Constructing Tweakable Block Ciphers in the Random Permutation Model

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ANSSI, France

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Based on joint work with Benoît Cogliati and Rodolphe Lampe

Outline

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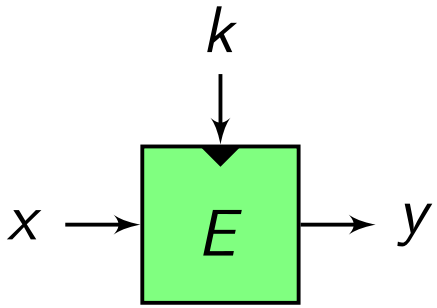
Tweakable Block Ciphers (TBCs)



- tweak t: brings variability to the block cipher
- t assumed public or even adversarially controlled
- each tweak should give an "independent" permutation
- few "natively tweakable" BCs:
  - Hasty Pudding Cipher [Sch98]
  - Mercy [Cro00]
  - Threefish [FLS+10]
  - CAESAR proposals KIASU, Deoxys, Joltik, (i)SCREAM, Minalpher

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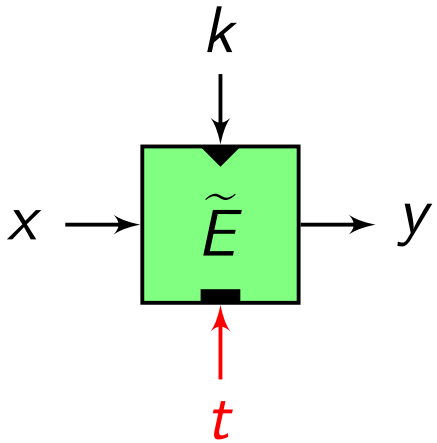

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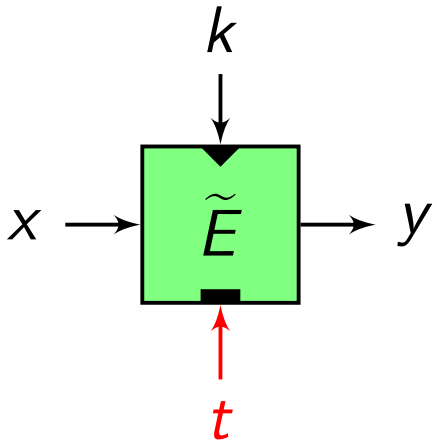

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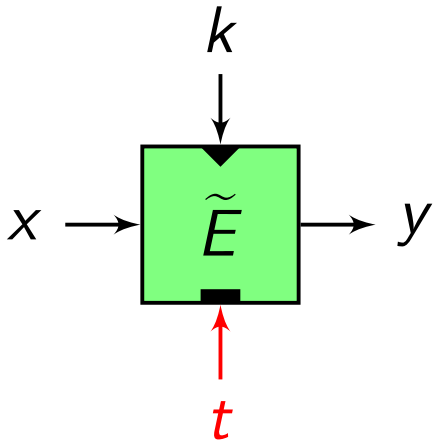

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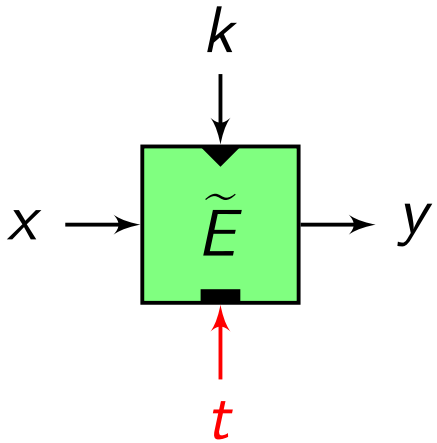

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Generic Constructions of TBCs: LRW

- A generic TBC construction turns a conventional block cipher E into a TBC $\widetilde{E}$
- example: LRW construction by Liskov *et al.* [LRW02]

- h is XOR-universal, e.g. $h_{k'}(t) = k' \otimes t$ (field mult.)
- secure up to $\sim 2^{n/2}$ queries
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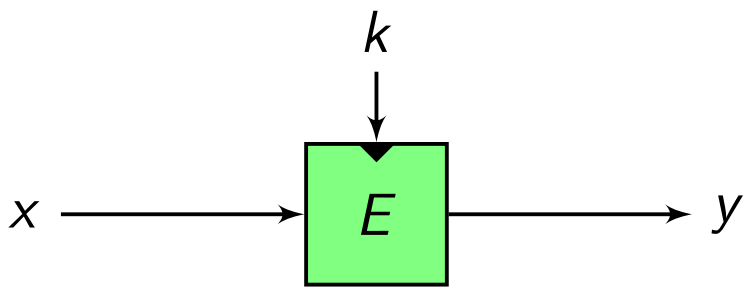

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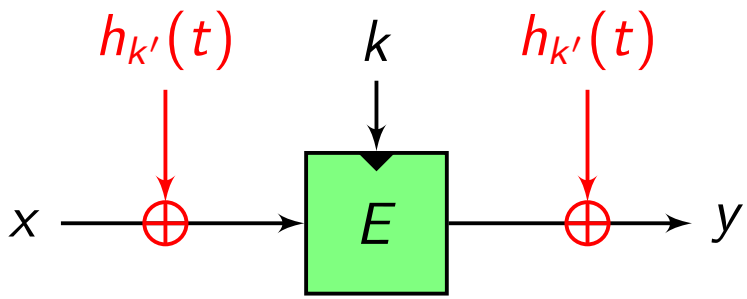

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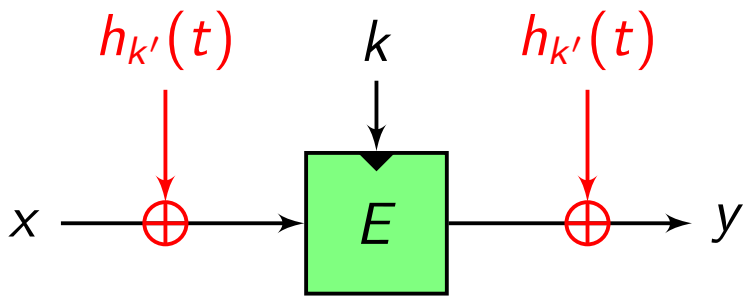

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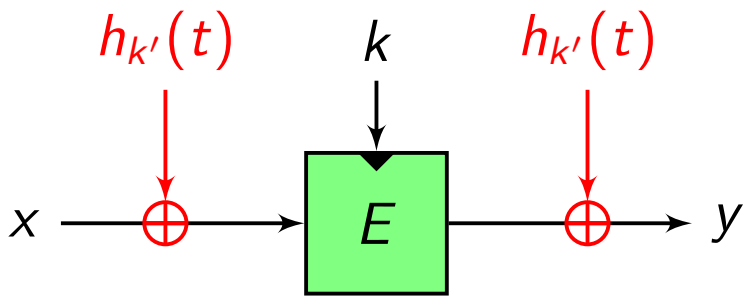

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- Minematsu [Min09]
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- Cascaded LRW [LST12, LS13]
  ☹ larger key length and block cipher calls
- Mennink [Men15]
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TBCs: Dedicated Designs

Our Goal

Provide provable security guidelines to design TBCs "from scratch" (rather than from an existing conventional block cipher).

