Improving Speed and Security in Updatable Encryption Schemes

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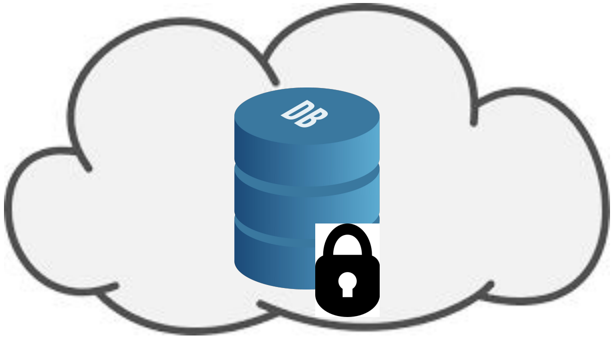
Key Rotation



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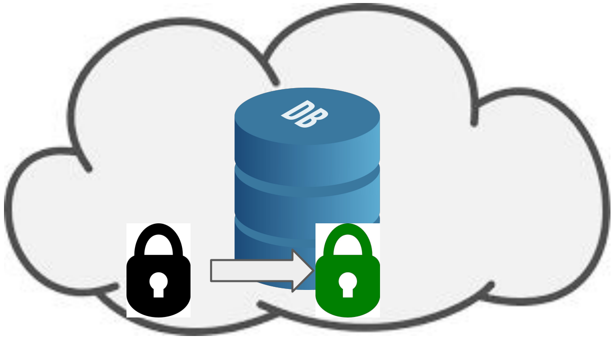

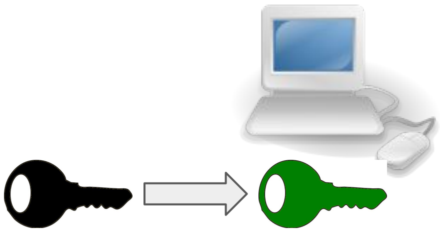

Good Reasons to Rotate Keys

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…But *Why?*

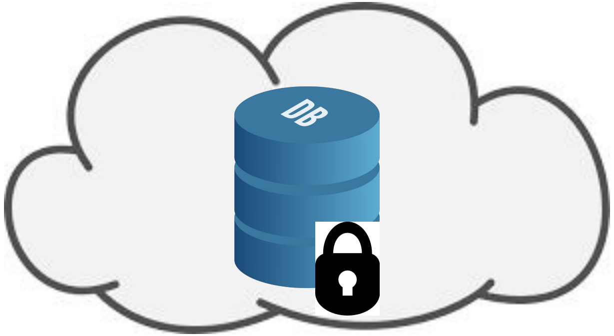
Good Reasons to Rotate Keys

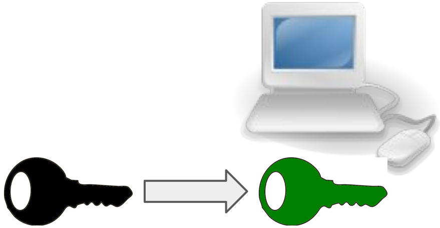
Reasons to rotate keys for data stored in the cloud:

- Compromised keys need to be taken out of use
- Proactive refresh of keys
- Access control enforcement

How to Rotate Keys in the Cloud?

Idea 1: send keys to cloud





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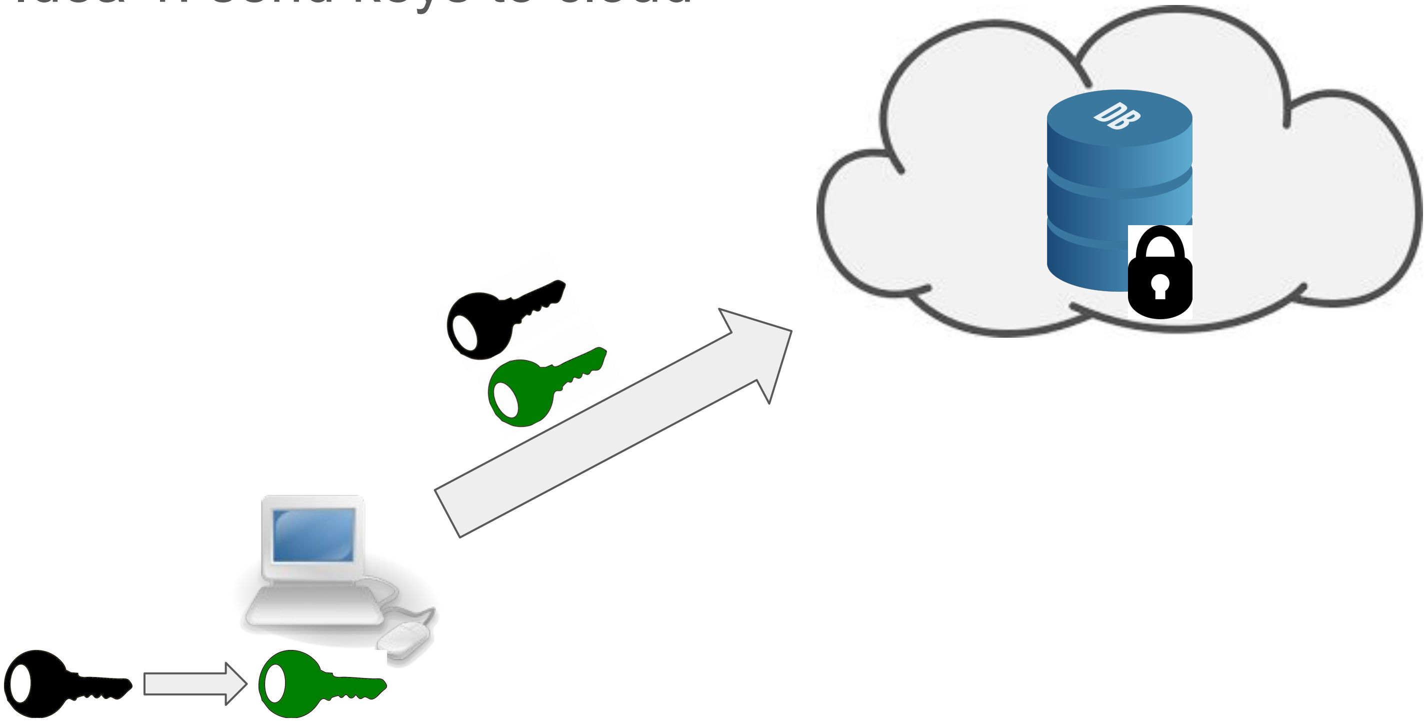

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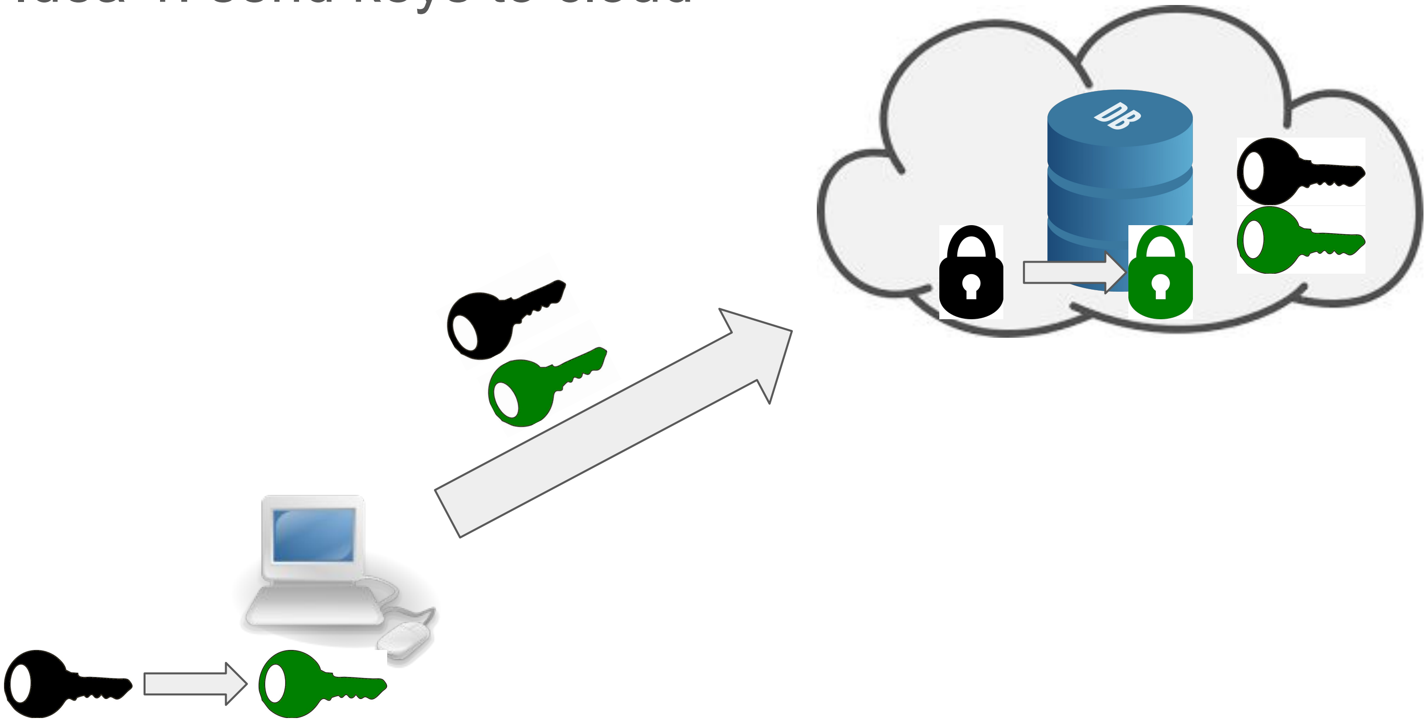

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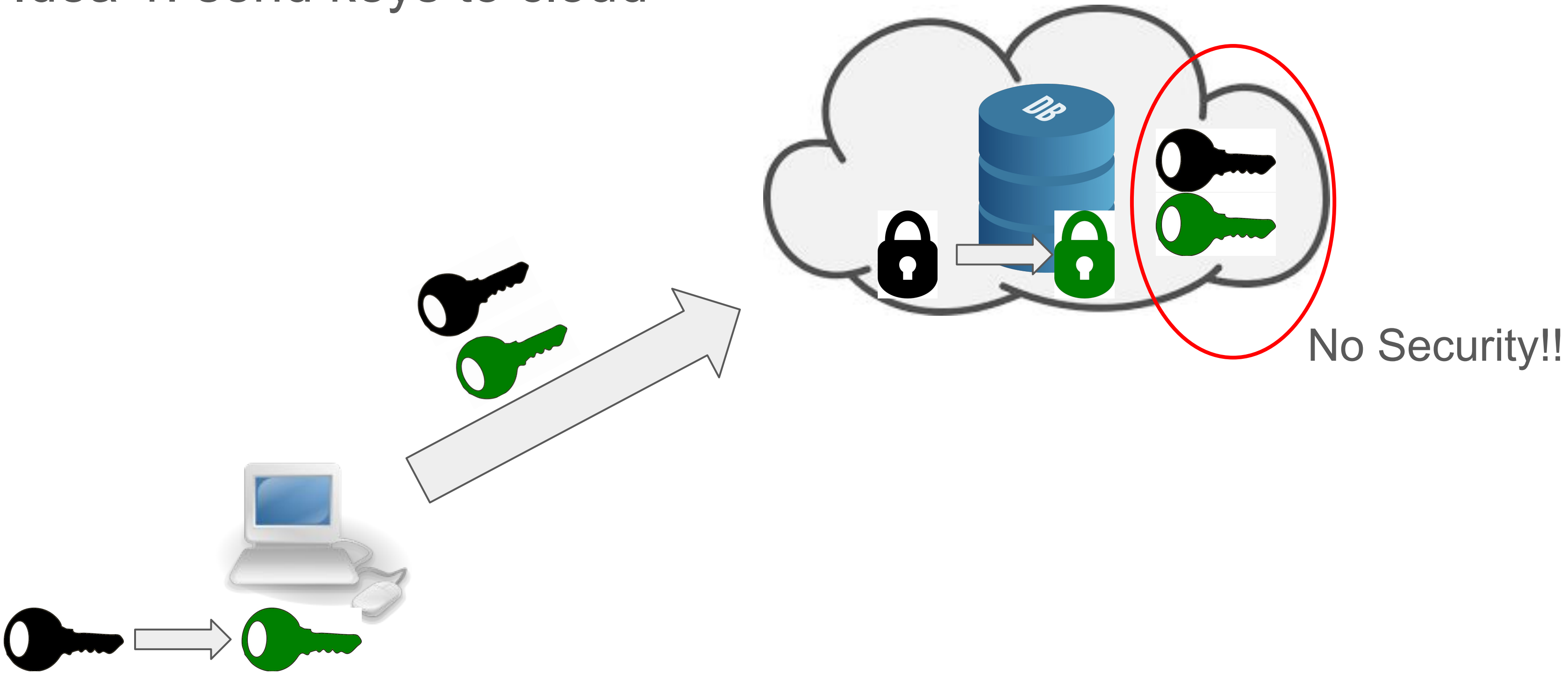

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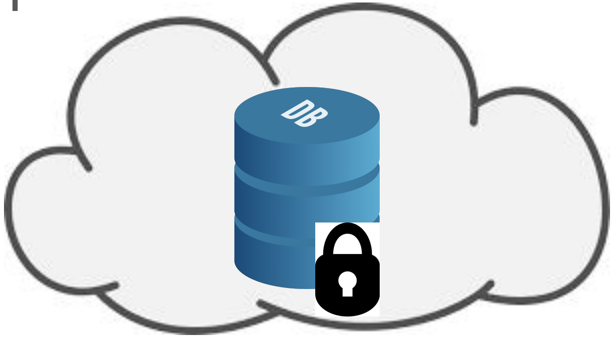

