New Multiple Encryption for Making Double Encryption Secure Against Meet-in-the-Middle & Related-Key Attacks

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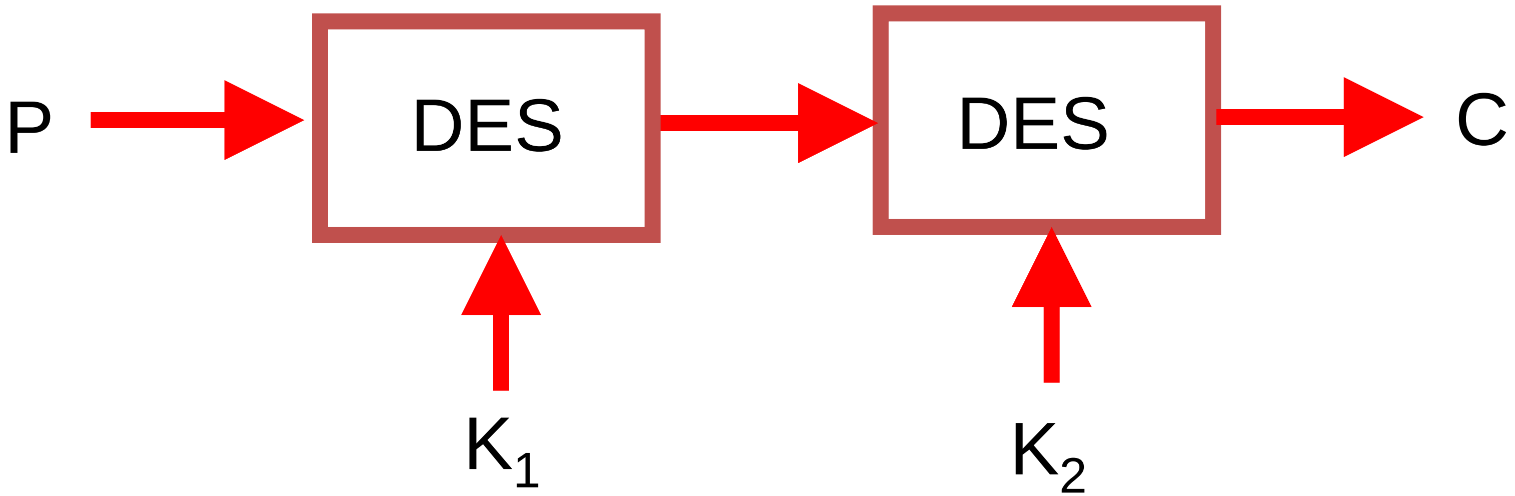
Introduction

- Single DES is not secure anymore because of too short key size
- But exhaustive key search is considered to be an only practical attack on DES
- How about Linear Cryptanalysis by Matsui in 1993?
  - in theory, faster than exhaustive key search
  - but 2^{43} pairs of known plaintext & ciphertext are required and it seems very difficult to do in practice
- Is there an easy & efficient way to increase the key size of block cipher such as DES in general without modifying the original block cipher?
  - Would also be useful for AES when it becomes vulnerable to some attack in the future
- If possible, fast DES hardware implementation can be reused

