A generic view on trace-and-revoke broadcast encryption schemes

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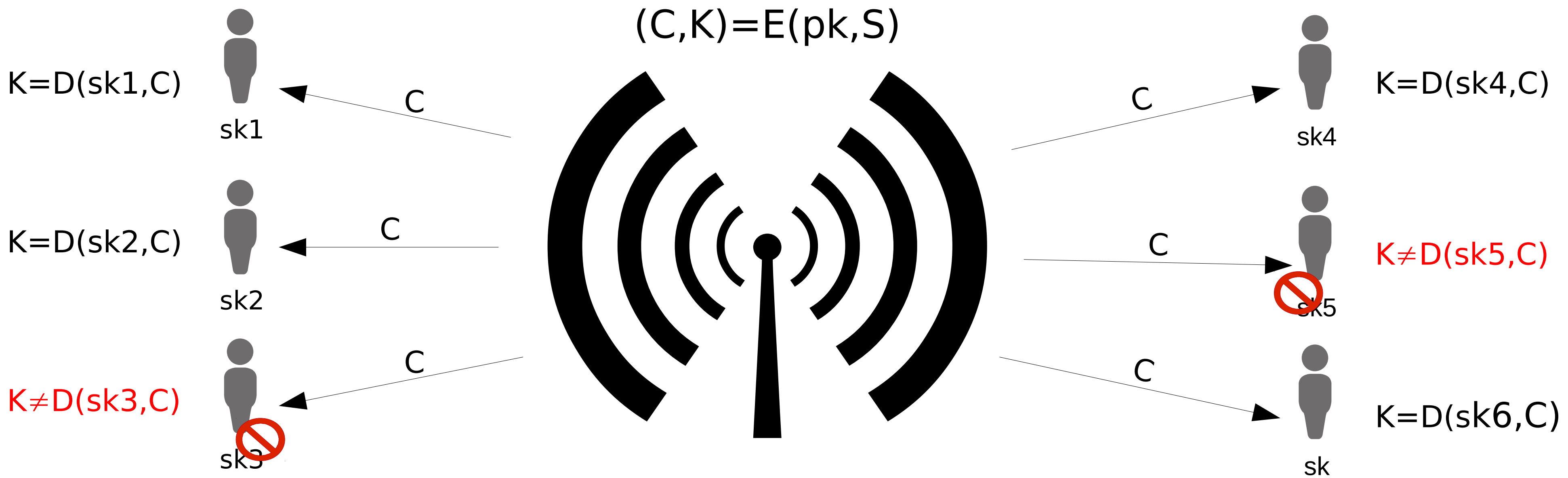
Overview

- New generic view on trace-and-revoke schemes from (generic) Extended DDH (EDDH) assumption [HO12]
- 1st result: EDDH-based threshold PKE/signatures, revocation schemes (extends [Wee11])
- 2nd result: (mild) traceability of EDDH-based revocation schemes
- 1st + 2nd: new (generic view of) EDDH-based trace-and-revoke schemes

Broadcast encryption [FN93]

Goal: est. a shared symm. key betw. sender and privileged set S of users, say, S={1,2,4,6}⊆{1,...,6}

(pk,sk1,...)=Gen(1^k,N=6)



Trivial system:	|C|=O(|S|)	|sk|=O(1)	|pk|=O(N)
[e.g.,BGW05*,D07,SF07,PPSS13,BZ13]:	|C|=O(1)	|sk|=O(1)	|pk|=O(N)
[GW09,PPSS13,BZ13]:	adapt. security		

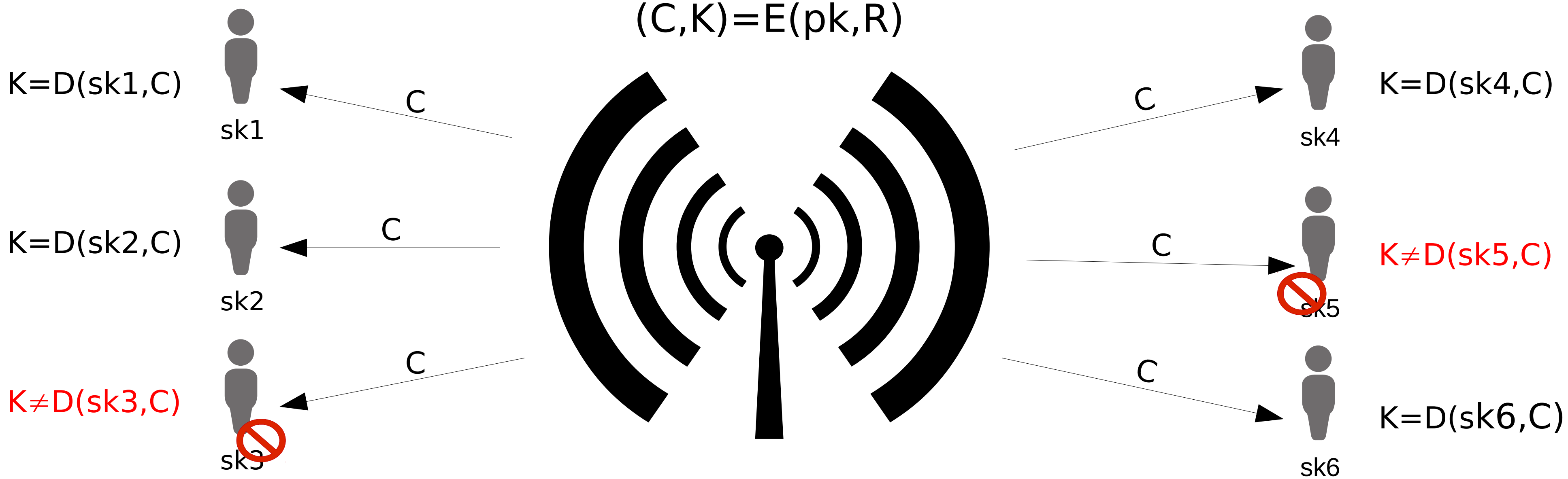
* provide also a system with |C|=O(√N) and |pk|=O(√N)

Our focus: revocation schemes

Consider a set of revoked users,
say, R={3,5}

$(pk,sk1,\ldots)=Gen(1^k,1^t,N=6)$

$(C,K)=E(pk,R)$



[e.g.,NP00,DF03,DPP07,W11]:	$\lvert C\rvert=O(\lvert R\rvert)$	$\lvert sk\rvert=O(1)$	$\lvert pk\rvert=O(\lvert R\rvert)$
[e.g.,NNL01*,HS02*,DF02]:	$\lvert C\rvert=O(\lvert R\rvert)$	$\lvert sk\rvert=O(\log N)$	$\lvert pk\rvert=O(1)$
[LSW10]:	$\lvert C\rvert=O(\lvert R\rvert)$	$\lvert sk\rvert=O(1)$	$\lvert pk\rvert=O(1)$

* only secret-key schemes; parameters improved by [GST04]

Generic revocation schemes and threshold extractable hash proof systems [Wee11]

- Previous revocation schemes use Shamir's secret sharing (i.e., Lagrange interpolation) in the exponent [e.g.,NP00]
- [W11] gives a simple and elegant view of revocation schemes using TEHPSs

- Gen(1^k,1^t,N): $pk = g^{a_0}, g^{a_1}, \ldots, g^{a_t}$

  $\text{sec. polyn. } f(x) = a_0 + a_1 x + \ldots + a_t x^t$

  $sk_j = f(j),\ j \in [N]$

- E(pk,R): $C = \left(R, u, \left(u^{f(i)}\right)_{i \in R}\right), u = g^r, \text{rand. } r, |R| = t$

  $K = G\left(u^{f(0)}\right)$

- D(sk_j,C): $j \notin R: \text{with } u^{sk_j} = u^{f(j)}, \text{all } \left(u^{f(i)}\right)_{i \in R}, \text{interpol. } u^{f(0)}$

  $\text{for Lagr. coeff. } L_j(0) = \prod \frac{-i}{j - i}$

  $K = G\left(u^{f(0)}\right)$

- Depending on G, this yields rev. schemes from factoring, CDH, and DDH

1st result: slightly different view of [W11]

- Based on Extended DDH assumpt. [HO12] (which general. DDH, DCR):

$$\left(g, g^{a}, g^{r}, g^{a \cdot r}\right) \approx \left(g, g^{a}, g^{r}, g^{a \cdot r} \cdot h\right)$$

$$\text{for } G', H \subseteq G, \text{ rand. } g \in G', h \in H, \text{exp. } a, r$$

- But now: order of G' might be unknown (i.e., with DCR); hence, difficult to interpolate in the exponent, i.e.,

$$\text{how to compute Lagr. coeff. } L_j(0) = \prod \frac{-i}{j-i} \text{ in the exponent?}$$

- Solution: "clearing the denominator in the exponent" [S00], i.e.,

$$\text{use } D = \text{lcm}\left\{\prod_{i,j,i \neq j} (j-i)\right\} \text{ s.t. } DL_j(0) \text{ is an integer}$$

- As a result: we derive EDDH-based TEHPSs, i.e., EDDH-based threshold PKE/signatures, revocation schemes

In detail: EDDH-based rev. schemes

- $\mathrm{Gen}(1^k, 1^t, N)$: $pk = g^{a_0}, g^{a_1}, \ldots, g^{a_t}$ with sec. polyn. $f(x) = a_0 + a_1 x + \ldots + a_t x^t$

  $sk_j = f(j),\ j \in [N]$

- $\mathrm{E}(pk, R)$: $C = \left(R, u_1, \left(u_1^{f(i)}\right)_{i \in R}, u_2\right), u_1 = g^r, u_2 = u_1^{f(0)} \cdot h$, rand. r, h

  $K = G(h)$

- $\mathrm{D}(sk_j, C)$: $j \notin R$: with $u_1^{sk_j} = u_1^{f(j)}$, all $\left(u_1^{f(i)}\right)_{i \in R}$, interpol. $u_1^{f(0)}$

  for Lagr. coeff. $L_j(0) = \prod \frac{-i}{j-i}$

  and $D = \mathrm{lcm}\left\{\prod_{i, j, i \neq j} (j - i)\right\}$ such that

  $$\left(\left(\prod u_1^{D L_j(0) f(j)}\right)^{-1} \cdot u_2^D\right)^{D^{-1} \bmod n} = h$$

  $K = G(h)$

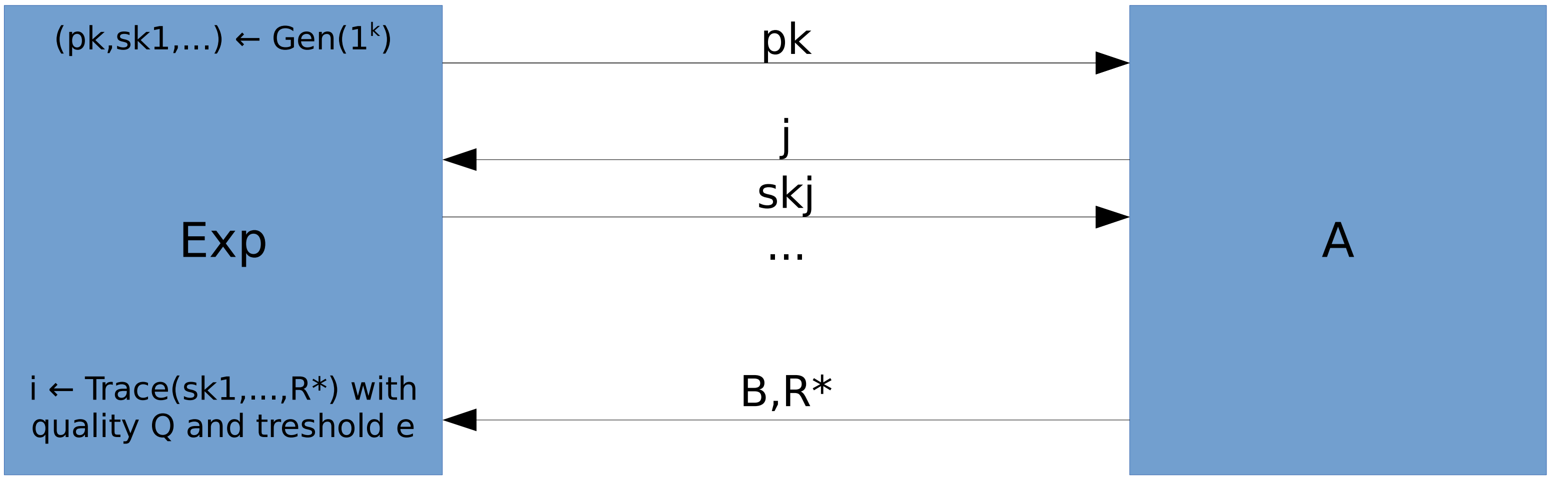
- Special case: yields DCR-based rev. schemes (uses a potential stronger assumpt. than Wee's fact.-based inst. but, via our 2nd result, yields new DCR-based trace-and-revoke schemes, which is not known from factoring)

Traceability [CFN94]

- Ability to trace a pirate dec. box back to its (corrupt.) creator(s)

[e.g.,NP98,BF99,GSY99,NP00,NNL01,TT01,KY01b,KY02,HS02,DF02,DF03, KHL03,DFKY05,BSW06,BW06,JL07,FA08,KP09,AKPS12,...]

- Here, consider traceability model in the rev. setting:



A wins iff Q>e and A never queried a secret key for i;
rev. system is traceable iff Pr[A wins]=negl.

- Results in trace-and-revoke schemes (non-trivial to achieve [BW06])

Traceability in our concrete setting

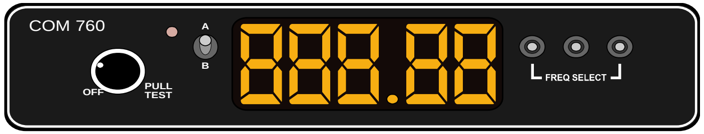
Ciphertext C

D(sk_j,C)=K'?

C

K'

(Stateless) black-box decoder B



- Observation: decryption of ciphertext C, where (C,K)=E(pk,R), does not depend on a user secret key (i.e., D(sk_j,C)=K, for all j∉R)
- Thus: we have to generate random ciphertexts
- But: these ciphertexts must be indistinguishable to real ctexts for B
- Further: B might only decrypt correctly down to some threshold e
- Previous work: [TT01] assumes e=1 and no adv. chosen R while [DFKY05] considered diff. scheme

2nd result: our tracing strategy of rev. instances

- Consider random ciphertexts in the EDDH-based rev. setting:

$$C_{rnd} = \left(R, u_{1,} \left(u_1^{f(i)} h^{z_i}\right)_i, u_1^{f(0)} h^{z_0}\right), \text{ for uniform } h \in H, z_i, z_0$$

- Under EDDH, C_{rnd} is indistinguishable from real ciphertexts (but only for one sk in B!)