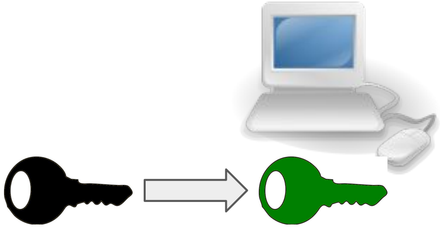

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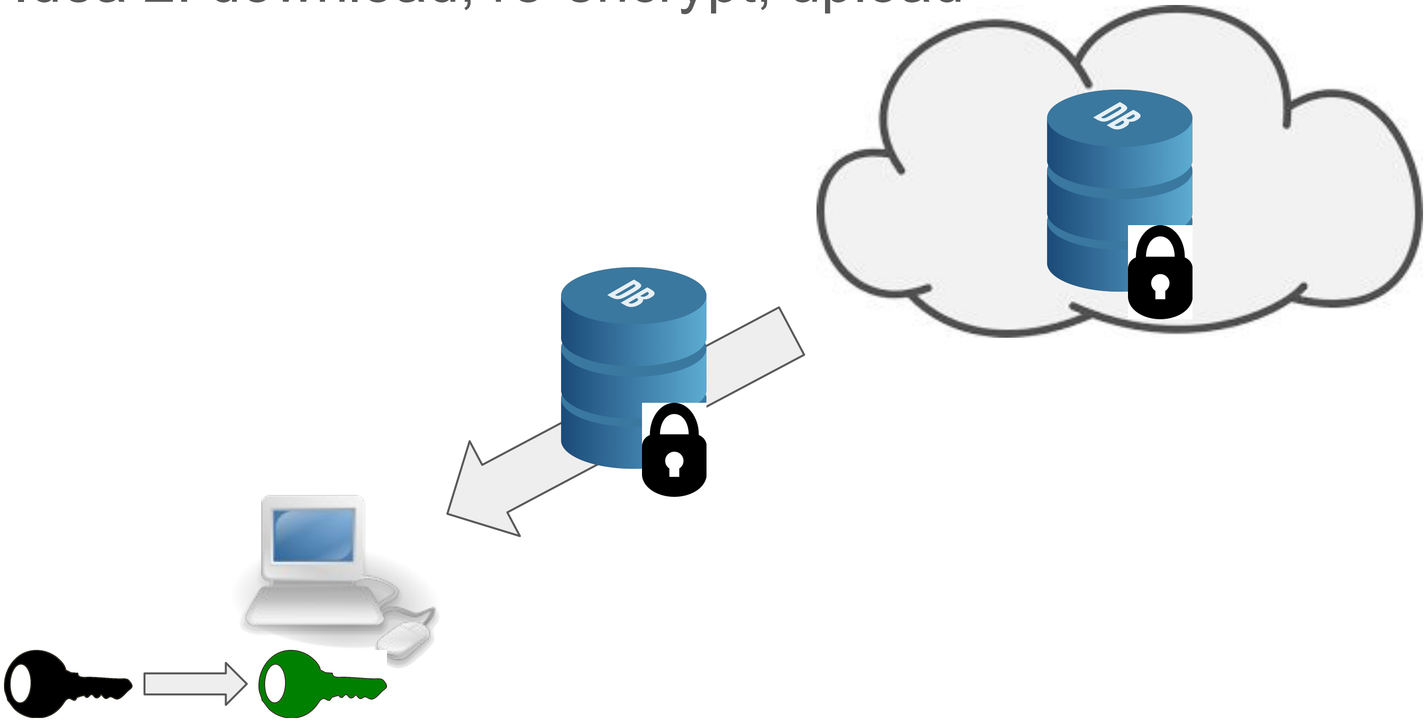

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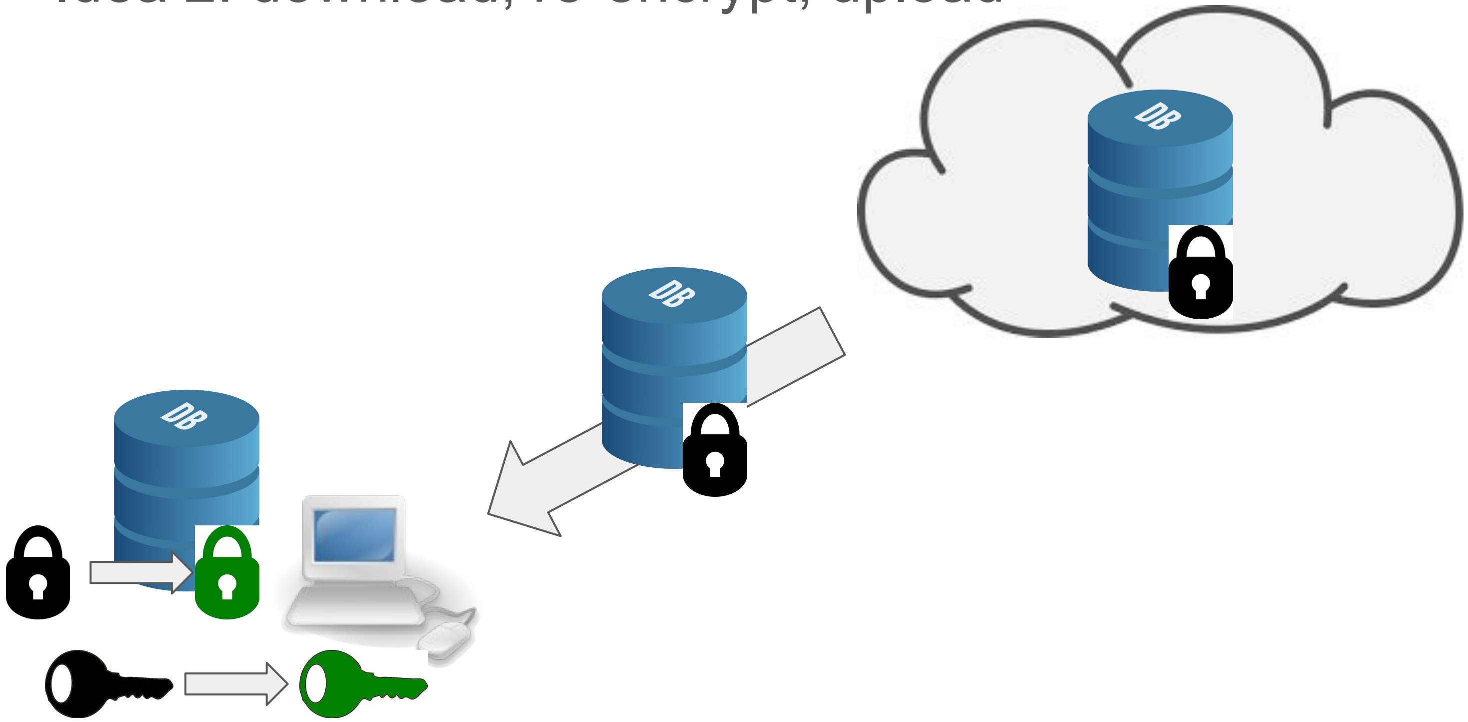

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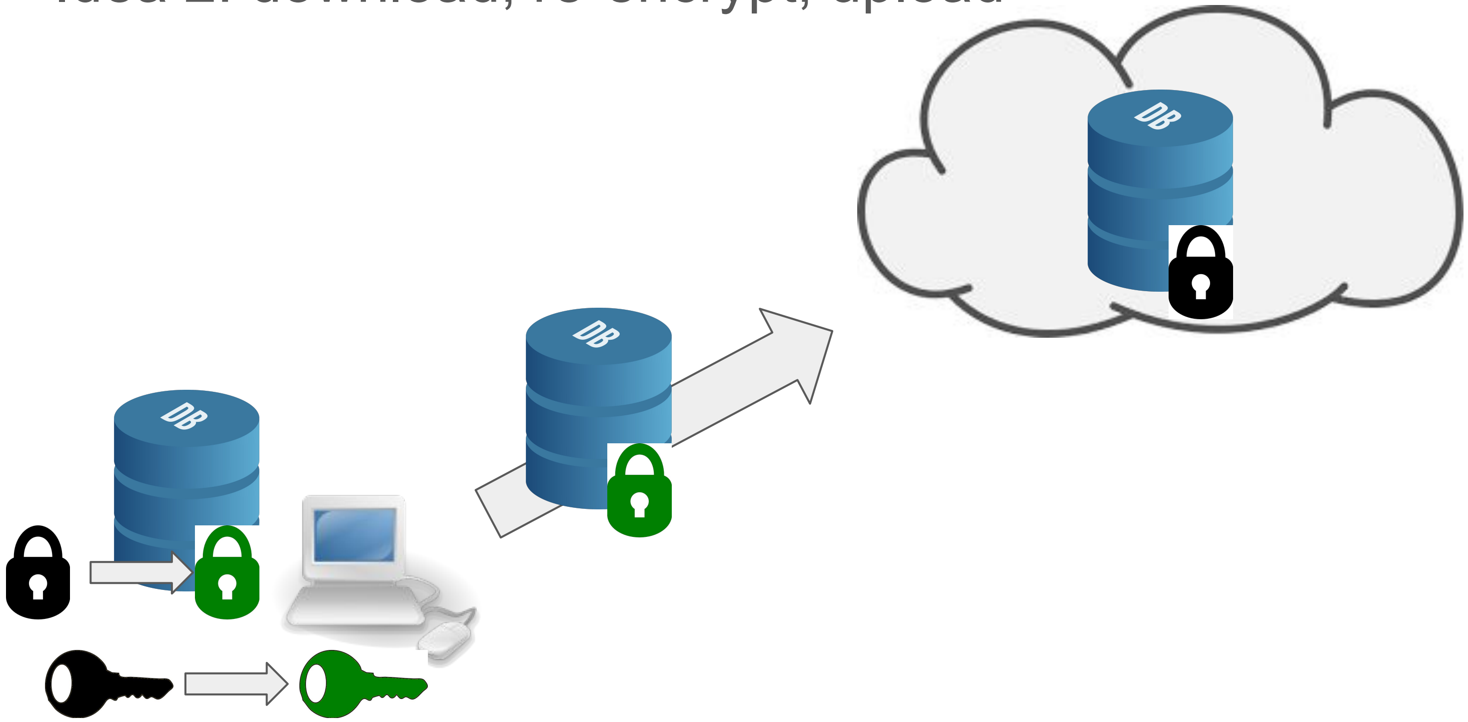

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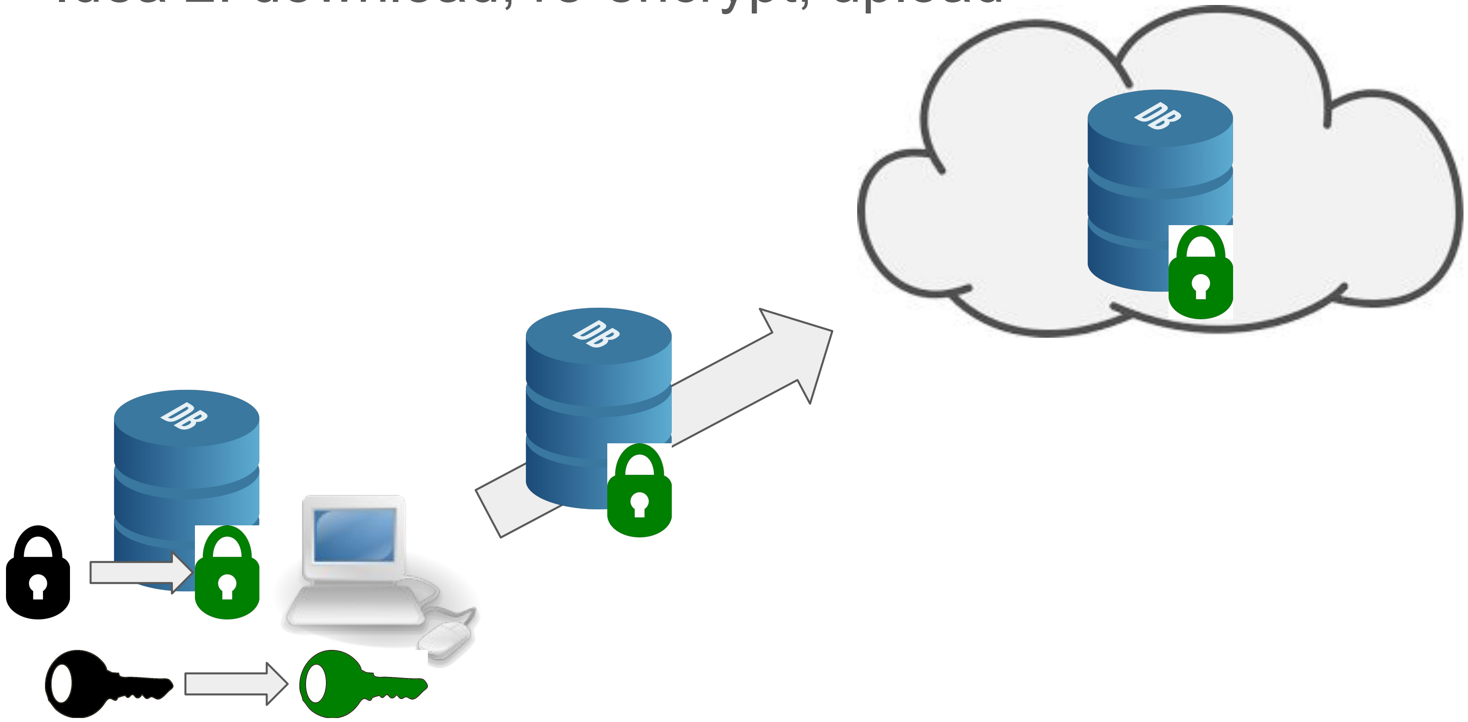

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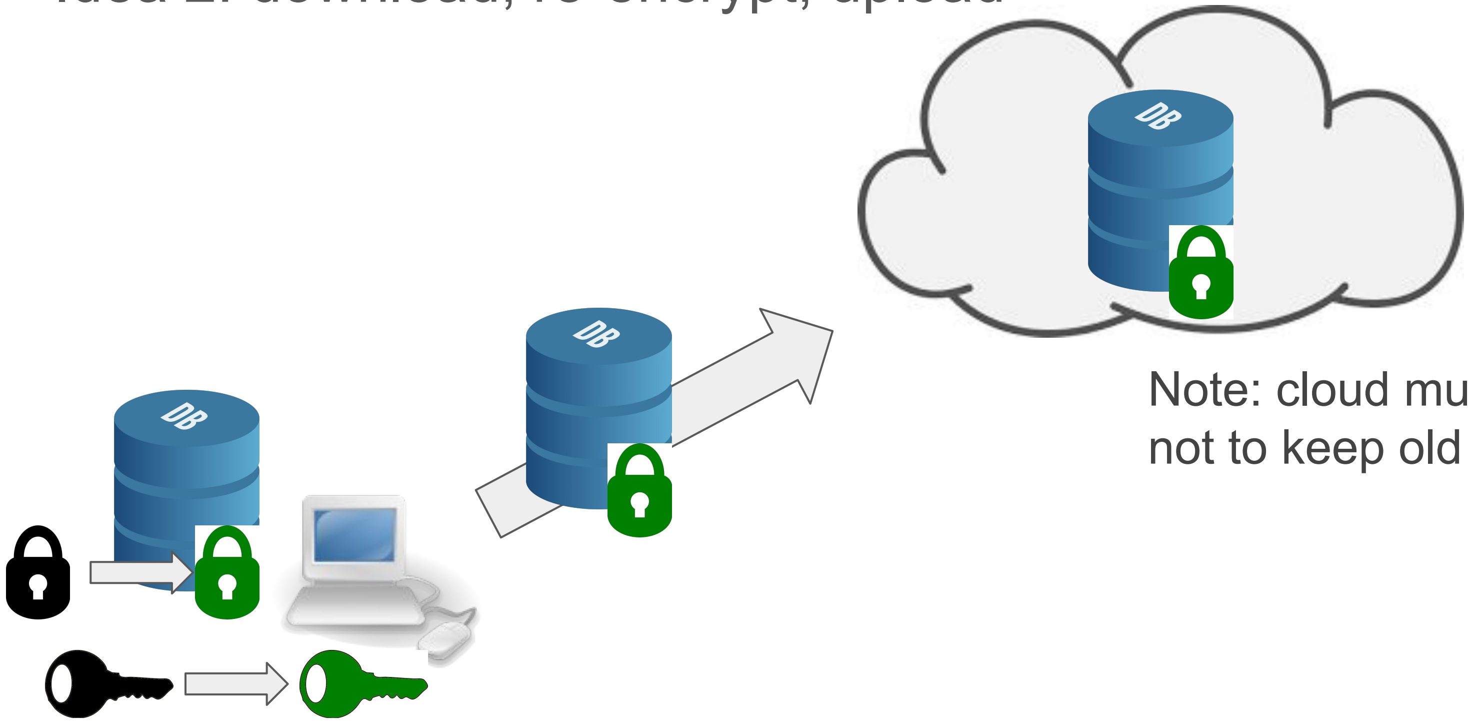