Multiple Encryption

- Double DES

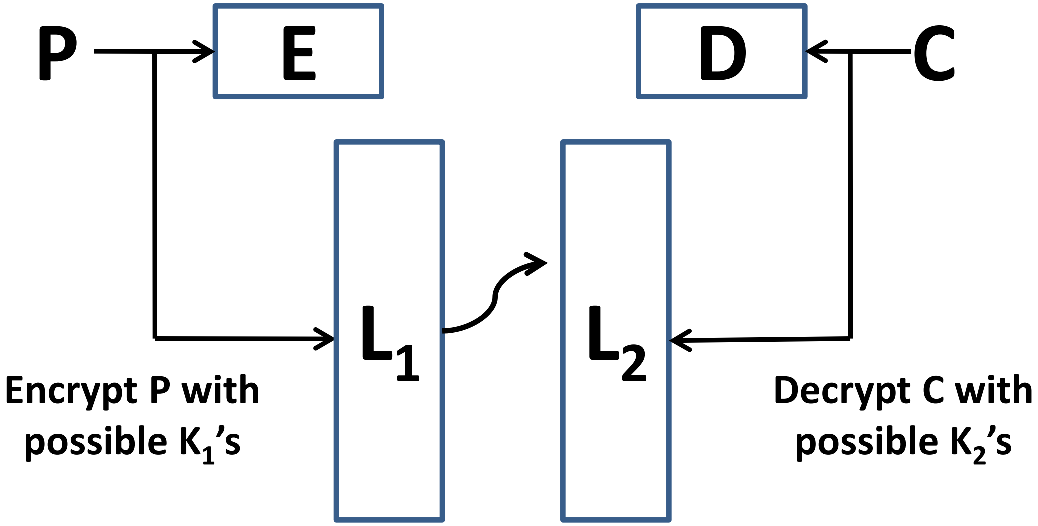


- How much security do we gain?
  - With n-bit K_1 and K_2, ideally, attack complexity should be $O(2^{2*n})$, but there is a meet-in-the-middle attack…

Meet-in-the-middle(MITM) Attack

Attack on double DES

1. Get valid pairs of (P,C),(P’,C’)
2. Compute lists L_1 & L_2 and sort L_1 & L_2
3. Find a match in L_1 & L_2 to determine K_1 ,K_2
4. Check validity of K_1 ,K_2 with (P’,C’)


P
E
D
C
L_1
L_2
Encrypt P with possible K_1’s
Decrypt C with possible K_2’s

$<K_1, E_{K_1}(P)>$ $<K_2, D_{K_2}(C)>$

$O(2^n)$ time complexity with $O(2^n)$ space where K_1,K_2 are n-bit

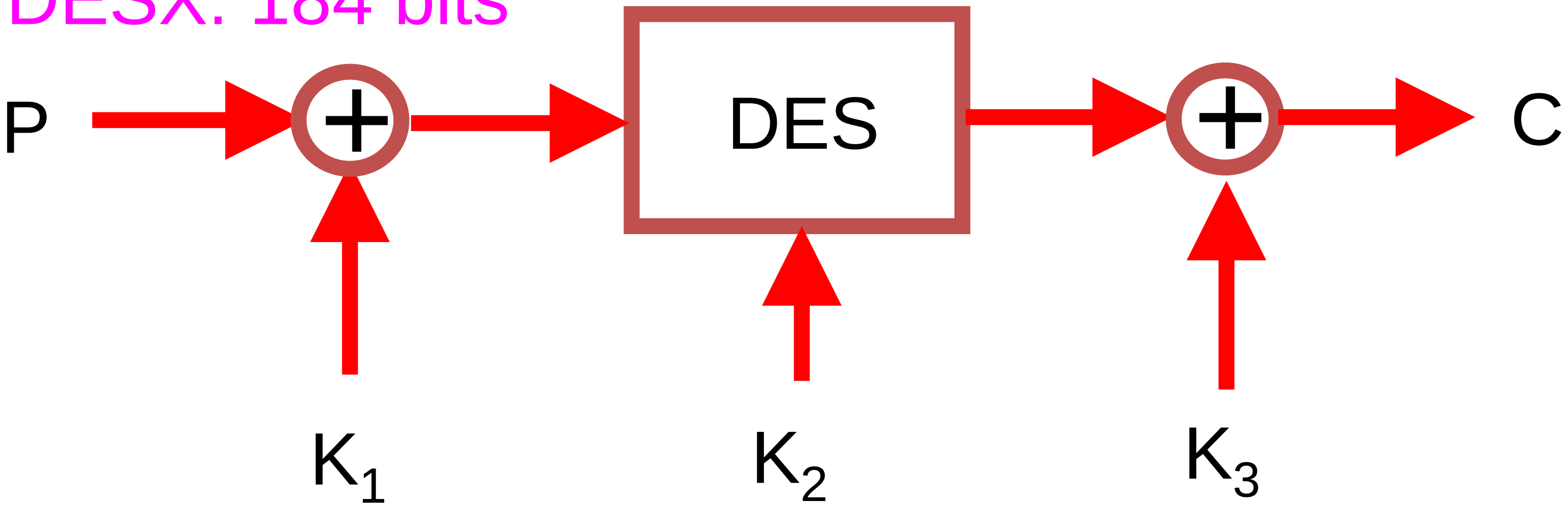
Countermeasure Against MITM Attack

- We should prevent an attacker from computing middle data
- There already exist several DES variants based on multiple encryption
  - DESX
  - Two-key Triple DES
  - DES-EXE
- Our new proposal: DES-XEEX