- "from scratch" $\rightarrow$ from some lower level primitive
- from a PRF: Feistel schemes [GHL+07, MI08]
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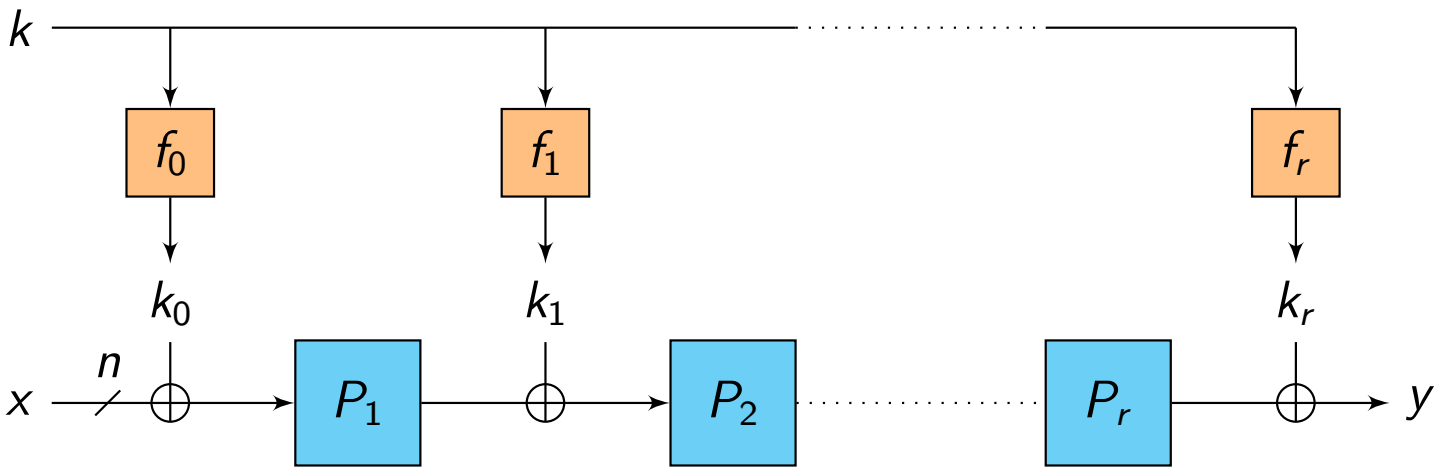

An r-round key-alternating cipher:

- the P_i's are public permutations on $\{0,1\}^n$
- the f_i's map k to n-bit "round keys"
- examples: most SPNs (AES, SERPENT, PRESENT, LED...)
- a.k.a. (iterated) Even-Mansour construction

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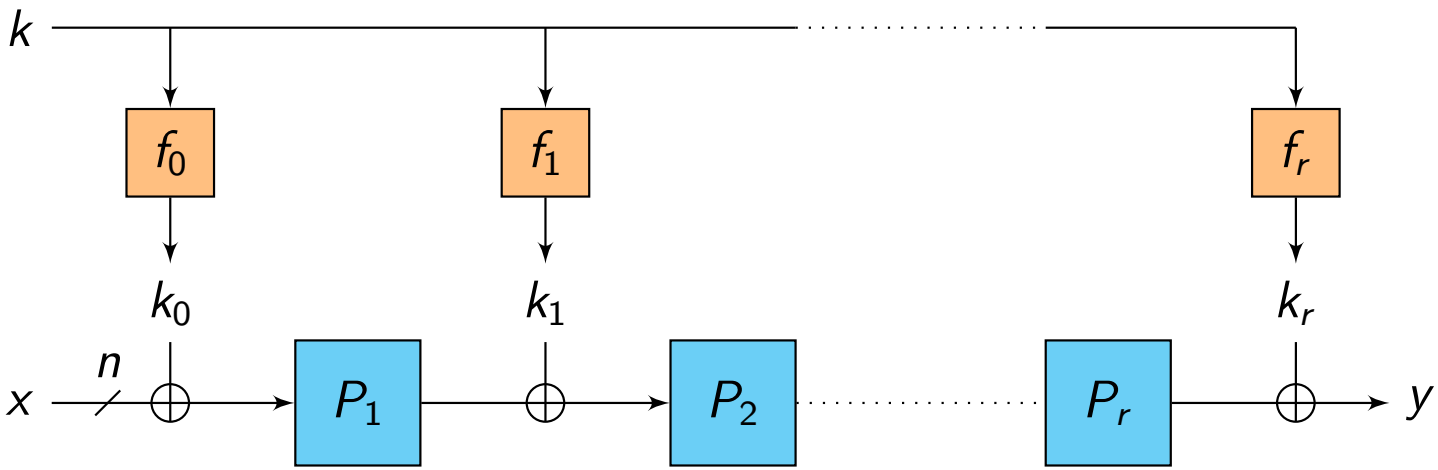

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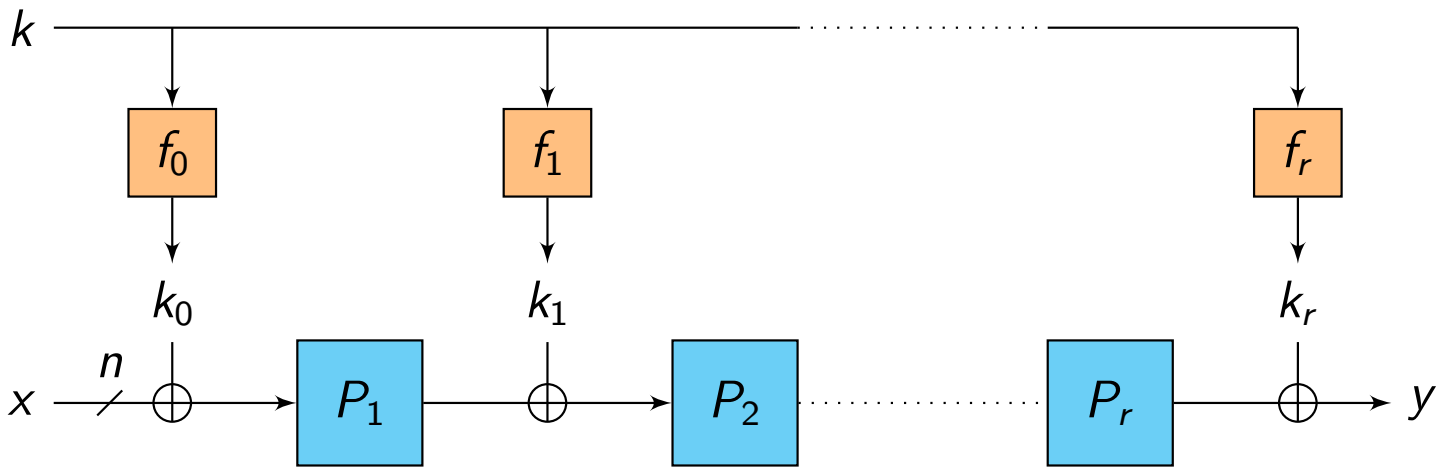

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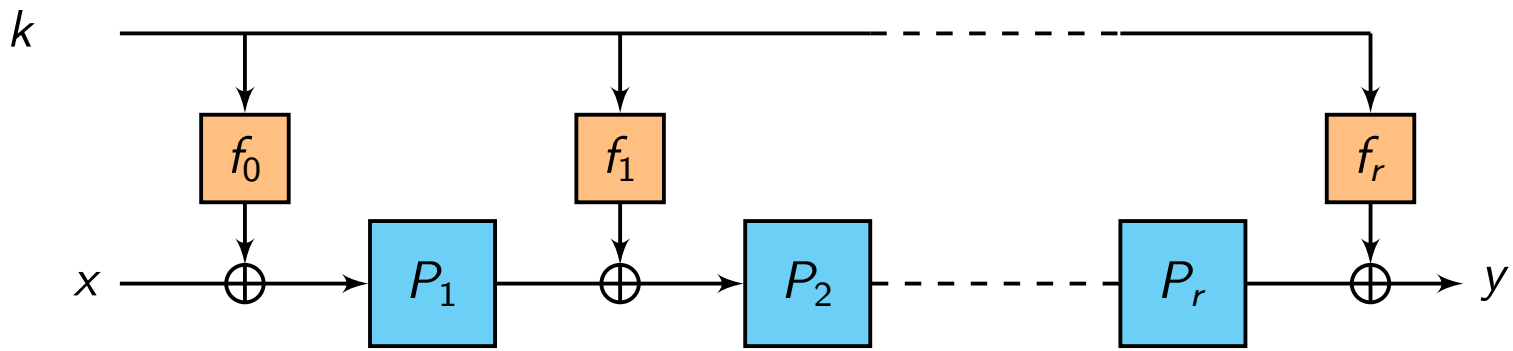