- Thus, adapt to allow more sks in B:

$$C_{rnd}^{I} = \left(R, u_{1,} \left(u_1^{f(i)} h^{f'(i)}\right)_i, u_1^{f(0)} h^{f'(0)}\right), \text{ with } f'(i) = 0 \text{ for } i \in I$$

- C^{I}_{rnd} is indist. to a real ciphertext (even when knowing sks for set I)

- Task: find "suspect set" I; unfort., only eff. for polyn. values of $\binom{N}{T}$ with number of traitors T≤(t+1)/2

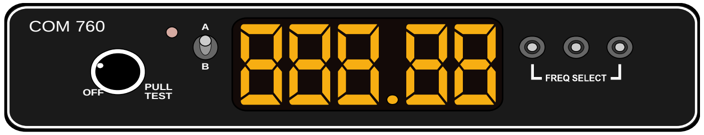
More on our tracing strategy

- If I is found, use standard techniques [e.g.,BF99,NNL01,TT01,KY02, DFKY05,BSW06]:

Rand. ciphertext C^{I}_{rnd} $\xrightarrow{C^{I}_{rnd}}$

$D(sk_j, C^{I}_{rnd}) = K'?$ $\xleftarrow{K'}$

(Stateless) black-box decoder B



Assume B has only user keys for user set ⊆ I

- 1st run: B will decrypt correctly with probability e (i.e., B cannot dist. random from real ciphertexts)

- 2nd run: remove one I-element j and try again with set I'=I\{j} (if B has no sk_j, B does not notice)

- i-th run: if decryption quality drops, we must have removed a traitor

Putting the pieces together

- 1st result: EDDH-based TEHPSs (extends [W11]), i.e., threshold PKE/signatures, revocation schemes from the EDDH assumption
- 2nd result: (mild) traceability of the EDDH-based revocation instances
- 1st + 2nd: new (generic view on) EDDH-based trace-and-revoke schemes which explains (known) DDH-based and (new) DCR-based constructions
- Open problem: not known if factoring-based revocation instances of [W11] are traceable

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Broadcast Steganography
or
How to Broadcast a Secret *Covertly*

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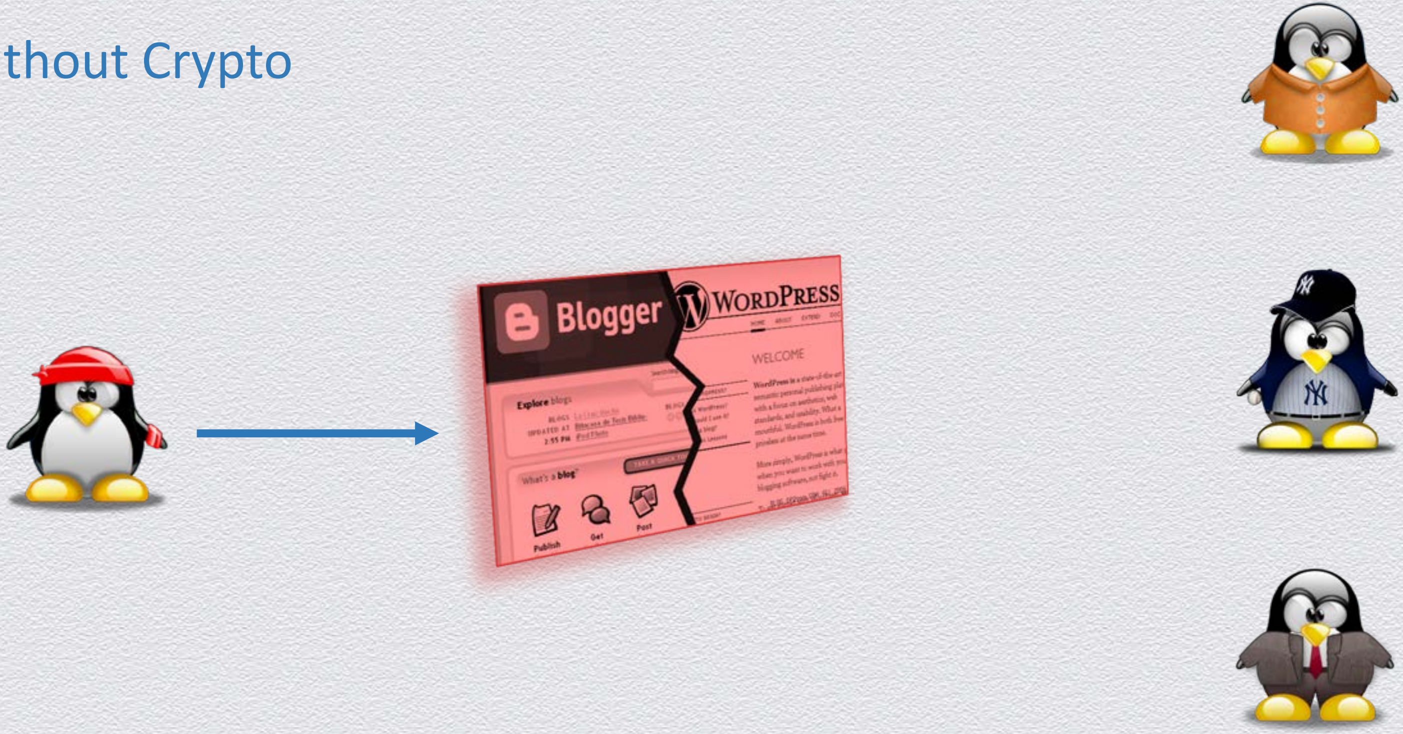
Without Crypto



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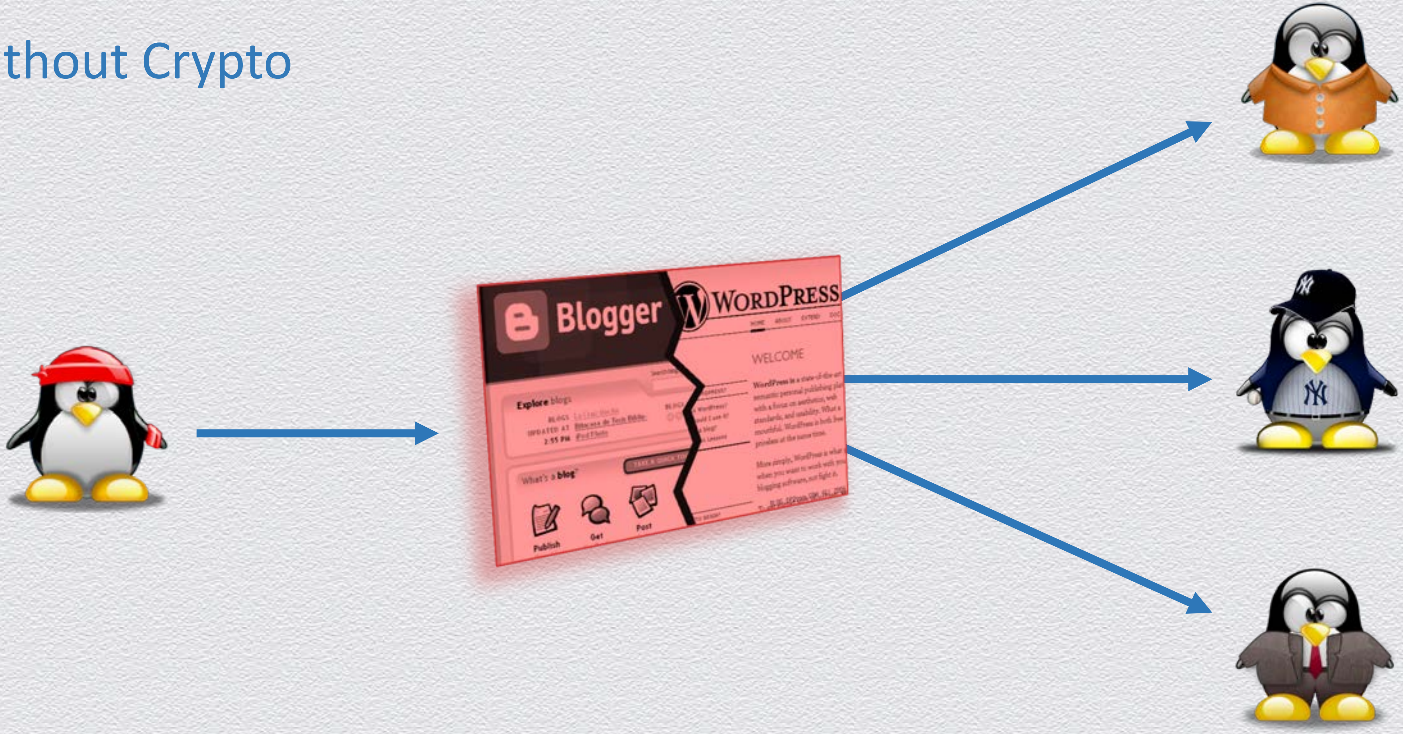

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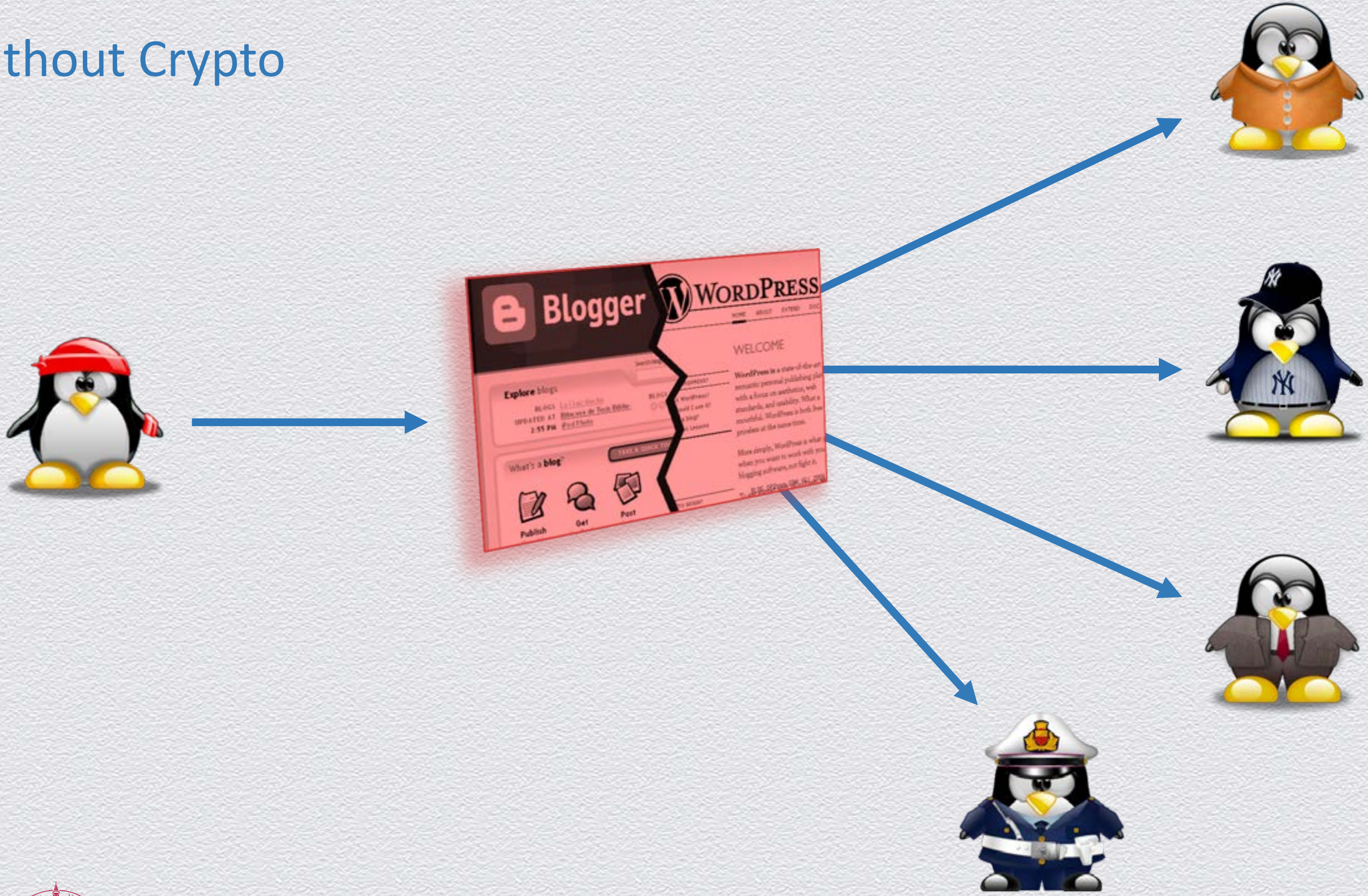
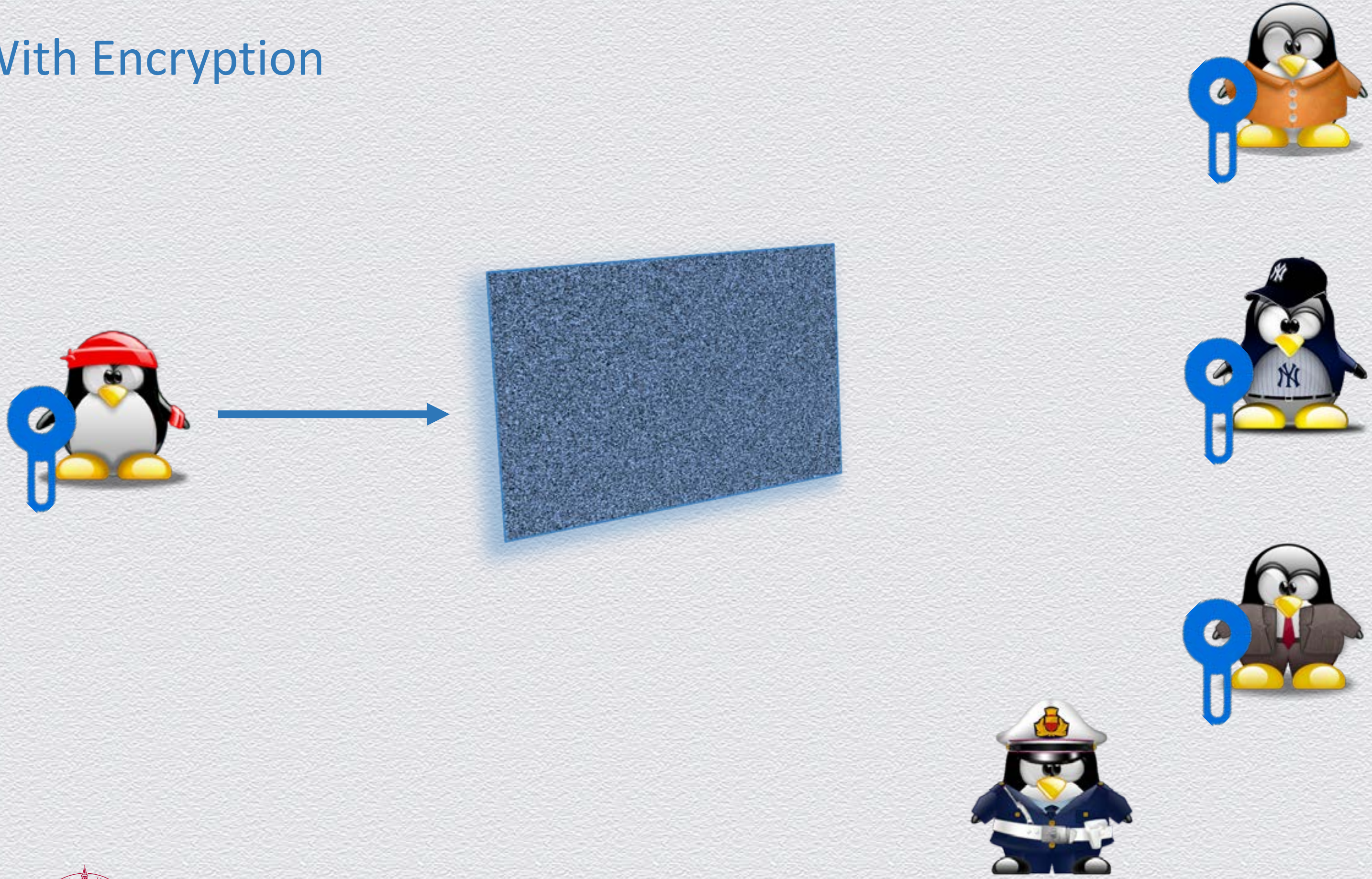