DESX

- Proposed by Rivest
  - used in the products of RSA Data Security, Inc.
  - Rogaway et al. gave soundness proof [Crypto’96]

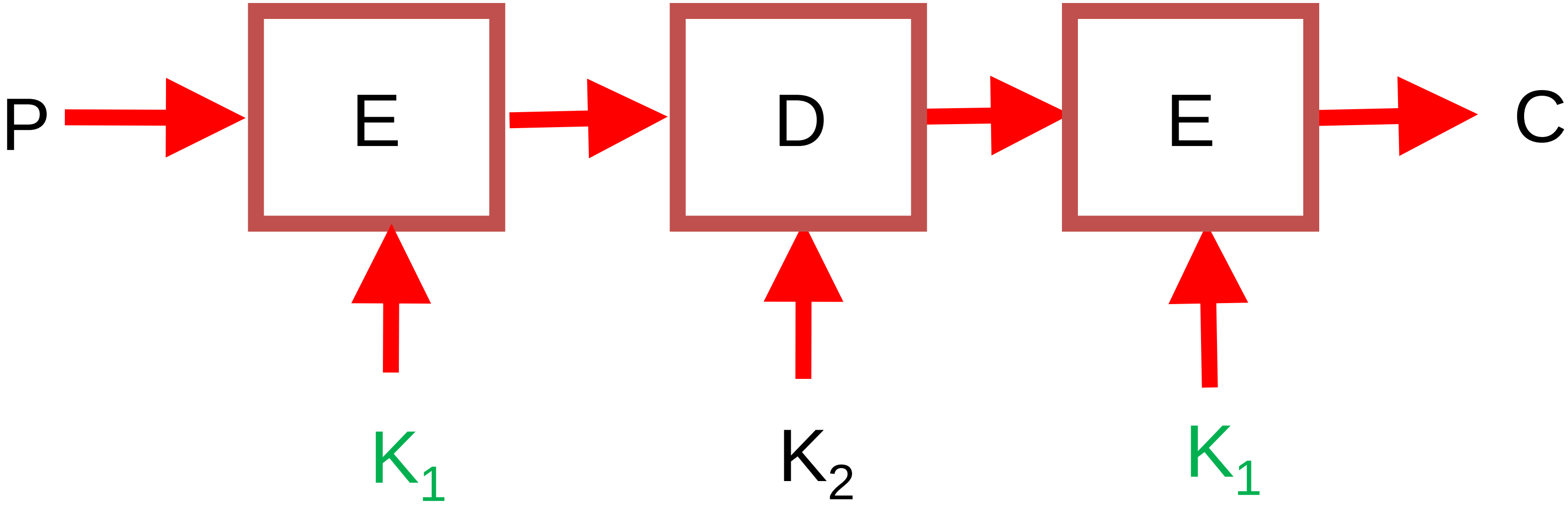
Key size in DESX: 184 bits



- However, another attack called related-key attack [Phan, Shamir’04] exists…

Two-key Triple DES

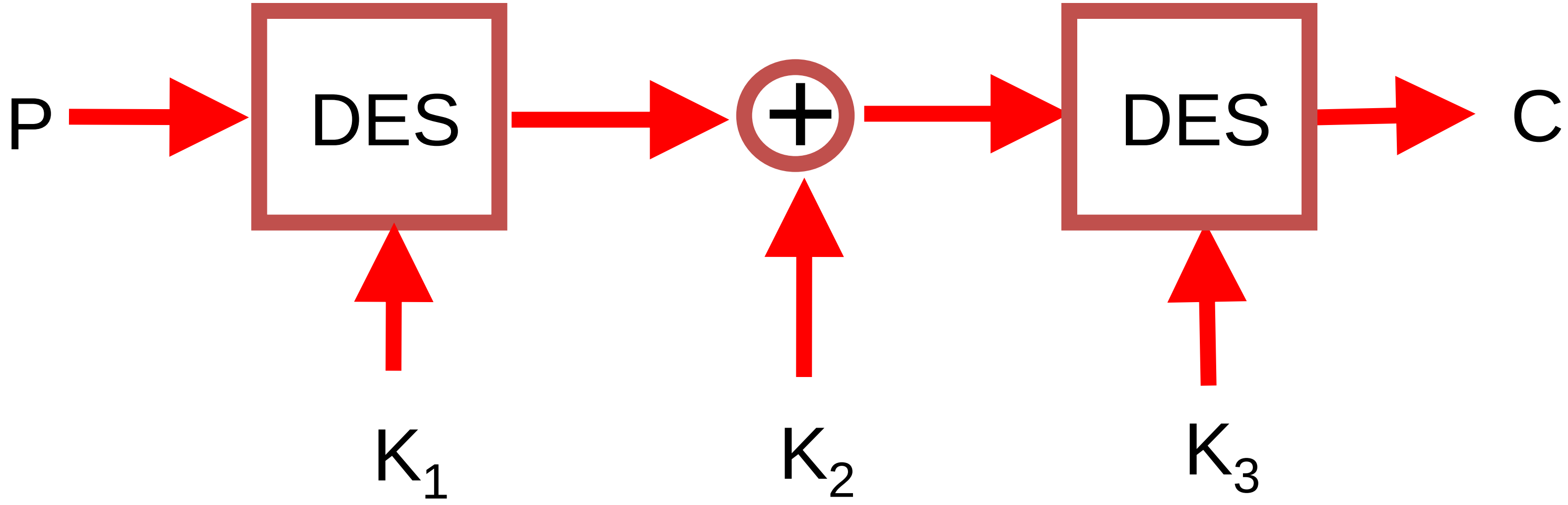
- Proposed by Tuchman in 1979



- There exists a variant of MITM attack faster than exhaustive key search
- Known-plaintext attack [Oorschot, et al ‘90]. So not optimal(only 80-bit(<112)security level).
- 3DES operations and slow performance