Note: cloud must be trusted not to keep old ciphertexts

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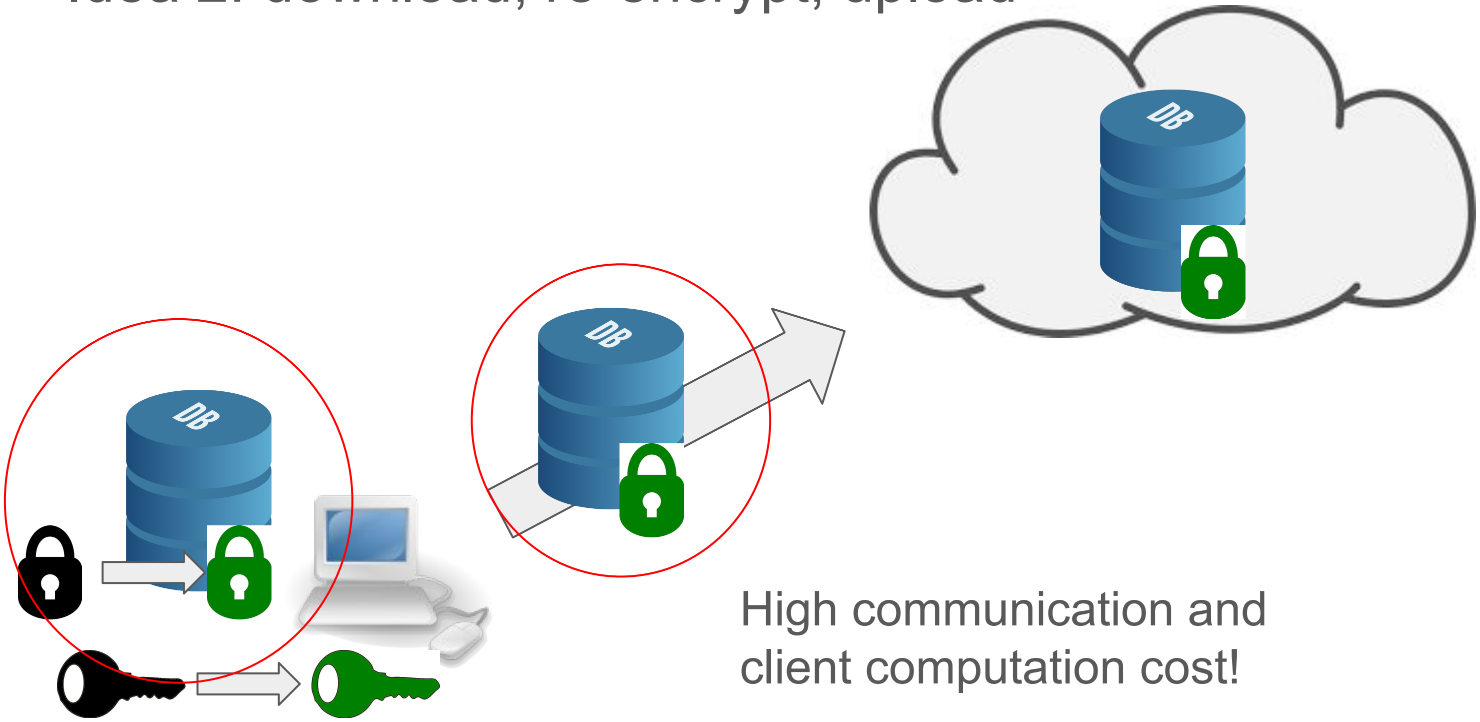

High communication and client computation cost!

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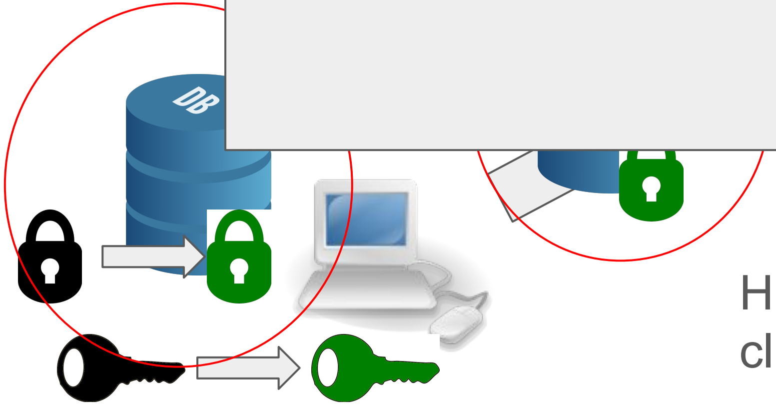
Can we do better?

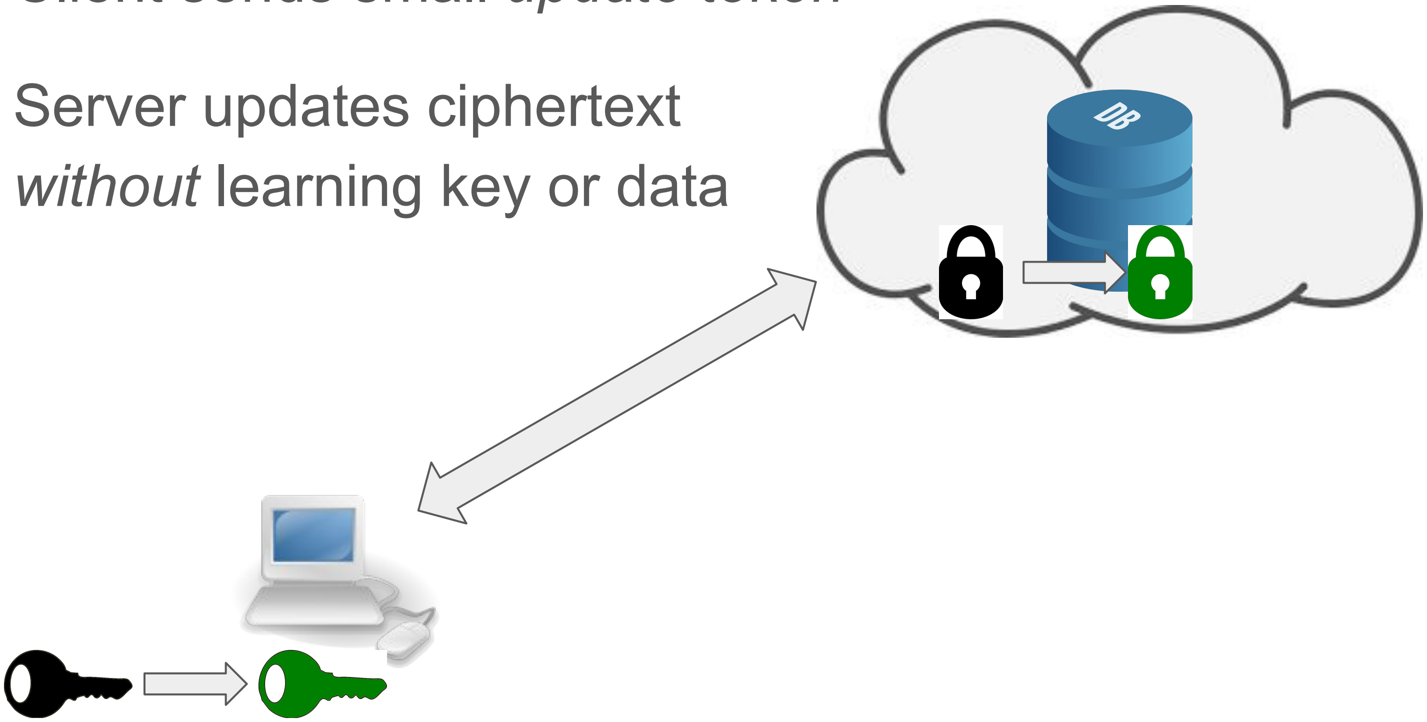


High communication and client computation cost!

Updatable Encryption [BLMR13, EPRS17, LT18, KLR19, BDGJ19]

Client sends small *update token*

Server updates ciphertext
without learning key or data



Our Contributions & Roadmap

Improvements over prior security definitions

- Additional requirements for security

Two new constructions of updatable encryption

- From Nested AES: very fast, only supports *bounded* updates
- From KH-PRF based on RLWE: ~500x faster than prior work

Performance evaluation and comparison to prior work

Recommendations for usage

Security and Functionality Goals

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Limitations

1. Server computation will be linear
2. Adversary with ongoing access to key updates will still get data

Defining Security [EPRS17]

Four properties to achieve:

- Correctness
- Compactness
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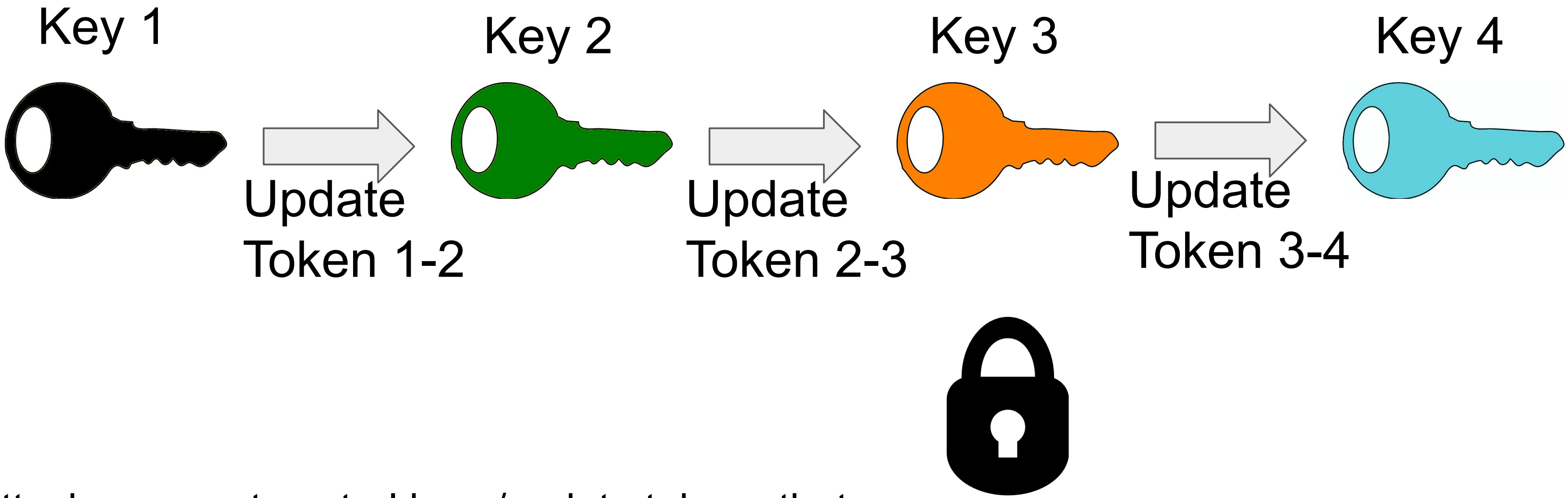

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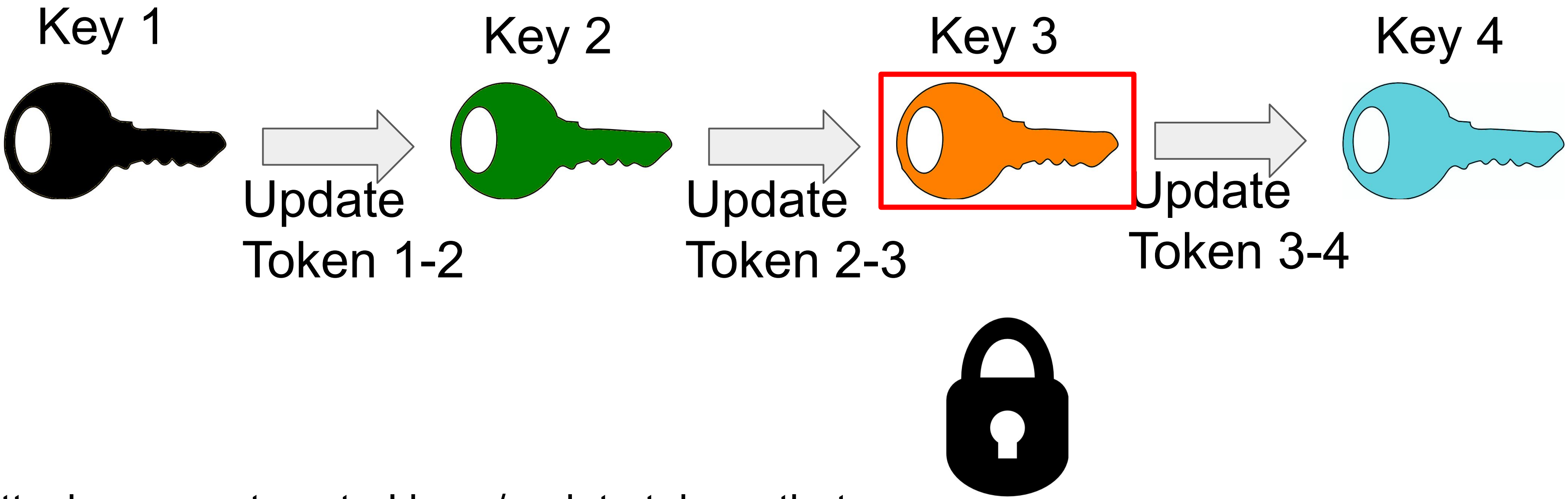