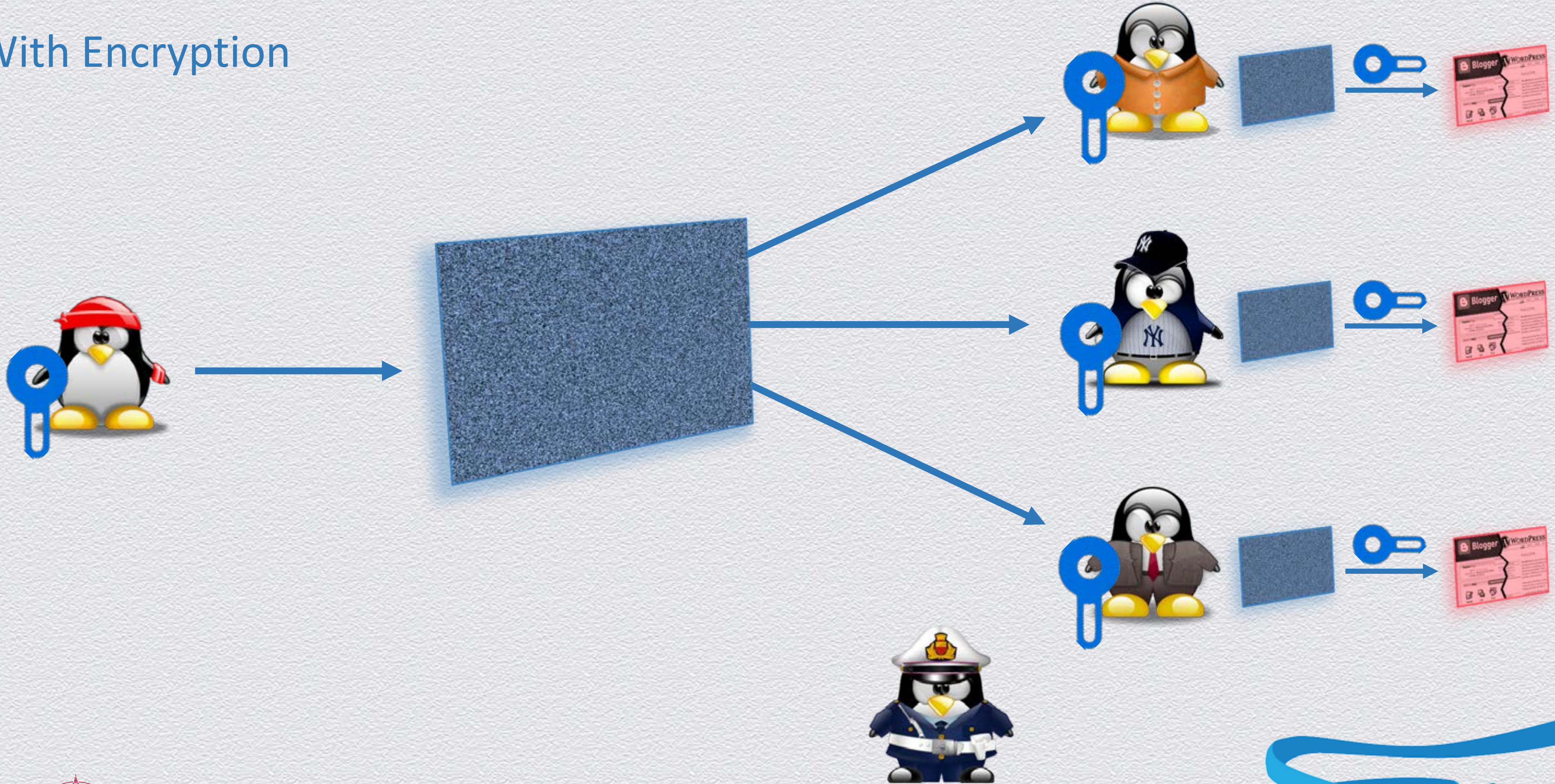
Without Crypto

With Encryption

With Encryption



With Encryption



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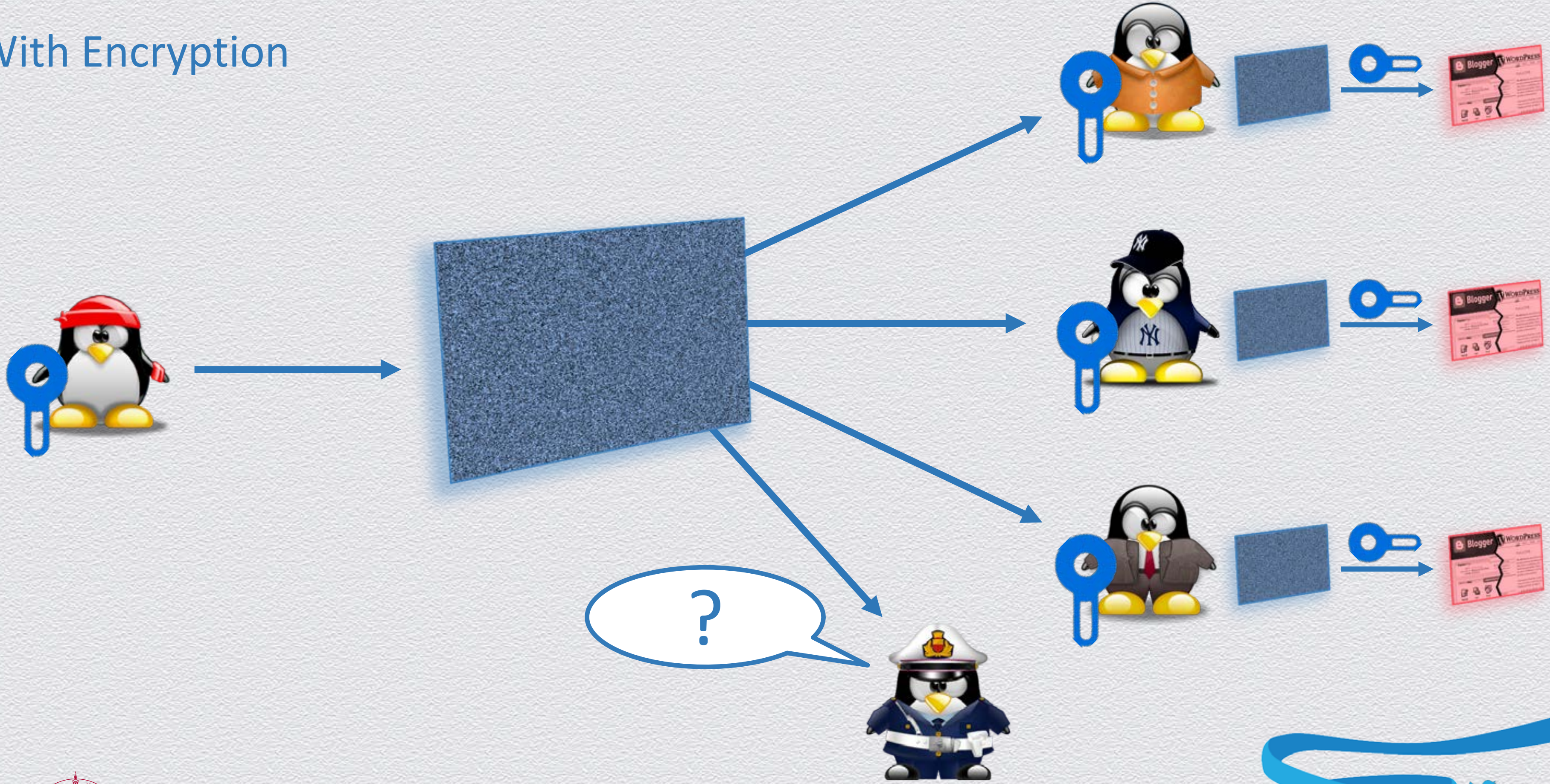

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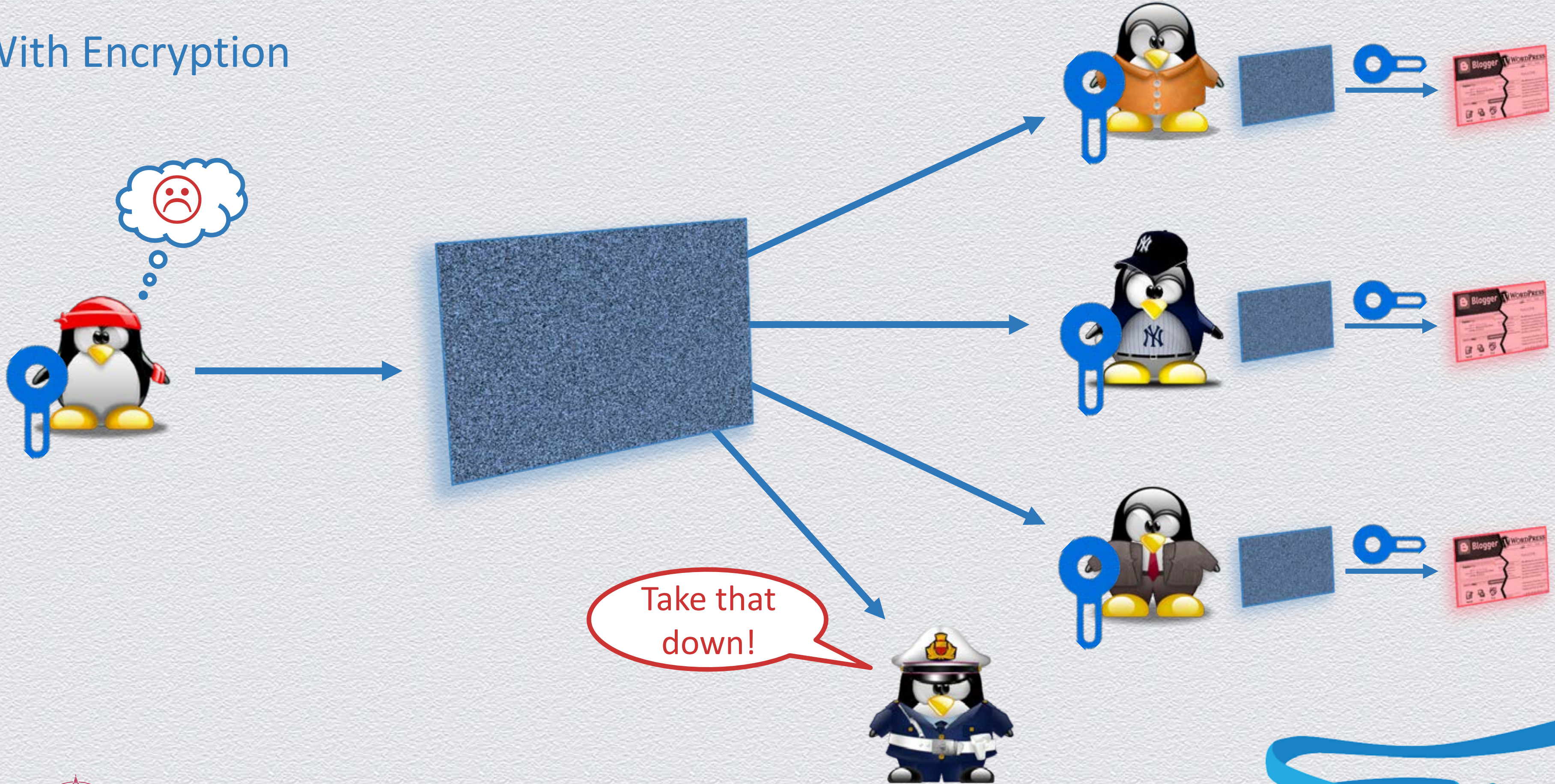
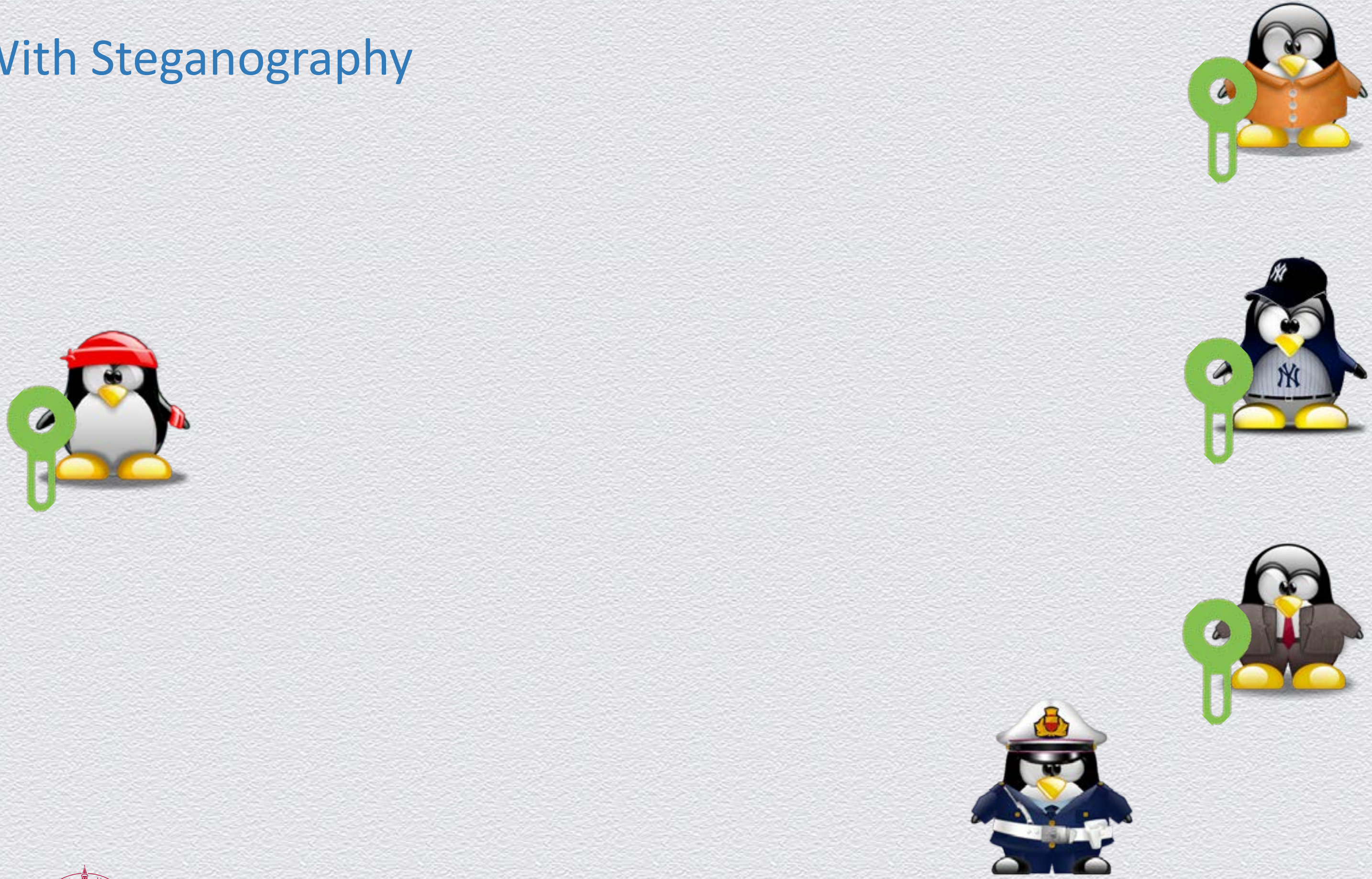


