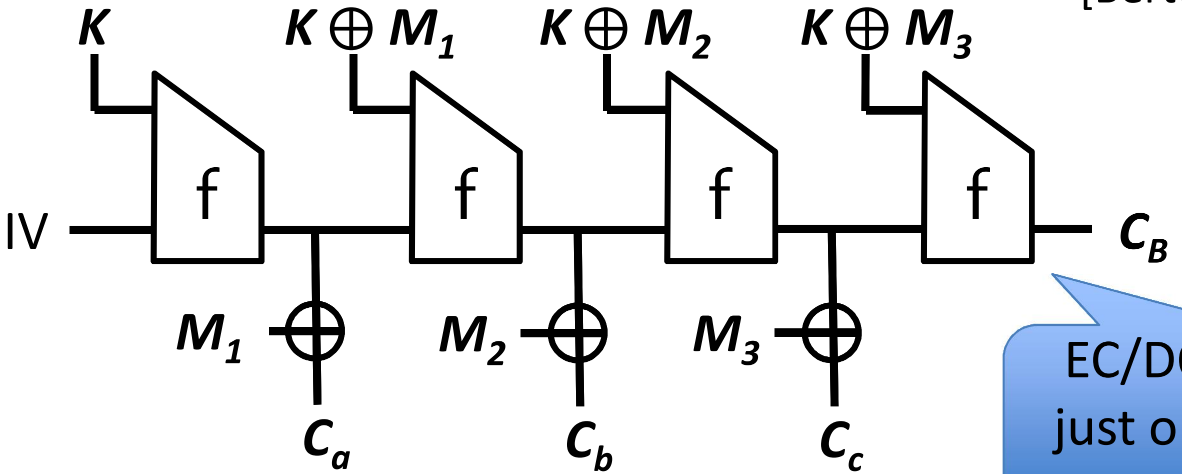
DO(K, C_1, C_B) runs MD, recovers message blocks, checks C_B
EVer(K, M, C_B) recomputes, checks C_B

Similar to AE from
[Cogliani et al. '10]
[Bertoni et al. '11]

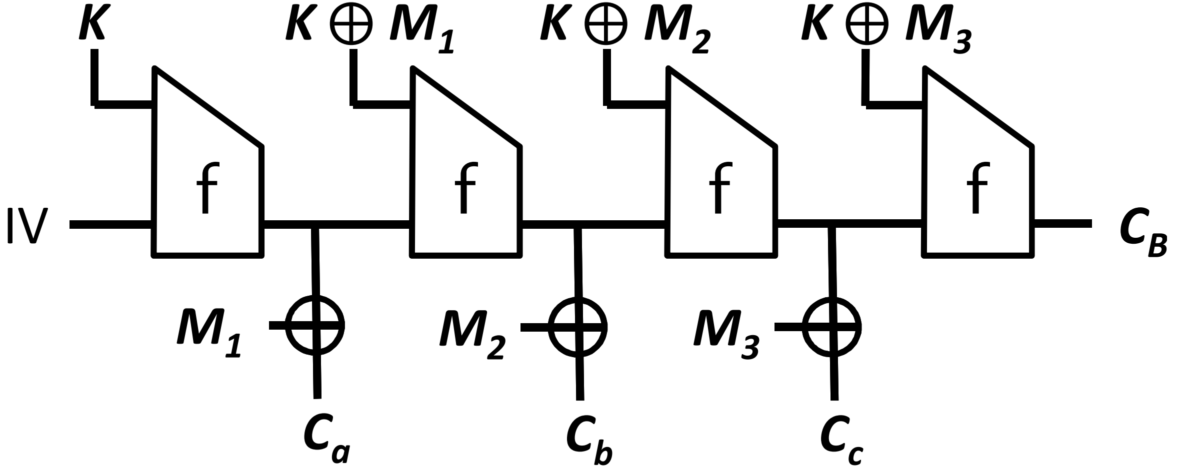


EC/DO/EVer require just one pass of hash function

(Fast) Encryptment => (Fast) ccAE

Construct fast ccAE from fast encryptment: 2 additional compression function calls