- let the round keys depend on the key and the tweak t
- $\Rightarrow$ "tweakable" Even-Mansour (TEM) construction(s)
- f_i's = "tweak and key schedule" (TKS)
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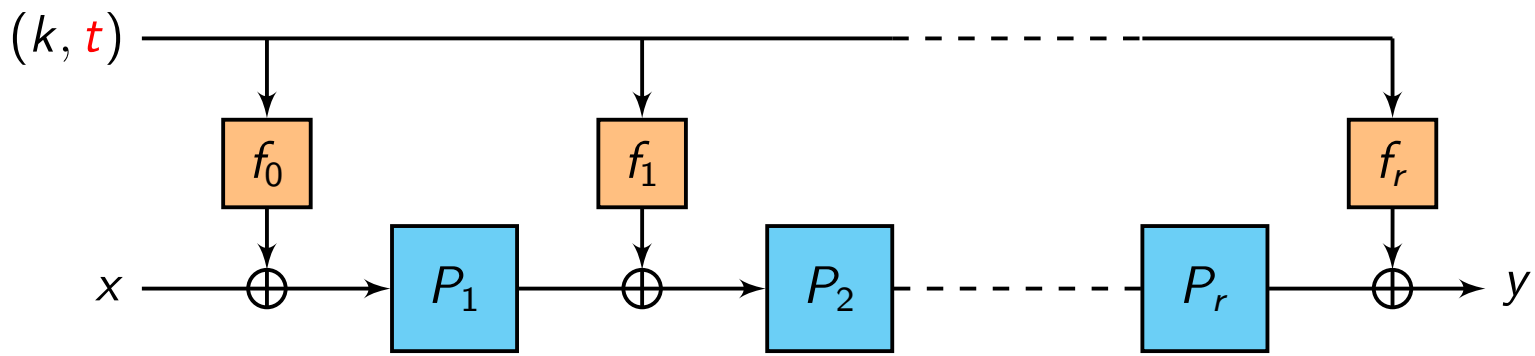

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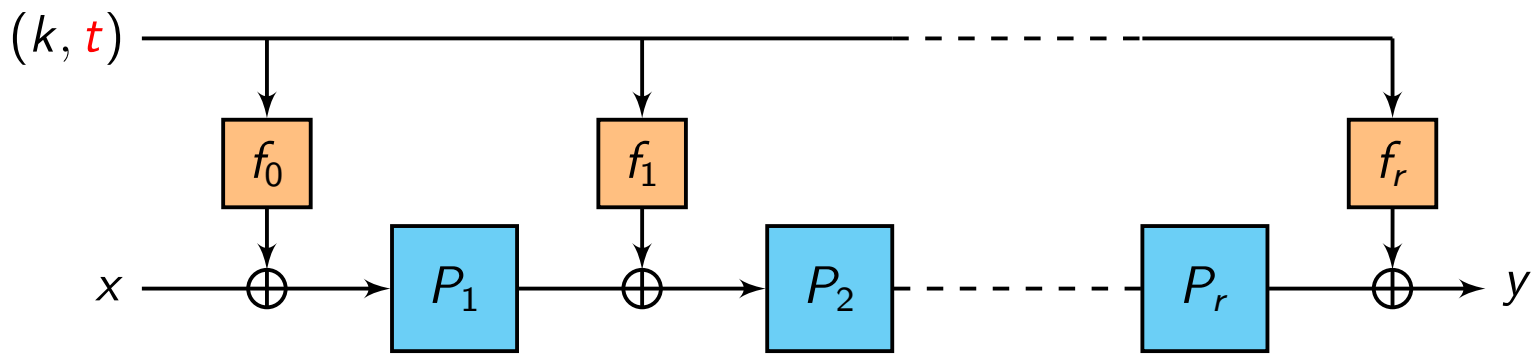

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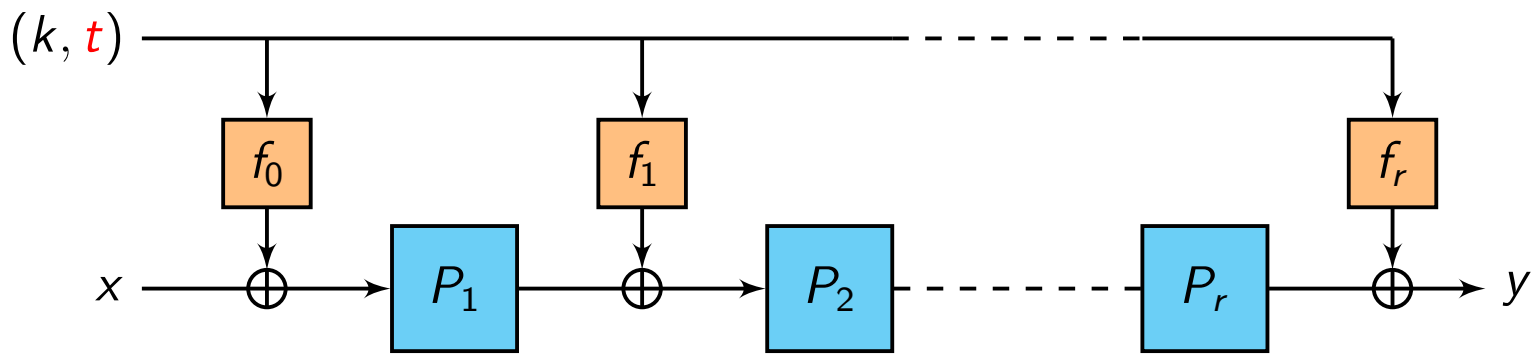

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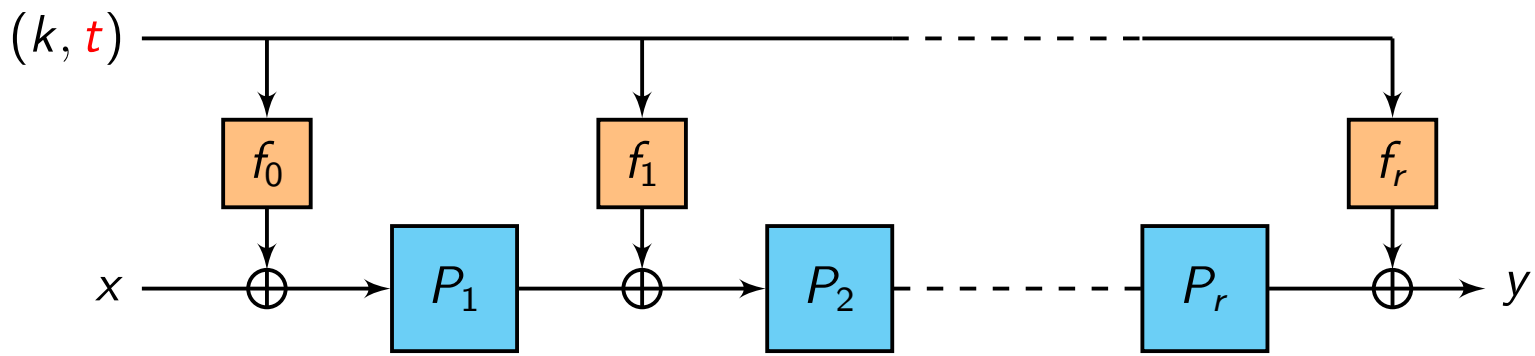

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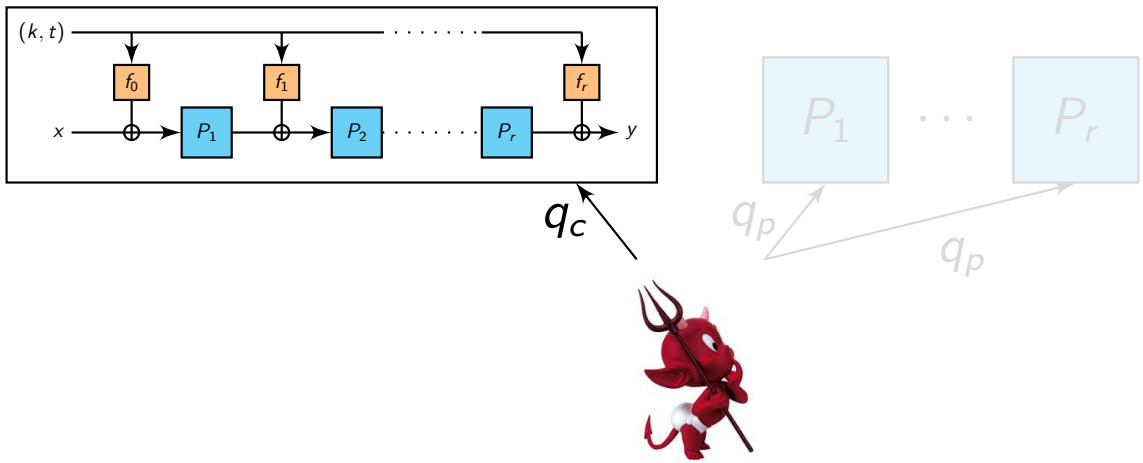