With Steganography



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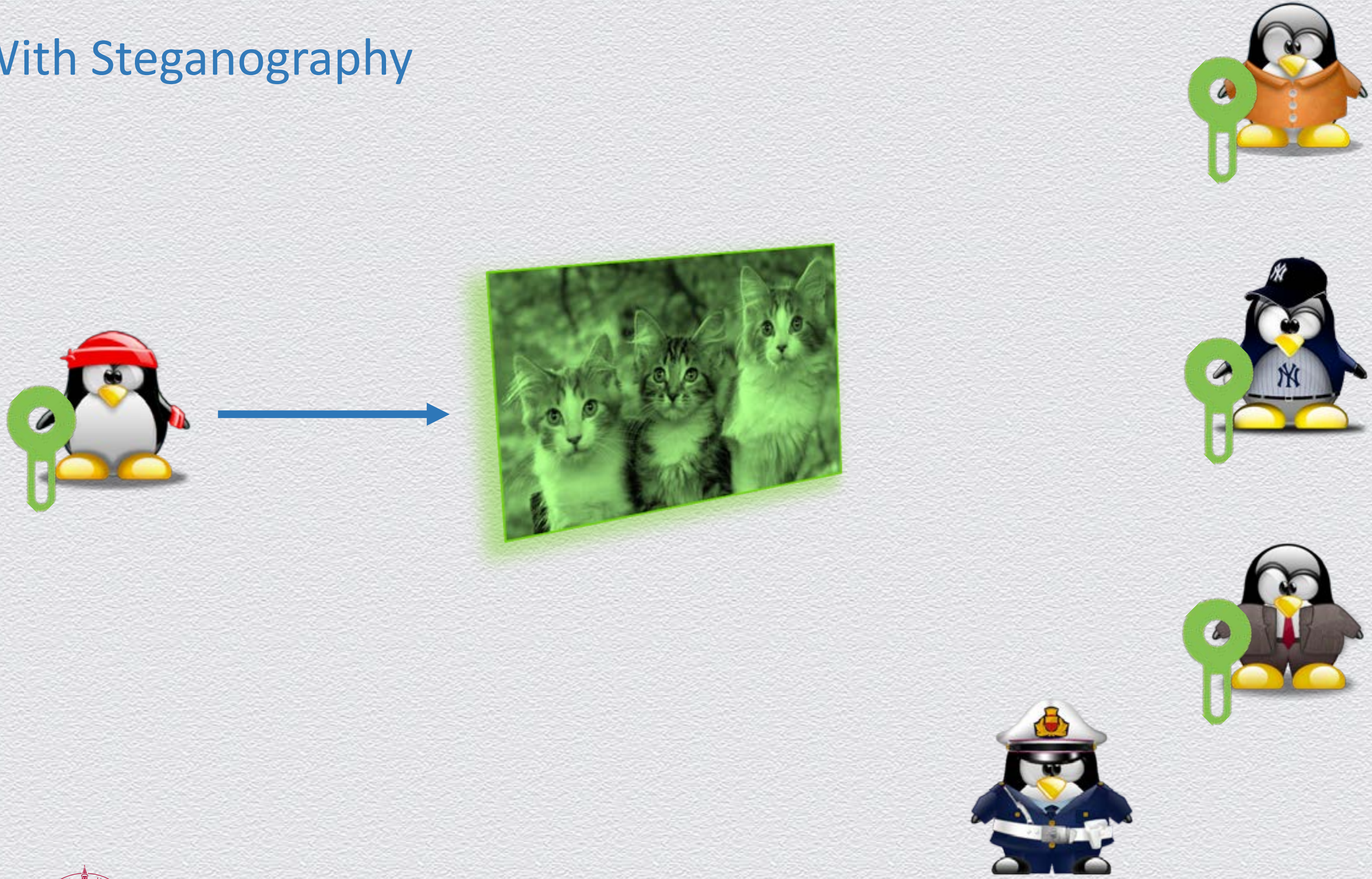

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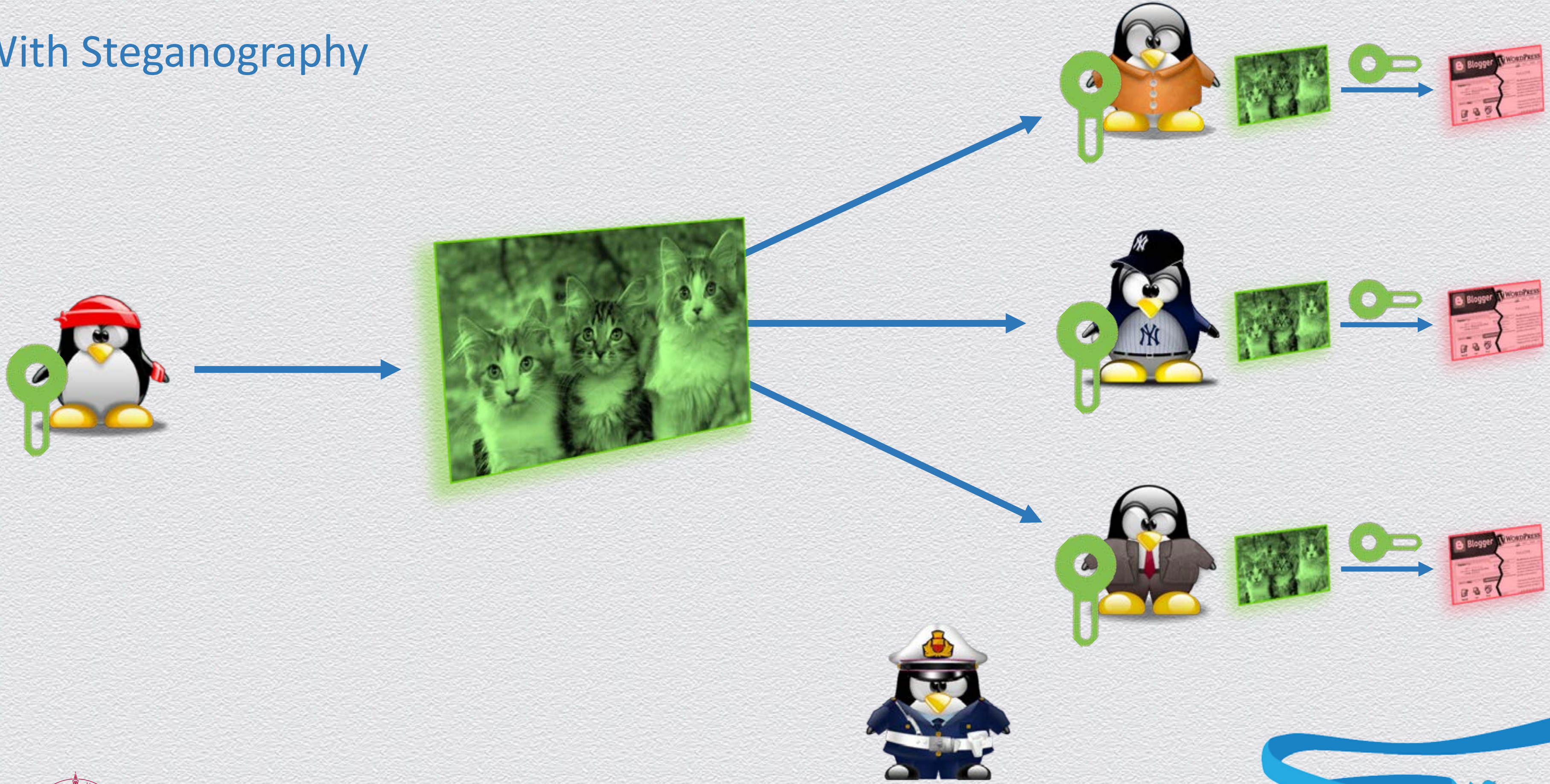

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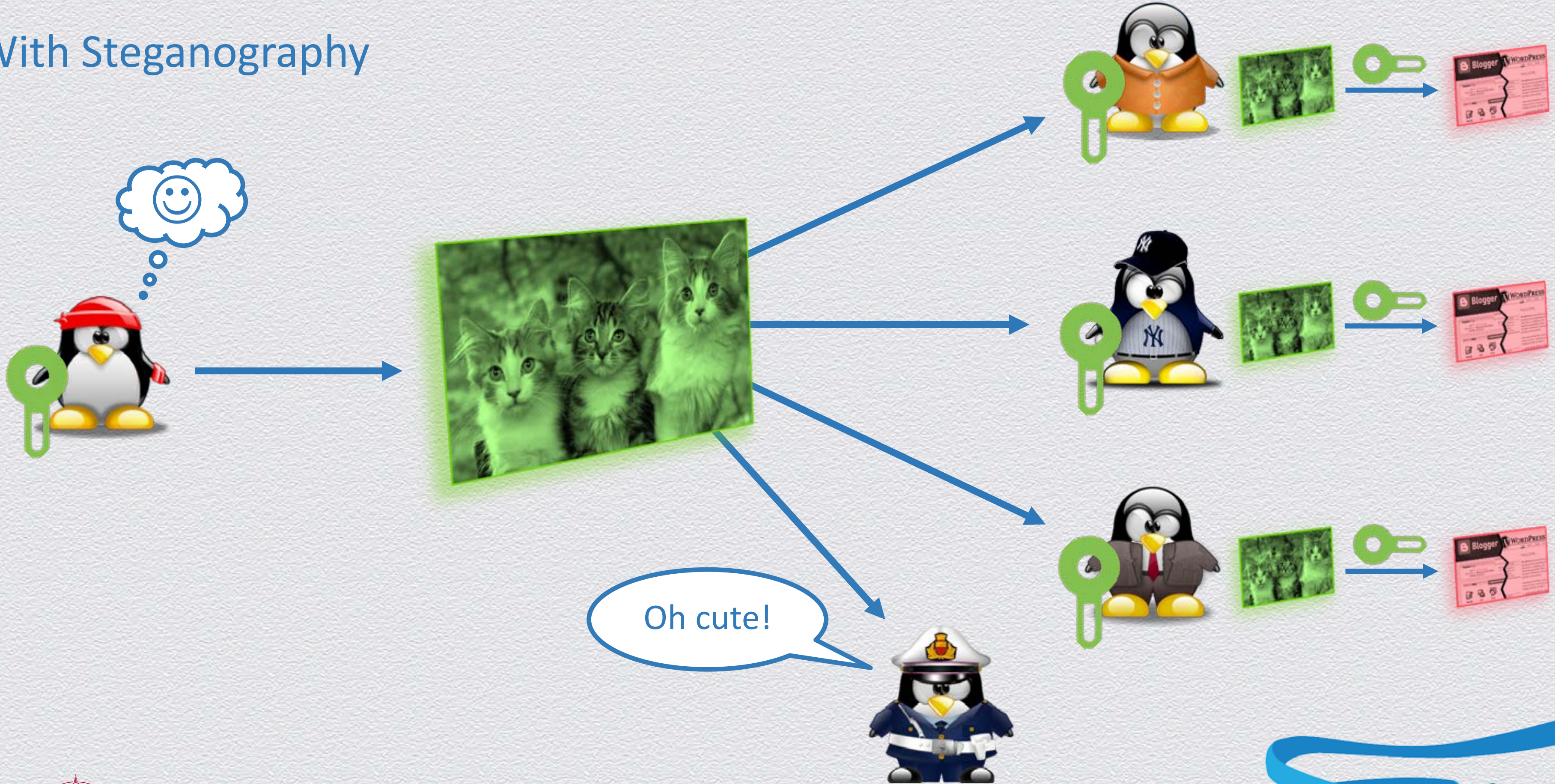

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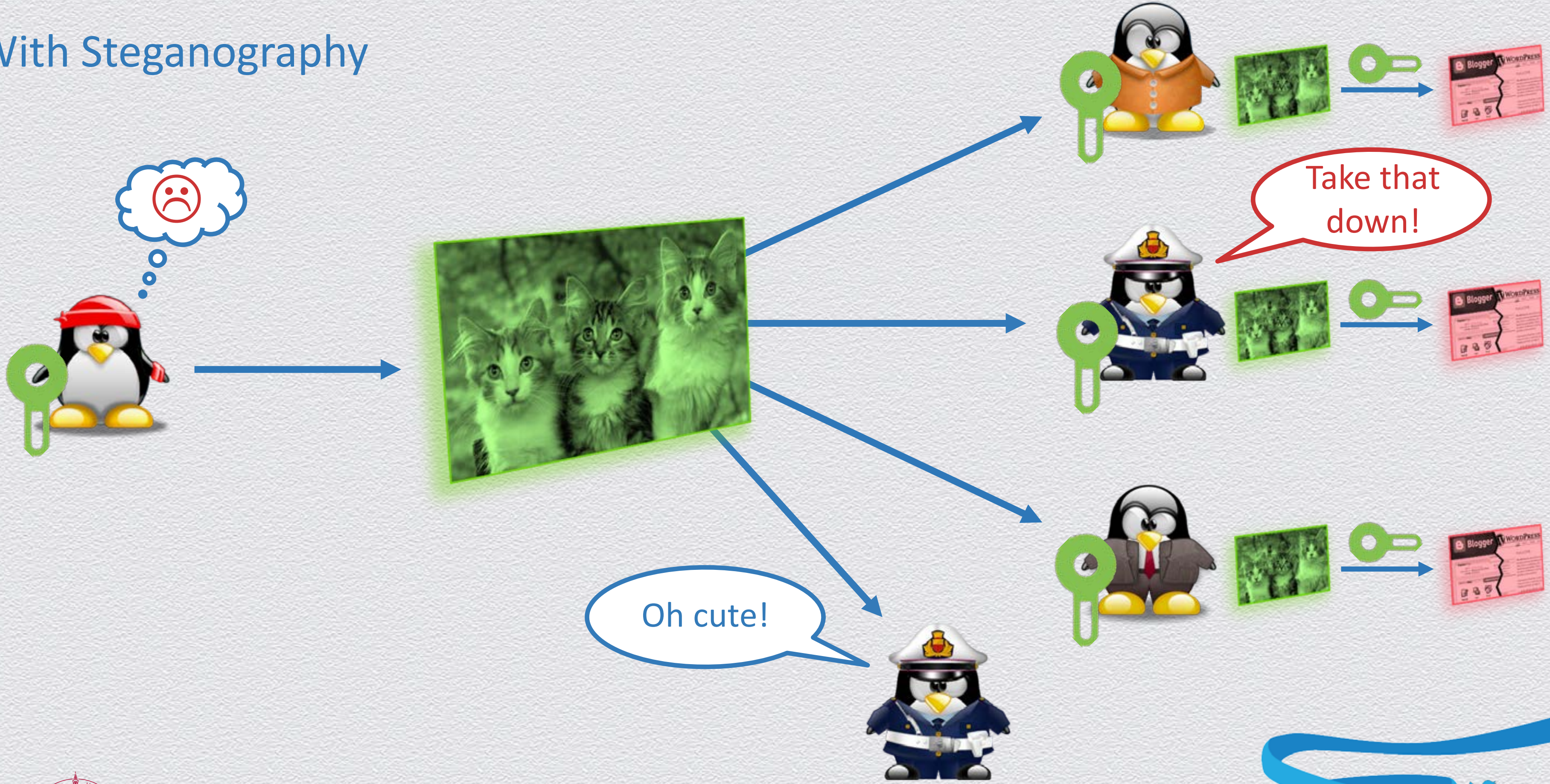

With Broadcast Steganography [This Work]