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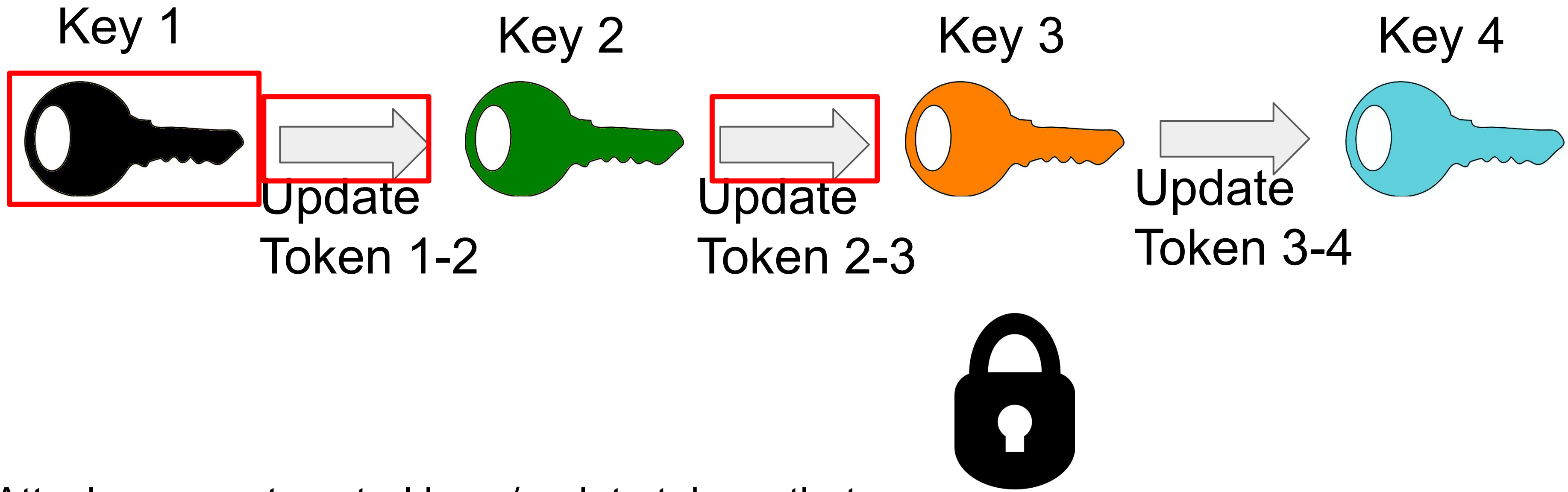

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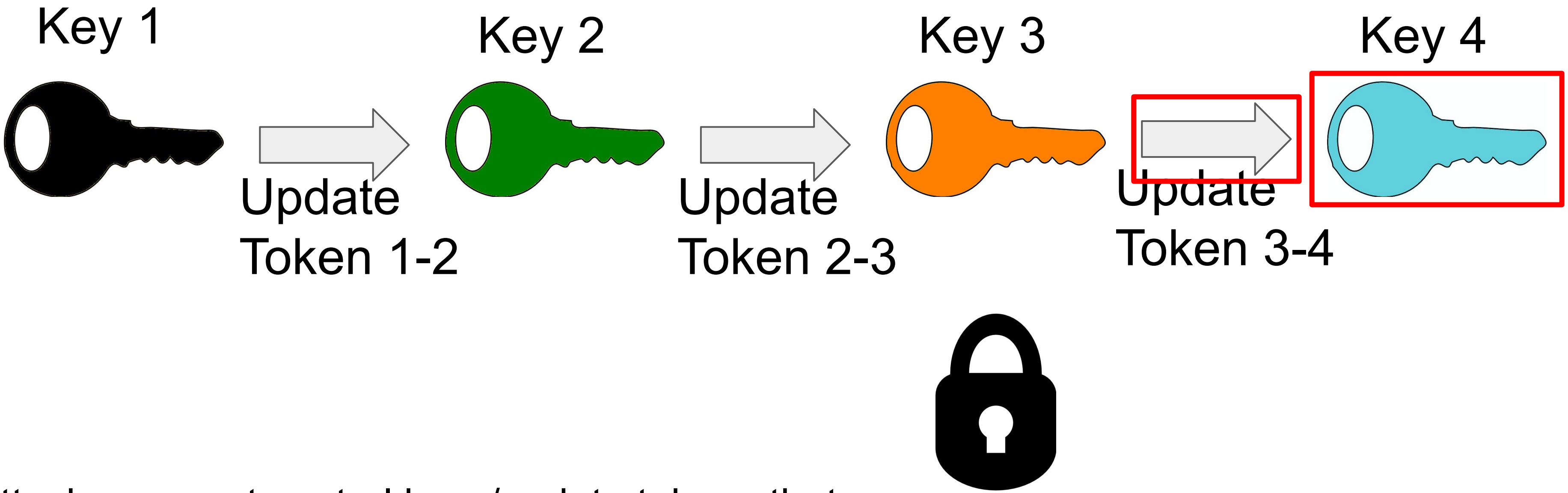

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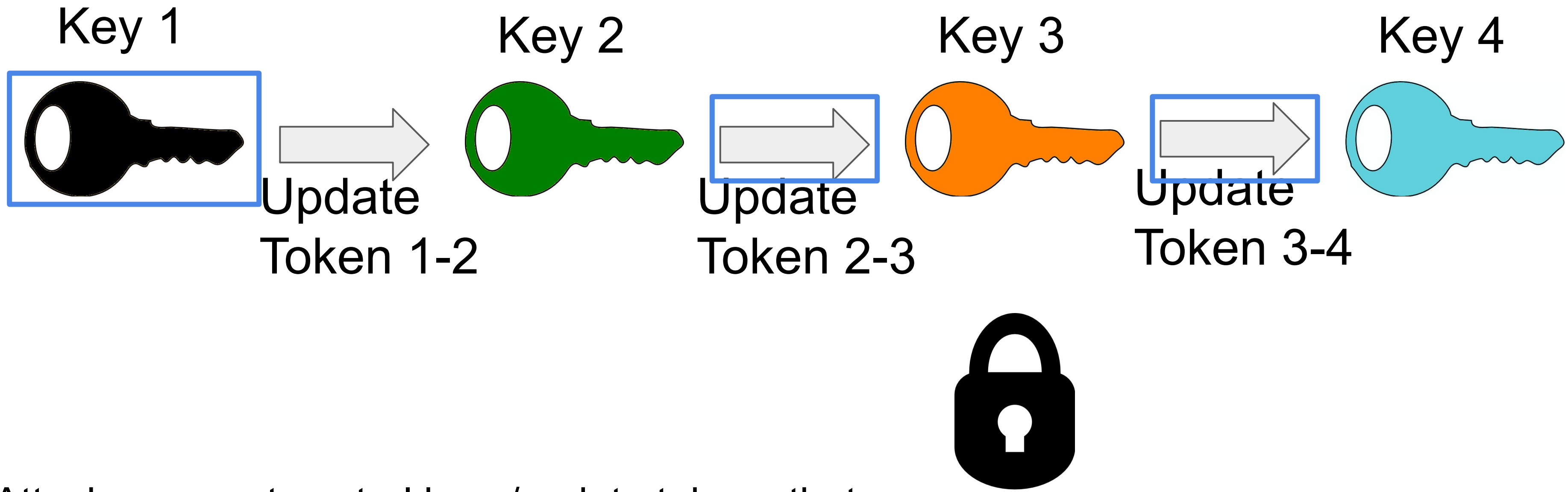

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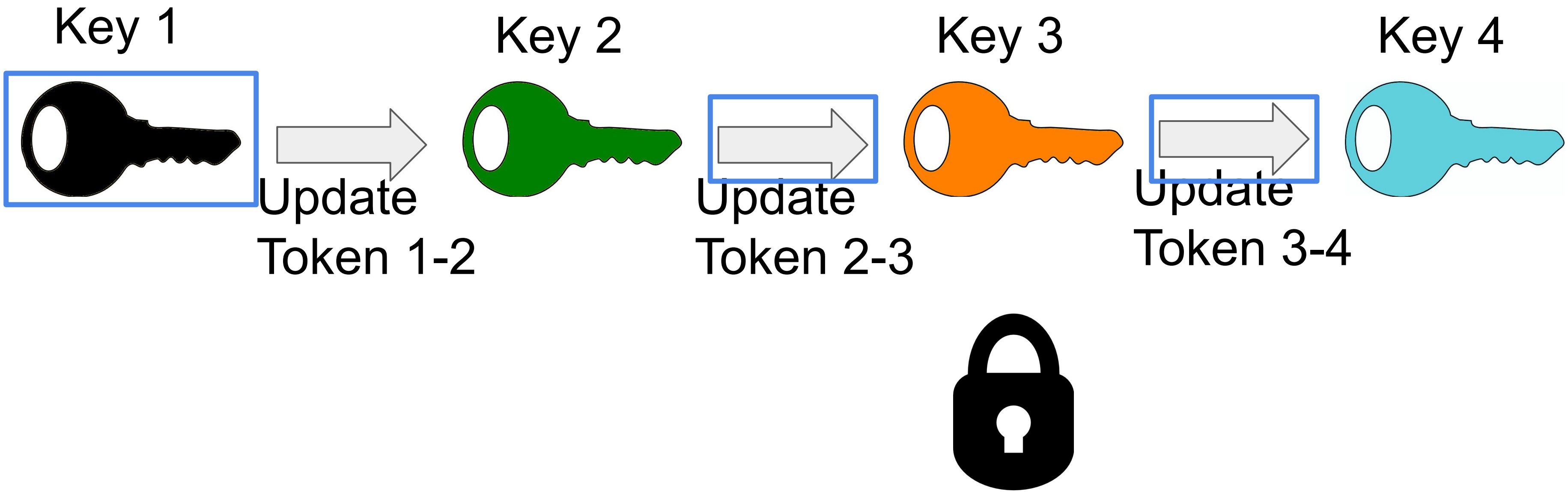
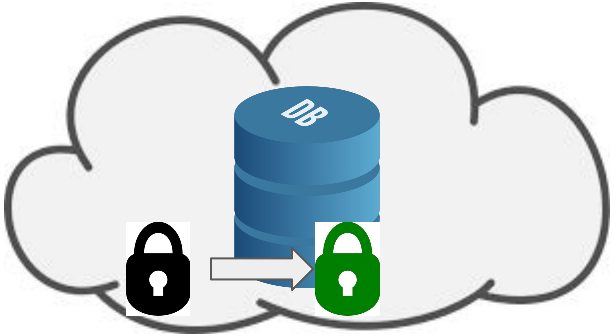
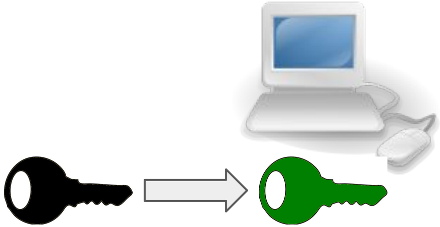


Our definitions additionally require hiding ciphertext age from attacker

Building Updatable Encryption [BLMR13, EPRS17]





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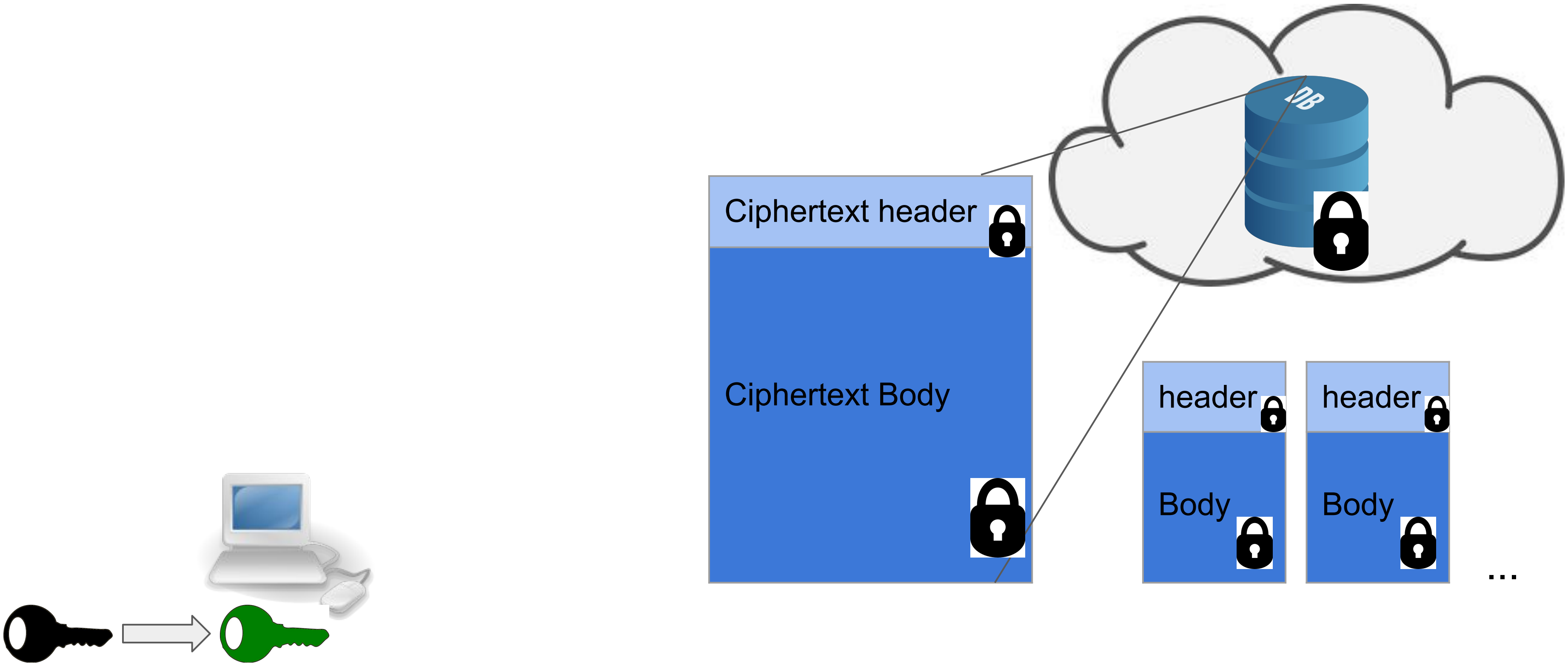

