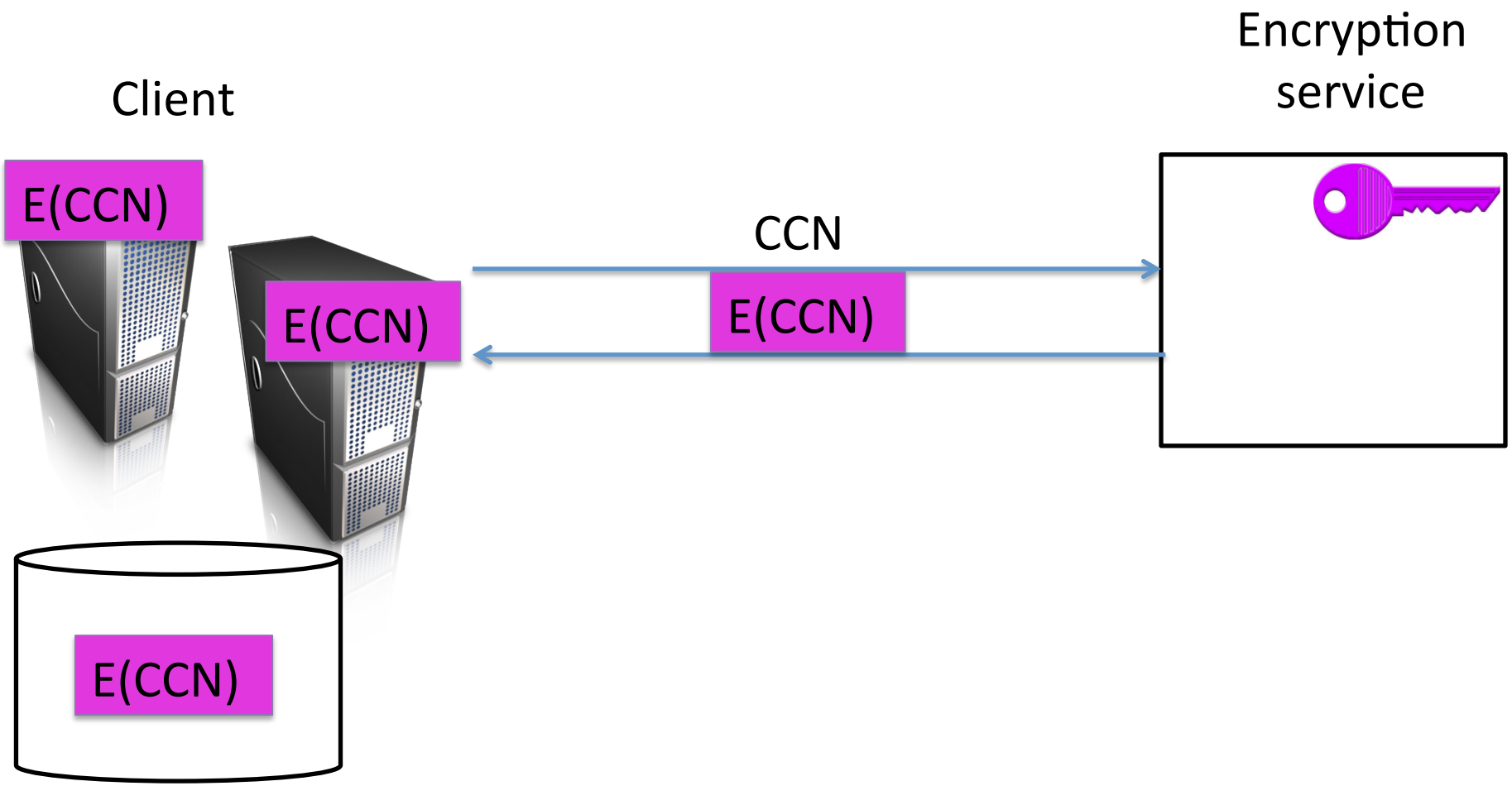
Modifying an Enciphering Scheme after Deployment

Paul Grubbs, Thomas Ristenpart, Yuval Yarom

Format-Preserving Encryption (FPE)