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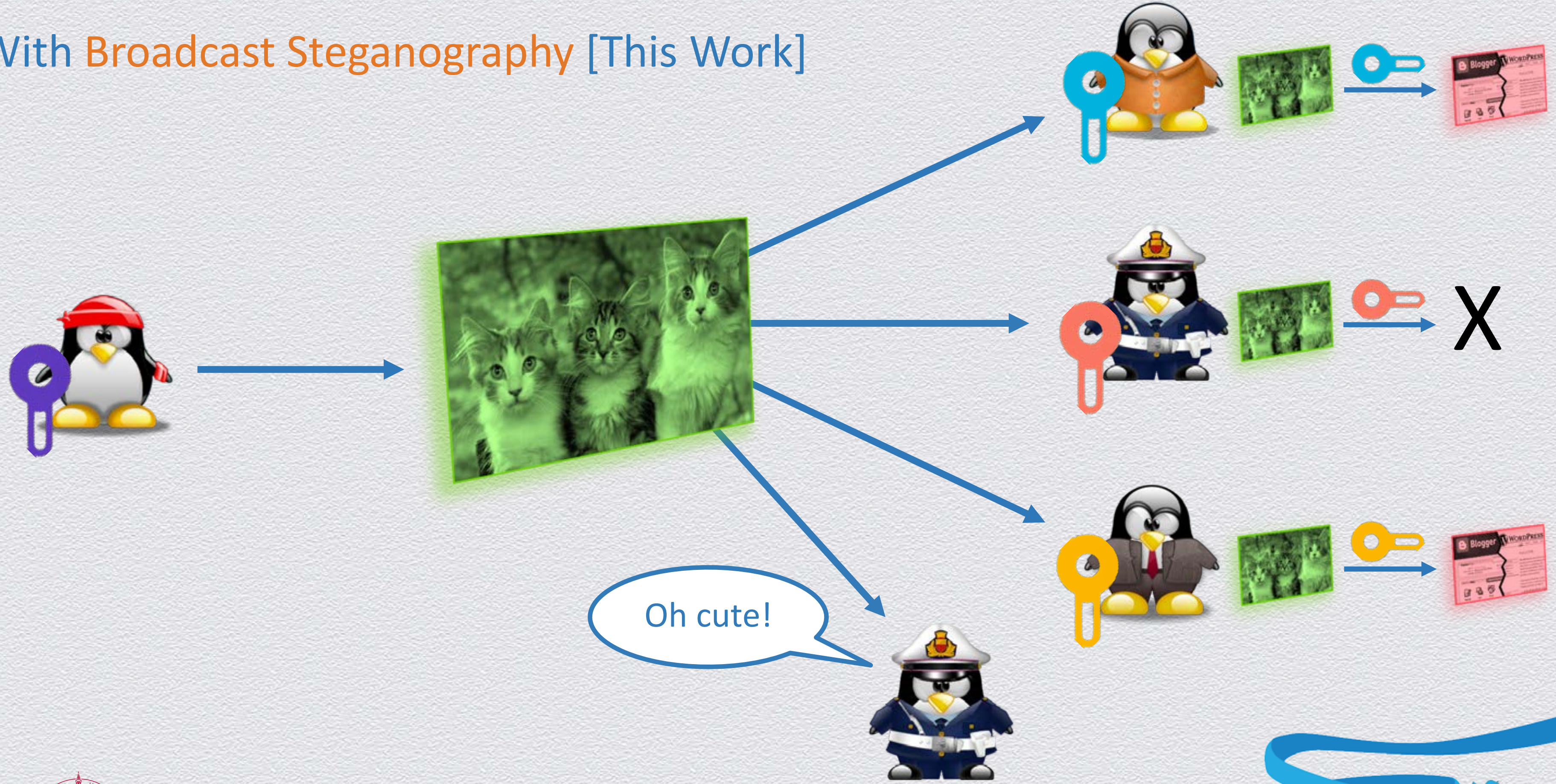

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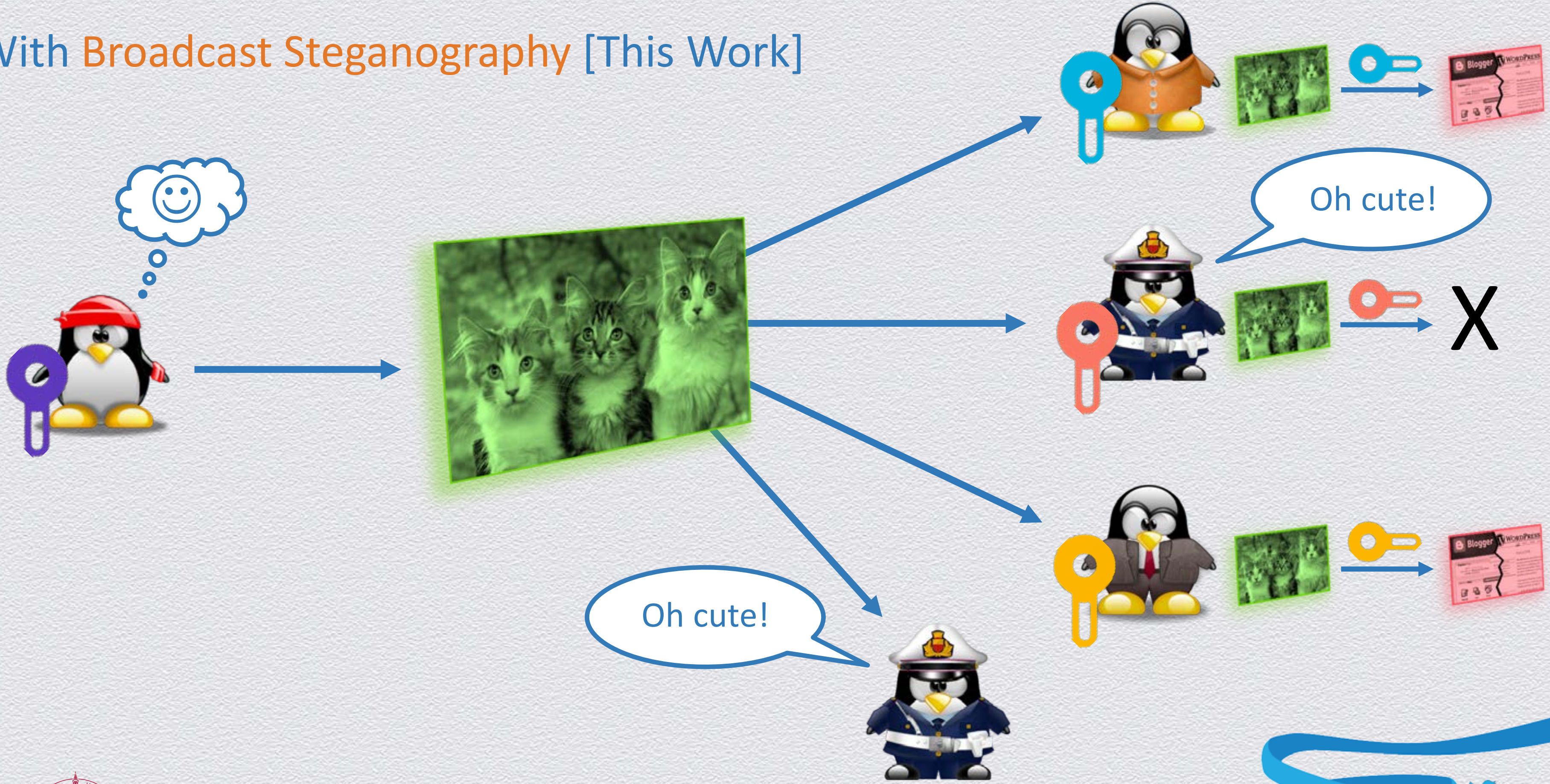
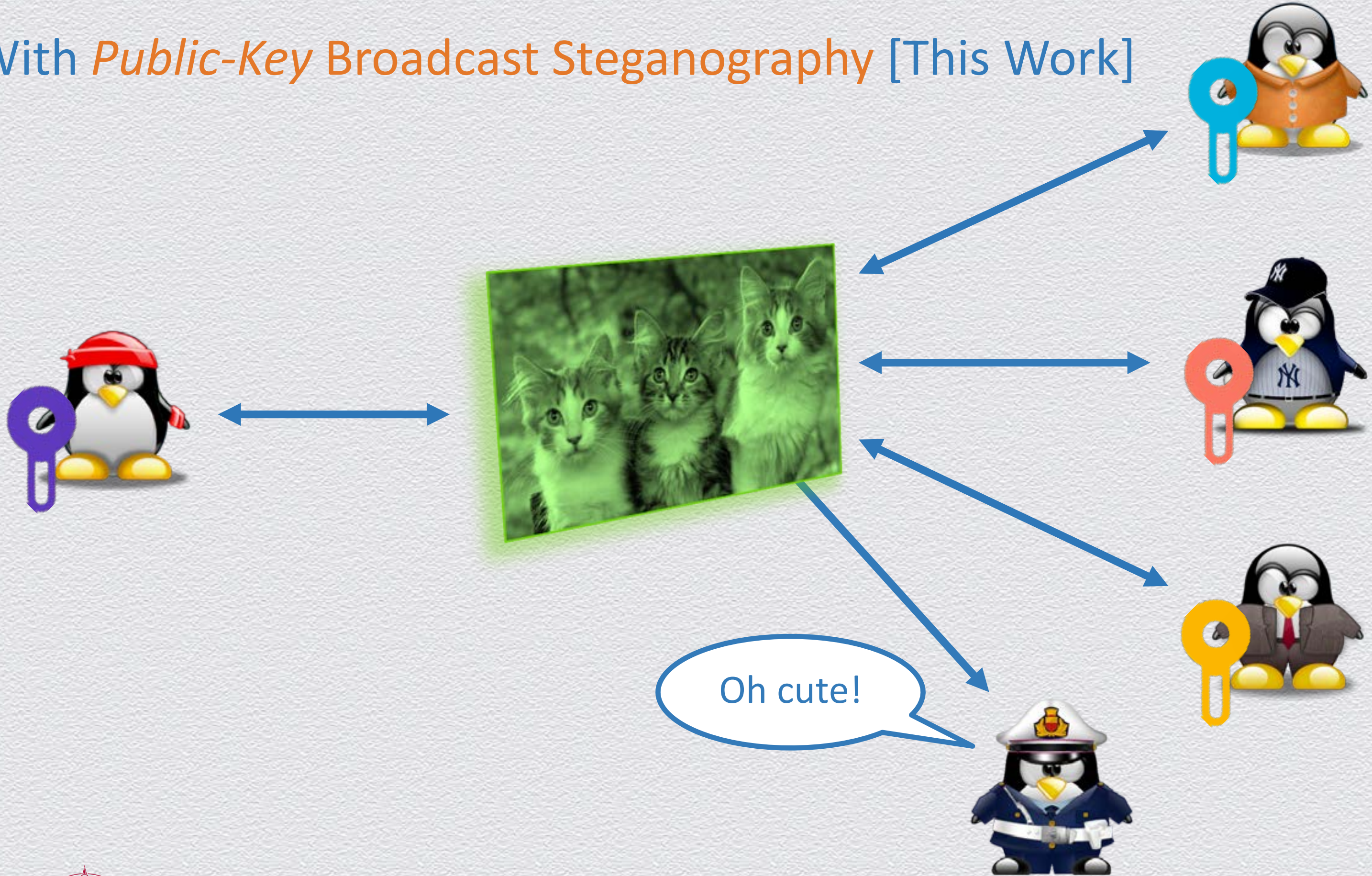


With *Public-Key* Broadcast Steganography [This Work]



- Broadcast Steganography (BS)
- Constructions
- Summary

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The Setting

Setup

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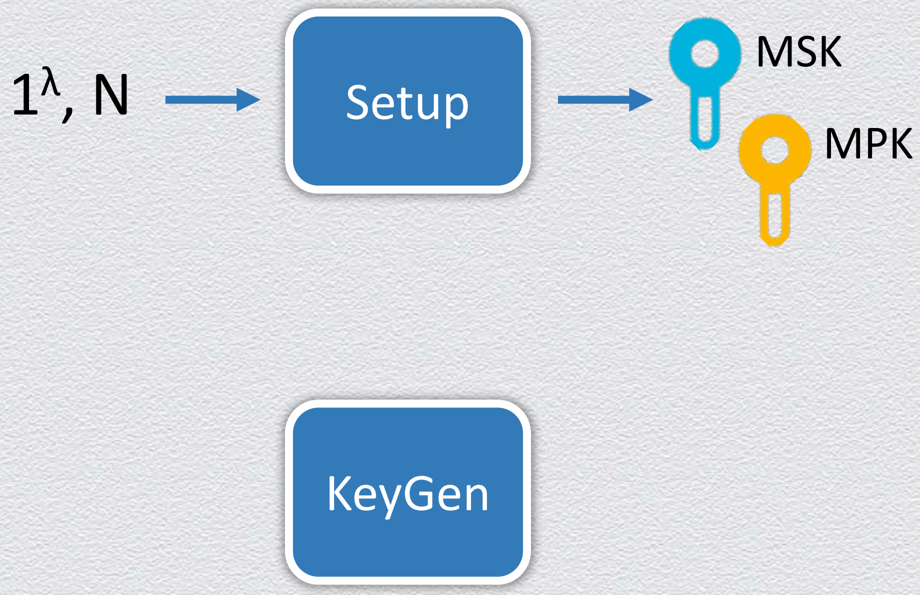

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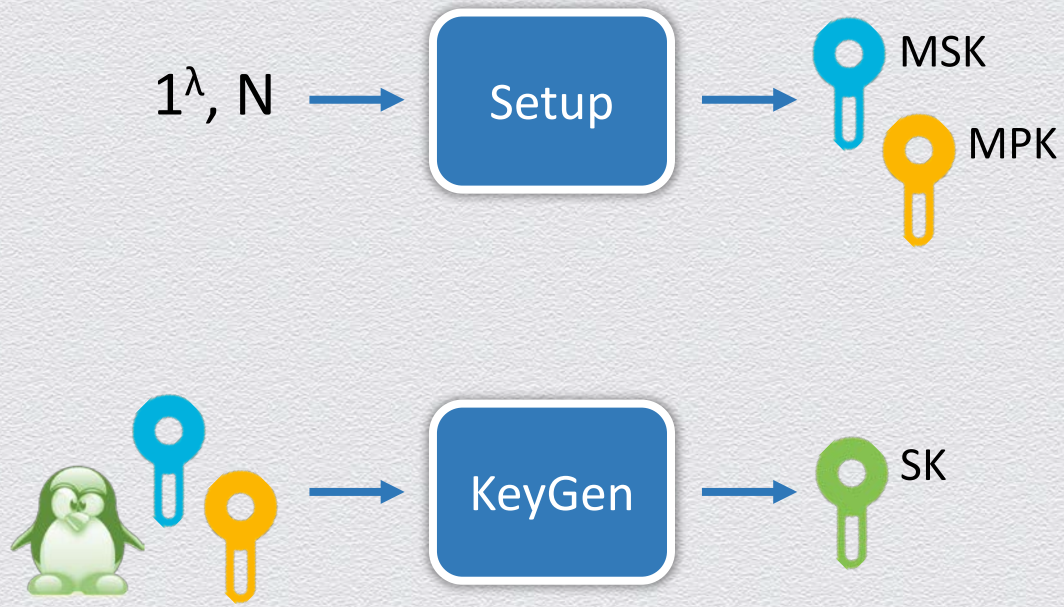
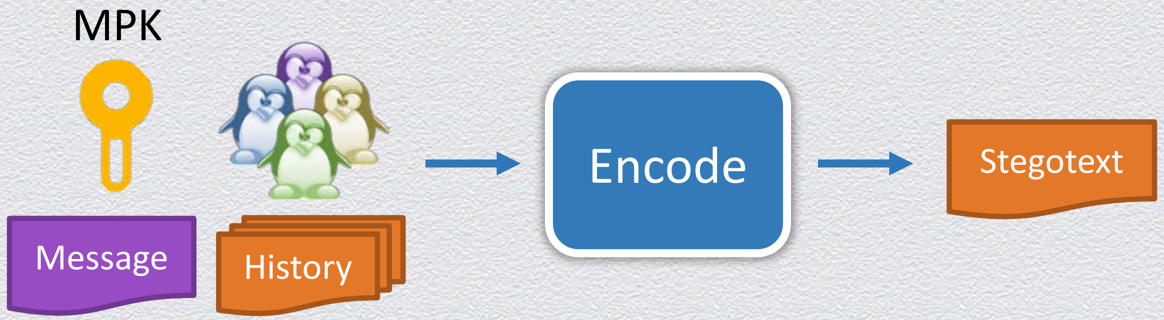