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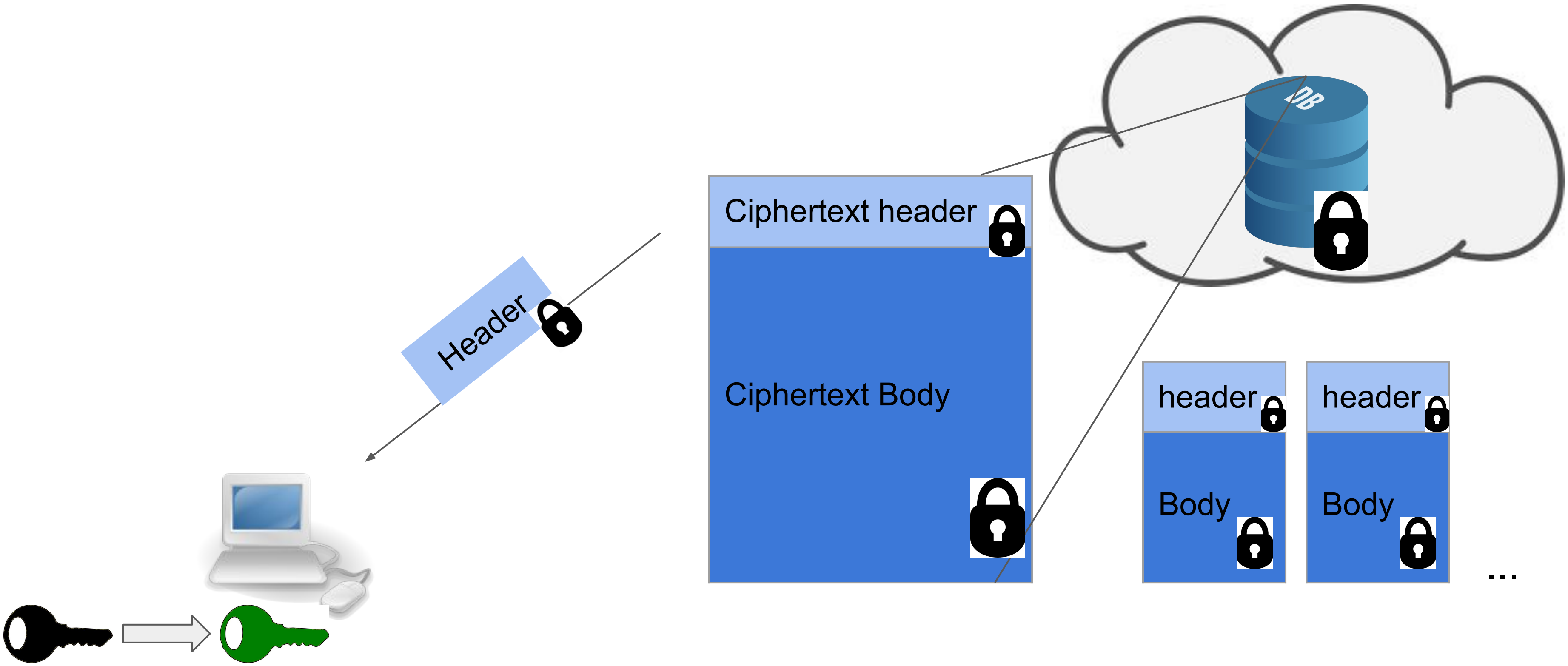

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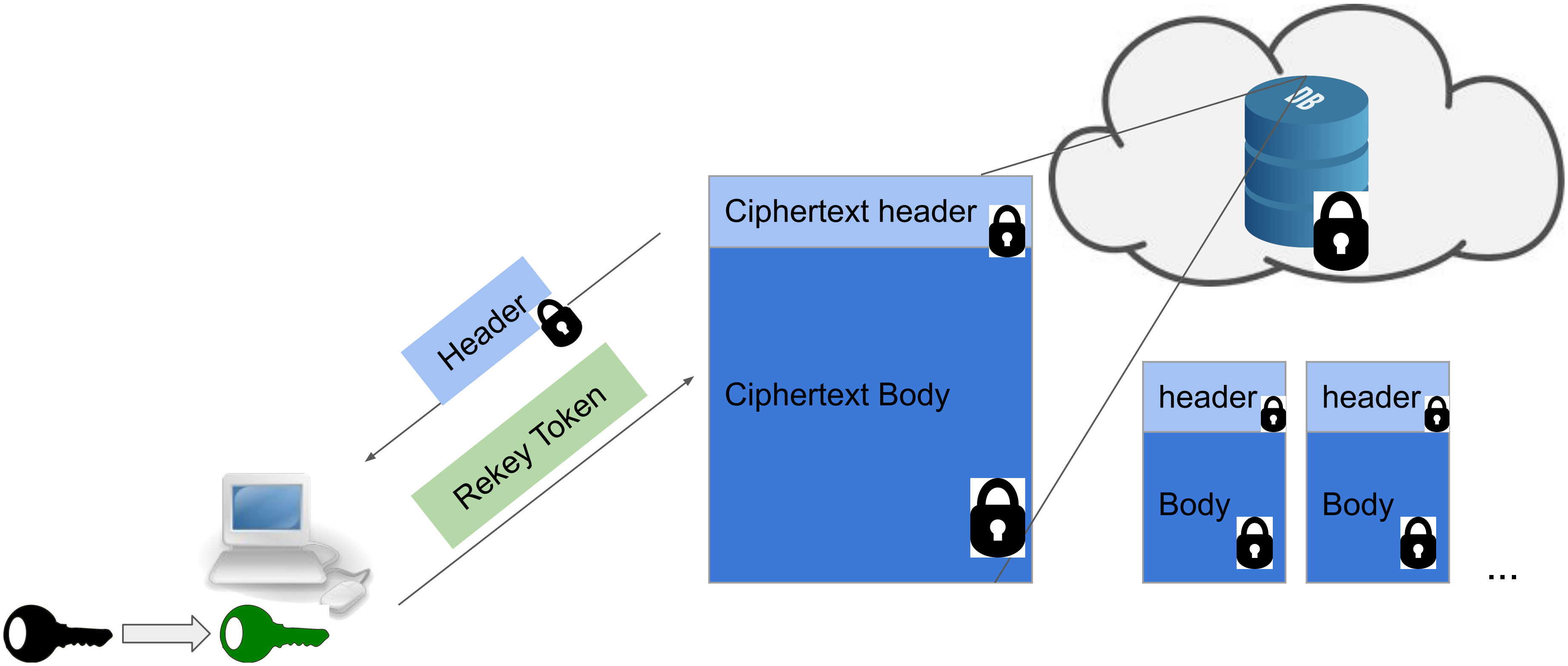

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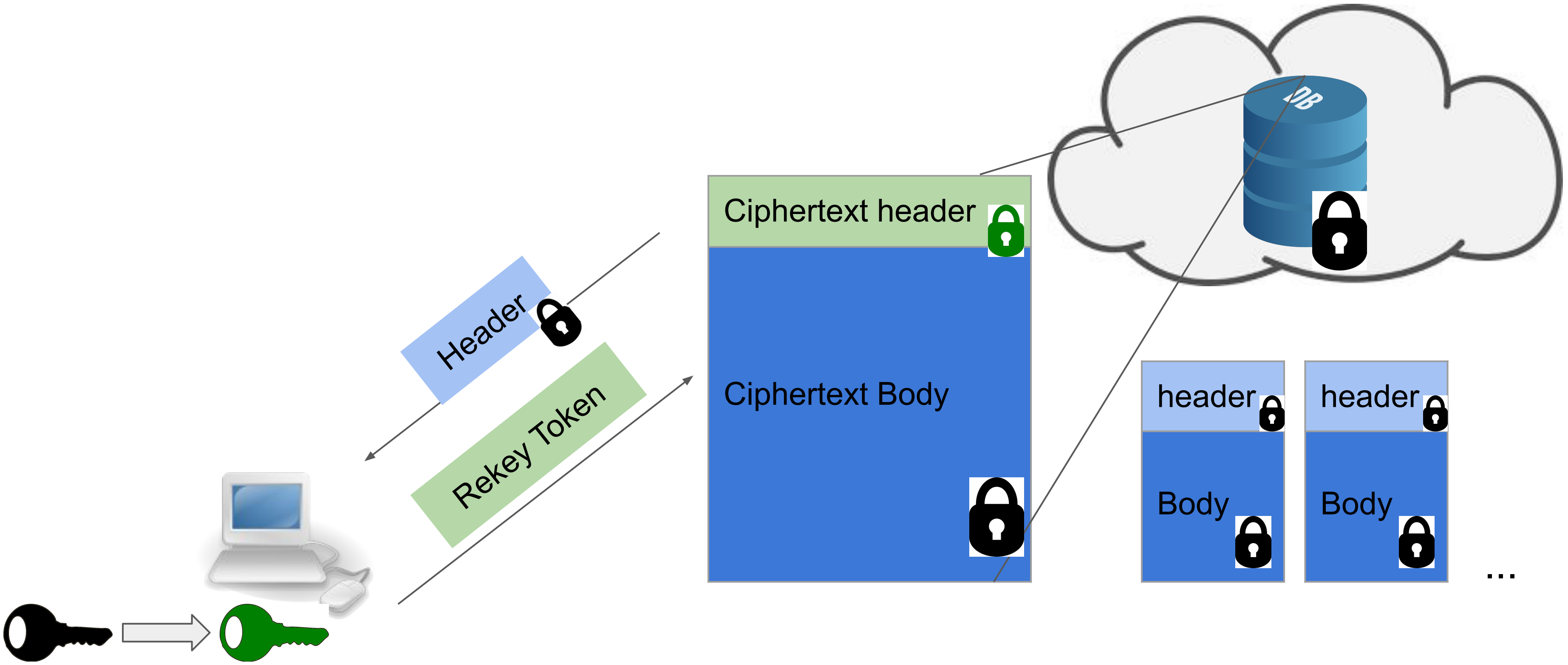

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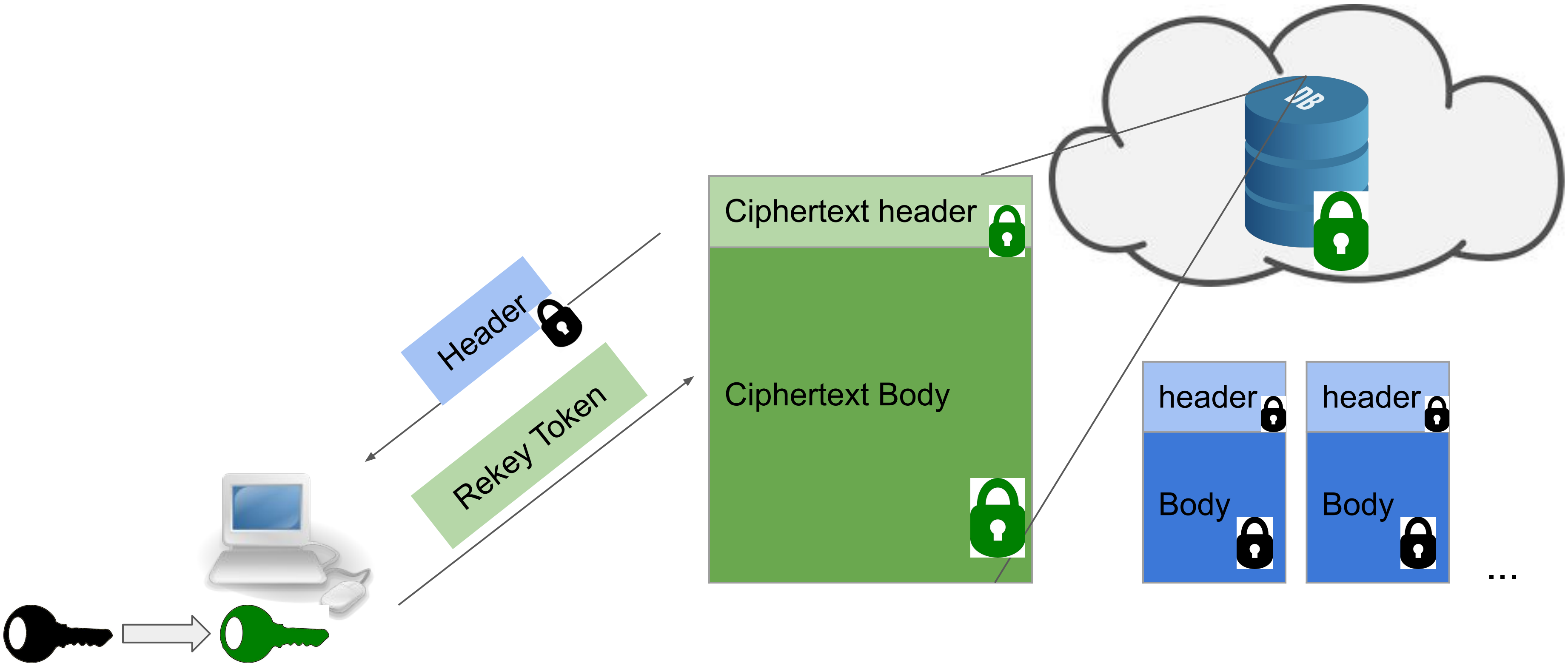

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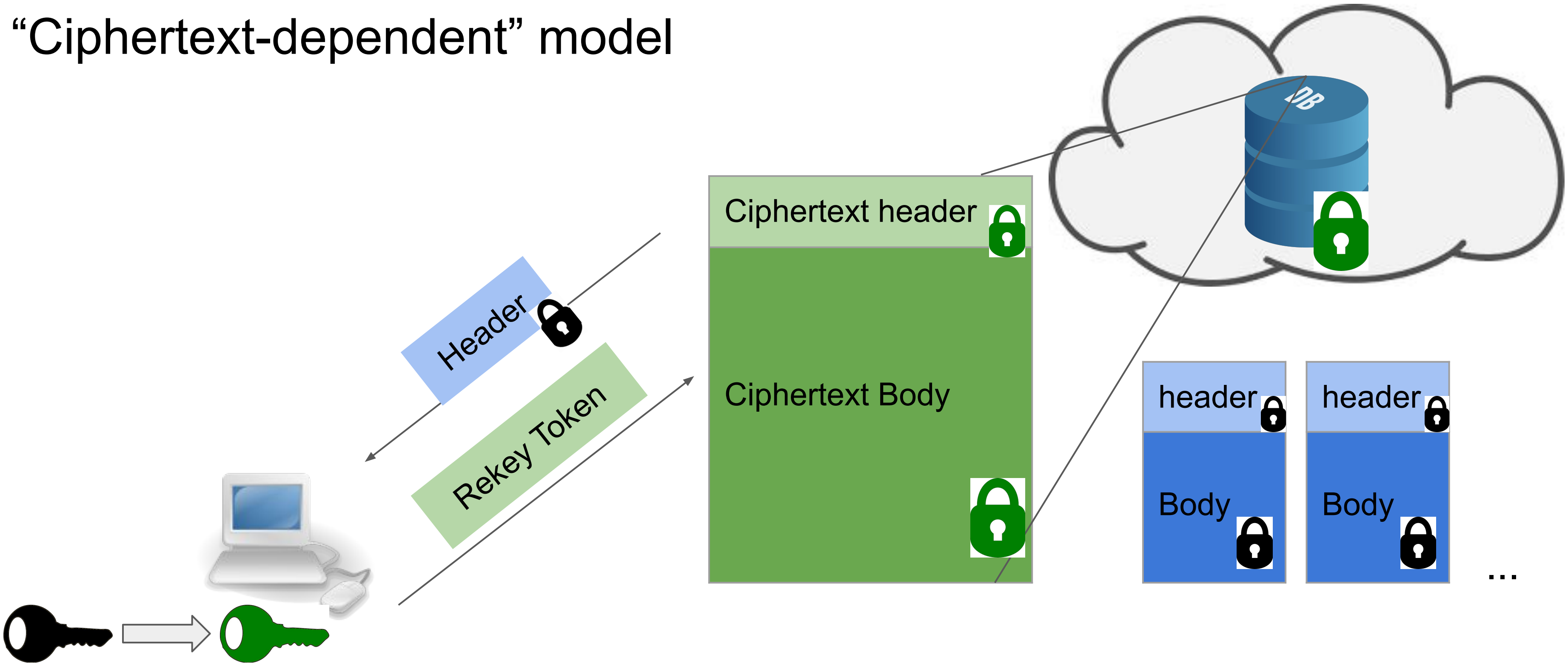
“Ciphertext-dependent” model