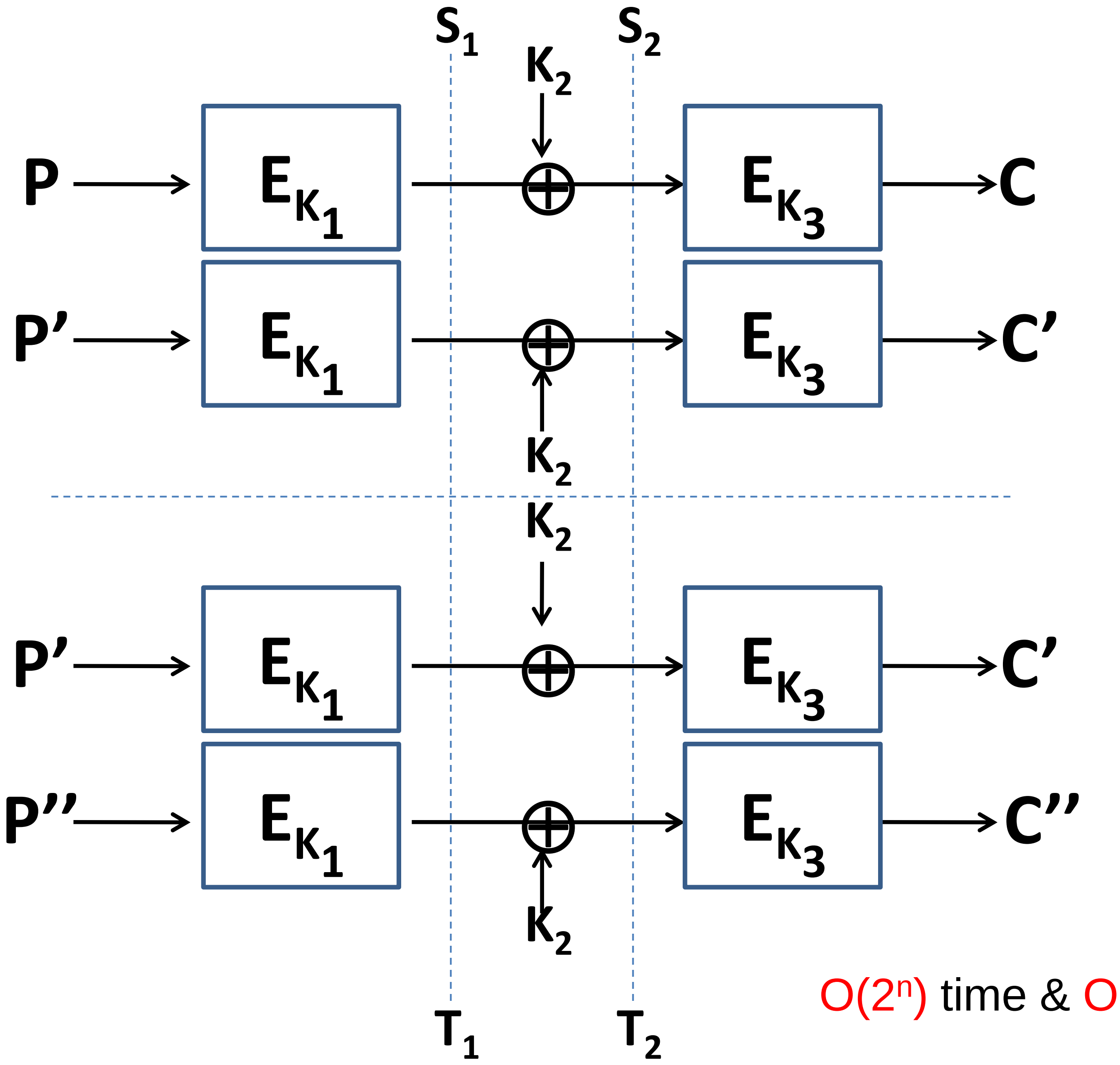
DES-EXE

- Proposed by Kaliski and Robshaw in 1996



- DES-EXE was designed s.t. MITM attack is not applicable
- However, elaborate MITM attack [Choi et al, ICCSA’05] was discovered…

MITM Attack on DES-EXE[Choi et al.]