The Setting

Encode

The Setting



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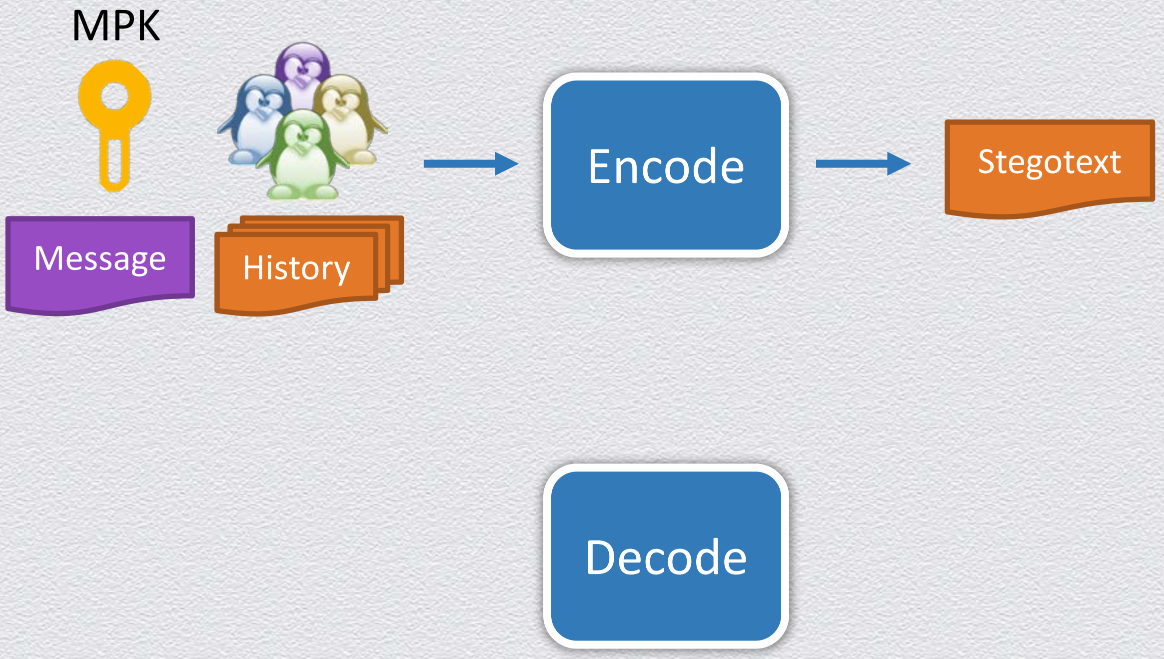

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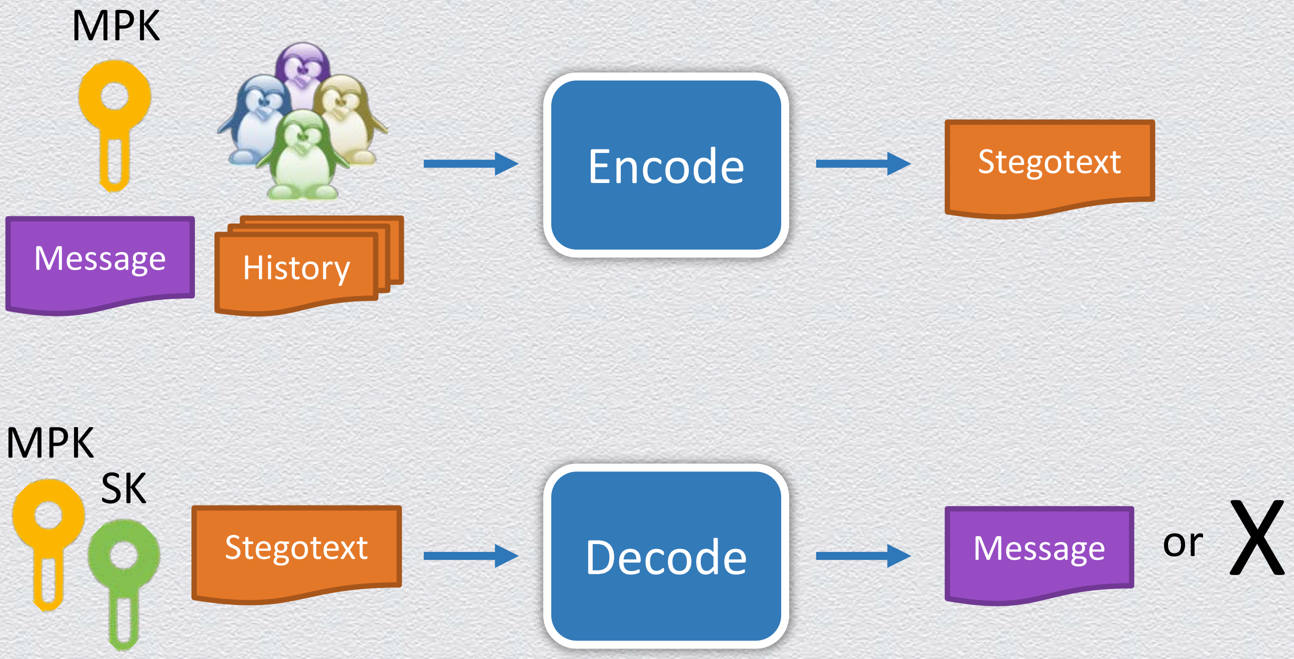
MPK
Message
History
Encode
Stegotext
MPK
SK
Stegotext
Decode
Message
or X

The Security Model

1. Chosen-Covertext Attack (BS-IND-CCA)
   - Analogous to BE-IND-CCA model
   - Adversary is allowed to corrupt users
   - Adversary is also given access to a decoding oracle
2. Publicly-Detectable Replayable Chosen Covertext Attack (BS-IND-PDR-CCA)
   - Similar to BS-IND-CCA, but with stricter restrictions on allowable decoding queries
3. Chosen-Hiddentext Attack (BS-IND-CHA)
   - Analogous to BE-IND-CPA model
   - Adversary is only allowed to corrupt users
   - No decoding queries

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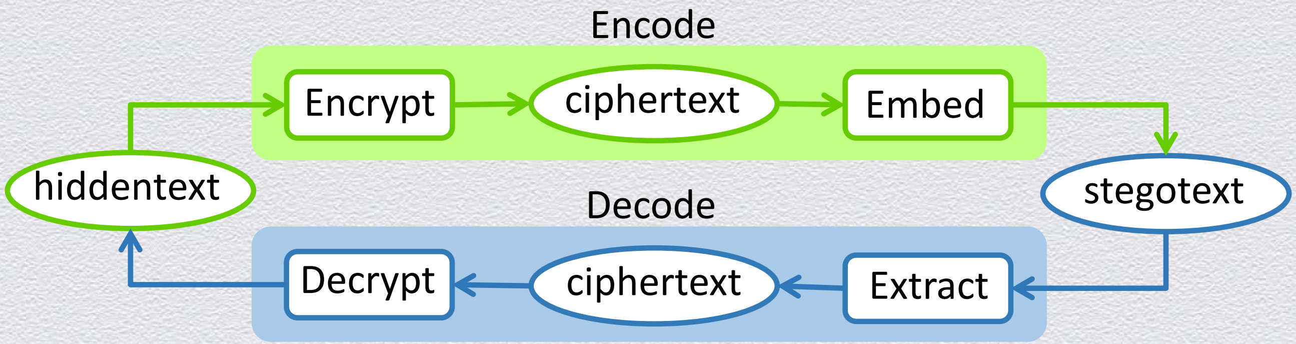
Realizing Broadcast Steganography

- Encrypt-then-Embed Paradigm [HLvA02, BaCa05]



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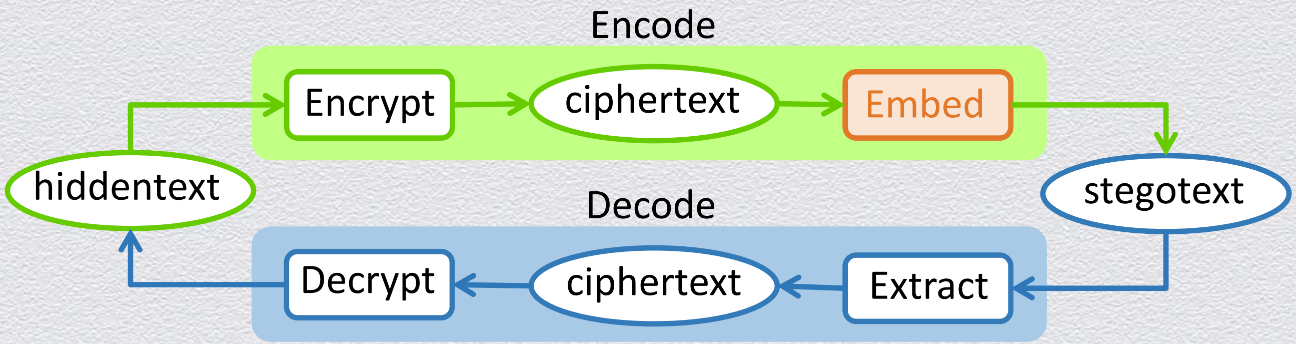

- Embed (rejection-sampling)
  1. Let H be a strongly universal hash function
  2. Break the ciphertext c into bits $c_1, c_2, \ldots, c_l$
  3. To embed c_i, sample s_i from the channel until $H(s_i) = c_i$
  4. Output $s = s_1 || s_2 || \cdots || s_l$

Realizing Broadcast Steganography

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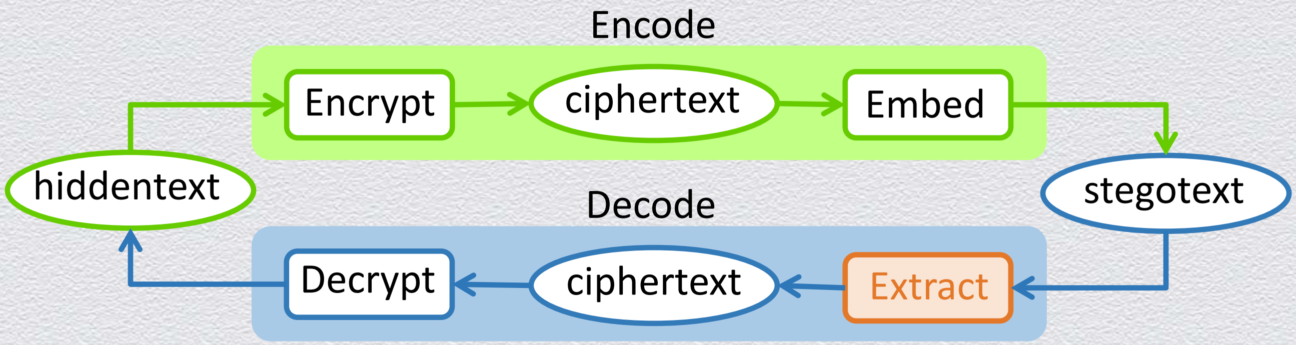

- Extract
  1. Break the stegotext s into documents $s_1, s_2, \ldots, s_l$
  2. Set $c_i = \mathrm{H}(s_i)$
  3. Output $c = c_1 || c_2 || \cdots || c_l$

Broadcast Encryption + Encrypt-then-Embed = Broadcast Steganography?

- Encrypt-then-Embed requires pseudorandom ciphertexts …
- … but, Broadcast ciphertexts have structure

header	body

broadcast ciphertext format

- Neither header nor body is pseudorandom

Outsider-Anonymous Broadcast Encryption [FaPe12]

- Motivation: Anonymous Broadcast Encryption with short ciphertexts
  - A fully anonymous ciphertext length is subject to a linear lower bound [KiSa12]
  - In some applications, content may give recipient set away
    - ⇒ Suffices to protect anonymity of receivers from outsiders

- Outsider-Anonymity in Broadcast Encryption
  - Trades some degree of anonymity for better efficiency
  - Allows constructions with sub-linear ciphertext length

oABE Encryption in [FaPe12]

- Encrypt(S, m)
  1. Group users in S into S’, a set of disjoint subsets
     - |S’| is sub-linear in |S|
  2. Generate a ciphertext c_i for each s_i in S’ (using anonymous IBE)
  3. Attach a tag t_i to each c_i (for efficient decryption at the receivers)
  4. Bundle all (t_i, c_i) components using one-time signature

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c_1	…	c_l

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$\boxed{t_0}\ \boxed{t_1 \mid c_1}\ \cdots\ \boxed{t_l \mid c_l}$

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$$\boxed{\sigma}\ \boxed{t_0}\ \boxed{t_1}\boxed{c_1}\ \cdots\ \boxed{t_l}\boxed{c_l}$$

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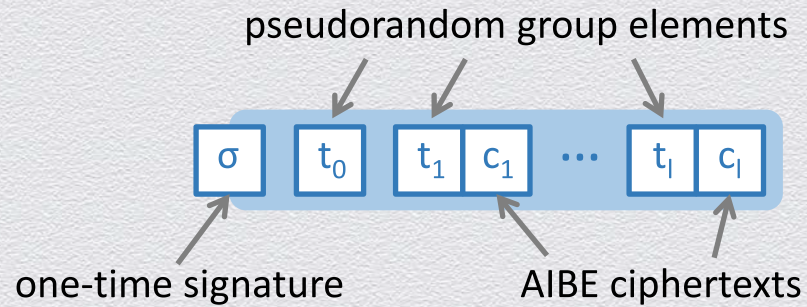
$$\boxed{\sigma}\ \boxed{t_0}\ \boxed{t_1 \mid c_1}\ \cdots\ \boxed{t_l \mid c_l}$$

- Notice that ciphertexts have no header …
- … but still exhibit structure due to tags and signature
- Idea: Toward a BS construction, make these components pseudorandom

oABE with Pseudorandom Ciphertexts (oABE$) [This Work]



- How to make oABE ciphertexts pseudorandom?
  1. Replace the underlying AIBE with AIBE$ [AgBo09]
  2. Apply an entropy smoothing hash to group elements
  3. Replace one-time signature with a MAC (implemented via PRF)

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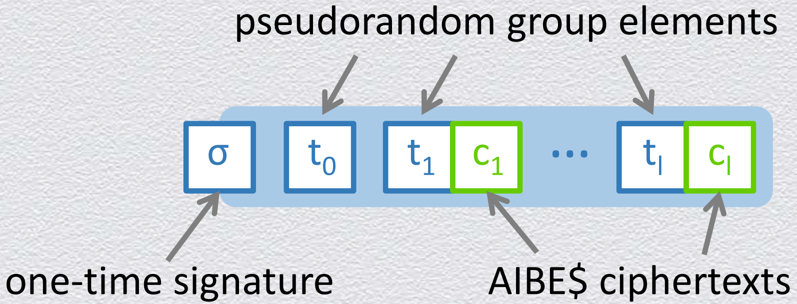

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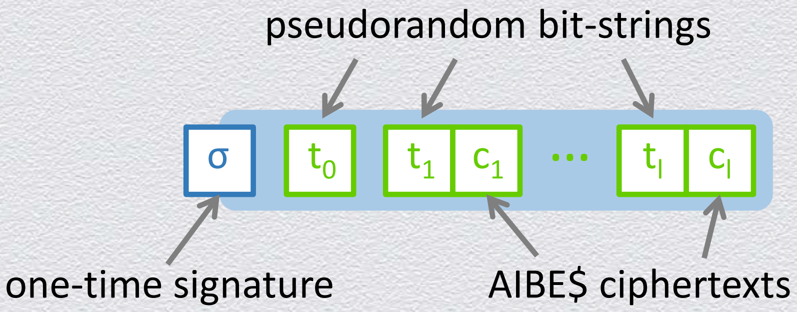

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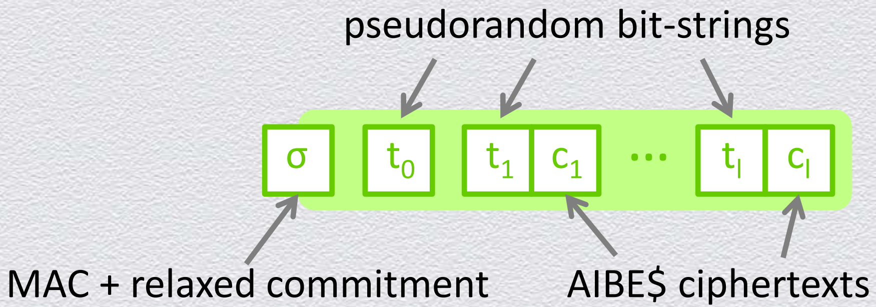

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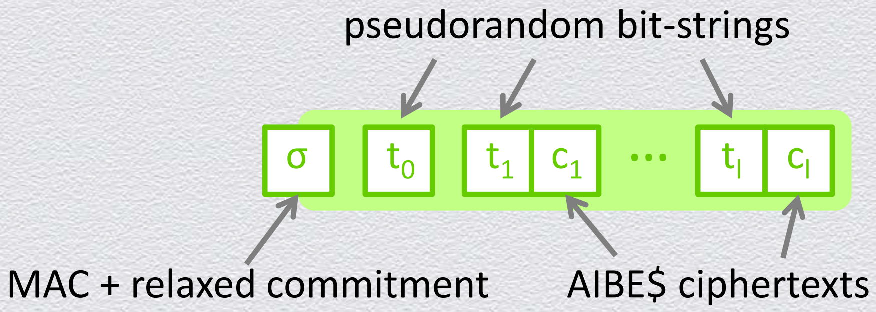

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  3. Replace one-time signature with a MAC (implemented via PRF)

Question: How to embed the MAC key in c_i's and still obtain CCA security?