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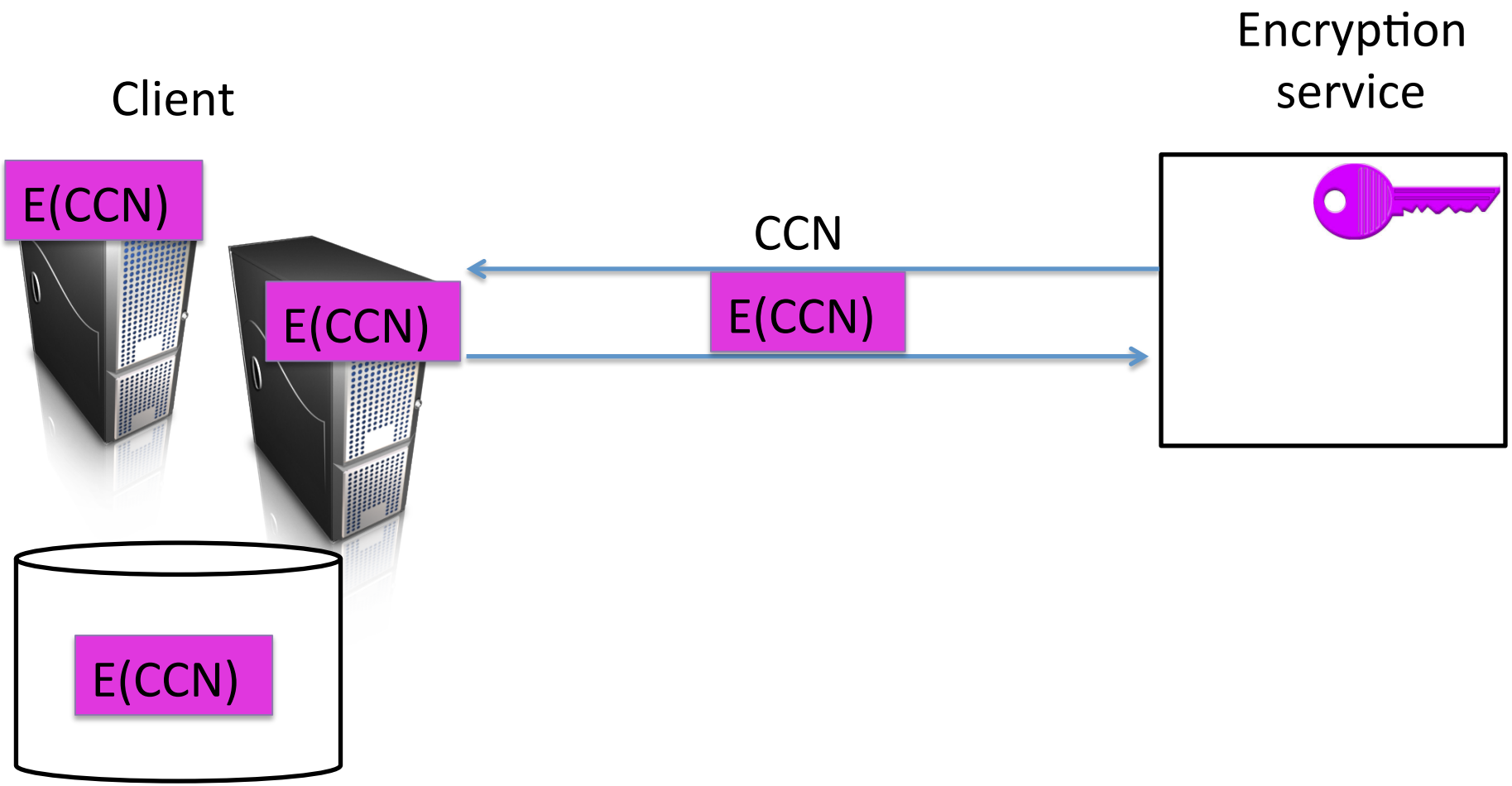
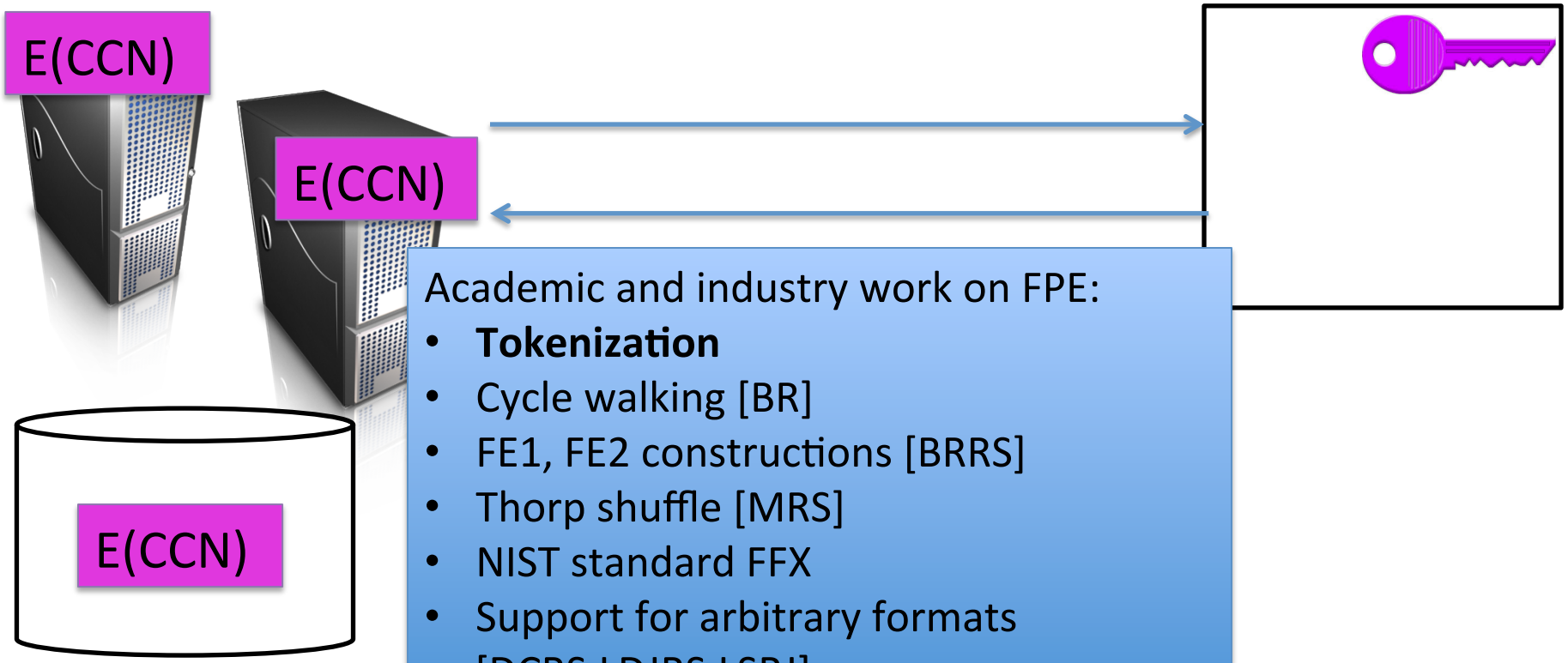


Format-Preserving Encryption (FPE)

This work:
Backwards-compatible FPE

Client

Encryption service



Academic and industry work on FPE:

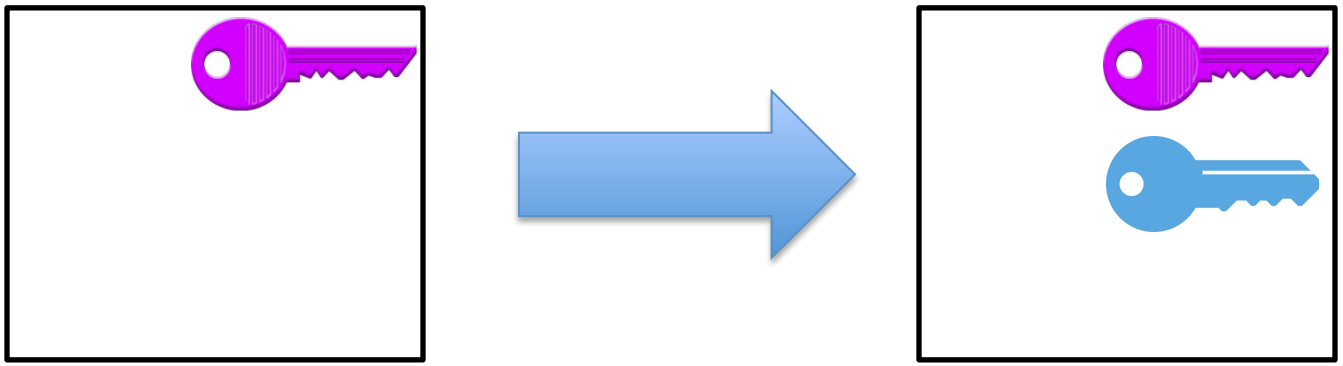
- **Tokenization**
- Cycle walking [BR]
- FE1, FE2 constructions [BRRS]
- Thorp shuffle [MRS]
- NIST standard FFX
- Support for arbitrary formats [DCRS,LDJRS,LSRJ]

Format-Preserving Encryption (FPE)