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Very fast, simple scheme

Only requires authenticated encryption (AES-GCM) and a PRG

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Caveats:

- Only works for a *bounded* number of re-encryptions, decided at encryption time
- Decryption time will be linear in the number of re-encryptions

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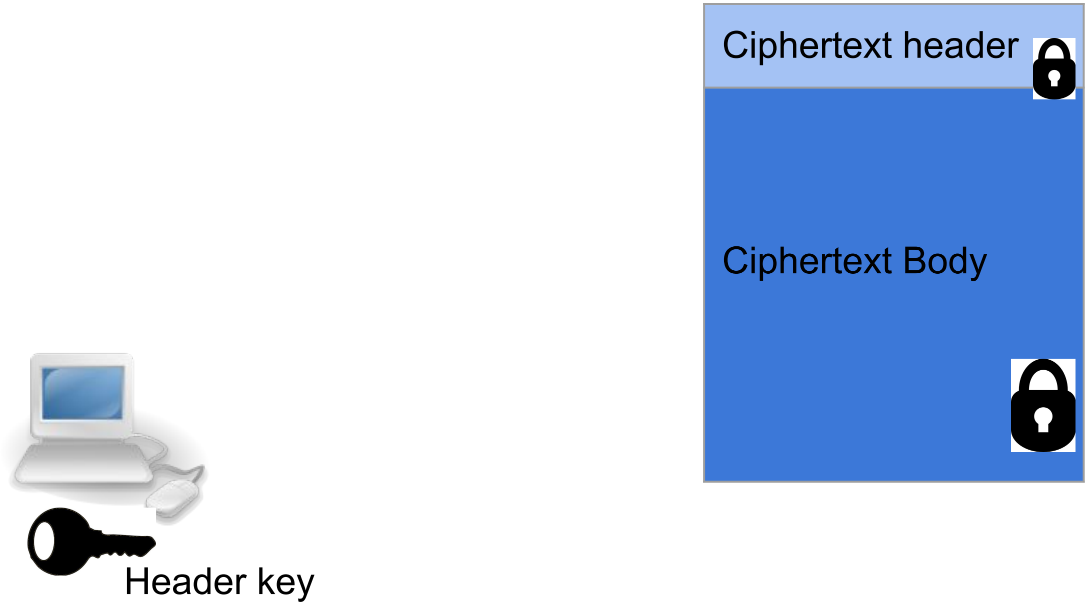

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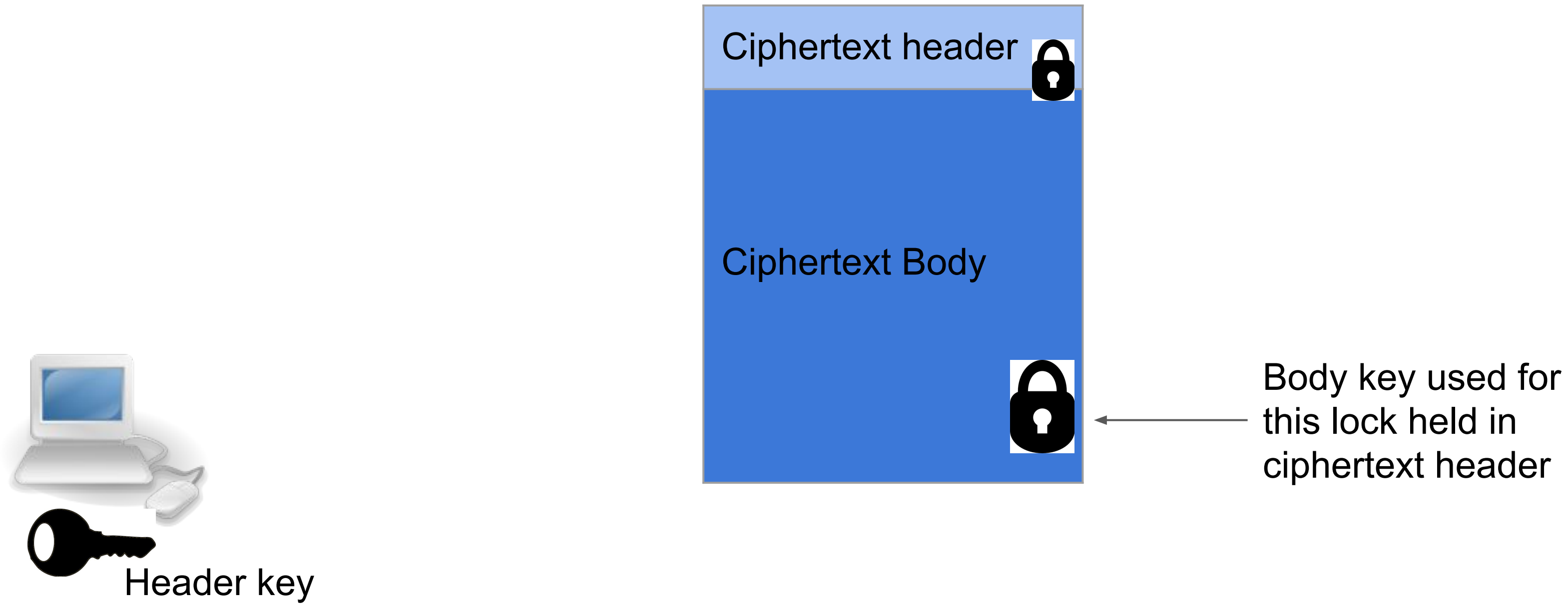

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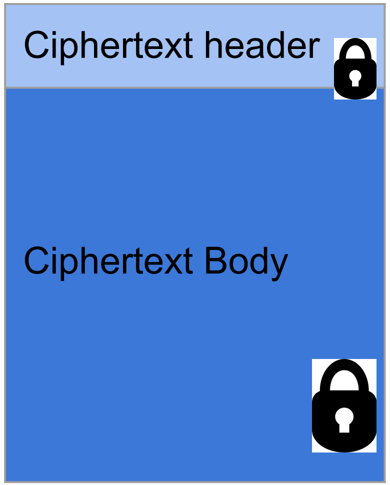

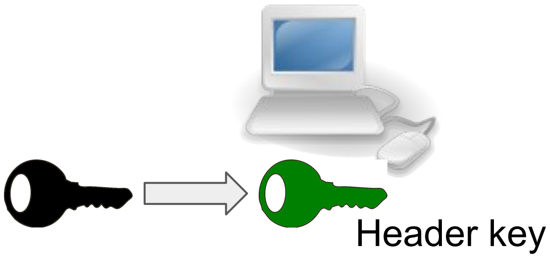

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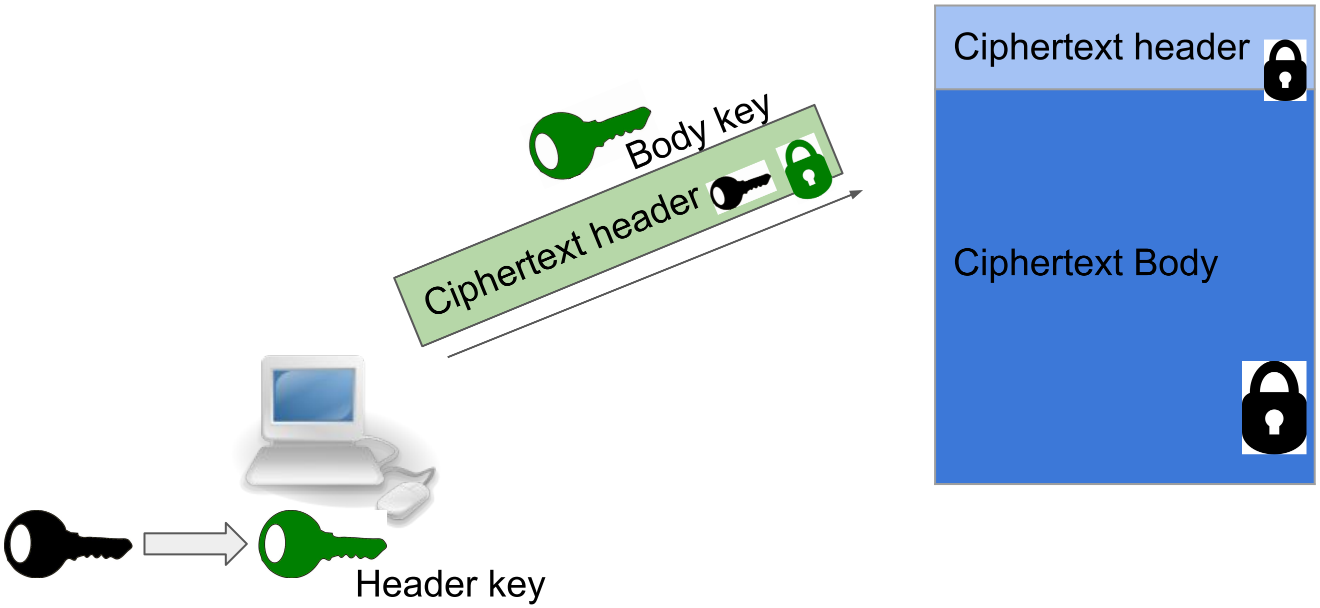

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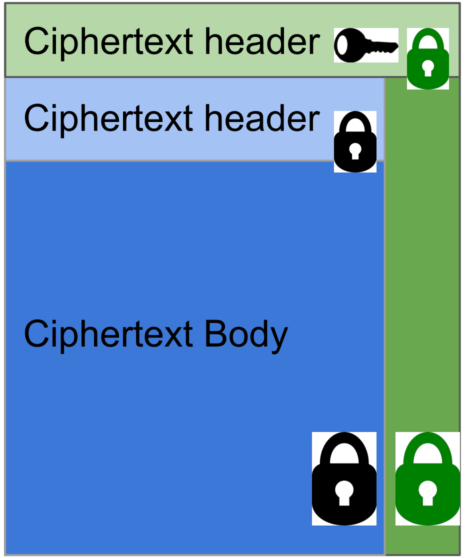

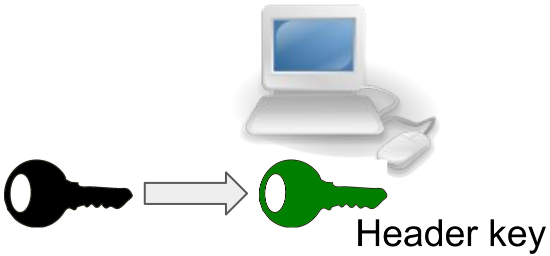

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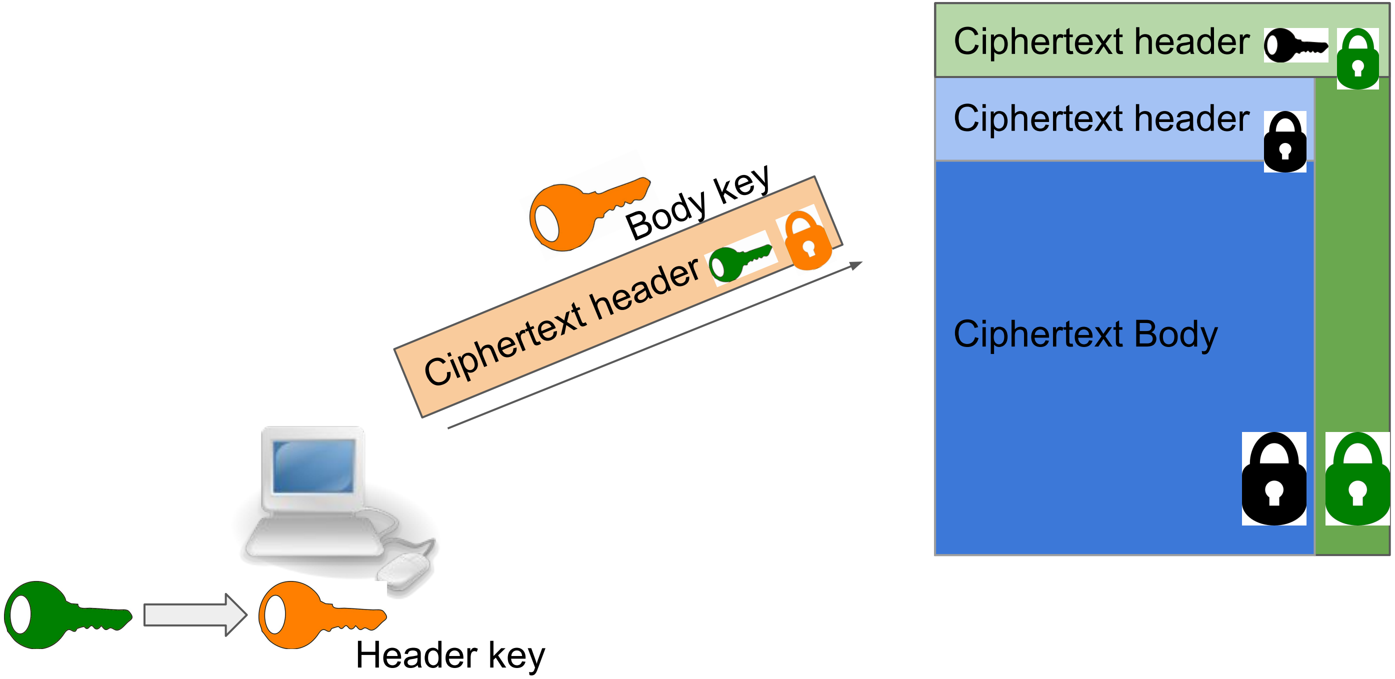