Solution: Construct an encapsulation mechanism [DoKa05, BoKa05] with pseudorandom commitments

Comparison of BE Schemes with Anonymity Properties

Scheme	|PK|	|sk|	|c|	Security Model	Anonymity
BBW06	O(N)	O(1)	O(N-r)	Static, RO	Full
LPQ12	O(N)	O(1)	O(N-r)	Adaptive, Standard	Full
FaPe12a	O(N)	O(log N)	O(r log (n/r))	Adaptive, Standard	Outsider
FaPe12b	O(N log N)	O(N)	O(r)	Adaptive, Standard	Outsider
This Work	O(N)	O(log N)	O(r log (n/r))	Adaptive, Standard	Outsider

N: total number of users, r: number of revoked users

- Only oABE$ provides pseudorandom ciphertexts

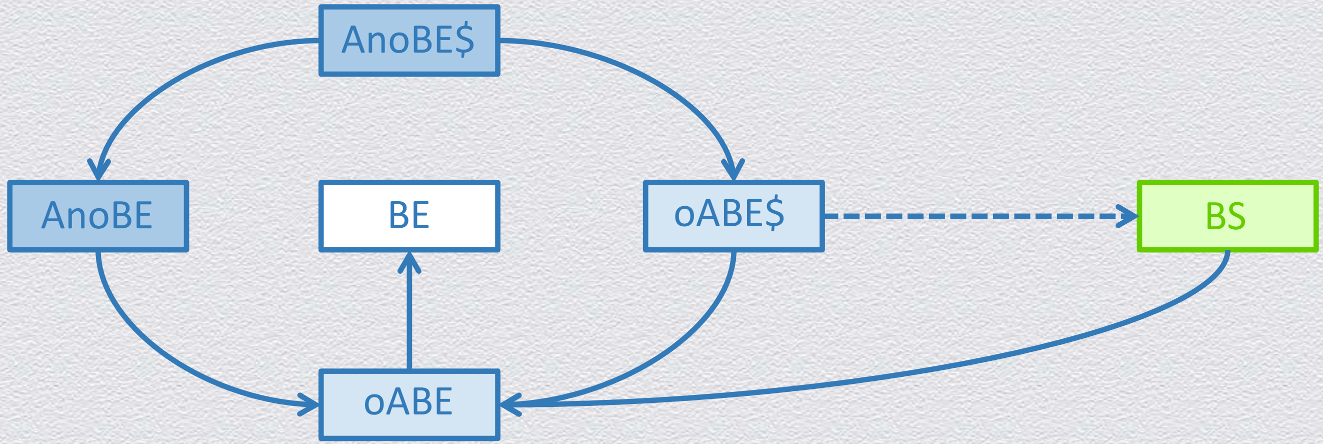
Our Construction of Broadcast Steganography

- Highlights
  - oABE$ + Encrypt-then-Embed = Broadcast Steganography
  - Our constructions have sub-linear stegotext length
  - For CCA security, requires stateless channel

- Constructions:
  1. BS-CHA
  2. BS-PDR-CCA
  3. BS-CCA

- Broadcast Steganography (BS)
- Constructions
- Summary

BE and Friends



Summary

- Initiated the study of Broadcast Steganography
  - A multi-recipient communication tool to plant undetectable messages in innocent-looking conversations
- Put forth sublinear constructions of broadcast steganography under a range of security notions
- In the process, devised efficient broadcast encryption schemes with pseudorandom ciphertexts and anonymity properties
  - Implementing CCA checks without imposing structure on broadcast ciphertexts required overcoming multiple technical hurdles

Practical Dual-Receiver Encryption

Soundness, Complete Non-malleability, and Applications

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Our Contributions

- Reformizing and recasting Dual-Receiver Encryption

- Defining soundness notions

- Practical DREs with soundness in the CRS model

- Applications:
  1. Complete non-malleable encryption
  2. Plaintext-aware encryption
  3. More applicatons---PKE with plaintext equality test, off-the-record messaging, ...

- Practical combined encryption of DRE and PKE
- Complete non-malleable DRE

[Diament, Lee, Keromytis, Yung 2001]

What's Dual-Receiver Encryption?

- Original DLKY notion:

  A kind of PKE allowing a ciphertext to be decrypted into the same plaintext by two independent receivers.

[Diament, Lee, Keromytis, Yung 2001]

What's Dual-Receiver Encryption?

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  A kind of PKE allowing a ciphertext to be decrypted into the same plaintext by two independent receivers.

Receiver 1
(pk_1, sk_1)

Encryptor
(pk_1, pk_2, m)

Receiver 2
(pk_2, sk_2)

[Diament, Lee, Keromytis, Yung 2001]

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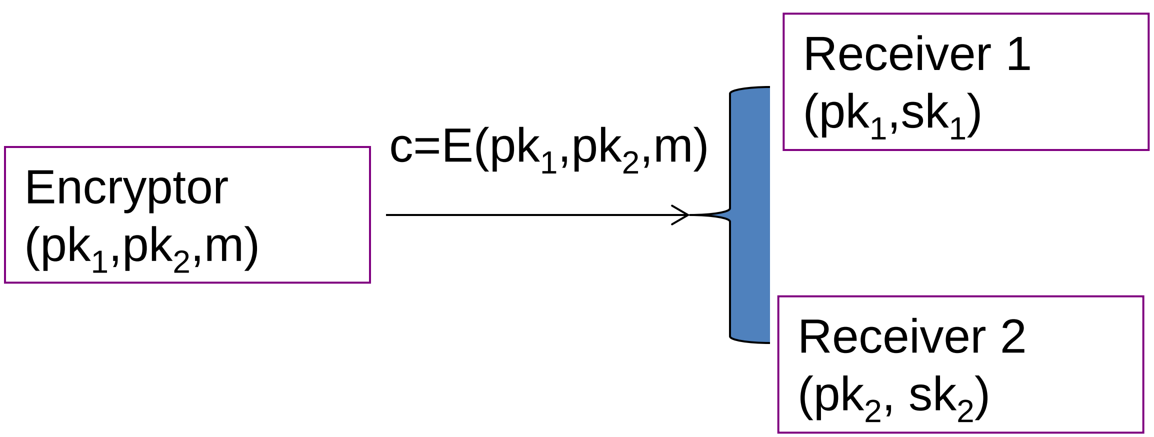

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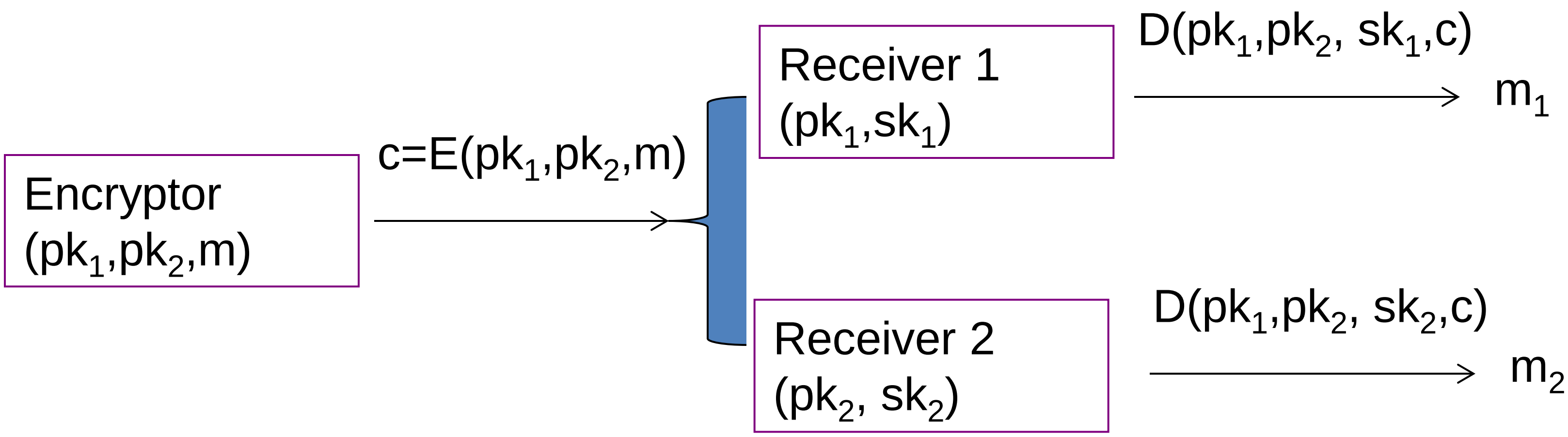

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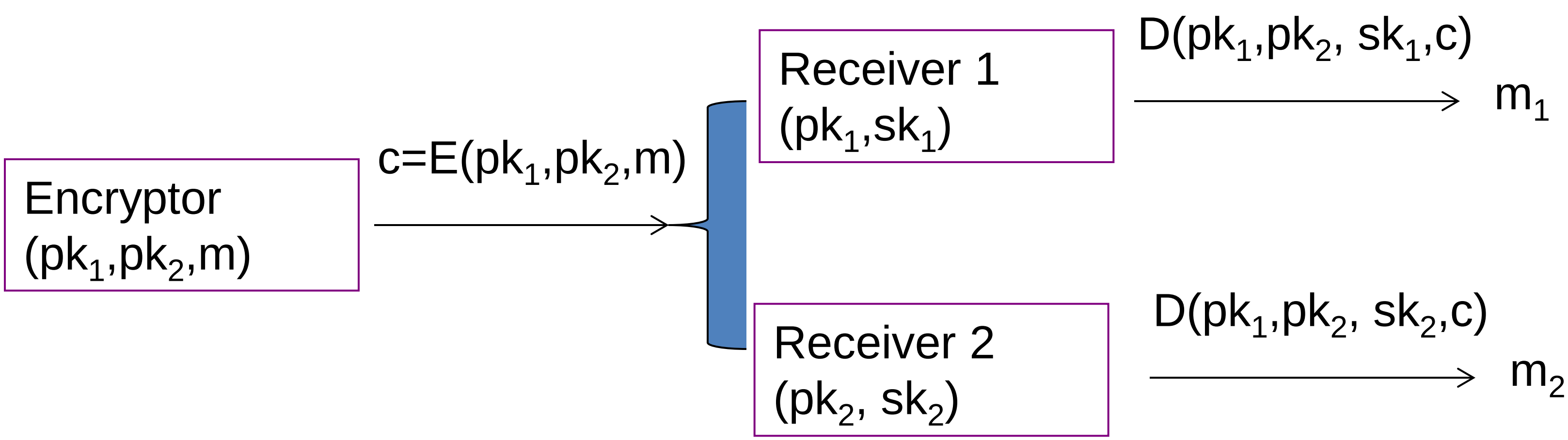

Basic consistency: $m=m_1=m_2$

DRE: A Useful Primitive

- DLKY: constructing useful security puzzle.

[Diament, Lee, Keromytis, Yung 2001]

Extending the DLKY notion---Soundness

- What about a cheating encryptor?
- "Bad" example: E(pk1,pk2,m) = E(pk1, m)||E(pk2, m)
- Soundness goals:

  1. Ensure adversary cannot "cheat."

  2. Both receivers "know" the ciphertext can be decrypted to the same result.

Extending the DLKY notion-Soundness

- Formally:

$$
\begin{array}{l}
\textbf{Experiment } \mathbf{Exp}^{\mathrm{sound}}_{\mathcal{DRE},\mathcal{A}}(k) \\
\quad \mathsf{crs} \xleftarrow{\$} \mathsf{CGen}_{\mathrm{DRE}}(1^k) \\
\quad (pk_1, sk_1) \xleftarrow{\$} \mathsf{Gen}_{\mathrm{DRE}}(\mathsf{crs}); (pk_2, sk_2) \xleftarrow{\$} \mathsf{Gen}_{\mathrm{DRE}}(\mathsf{crs}) \\
\quad C \xleftarrow{\$} \mathcal{A}(\mathsf{crs}, pk_1, sk_1, pk_2, sk_2) \\
\quad \textbf{if } \mathsf{Dec}_{\mathrm{DRE}}(sk_1, C) \neq \mathsf{Dec}_{\mathrm{DRE}}(sk_2, C) \textbf{ then} \\
\quad \textbf{return } 1 \textbf{ else return } 0
\end{array}
$$

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\mathbf{Adv}^{\text{sound}}_{\mathcal{DRE},\mathcal{A}}(k) = \Pr[\mathbf{Exp}^{\text{sound}}_{\mathcal{DRE},\mathcal{A}}(k) = 1].
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$$\mathbf{Adv}^{\text{sound}}_{\mathcal{DRE},\mathcal{A}}(k) = \Pr[\mathbf{Exp}^{\text{sound}}_{\mathcal{DRE},\mathcal{A}}(k) = 1].$$

We show DRE with soundness is even more useful.