This work:
Backwards-compatible FPE

Encryption service

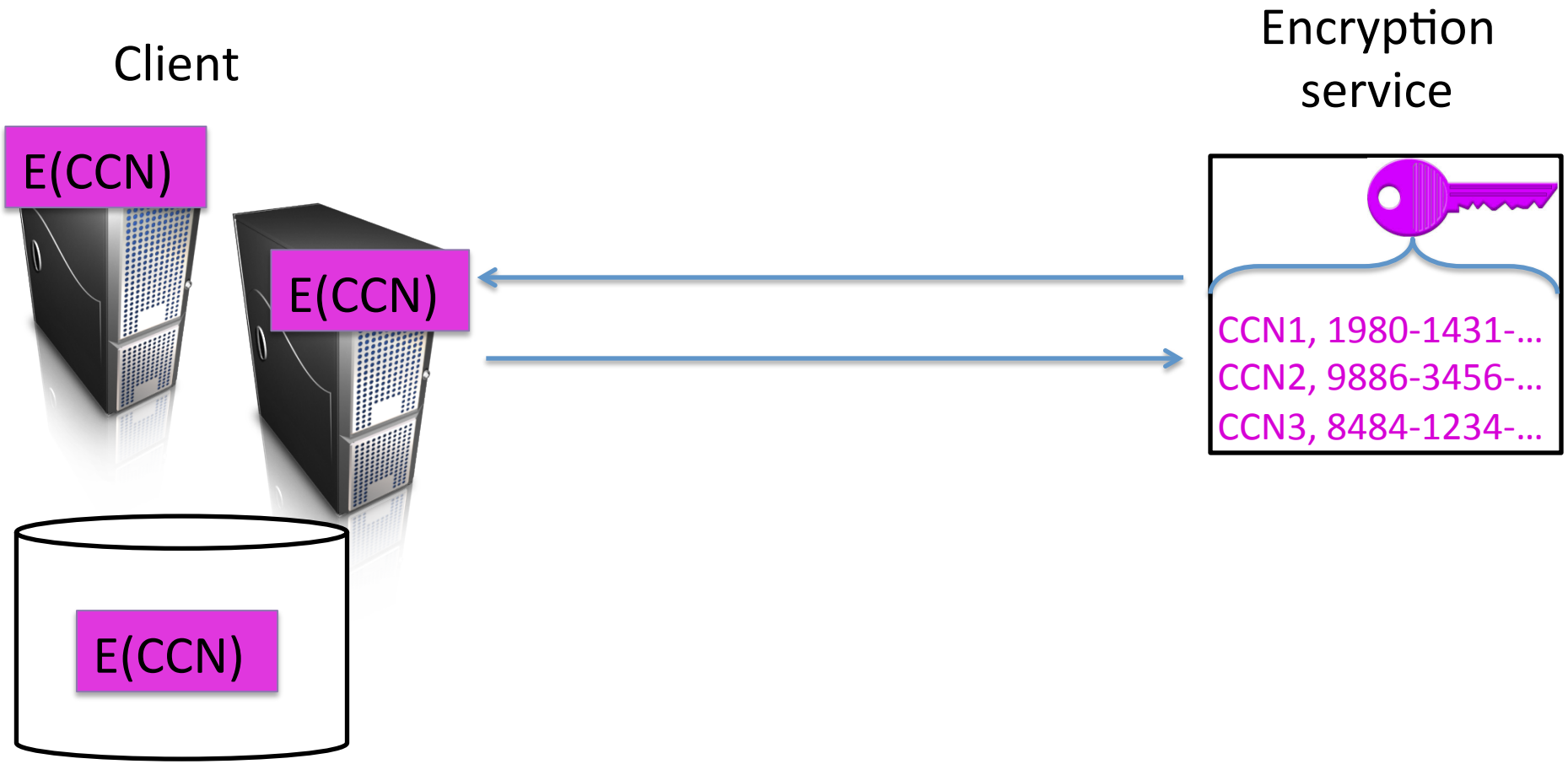
New encryption service



- Includes new features
- Decrypts old ciphertexts properly
- Not just key rotation, FPE scheme changes

Example: Upgrading from tokenization

Tokenization: implement FPE using look-up table of random ciphertexts
(encryption key is the table)



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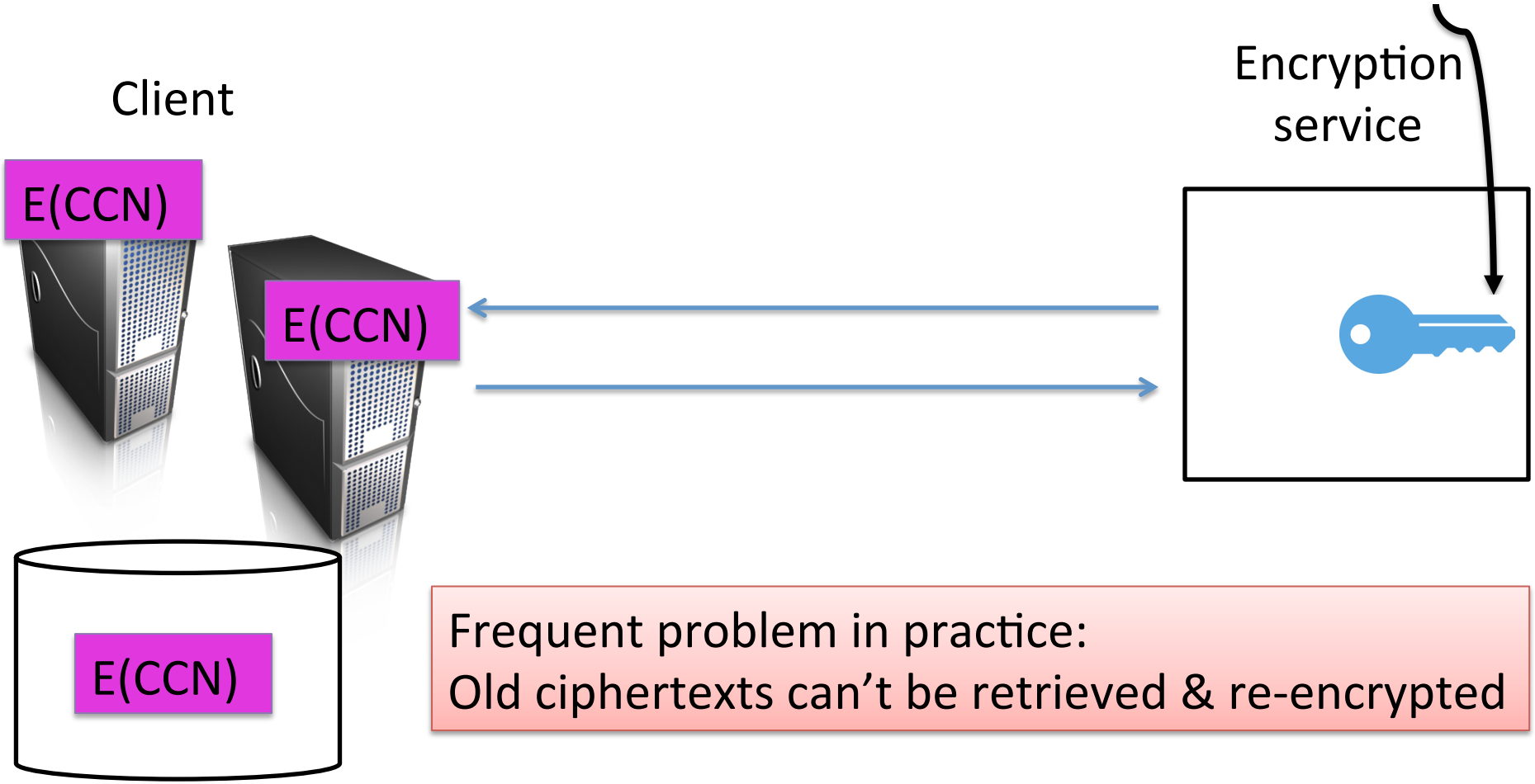