$<K_1, S_1, T_1>$ where

$S_1 = E_{K_1}(P) \oplus E_{K_1}(P')$

$T_1 = E_{K_1}(P') \oplus E_{K_1}(P'')$

$<K_3, S_2, T_2>$ where

$S_2 = D_{K_3}(C) \oplus D_{K_3}(C')$

$T_2 = D_{K_3}(C') \oplus D_{K_3}(C'')$

Find

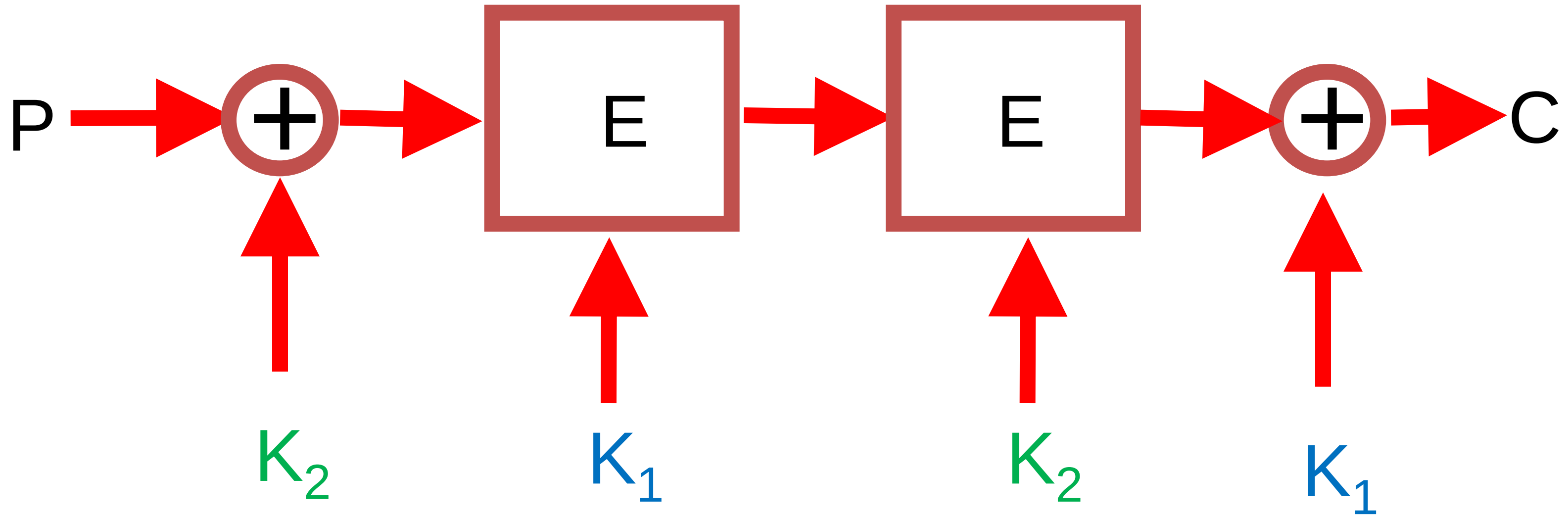
$<K_1, S_1, T_1>$

$<K_3, S_2, T_2>$

s.t. $S_1=S_2$ & $T_1=T_2$

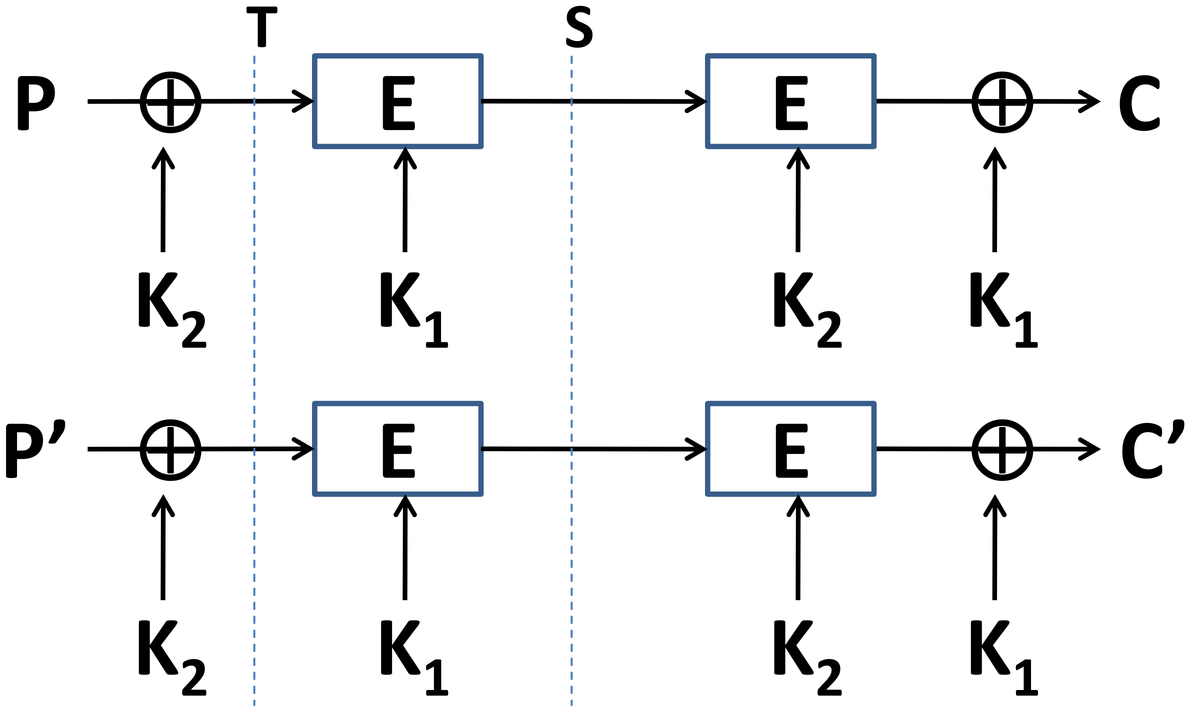
$O(2^n)$ time & $O(2^n)$ space

Proposal: DES-XEEX



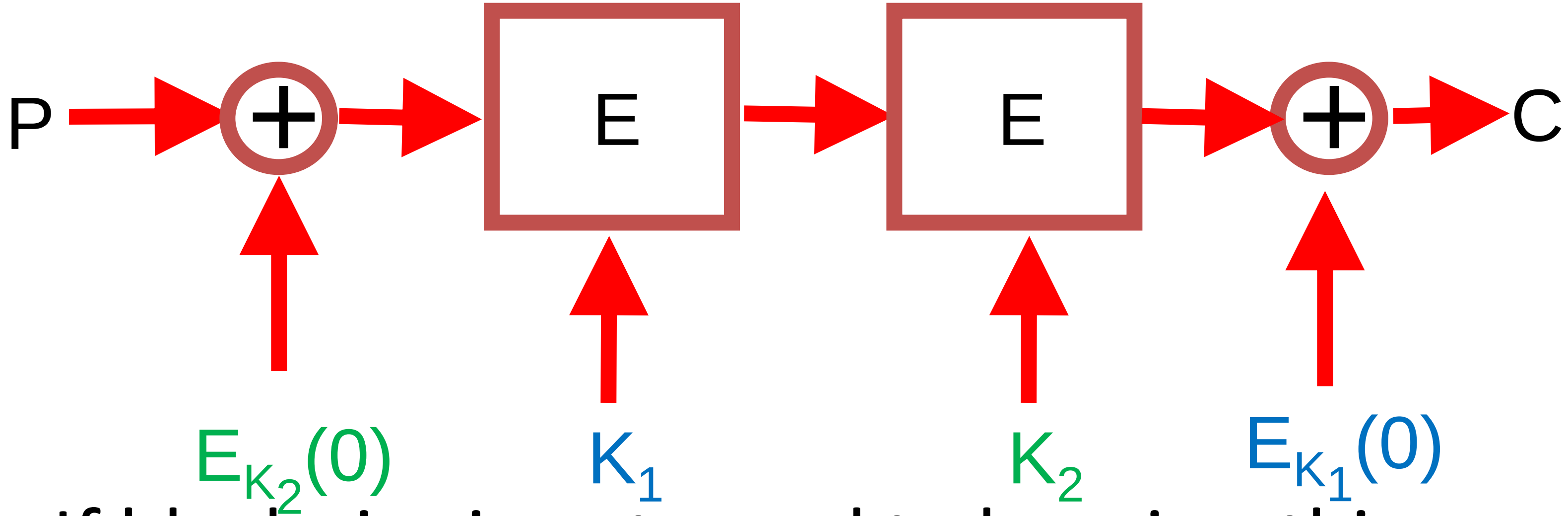
- MITM attack/Related-key attack on DES-EXE will not work
- Seems that no attack faster than exhaustive key search exists
  - Heuristic analysis given in the paper
- Detailed security analysis is still underway…

MITM Attack on DES-XEEX?



- Intuitively, to compute middle data at S, both K_1 & K_2 must be specified, so $O(2^{2n})$ space will be needed
- Also the attack time complexity will be $O(2^{2n})$

Variant of DES-XEEX



- If block size is not equal to key size, this variant is useful
  - $E_{K_2}(0)$ & $E_{K_1}(0)$ can be pre-computed
- Also can erase DES complementation property
  - $\overline{DES_K(P)} = DES_{\overline{K}}(\overline{P})$
  - $DES_{\overline{K_2}}\left(DES_{\overline{K_1}}\left(P \oplus DES_{\overline{K_2}}(0)\right)\right) \oplus DES_{\overline{K_1}}(0) =$ $DES_{K_2}\left(DES_{K_1}\left(P \oplus DES_{K_2}(\bar{0})\right)\right) \oplus DES_{K_1}(\bar{0})$

Summary

- We considered a multiple encryption scheme secure against
  - MITM attack
  - Related-key attack
  - Known-plaintext attack
- Existing DES variants are vulnerable to these attacks
- We gave one new construction which we call DES-XEEX and its variant
  - Generic and applicable to any block cipher

Thank you for you attention!