- the P_i's are modeled as public random permutation oracles (adversary can only make black-box queries)
- adversary cannot exploit any weakness of the P_i's
  $\Rightarrow$ generic attacks
- complexity measure of the adversary:
  - q_c = # construction queries = pt/ct pairs (data D)
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  - but otherwise computationally unbounded
- $\Rightarrow$ information-theoretic proof of security

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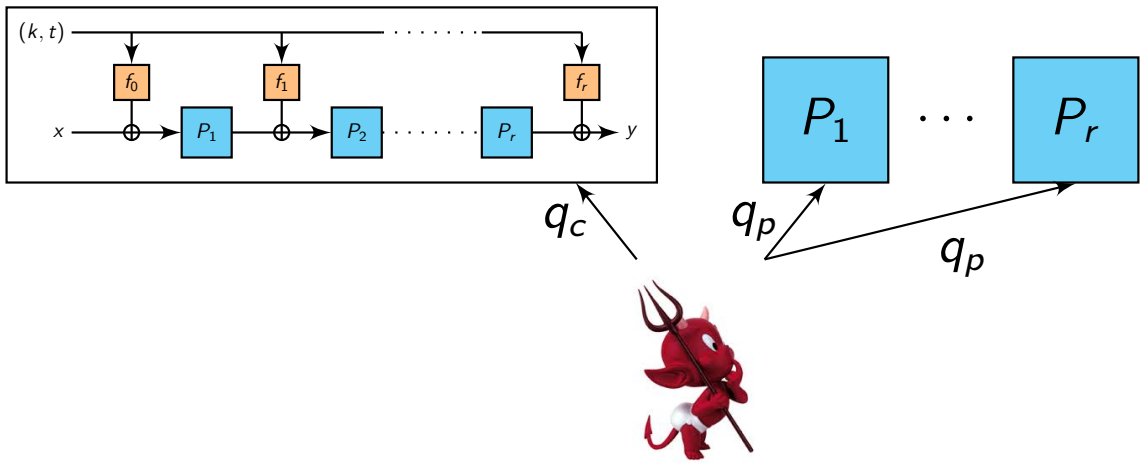

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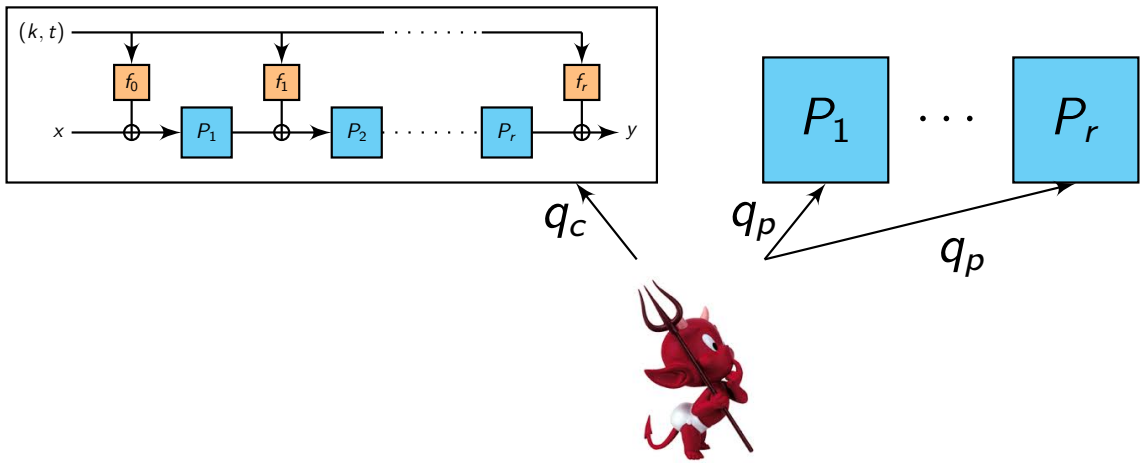

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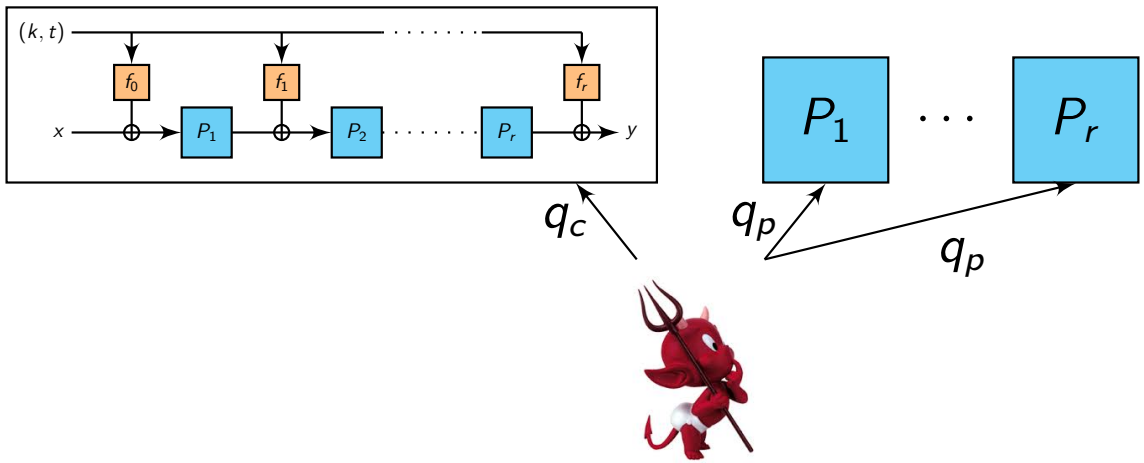

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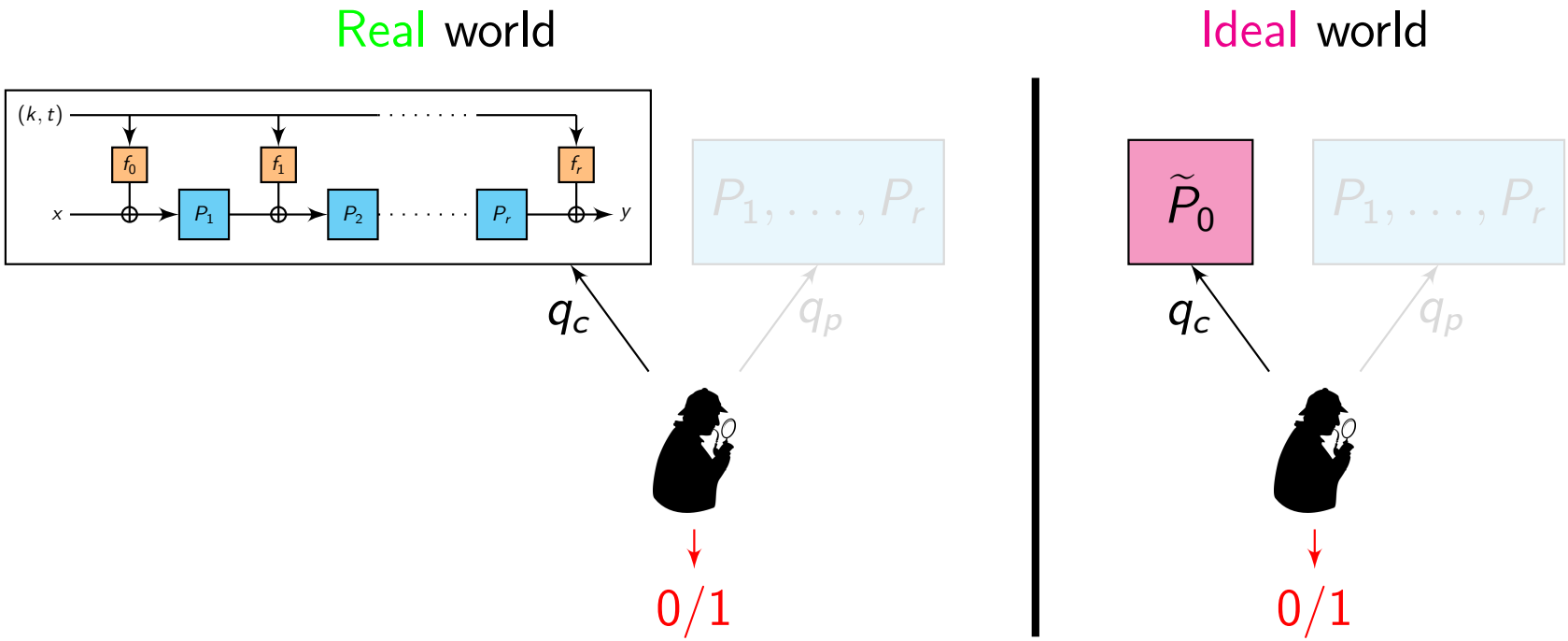