Frequent problem in practice:
Old ciphertexts can't be retrieved & re-encrypted

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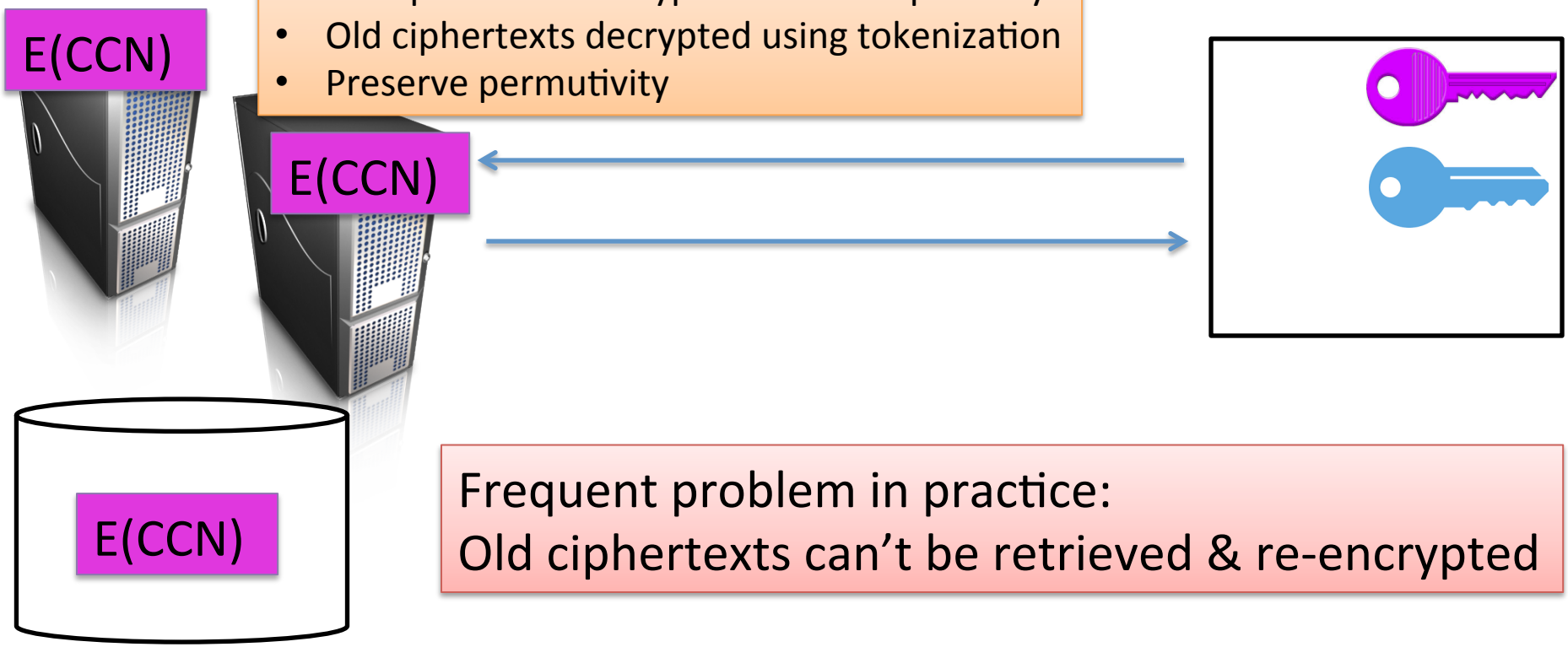
Need a backwards-compatible FPE:

- New plaintexts encrypted with compact key
- Old ciphertexts decrypted using tokenization
- Preserve permutivity

Encryption service



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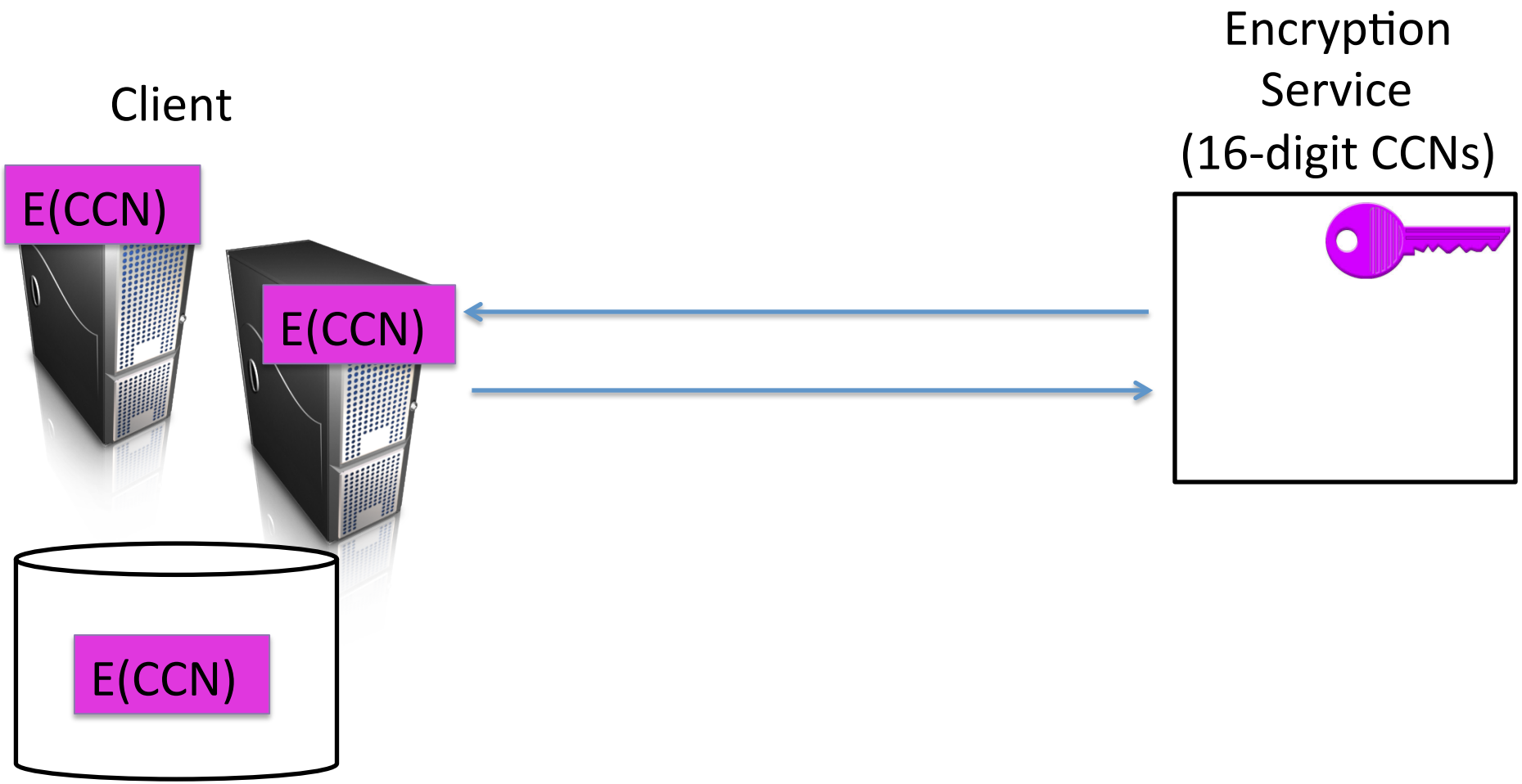
Example: Expanding format