1. Use long-term key $\mathbf{K_{lt}}$
2. Derive encryptment key via f
3. MAC the binding tag $\mathbf{C_B}$



(Fast) Encryptment => (Fast) ccAE

Construct fast ccAE from fast encryptment: 2 additional compression function calls

<u>Thm</u>**.** If **EC** is a secure encryptment scheme
and compression function is PRF,
this construction is ccAE

Encryptment is useful elsewhere,
gives single-pass:
- concealments [DH03]
- remotely-keyed AE [BFN98]
- robust AE [FOR17]

See paper for details

Conclusion

Show vulnerability in Facebook's scheme:

invisible salamanders

Lower bound on efficiency of ccAE

New symmetric-key primitive: ***encryptment.***

Hash-Function-Chaining (HFC):

single-pass encryptment construction

Generic, fast transform:

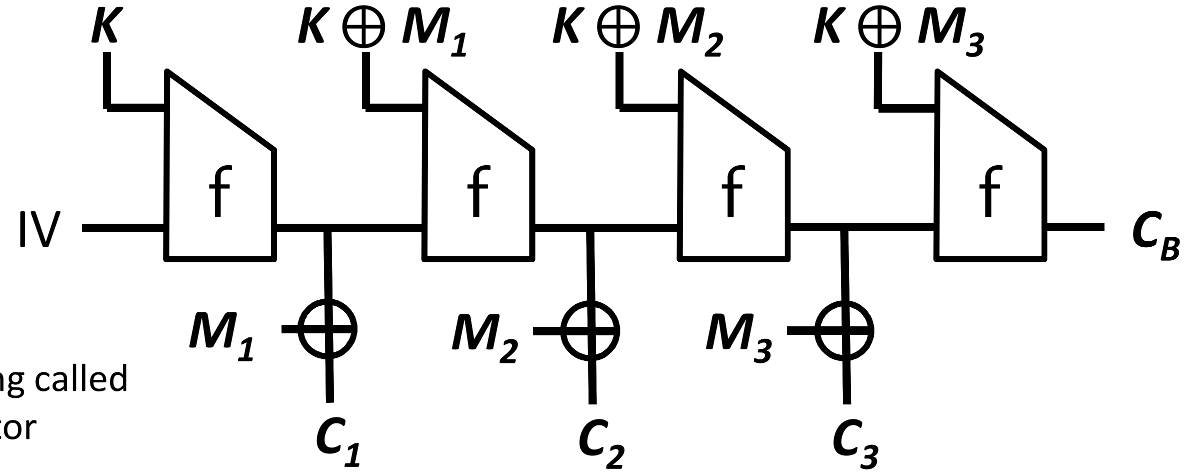
encryptment + compression function=ccAE

Thanks for listening! Any questions?

Security of HFC

<u>Theorem (informal)</u>:
HFC is a secure encryptment scheme

See paper for details!