- real world: TEM construction with random master key k
- ideal world: random tweakable permutation $\widetilde{P}_0$ independent from $P_1, \ldots, P_r$
- RPM: $\mathcal{D}$ has oracle access to $P_1, \ldots, P_r$ in both worlds

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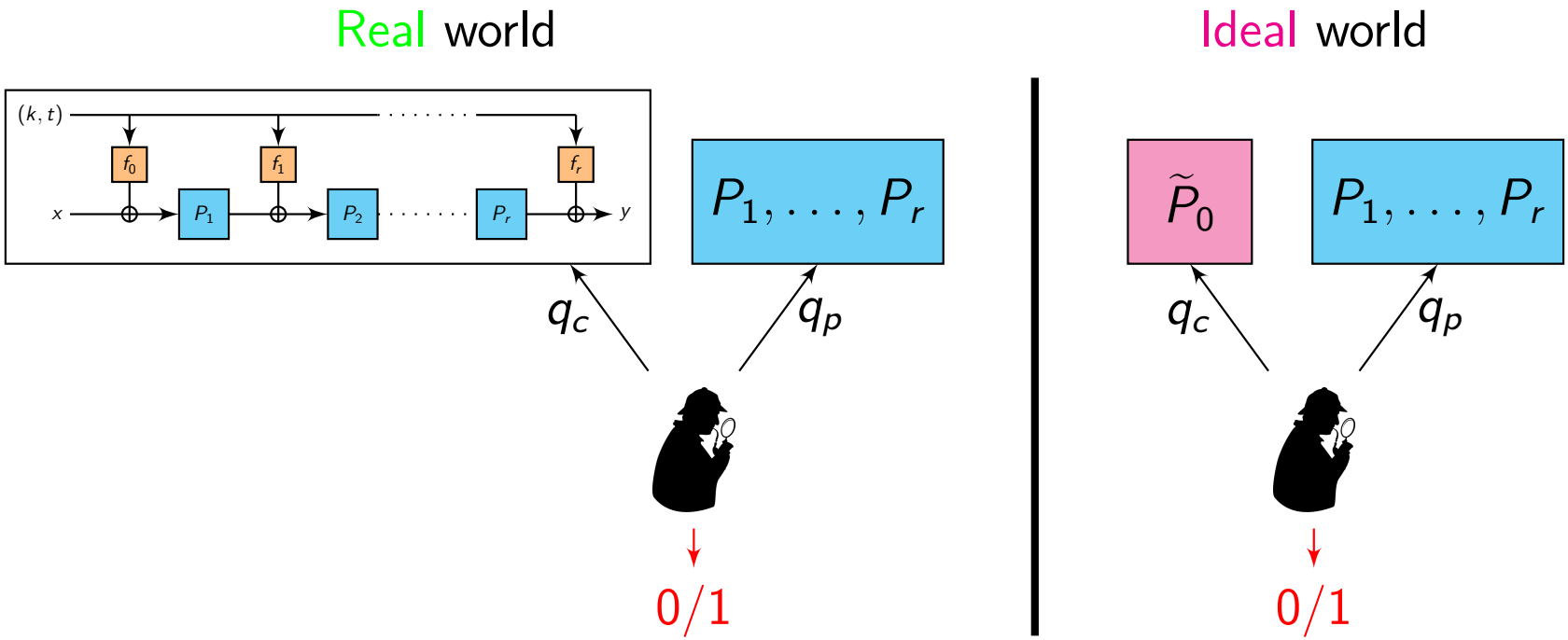

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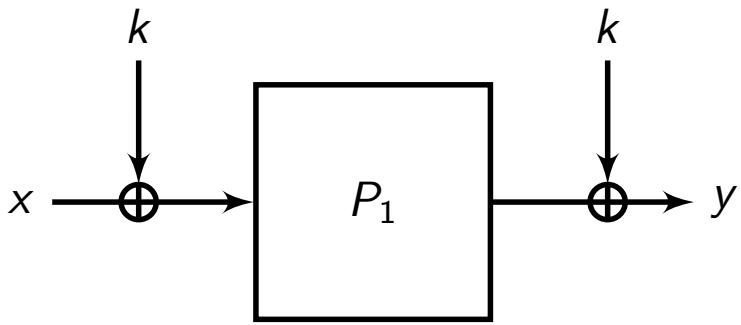

- 2 queries to the encryption oracle, 0 queries to P_1
- $(*)$ holds with proba. 1 for the TEM construction
- $(*)$ holds with proba. 2^{-n} for a random tweakable permutation
- works for any linear TKS

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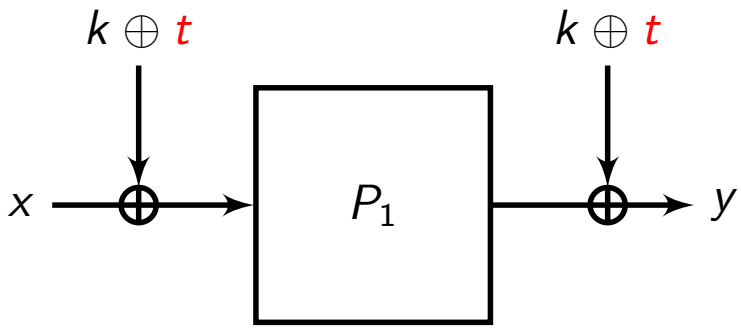

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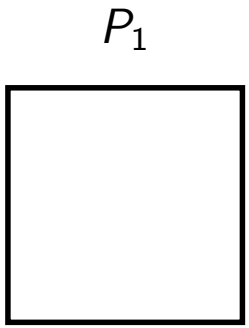