Chosen Ciphertext Security of DRE

- DRE's soundness makes one of the two decryption oracles redundant.
- Formally:

$$\begin{array}{l}
\textbf{Experiment } \mathbf{Exp}^{\mathrm{cca}}_{\mathcal{DRE},\mathcal{A}}(k) \\
\quad \mathsf{crs} \xleftarrow{\$} \mathsf{CGen}_{\mathrm{DRE}}(1^k) \\
\quad (pk_1, sk_1) \xleftarrow{\$} \mathsf{Gen}_{\mathrm{DRE}}(\mathsf{crs});\ (pk_2, sk_2) \xleftarrow{\$} \mathsf{Gen}_{\mathrm{DRE}}(\mathsf{crs}) \\
\quad (M_0, M_1, \mathsf{s}) \xleftarrow{\$} \mathcal{A}^{\mathsf{Dec}_{\mathrm{DRE}}(sk_1,\cdot)}(\mathsf{find}, \mathsf{crs}, pk_1, pk_2) \\
\quad b \xleftarrow{\$} \{0,1\};\ C^* \xleftarrow{\$} \mathsf{Enc}_{\mathrm{DRE}}(\mathsf{crs}, pk_1, pk_2, M_b) \\
\quad b' \xleftarrow{\$} \mathcal{A}^{\mathsf{Dec}_{\mathrm{DRE}}(sk_1,\cdot)}(\mathsf{guess}, C^*, \mathsf{s}) \\
\quad \textbf{if } b' = b \textbf{ then return } 1 \textbf{ else return } 0
\end{array}$$

$$\mathbf{Adv}^{\mathrm{cca}}_{\mathcal{DRE},\mathcal{A}}(k) = \Pr[\mathbf{Exp}^{\mathrm{cca}}_{\mathcal{DRE},\mathcal{A}}(k) = 1] - 1/2.$$

Properties of a Desirable DRE

- Efficient; standard model; well-studied assumption
- Symmetry
- Public verifiability

Constructing DRE

- Previous constructions: either in ROM or rely on general and inefficient NIZK proofs

- We construct DRE in the CRS model.

  Our CRS is simply a benign bilinear group such that two receivers pick their keys from the group.

- We also construct DKEM

  DKEM=Dual-receiver Key Encapsulation Mechanism.

Practical DRE and DKEM from BDDH Assumption

- Basic ideas: Boneh and Boyen, Identity-based techniques

[Boneh and Boyen, 2004]

- DRE similar to: Kiltz tag-based encryption

[Kiltz, TCC 2006]

- DKEM similar to: Kiltz KEMs and BMW KEM

[Kiltz, TCC 2006][Kiltz, PKC 2007] [Boyen, Mei, and Waters, 2005]

Practical DRE from BDDH Assumption

$\mathsf{CGen}_{\mathrm{DRE}}(1^k)$	$\mathsf{Enc}_{\mathrm{DRE}}(\mathcal{BG}, pk_1, pk_2, M)$	$\mathsf{Dec}_{\mathrm{DRE}}(\mathcal{BG}, pk_1, pk_2, sk_1, C)$
$\textbf{return } \mathcal{BG}$	$(\mathsf{vk}, \mathsf{sk}) \xleftarrow{\$} \mathsf{Gen}_{\mathrm{OT}}(1^k)$	$\textbf{parse } C \textbf{ as } (\mathsf{vk}, c, \pi_1, \pi_2, \phi, \sigma)$
$\mathsf{Gen}_{\mathrm{DRE}}(1^k, \mathcal{BG})$	$r \xleftarrow{\$} \mathbb{Z}_q^*;\ c \leftarrow g^r$	$\textbf{if } \mathsf{Vrf}_{\mathrm{OT}}(\mathsf{vk}, \sigma, (c, \pi_1, \pi_2, \phi)) \neq 1 \textbf{ or}$
$x_i, y_i \xleftarrow{\$} \mathbb{Z}_q^*$	$\pi_1 \leftarrow (u_1^{\mathsf{vk}} v_1)^r$	$e(g, \pi_1) \neq e(c, u_1^{\mathsf{vk}} v_1) \textbf{ or}$
$u_i \leftarrow g^{x_i};\ v_i \leftarrow g^{y_i}$	$\pi_2 \leftarrow (u_2^{\mathsf{vk}} v_2)^r$	$e(g, \pi_2) \neq e(c, u_2^{\mathsf{vk}} v_2)$
$pk_i \leftarrow (u_i, v_i)$	$\phi \leftarrow e(u_1, u_2)^r \cdot M$	$\textbf{return } \perp$
$sk_i \leftarrow x_i$	$\sigma \xleftarrow{\$} \mathsf{Sig}_{\mathrm{OT}}(\mathsf{sk}, (c, \pi_1, \pi_2, \phi))$	$M \leftarrow \phi \cdot e(c, u_2)^{-x_1}$
$\textbf{return } (pk_i, sk_i)$	$\textbf{return } C \leftarrow (\mathsf{vk}, c, \pi_1, \pi_2, \phi, \sigma)$	$\textbf{return } M$

- Efficient and practical
- Well-studied assumption---BDDH assumption
- Symmetric
- Public verifiable

Practical DKEM from BDDH Assumption

$\mathsf{CGen}_{\mathrm{DKEM}}(1^k)$	$\mathsf{Enc}_{\mathrm{DKEM}}(\mathcal{BG}, pk_1, pk_2)$	$\mathsf{Dec}_{\mathrm{DKEM}}(\mathcal{BG}, pk_1, pk_2, sk_1, C)$
return $\mathcal{BG}$	$r \xleftarrow{\$} \mathbb{Z}_q^*;\ c \leftarrow g^r$	**parse** C **as** (c, π_1, π_2)
$\mathsf{Gen}_{\mathrm{DKEM}}(1^k, \mathcal{BG})\ i \in \{1,2\}$	$t \leftarrow \mathsf{TCR}(c)$	$t \leftarrow \mathsf{TCR}(c)$
$x_i, y_i \xleftarrow{\$} \mathbb{Z}_q^*$	$\pi_1 \leftarrow (u_1^t v_1)^r$	**if** $e(g, \pi_1) \neq e(c, u_1^t v_1)$ **or**
$u_i \leftarrow g^{x_i};\ v_i \leftarrow g^{y_i}$	$\pi_2 \leftarrow (u_2^t v_2)^r$	$e(g, \pi_2) \neq e(c, u_2^t v_2)$
$pk_i \leftarrow (u_i, v_i)$	$K \leftarrow e(u_1, u_2)^r$	**return** $\perp$
$sk_i \leftarrow x_i$	$C \leftarrow (c, \pi_1, \pi_2)$	$K \leftarrow e(c, u_2)^{x_1}$
return (pk_i, sk_i)	**return** (C, K)	**return** K

Plaintext-Aware (PA) Encryption via Registration

- Plaintext aware encryption

1. "Any adversary can decrypt any ciphertext that it creates"

2. PA+IND-CPA-->IND-CCA2

3. PA encryption in the standard model --- difficult to analyze.

Plaintext-Aware (PA) Encryption via Registration

PA via registration --- "Any adversary can decrypt any ciphertext it creates, as long as the adversary registered its sending key."

[Herzog, Liscov, Micali (HLM) 2003]

HLM is relatively simple but relies on generic NIZK proofs.

Plaintext Aware Encryption via Registration from DRE

- General transformation:
  Given a DRE with (pk1,sk1) and (pk2,sk2),

  pk1 is the sender and pk2 is the receiver;
  pk1 further runs a zero-knowledge PoK of its secret key.

- Efficient; symmetric; general; simple to analyze.

Complete Non-Malleable (CNM) PKE from DRE

- CNM----another strong notion than IND-CCA2/NM-CCA2.

[Fischlin 2005] [Ventre and Visconti 2008]

- CNM prohibits adversary from computing encrypted ciphertext of related plaintext even with adverserial public keys.

- DRE with soundness implies CNM PKE in the CRS model.

- The transformation is even simpler:

Given a DRE with (pk1,sk1) (pk2,sk2).

crs---pk1, PKE's (pk,sk)=DRE's (pk2,sk2).

Public key encryption with equality test (PET) from DRE

- Two types of PET:

- 1. Probabilistic PKE with equality test:
  one-way CCA [Yang, Tan, Huang, Wong 2010]
  a stronger notion (still weak than one for PKE) [Lu, Zhang, Lin 2012]

- 2. e-voting and verifiable dual encryption (chosen-plaintext attack model):
  e.g.,[Jakobsson and Juels 2000]
  [Zhou, Marsh, Schneider, Redz 2005]

Our DRE with soundness strengthens two types of PET.

Off-the-record messaging with stronger undeniability from DRE

- Off-the-record messaging (OTR) protocol.

[Borisov, Goldberg, Brewer, 2000]

- DKSW proposed stronger notion for undenaiability. The bottleneck is jus the efficiency of DRE.

[Dodis, Katz, Smith, and Walfish 2009]

- OTR made practical with our DREs.

Other Applications

- Key exchange protocols.

[Suzuki and Yoneyama 2013]

[Purushothama and Amberker 2013]

Combined Encryption of DRE and PKE

- Combined encryption of DRE and PKE without key separation.

$\mathsf{CGen}(1^k)$
 return $\mathcal{BG}$
$\mathsf{Gen}_{\mathrm{COM}}(1^k, \mathcal{BG})$
 $x_i, y_i \xleftarrow{\$} \mathbb{Z}_q^*$
 $u_i \leftarrow g^{x_i};\ v_i \leftarrow g^{y_i}$
 $w_i \leftarrow g^{z_i}$
 $pk_i \leftarrow (u_i, v_i, w_i)$
 $sk_i \leftarrow x_i$
 return (pk_i, sk_i)

$\mathsf{Enc}_{\mathrm{DRE}}(\mathcal{BG}, pk_1, pk_2, M)$
 $(\mathsf{vk}, \mathsf{sk}) \xleftarrow{\$} \mathsf{Gen}_{\mathrm{OT}}(1^k)$
 $r \xleftarrow{\$} \mathbb{Z}_q^*$
 $c \leftarrow g^r$
 $\pi_1 \leftarrow (u_1^{\mathsf{vk}} v_1)^r$
 $\pi_2 \leftarrow (u_2^{\mathsf{vk}} v_2)^r$
 $\phi \leftarrow e(u_1, u_2)^r \cdot M$
 $\sigma \xleftarrow{\$} \mathsf{Sig}_{\mathrm{OT}}(\mathsf{sk}, (c, \pi_1, \pi_2, \phi))$
 return $C \leftarrow (\mathsf{vk}, c, \pi_1, \pi_2, \phi, \sigma)$

$\mathsf{Dec}_{\mathrm{DRE}}(\mathcal{BG}, pk_1, pk_2, sk_1, C)$
 parse C **as** $(\mathsf{vk}, c, \pi_1, \pi_2, \phi, \sigma)$
 if $\mathsf{Vrf}_{\mathrm{OT}}(\mathsf{vk}, \sigma, (c, \pi_1, \pi_2, \phi)) \neq 1$ **or**
  $e(g, \pi_1) \neq e(c, u_1^{\mathsf{vk}} v_1)$ **or**
  $e(g, \pi_2) \neq e(c, u_2^{\mathsf{vk}} v_2)$
 return $\perp$
 $M \leftarrow \phi \cdot e(c, u_2)^{-x_1}$
 return M

$\mathsf{Enc}_{\mathrm{PKE}}(\mathcal{BG}, pk_1, M)$
 $(\mathsf{vk}, \mathsf{sk}) \xleftarrow{\$} \mathsf{Gen}_{\mathrm{OT}}(1^k)$
 $r \xleftarrow{\$} \mathbb{Z}_q^*;\ c \leftarrow g^r$
 $\pi \leftarrow (u_1^{\mathsf{vk}} v_1)^r$
 $\phi \leftarrow e(u_1, w_1)^r \cdot M$
 $\sigma \xleftarrow{\$} \mathsf{Sig}_{\mathrm{OT}}(\mathsf{sk}, (c, \pi, \phi))$
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 return $\perp$
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 return M

Complete Non-Malleable DRE

- Motivated by
  1. same reason as CNM PKE---stonger security for DRE
  2. stronger security for PETs
  3. dual-receiver non-malleable commitment scheme

Paradigms for CNM-DRE (1): Groth-Sahai Proof System

- Naor-Yung Paradigm and Groth-Sahai Proof system

[Naor, Yung, 1990] [Groth, Sahai, 2008]

$\mathsf{CGen}_{\mathrm{DRE}}(1^k)$	$\mathsf{Enc}_{\mathrm{DRE}}(\mathsf{crs}, pk_1, pk_2, m)$	$\mathsf{Dec}_{\mathrm{DRE}}(\mathsf{crs}, pk_1, pk_2, sk_1, C)$
$\textbf{return}\ \mathsf{crs} \xleftarrow{\$} \mathsf{CGen}(1^k)$	$c_1 \leftarrow \mathsf{Enc}(pk_1, m; r_1)$	$\textbf{parse}\ C\ \textbf{as}\ (c_1, c_2, \pi)$
	$c_2 \leftarrow \mathsf{Enc}(pk_2, m; r_2)$	$\textbf{if}\ \mathsf{V}(\mathsf{crs}, c_1, c_2, pk_1, pk_2, \pi) \neq 1$
$\mathsf{Gen}_{\mathrm{DRE}}(1^k)\quad i \in \{1,2\}$	$\pi \xleftarrow{\$} \mathsf{P}(\mathsf{crs}, (c_1, c_2, pk_1, pk_2), (m, r_1, r_2))$	$\quad \textbf{return}\ \perp$
$(pk_i, sk_i) \xleftarrow{\$} \mathsf{Gen}(1^k)$	$c \leftarrow (c_1, c_2, \pi)$	$m \leftarrow \mathsf{Dec}(c_1, pk_1, sk_1)$
$\textbf{return}\ (pk_i, sk_i)$	$\textbf{return}\ c$	$\textbf{return}\ m$

- (P,V) is simulation-sound and simulation-sound extractable NIZK proof of knowledge proof system
- can be realized via Groth-Sahai proof system
- SXDH and DLIN assumptions

Paradigms for CNM-DRE (2): Lossy Trapdoor Functions

- Lossy trapdoor functions (DDH, LWE, and CR assumptions)

[Peikert, Waters2008][Freeman, Goldreich, Kiltz, Segev2010]

$\mathsf{CGen}_{\mathrm{DRE}}(1^k)$
- $b_0 \xleftarrow{\$} \{0,1\}^n$
- $(s_0, t_0) \xleftarrow{\$} \mathcal{S}_{abo}(1^k, b_0)$
- $h \xleftarrow{\$} \mathcal{H}$
- **return** $\mathsf{crs} \leftarrow (s_0, h)$

$\mathsf{Gen}_{\mathrm{DRE}}(1^k) \quad i \in \{1,2\}$
- $(s_i, t_i) \xleftarrow{\$} \mathcal{S}(1^k, 1)$
- **return** (s_i, t_i)

$\mathsf{Dec}_{\mathrm{DRE}}(\mathsf{crs}, s_1, s_2, t_1, C)$
- **parse** C **as** $(C_1, C_2, C_3, C_4, pk_1, pk_2, \sigma)$
- **if** $\mathsf{Vrf}_{\mathrm{OT}}(\mathsf{vk}, \sigma, (C_1, C_2, C_3, C_4, pk_1, pk_2)) \neq 1$ **then**
  - **return** $\perp$
- $r \leftarrow \mathcal{F}^{-1}(t_1, C_1)$
- **if** $C_2 \neq \mathcal{F}(s_2, r)$ **or** $C_3 \neq \mathcal{F}(s_0, r)$ **then**
  - **return** $\perp$
- $m \leftarrow C_4 \oplus \mathsf{H}_h(r)$
- **return** m

$\mathsf{Enc}_{\mathrm{DRE}}(\mathsf{crs}, s_1, s_2, m; r)$
- $(\mathsf{vk}, \mathsf{sk}) \xleftarrow{\$} \mathsf{Gen}_{\mathrm{OT}}(1^k)$
- $r \xleftarrow{\$} \{0,1\}^n$
- $C_1 \leftarrow \mathcal{F}(s_1, r)$
- $C_2 \leftarrow \mathcal{F}(s_2, r)$
- $C_3 \leftarrow \mathcal{G}_{abo}(s_0, \mathsf{vk}, r)$
- $C_4 \leftarrow M \oplus \mathsf{H}_h(r)$
- $\sigma \xleftarrow{\$} \mathsf{Sig}_{\mathrm{OT}}(\mathsf{sk}, (C_1, C_2, C_3, C_4, pk_1, pk_2))$
- **return** $C \leftarrow (\mathsf{vk}, C_1, C_2, C_3, C_4, \sigma)$

Thank you!