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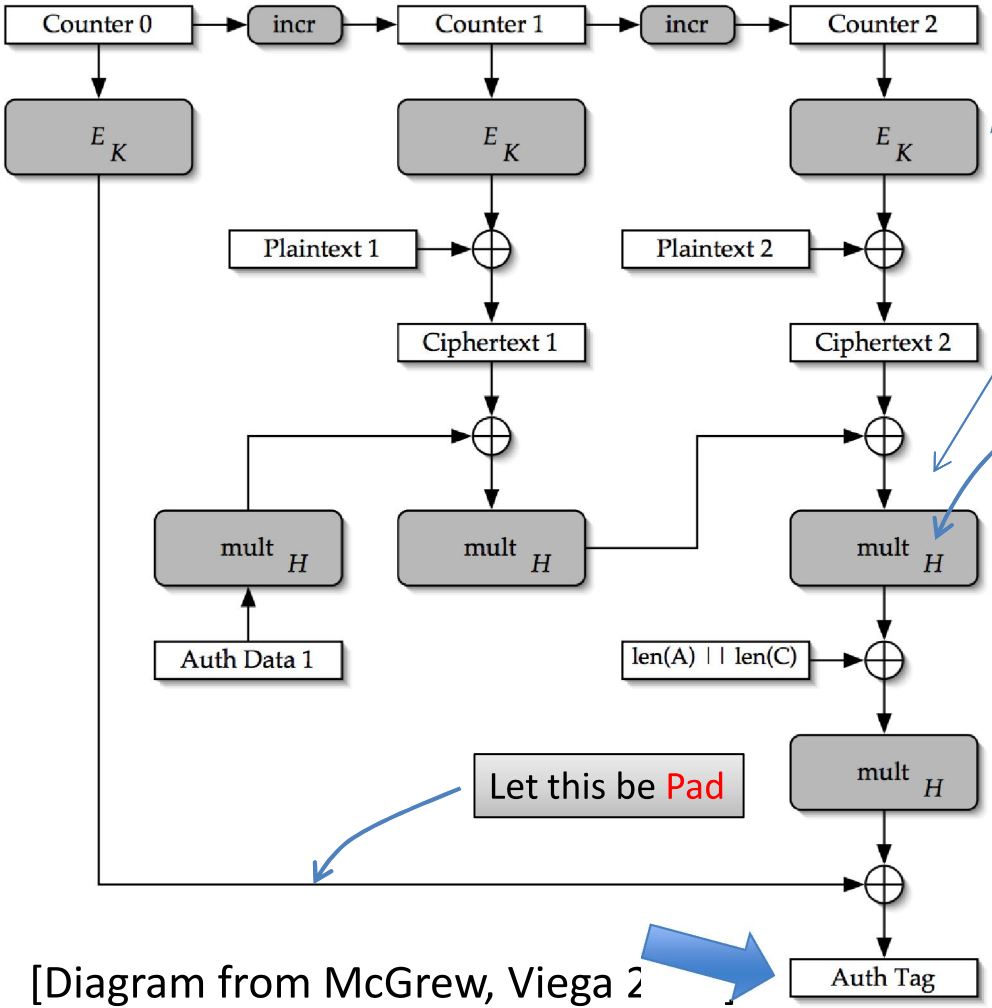

[Diagram from McGrew, Viega 2]

CTR mode encryption with AES blockcipher E

Universal hash-based message authentication (called GMAC)

$H = E_K(0^{128})$

Can rewrite GMAC as:

$$\textit{Tag} = C_1 * H^3 + C_2 * H^2 + \text{len} * H + \text{Pad}$$

1) Pick key K_{file}, derive H1, Pad1
2) Pick block of plaintext
3) Let C_1 be ciphertext block using K_{file}
4) Pick key K_{file2}, derive H2, Pad2
5) Solve *Tag* equation for C_2:

$$\textit{Tag} = C_1 * H1^3 + C_2 * H1^2 + \text{len} * H1 + \text{Pad1}$$
$$= C_1 * H2^3 + C_2 * H2^2 + \text{len} * H2 + \text{Pad2}$$

6) Output K_{file}, K_{file2}, C_1, C_2, *Tag*

Our contributions

Show vulnerability in Facebook's scheme:
invisible salamanders

Introduce new symmetric-key primitive:
encryptment

Lower bound on efficiency of encryptment

Construct optimally-efficient encryptment:
gives fastest-known ccAEAD, robust encryption, remotely-keyed AE, etc.