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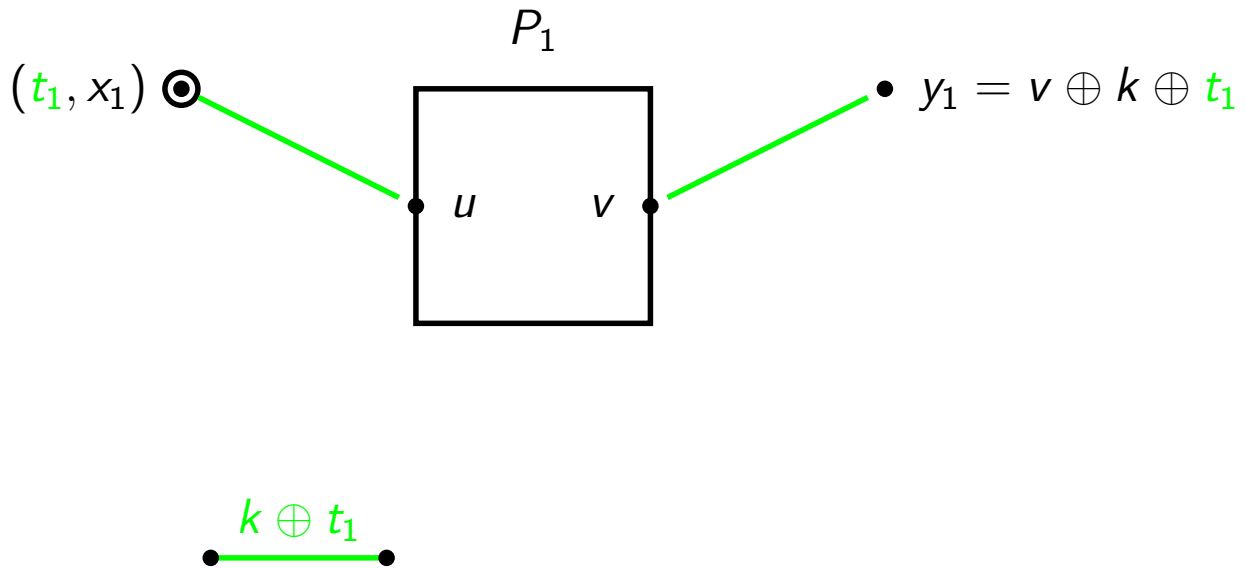

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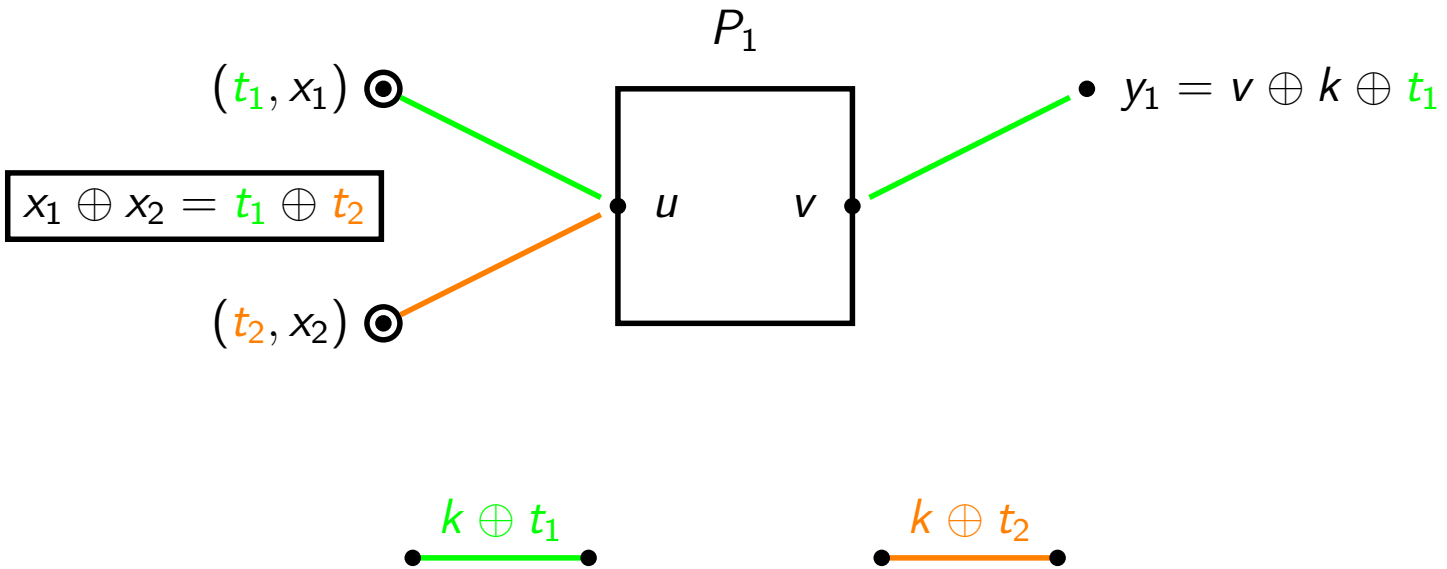

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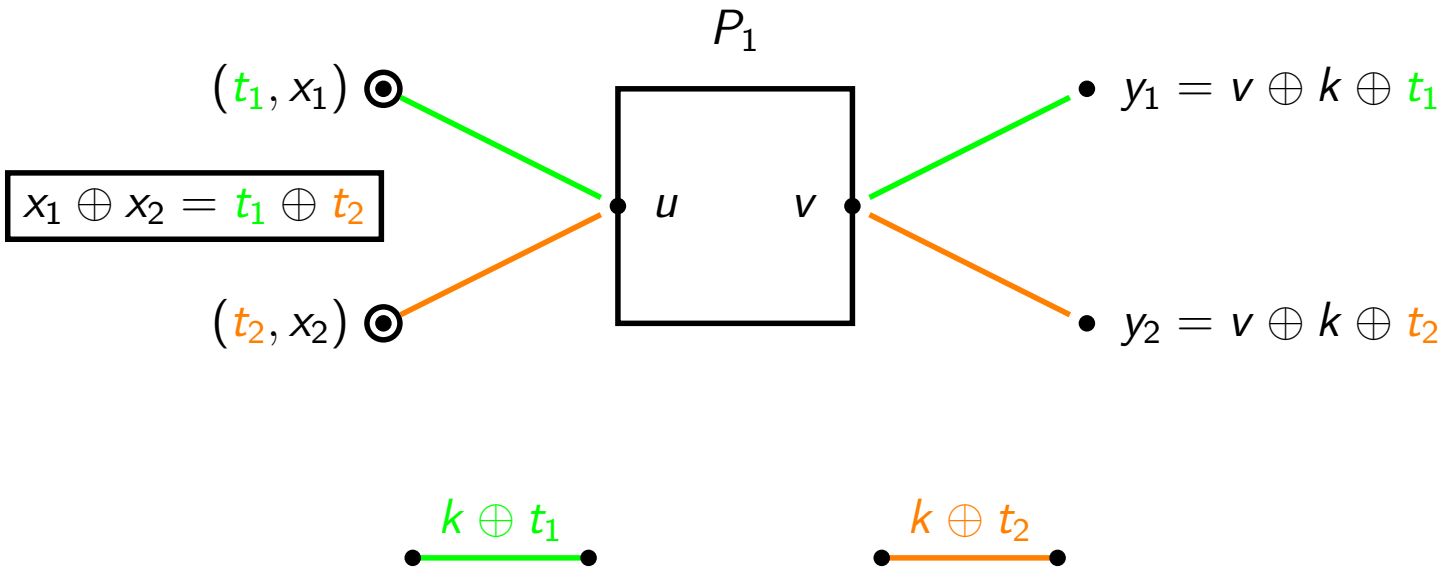