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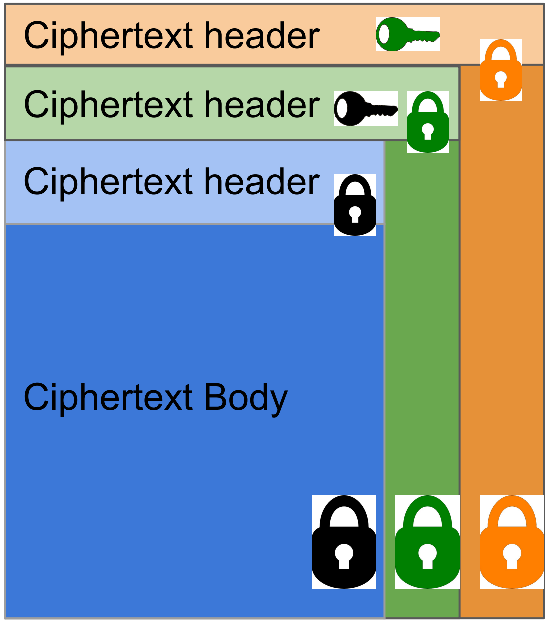

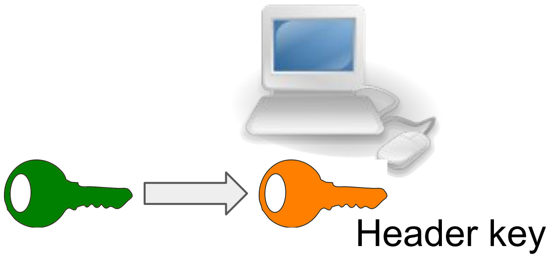

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Re-Encryption: wrap previous layer

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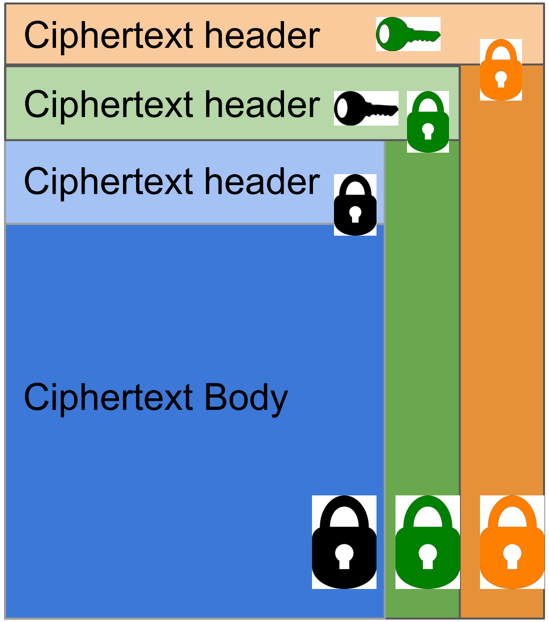

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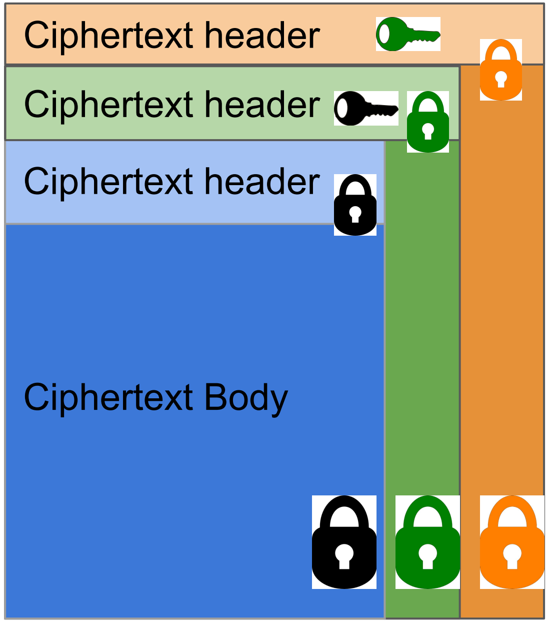

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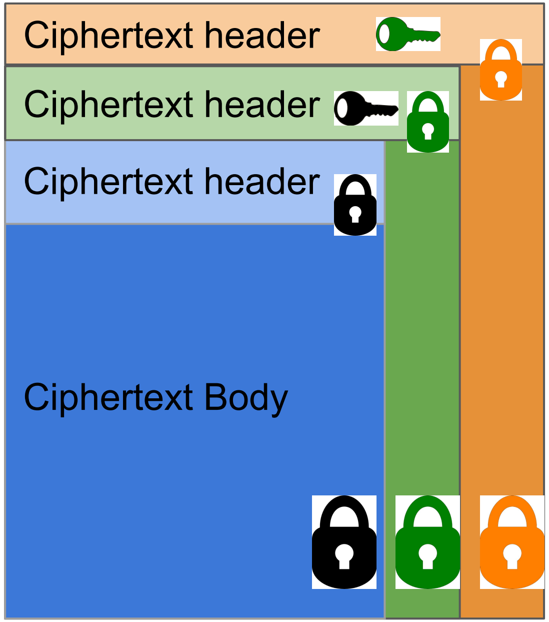

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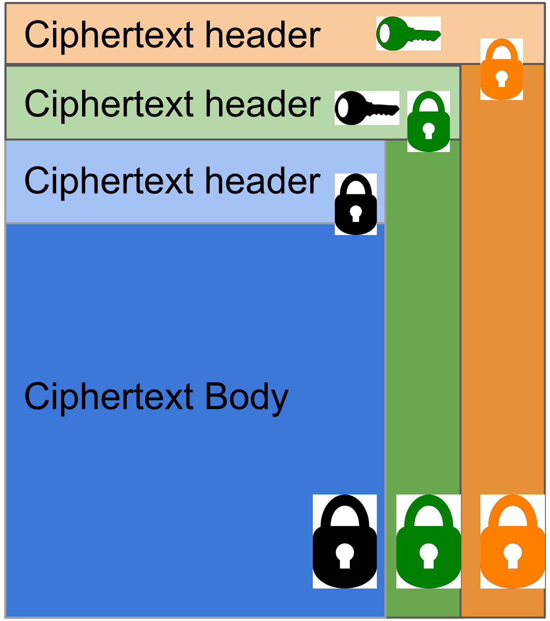

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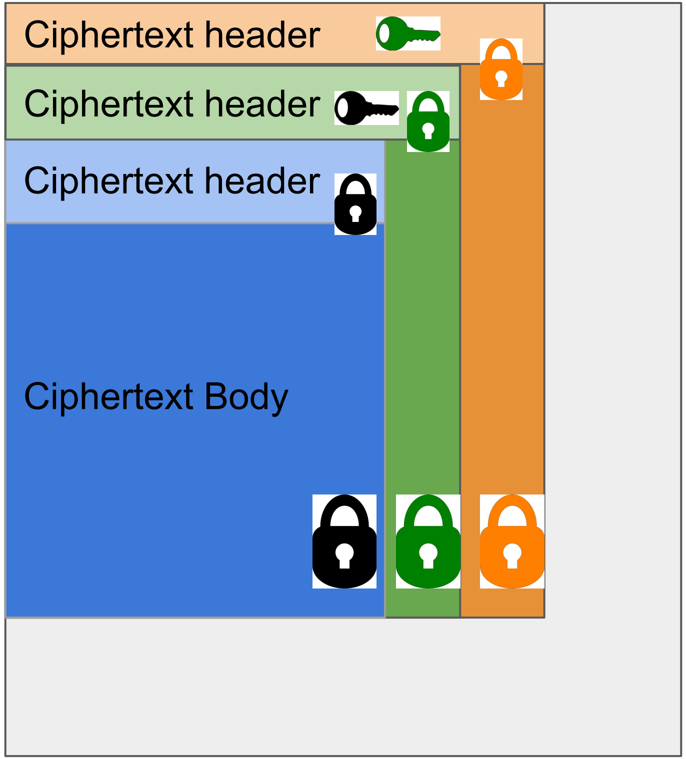

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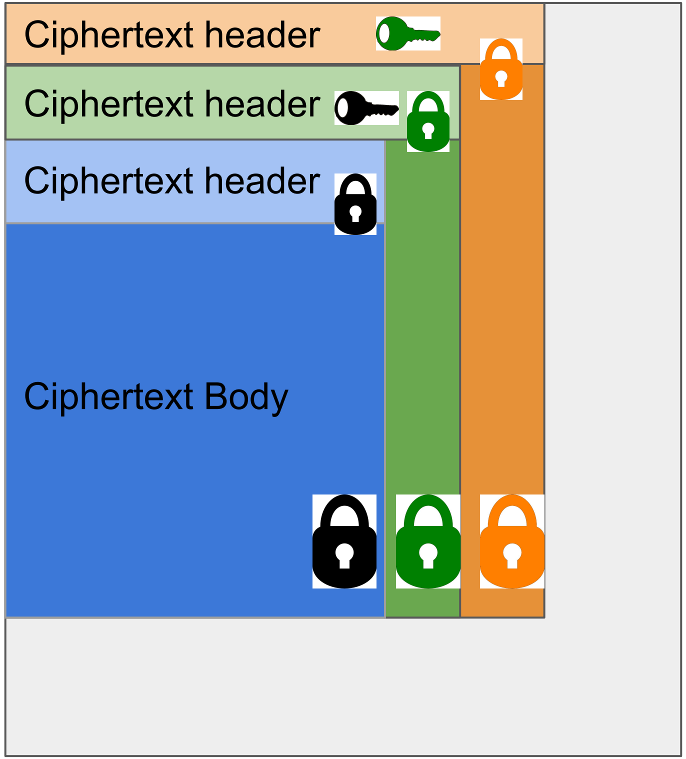

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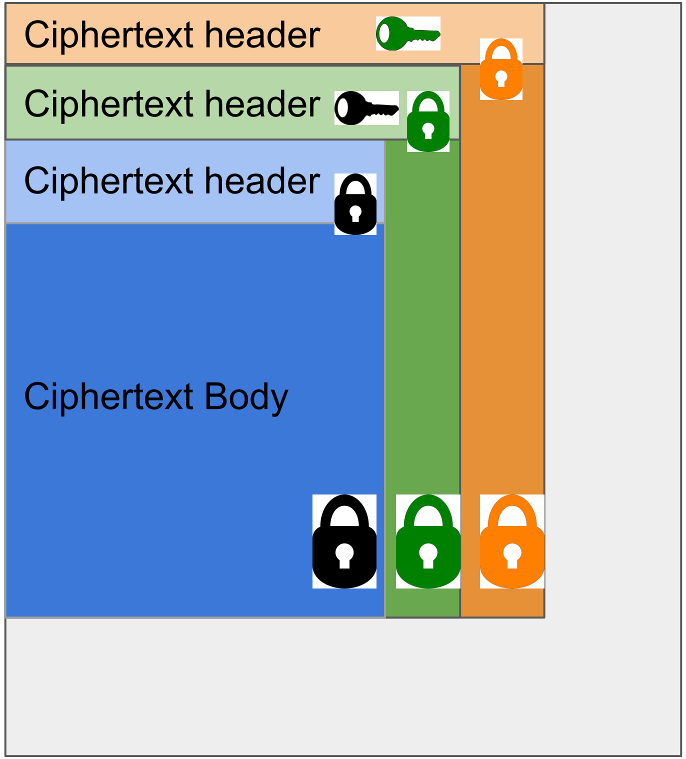

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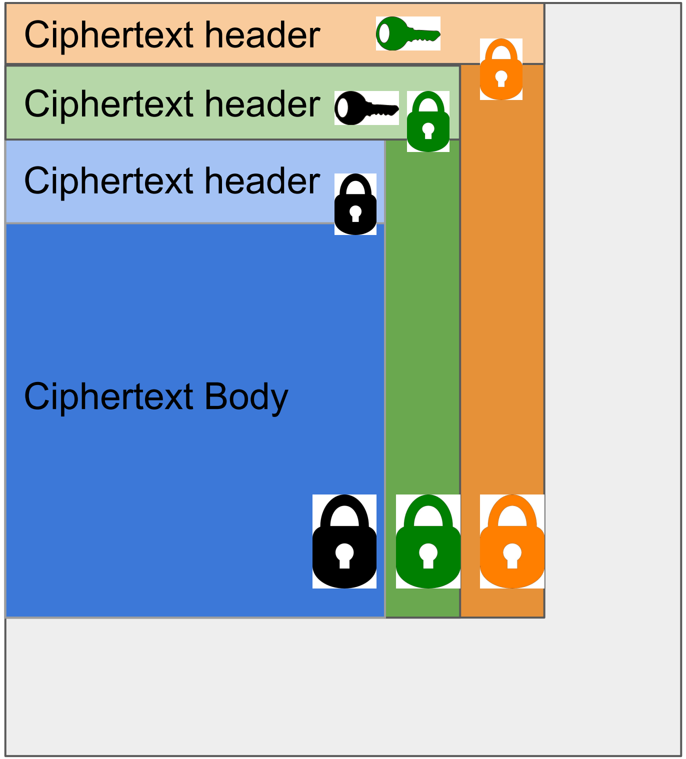
See paper for full scheme



Updatable Encryption from KH-PRFs [BLMR13, EPRS17]

Supports as many re-encryptions as you want

Decryption time does not depend on number of re-encryptions

Still fast, but slower than nested scheme

New caveat: somewhat weaker integrity and age-hiding guarantee

Tool: Key-Homomorphic PRFs (KHPRFs) [NPR99]

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$$F(k_1, x) * F(k_2, x) = H(x)^{k1} * H(x)^{k2} = H(x)^{k1+k2} = F(k_1 + k_2, x)$$

Updatable Encryption from KH-PRFs [EPRS17]

Ciphertext header:

Authenticated Encryption of *H(msg)* and KH-PRF key k_1

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Encryption of msg in counter mode using KH-PRF

$c_0 = m_0 + F(k_1, 0)$
$c_1 = m_1 + F(k_1, 1)$
…
$c_n = m_n + F(k_1, n)$

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Ciphertext body:

Encryption of msg in counter mode using KH-PRF

$c_0 = m_0 + F(k_1, 0)$
$c_1 = m_1 + F(k_1, 1)$
…
$c_n = m_n + F(k_1, n)$

Update process:

1. Download/decrypt header
2. Pick key k_2
3. Upload new header and $k_{up} = k_2 - k_1$

Server updates body encryptions with k_{up}

Updatable Encryption from KH-PRFs [EPRS17]

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Almost KH-PRFs [BLMR13]

EPRS17 uses a KH-PRF based on the DDH assumption*

$$F(k_1, x) + F(k_2, x) = F(k_1 + k_2, x)$$

*In Random Oracle model

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Result: ~500x faster performance

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Result: ~500x faster performance …but how to handle the noise?