Problem: deployed with one format in mind (e.g., just 16 digit CCN's)
but need to support others as well (e.g., also 15 digit CCN's)



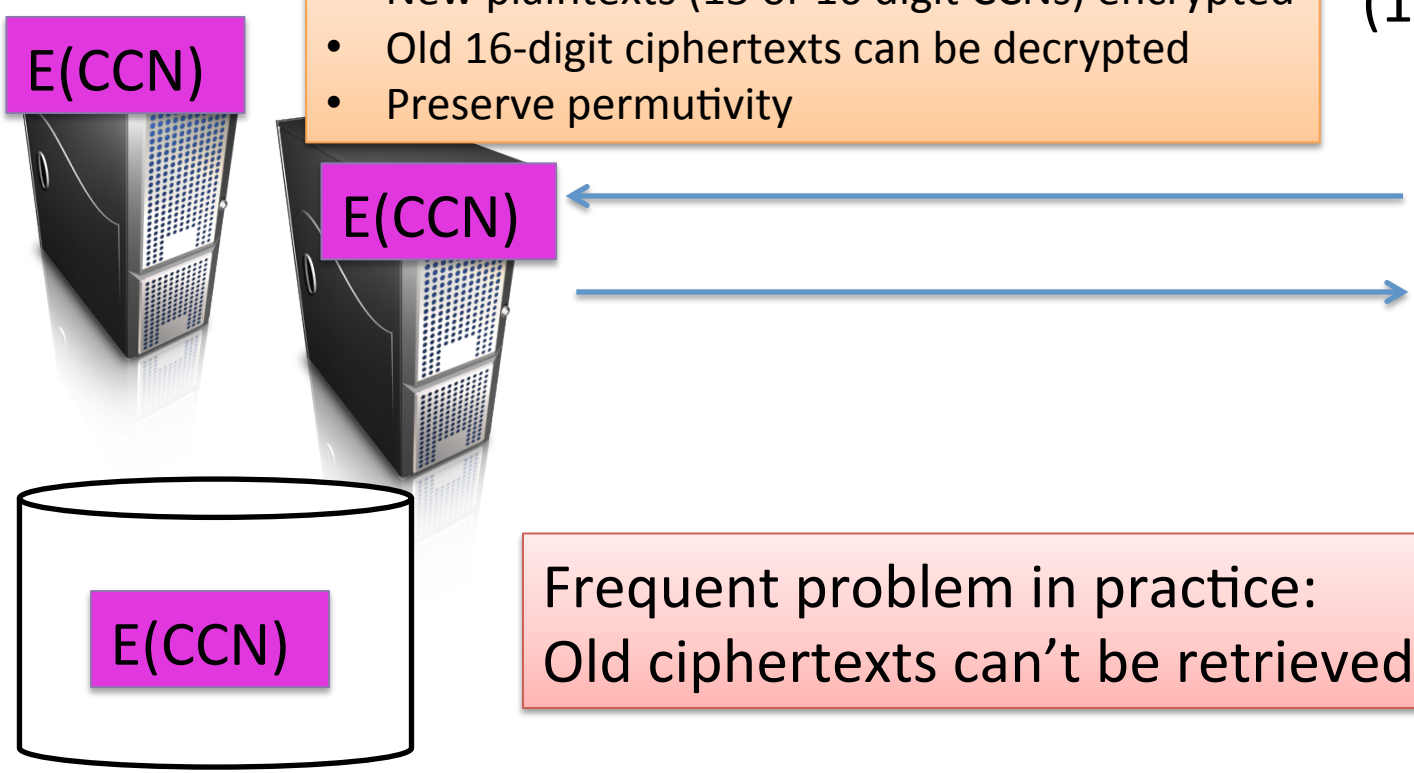
Example: Expanding format

Problem: deployed with one format in mind (e.g., just 16 digit CCN's)
but need to support others as well (e.g., also 15 digit CCN's)

Client

Need a backwards-compatible FPE:

- New plaintexts (15 or 16 digit CCNs) encrypted
- Old 16-digit ciphertexts can be decrypted
- Preserve permutivity



Encryption Service (15- & 16-digit CCNs)

Frequent problem in practice:
Old ciphertexts can't be retrieved & re-encrypted

Our contributions

Give generic algorithm (Zig-Zag) for backwards-compatible FPE

Domain completion (tokenization upgrade example)

- Prove “natural” security
- Analyze runtime

Domain extension (expanding format example)

- “Natural” security is impossible
- Give new security goal, analyze

Domain completion (formally)

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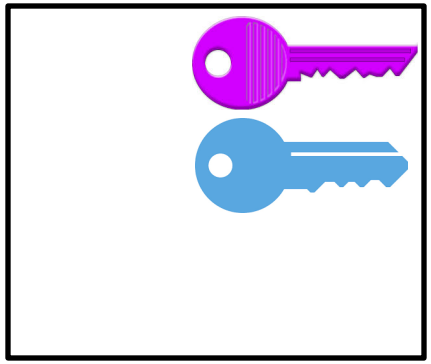