Check that $y_1 \oplus y_2 = t_1 \oplus t_2$ $(*)$

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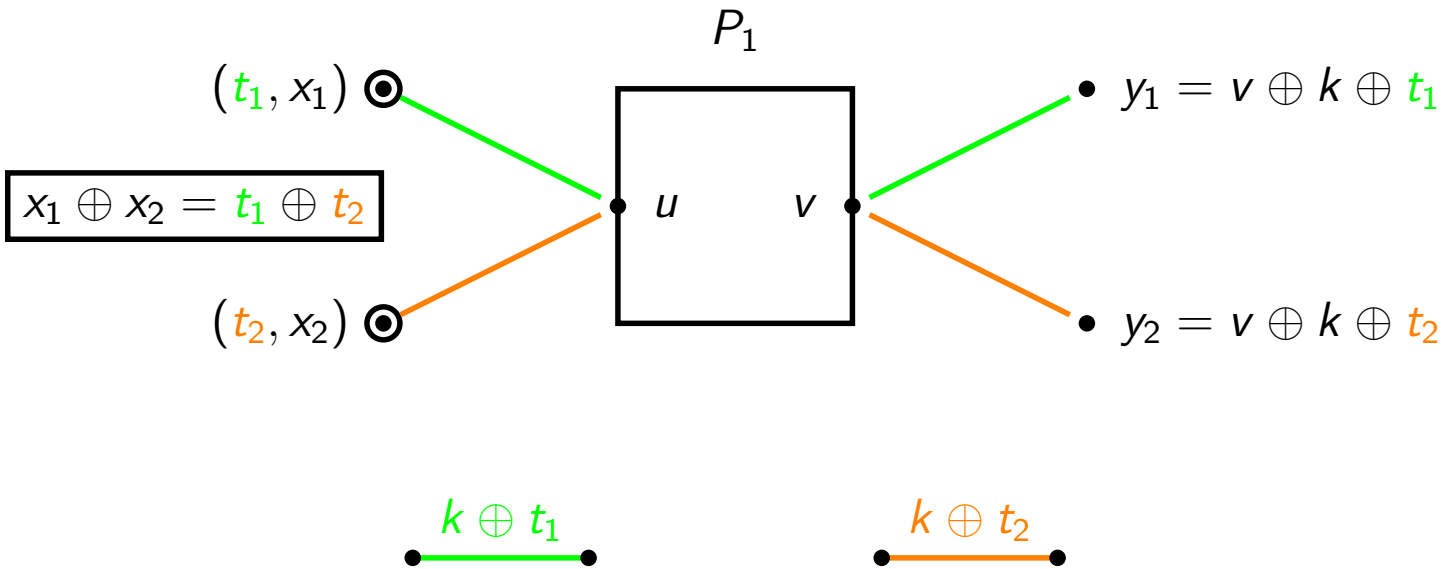

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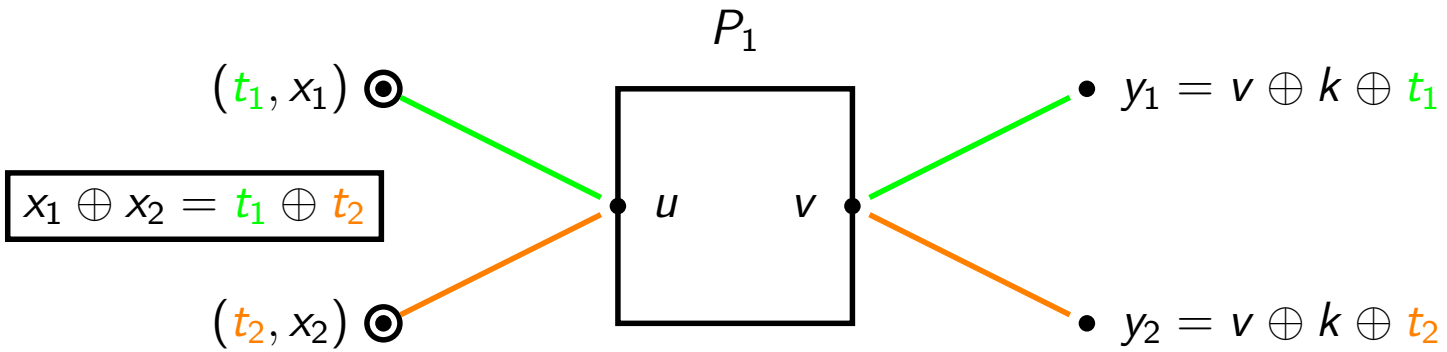

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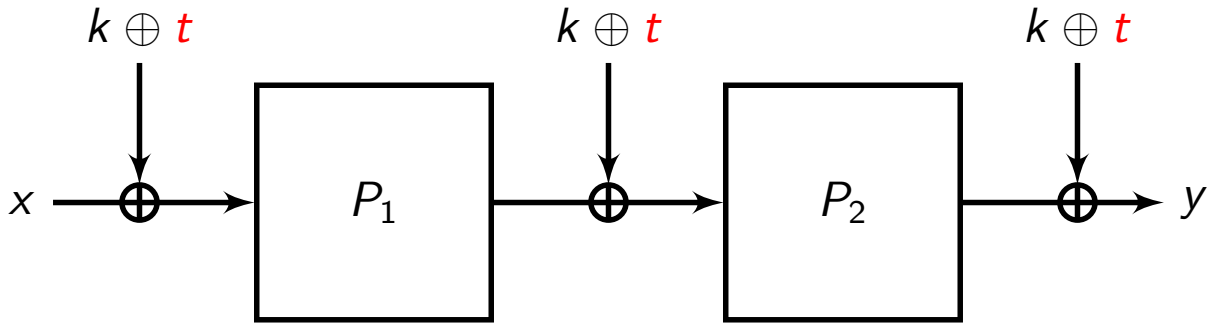

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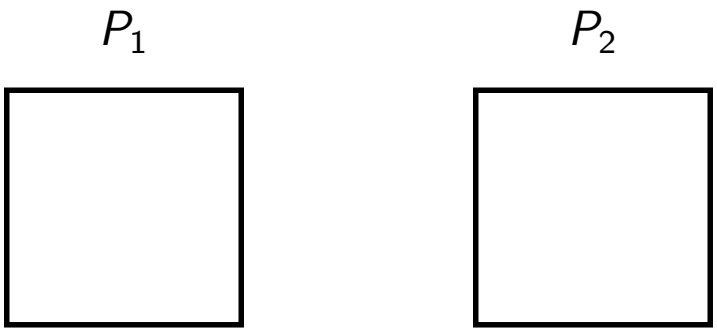

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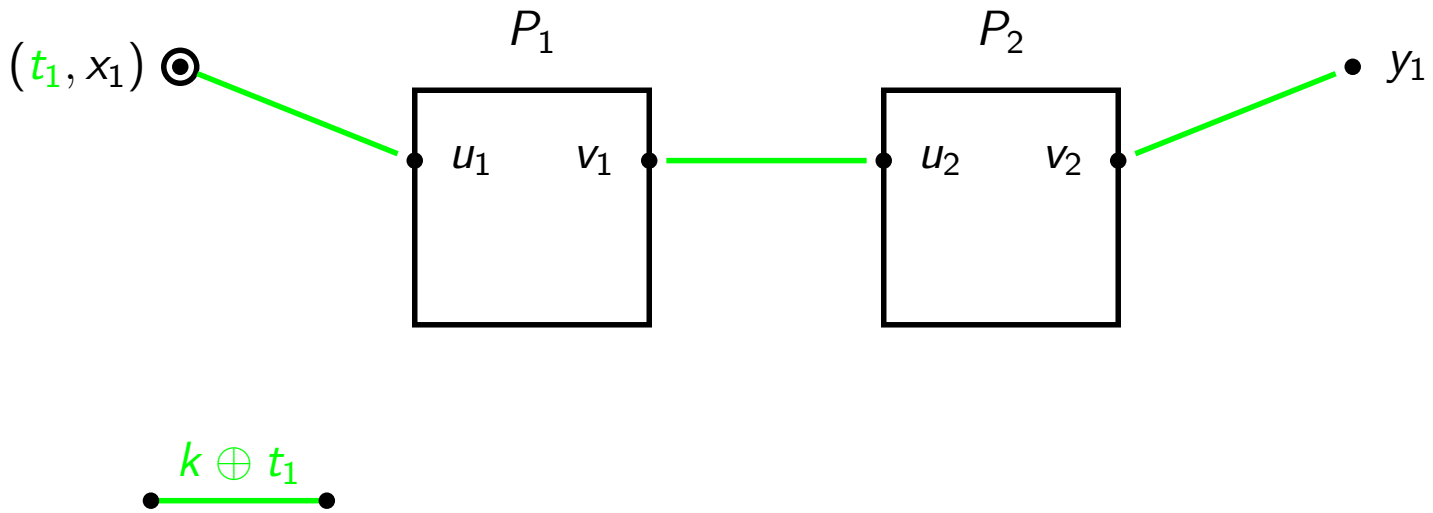