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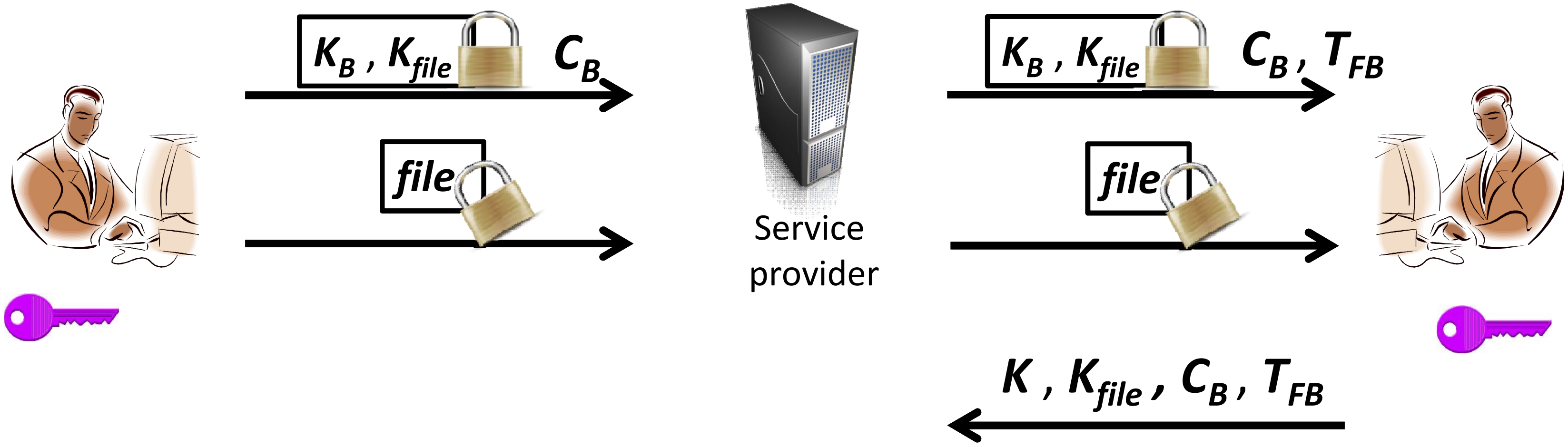

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Craft special ***AES-GCM*** ciphertext:

1) Decrypts under $\boldsymbol{K_{file}}$ to innocuous image
2) Decrypts under $\boldsymbol{K_{file2}}$ to abuse image

Adversary can use to violate sender binding:

i. Craft special ciphertext and keys
ii. Send ciphertext twice as distinct encrypted attachments
iii. Victim sees both plaintext attachments
iv. Abuse report will omit first (chosen) attachment

How do we build faster ccAE?

Define new primitive: ***encryptment*** simpler than ccAE

Introduce Hash-Function-Chaining (HFC): optimally-efficient encryptment

Generic, efficient transforms from encryptment to ccAE

+

Encryptment-to-ccAE transform from fixed-length AE (others too, see paper)

Fastest-possible ccAE!

Encryptment:
syntax, semantics, security

Should be short: e.g. 256 bits

$EC(K, H, M) = C_1, C_B$ **encrypts** M and **commits** to (H, M)

$DO(K, H, C_1, C_B) = M / \perp$ **decrypts** (C_1, C_B) and **opens** to M

$EVer(H, M, K, C_B) = 0/1$ **verifies** commitment C_B of (H,M)

Confidentiality

One-time real-or-random (**otROR**): cannot distinguish between EC oracle and random bits oracle

Integrity

Second ctxt unforgeability (**SCU**): cannot forge new ciphertext for fixed K, C_B

Binding

Strong receiver binding (**srBIND**): cannot verify two (H, M, K) tuples with same C_B .
Sender binding as in [**G**LR]

Encryptment => Concealment, RKAE, Robust AE,…

Construct ccAEAD from encryptment with same performance profile

<u>ccAEAD-Enc(K, H, M)</u>:

K_{EC} <-\$ **ECKeyGen**()
C_1, B_{EC} <- **EC**(K_{EC}, H, M)
C_2 <-\$ AEAD-Enc(K, B_{EC}, K_{EC})
Return C_1, $B_{EC}||C_2$

Encryptment is "core" primitive for other interesting applications:

- concealments [DH03]
- remotely-keyed AE [BFN98]
- robust AE [FOR17]

See paper for details

Encryptment => ccAEAD

Construct ccAEAD from encryptment with same performance profile

Use a fixed-input-length AEAD scheme with header B_{EC} to encrypt K_{EC}

<u>ccAEAD-Enc(K, H, M)</u>:

K_{EC} <-$ **ECKeyGen**()
C_1, B_{EC} <- **EC**(K_{EC}, H, M)
C_2 <-$ AEAD-Enc(K, B_{EC}, K_{EC})
Return C_1, $B_{EC} || C_2$

<u>Theorem (informal)</u>: If **EC** is a secure encryptment scheme and AEAD is secure AE scheme, this construction is ccAE