An FPE scheme FPE_k : D -> D with key K is a permutation of D for every K

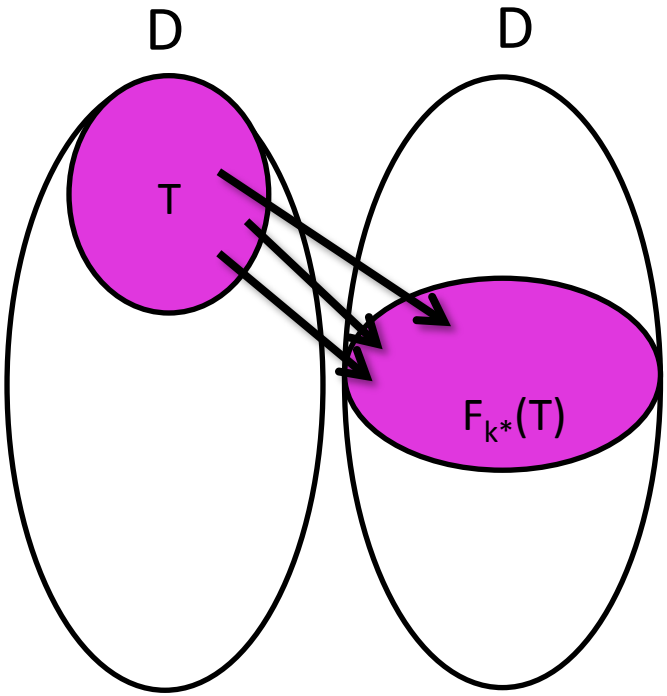
Call old FPE (partial permutation) F_{k*} : D ⇀ D and T = Dom(F_{k*}).

Need new FPE $ZZ_{k'}$: D -> D so that

$\forall t \in T, ZZ_{k'}(t) = F_{k*}(t)$

Security goal is

Strong Pseudorandom Permutation: indistinguishable from random permutation **even if adversary knows T**



The obvious approach doesn't work

What about simply using a tokenization scheme and a new FPE in parallel?

= table Tok[ ] (F_{k*})

= FFX E with secret key K

Encrypt((Tok[], K) , M):

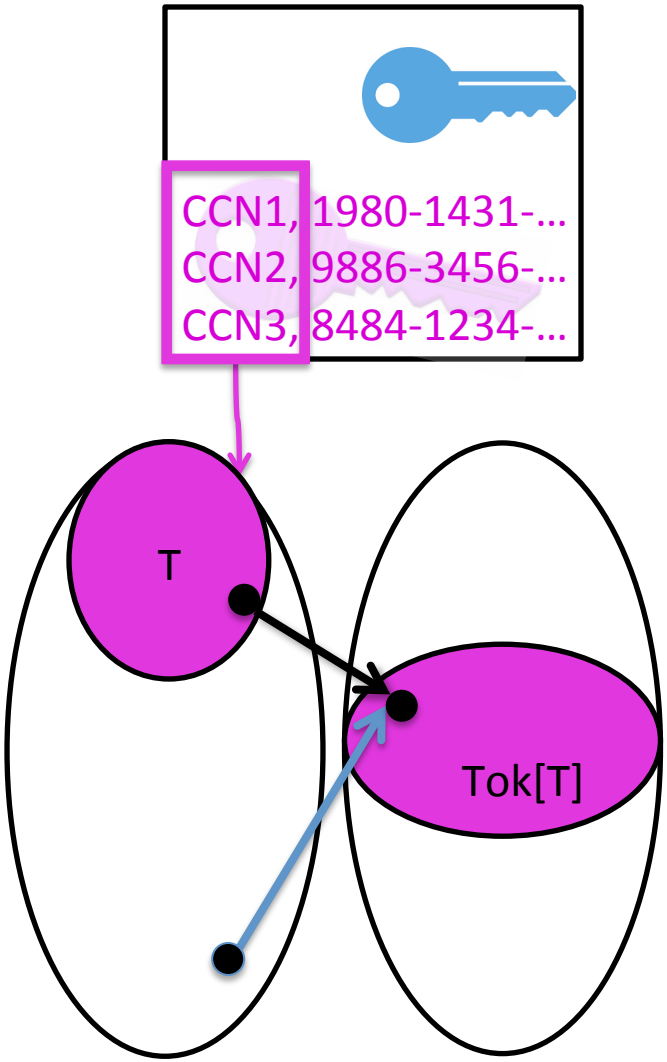
If M in T then:

Return Tok[M]

Else:

Return $E_K(M)$

This doesn't define a permutation for every (T,K)!



The Zig-Zag Construction

Uses a form of cycle walking to ``repair'' permutation on colliding points

= table Tok[ ] (F_{k*})

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Encrypt((Tok[], K) , M):

If M in T then:

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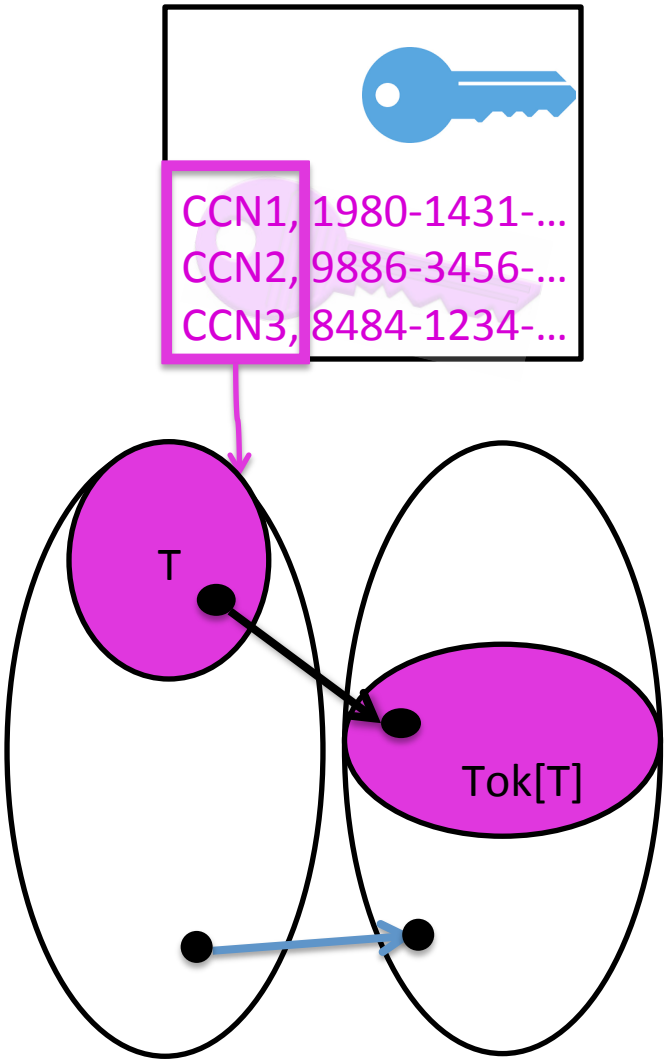
$C = E_K(M)$

while ($Tok^{-1}[C]$!= null):