*In Random Oracle model

Updatable Encryption from *Almost* KH-PRFs

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Observation: noise is always on low-order bits

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Observation: noise is always on low-order bits

Simple solution: pad low-order bits of each block with zeros

Evaluation

Encryption and Re-encryption

Throughput for encrypting/re-encrypting 32KB messages (MB/sec)

	ReCrypt [EPRS17]	Almost KH-PRF	Nested (128 layers)
Encrypt	0.12	61.90	1836.9
Re-encrypt	0.15	83.06	2606.8

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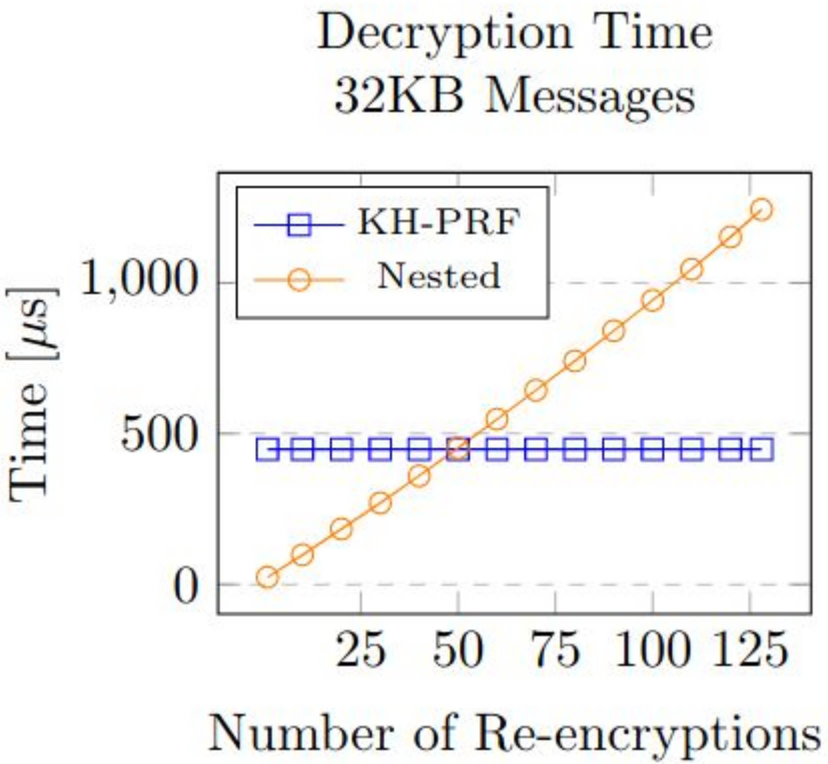
Almost KH-PRF is ~500x faster than ReCrypt

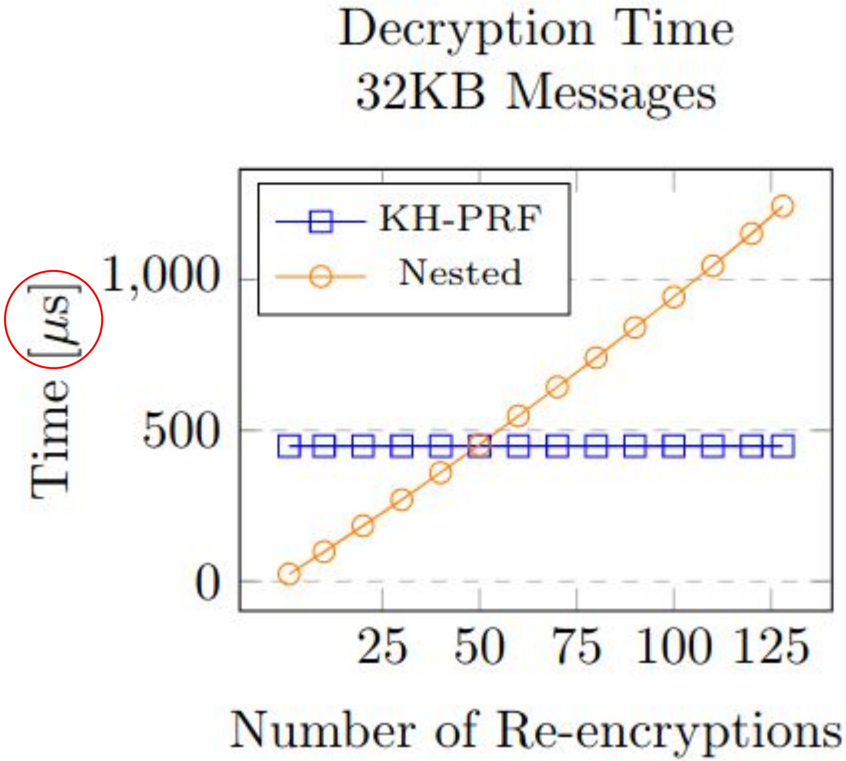
Nested AES is ~30x faster than almost KH-PRF

Decryption



Decryption Time
32KB Messages
KH-PRF
Nested
Time [μs]
1,000
500
0
25
50
75
100
125
Number of Re-encryptions

Decryption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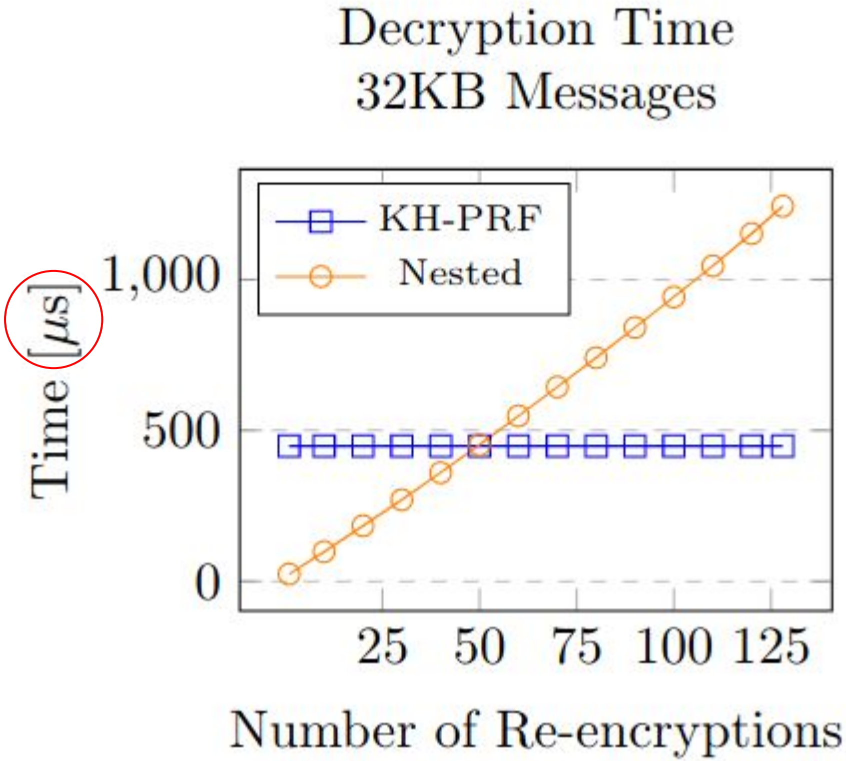
Nested construction faster for up to 50 re-encryptions

ReCrypt (not shown) 500x slower than KH-PRF construction



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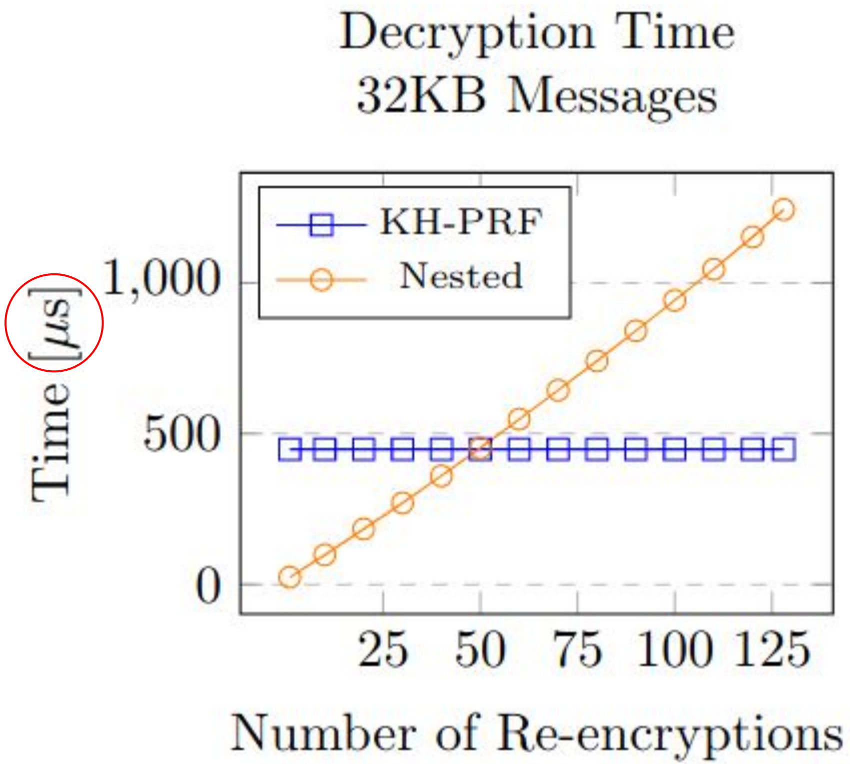
<u>Recommendations</u>
Use nested AES construction for infrequent, routine re-keying

Use KH-PRF for frequent re-keying



Ciphertext Expansion

Nested AES and ReCrypt have smallest ciphertext expansion

Ciphertext Expansion 32KB Messages	
KH-PRF UAE	
$\|q\| = 28$	133%
$\|q\| = 60$	36%
$\|q\| = 120$	20%
$\|q\| = 128$	19%
Nested UAE	
$t = 20$	3%
$t = 128$	19%
ReCrypt [EPRS17]	3%

Ciphertext Expansion

Nested AES and ReCrypt have smallest ciphertext expansion

Recommendations

Use nested AES construction for infrequent, routine re-keying

If space is costly and computation is cheap, use ReCrypt for frequent rekeying

Ciphertext Expansion 32KB Messages	
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Can we do Better?

Speed: Not by much

- Nested scheme: already close to AES throughput
- Almost KH-PRF: KH-PRF implies key exchange [AMP19]

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Speed: Not by much

- Nested scheme: already close to AES throughput
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Ciphertext expansion: Good place for improvement

One potential approach: more elaborate error-correction to reduce bits wasted by padding

Improving Updatable Encryption

Improved security definitions for updatable encryption

Two new constructions -- from Nested AES and RLWE-based KH-PRF

Orders of magnitude performance improvement over prior work

Paper: `eprint.iacr.org/2020/222.pdf`

Source Code: `https://github.com/moshih/UpdateableEncryption_Code`

Contact: `saba@cs.stanford.edu`

Encryption and Re-encryption

Encrypt and ReEncrypt Throughput (MB/sec)

	KH-PRF UAE					ReCrypt	Nested
	$\lvert q\rvert = 28$	$\lvert q\rvert = 28$ (AVX)	$\lvert q\rvert = 60$	$\lvert q\rvert = 120$	$\lvert q\rvert = 128$	[EPRS17]	$t = 128$
4KB Messages							
Encrypt	24.85	**31.97**	20.32	0.76	0.70	0.12	406.69
ReEncrypt	29.80	**41.03**	32.13	0.82	0.74	0.14	706.37
32KB Messages							
Encrypt	29.85	39.89	**61.90**	5.94	5.50	0.12	1836.9
ReEncrypt	32.33	44.51	**83.06**	6.43	5.85	0.15	2606.8
100KB Messages							
Encrypt	31.03	41.63	**65.11**	9.42	9.12	0.12	3029.5
ReEncrypt	33.30	45.77	**79.63**	9.92	8.70	0.14	3766.2

- $H_0 : \{0,1\}^\ell \to \mathcal{R}_q$,
- $H_1 : \mathcal{R}_q \times \{0,1\}^\ell \to \{0,1\}^r$.

We define our pseudorandom function $F : \mathcal{R}_q \times \{0,1\}^\ell \to \mathcal{R}_q$ as follows:

$F(s,x)$:

1. Evaluate $a \leftarrow H_0(x)$, $\rho \leftarrow H_1(s,x)$.
2. Sample $e \leftarrow \mathsf{Samp}_\chi(\rho)$.
3. Output $y \leftarrow a \cdot s + e$.

Where $R_q = Z_q[X]/(X^n+1)$

Confidentiality Security Game [EPRS17]

Adversary

Setup

Send dishonest keys ←

Challenger

Generate *h* “honest keys” and *d* “dishonest keys”

Game

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Encrypt

Encrypt message *m* under key *i* →

Enc(k_i, m) ←

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Encrypt message m under key i →

$\mathrm{Enc}(k_i, m)$ ←

Challenge

Encrypt message m_0 or m_1 under honest key i →

$\mathrm{Enc}(k_i, m_b)$ ←

Guess b →

Adversary wins if it guesses b correctly.
A scheme is secure if the adversary has negligible advantage in guessing b.

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Game

Encrypt

Get update token to Re-encrypt ciphertext *c* from key *i* to key *j*

Update Token

Rekey

Update ciphertext *c* from key *i* to key *j*

Re-encrypted Ciphertext

Challenge

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Challenger

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Game

Encrypt

Rekey

Challenger rejects any query that results in a “trivial win”
e.g., update challenge ciphertext from key *i* to a dishonest key

Challenge

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Confidentiality Security Game**s** [EPRS17]

Challenge

Confidentiality Security Game**s** [EPRS17]

Challenge

Encrypt message m_0 or m_1
under honest key i

→

Enc(k_i, m_b)

←

Guess b

→

Confidentiality Security Game**s** [EPRS17]

Challenge

Encrypt message m_0 or m_1 under honest key i →

← Enc(k_i, m_b)

Guess b →

Re-encrypt ciphertext c_0 or c_1 from key i to honest key j →

← Re-encrypted ciphertext

Guess b →

Confidentiality Security Games [EPRS17]

Challenge

Encrypt message m_0 or m_1 under honest key i

Enc(k_i, m_b)

Guess b

Re-encrypt ciphertext c_0 or c_1 from key i to honest key j

Re-encrypted ciphertext

Guess b

Prior definitions permit leaking both whether and how many times a ciphertext has been re-encrypted.

A Unified Confidentiality Definition

Encrypt message m_0 or m_1
under honest key i

Enc(k_i, m_b)

Guess b

Re-encrypt ciphertext c_0 or c_1
from key i to honest key j

Re-encrypted ciphertext

Guess b

Encrypt message m_0 under honest key j
OR Re-encrypt ciphertext c_1 from key i to honest key j

Fresh ciphertext or re-encrypted ciphertext

Guess b

A Unified Confidentiality Definition

Encrypt message m_0 or m_1 under honest key i →

← $Enc(k_i, m_b)$

Guess b →

Re-encrypt ciphertext c_0 or c_1 from key i to honest key j →

← Re-encrypted ciphertext

Guess b →

Encrypt message m_0 under honest key j
OR Re-encrypt ciphertext c_1 from key i to honest key j →

← Fresh ciphertext or re-encrypted ciphertext

Guess b →

See paper for details