Return C



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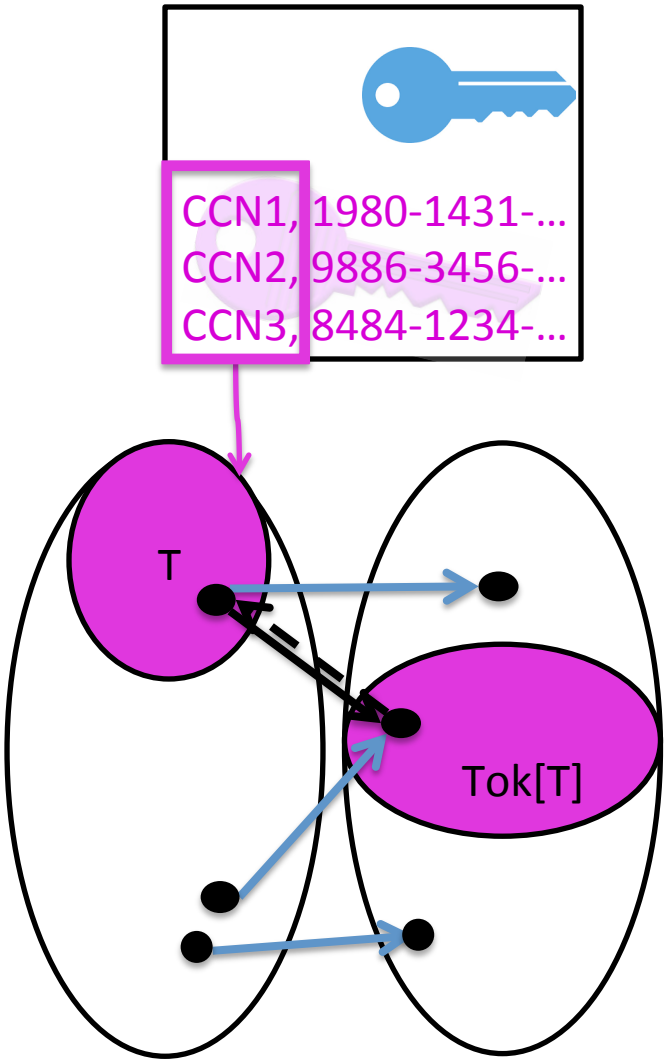
        M' = Tok^{-1}[C]

        C = E_K(M')

    Return C



Zig-Zag analysis

<u>Theorem (informal)</u>: If |T| <= |D|/2, the Zig-Zag algorithm runs in amortized constant time, except with negligible probability

Key intuition: With random permutations, can use hypergeometric tail bound to upper-bound drawing many collisions in a row.

<u>Theorem (informal)</u>: The Zig-Zag algorithm is as secure as the underlying permutations (E) even if the adversary knows T

Domain extension (formally)

Need a backwards-compatible FPE:

- New plaintexts (15 or 16 digit CCNs) encrypted
- Old 16-digit ciphertexts can be decrypted
- Preserve permutivity

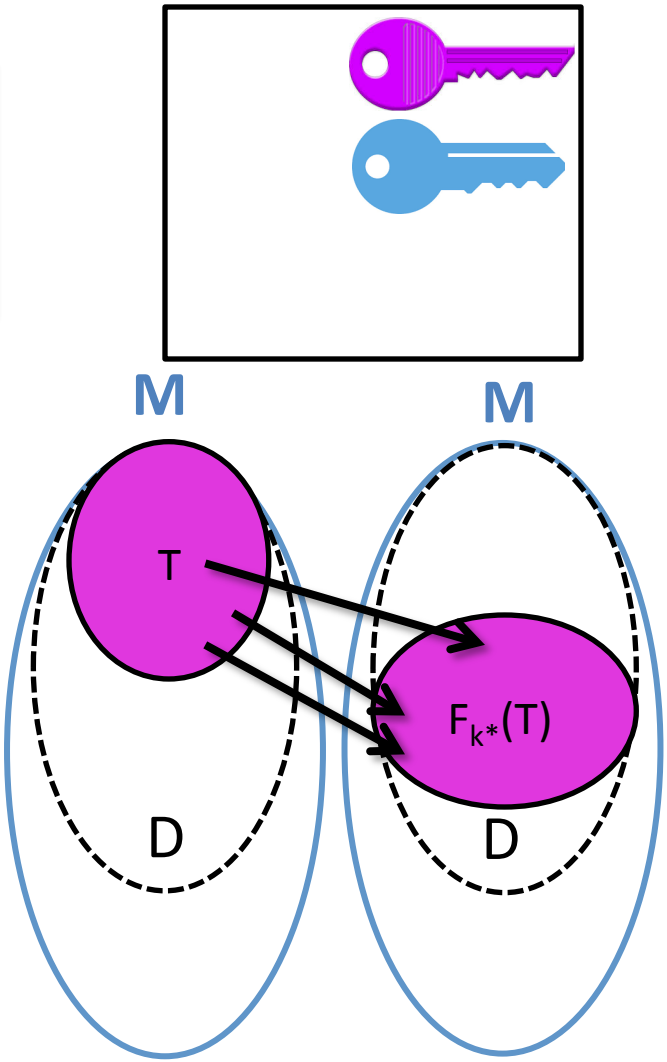
Call old FPE (partial permutation)

$F_{k*} : D \rightharpoonup D$, $T = Dom(F_{k*})$,

and **new domain M (D ⊆ M).**

Need FPE $ZZ_{k'}$: ***M -> M*** so that

$\forall t \in T, ZZ_{k'}(t) = F_{k*}(t)$

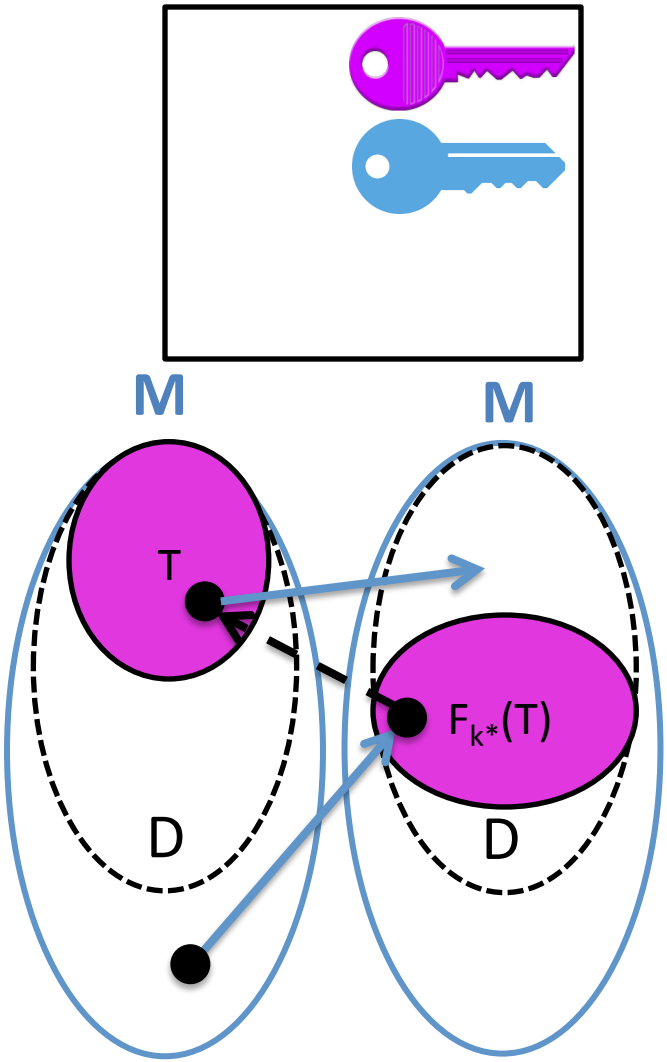


Zig-Zag works for domain extension

= Old secret key K^* for $F_{k^*} : D \to D$

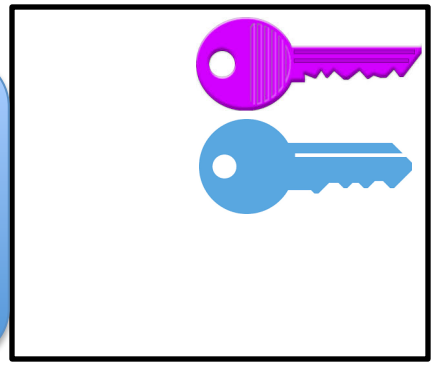
= FFX secret key K for $E_k : M \to M$

Encrypt((K^*, K) , M):
If M in T then:
    Return $F_{k^*}(M)$
Else:
    $C = E_K(M)$
    while $(F_{k^*}^{-1}(C) \in T)$:
        $C = E_K(F_{k^*}^{-1}(C))$
    return C



Zig-Zag works for domain extension

What security does this achieve?



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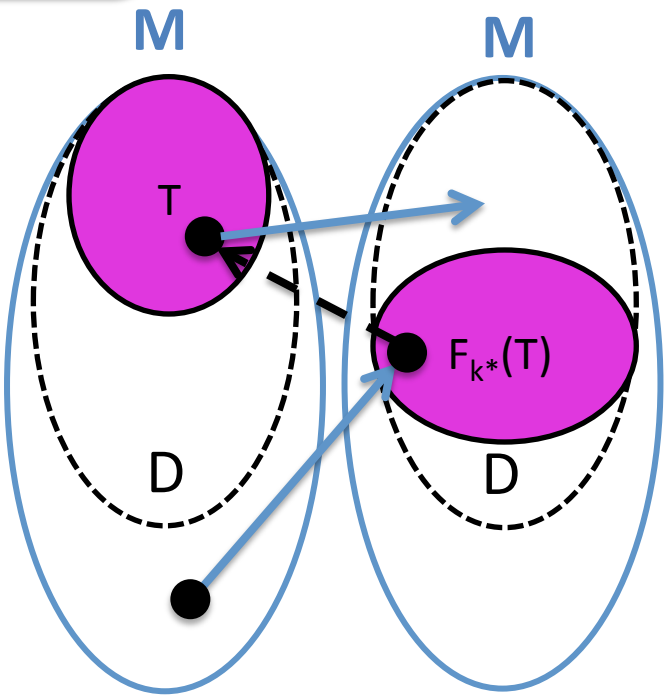


SPRP security is impossible

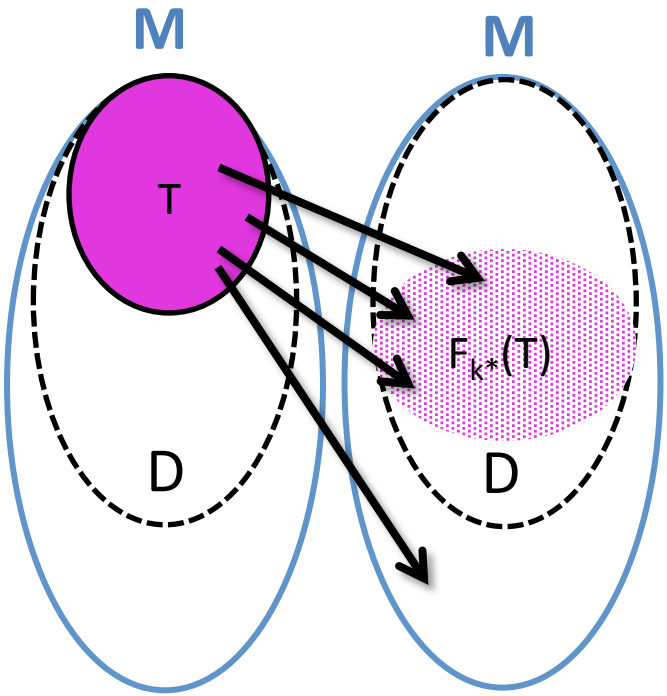
When adversary knows $T=\{t_1 \ldots t_{|T|}\}$, there is a trivial distinguisher ***for any DE cipher***

$$\text{Advantage} = 1 - \frac{|D|!(|M|-q)!}{|M|!(|D|-q)!}$$

```
for i in [1 … q]:
    if ZZ_k'(t_i) ∉ D:
        return "ideal"
return "real"
```

Key intuition: Unlikely for random permutation that all queries fall in D.

Can we prove any meaningful security?



Can we achieve any meaningful security?

Weaken SPRP security notion, target indistinguishability from different ideal object

"Strong extended pseudorandom permutation"

SEPRP security

A permutation is an SEPRP if indistinguishable from permutation sampled uniformly subject to $\forall t \in T$, $ZZ_{k'}(t) = F_{k*}(t)$

<u>Theorem (informal)</u>: Zig-Zag is an SEPRP.

<u>Theorem (informal)</u>: SEPRP gives at most a factor-of-2 speedup in message recovery game from [BRRS].

Key intuition: Generalize message recovery notion from [BRRS].
One hidden bit (membership in T), so 2x queries

Other considerations

- If adversary only knows |T|, modified Zig-Zag can meet SPRP (see paper)
- Variable timing for some inputs
  - + Timing side channel only leaks membership in T
- Rank-encipher-unrank construction
  - + Fast in worst case
  - – High storage overhead, cache side channels

Summary

Introduce backwards-compatible crypto

We give generic algorithm (Zig-Zag) for backwards-compatible FPE

Achieved *domain completion* and *domain extension* for FPE using the Zig-Zag algorithm. Our techniques are efficient, provably secure, and solve real problems for practitioners

Thanks for listening! Any questions?