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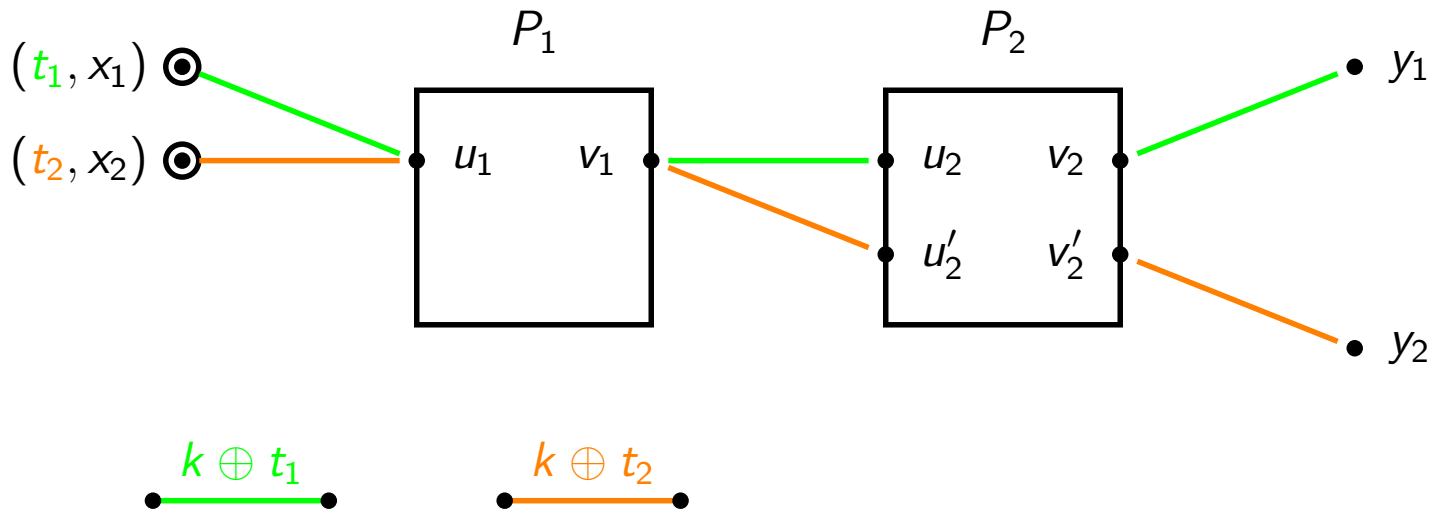

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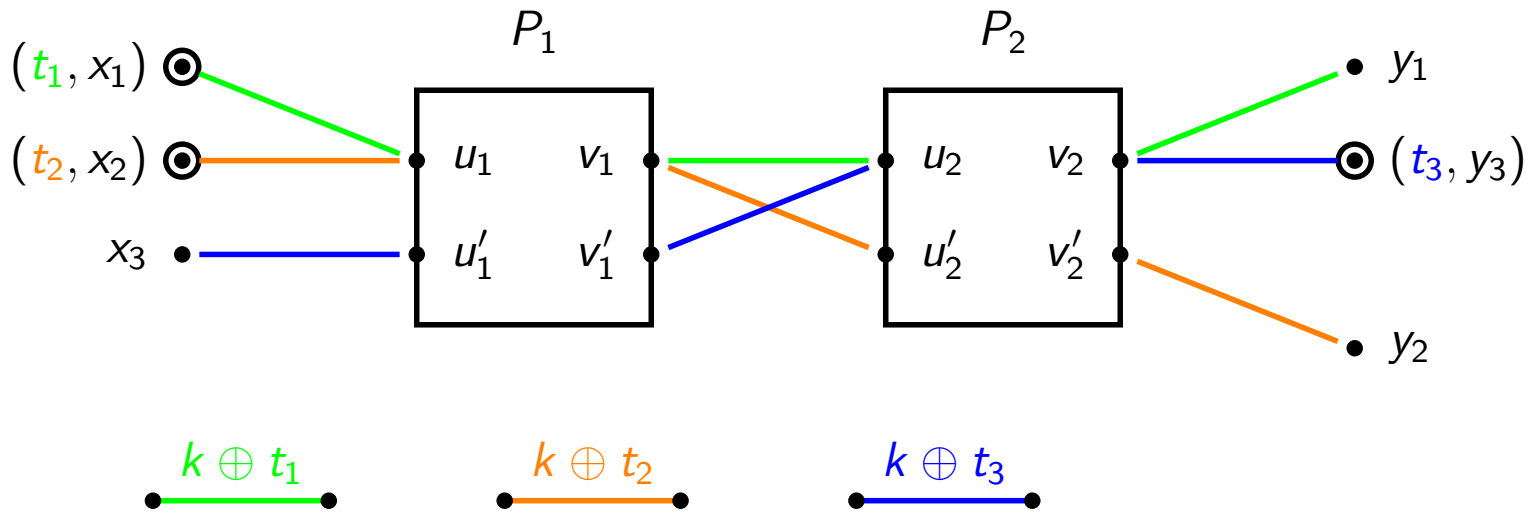

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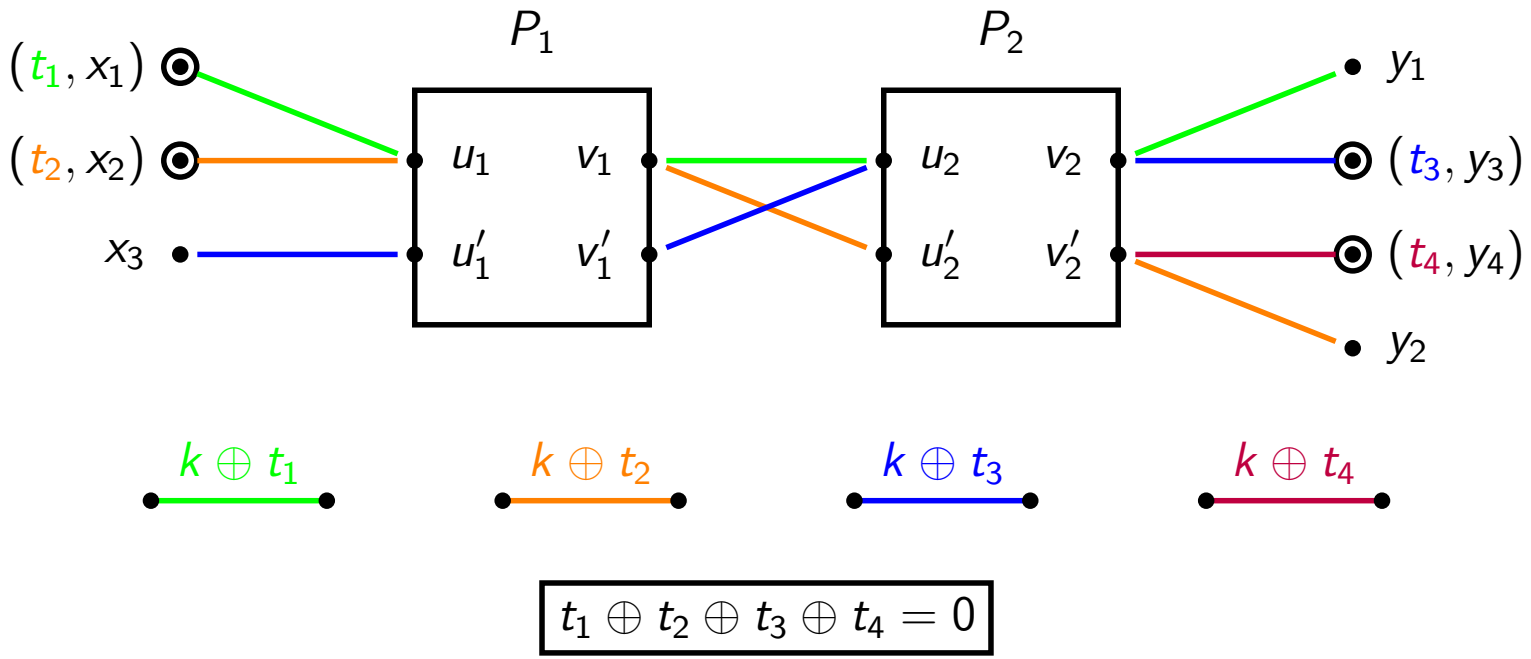

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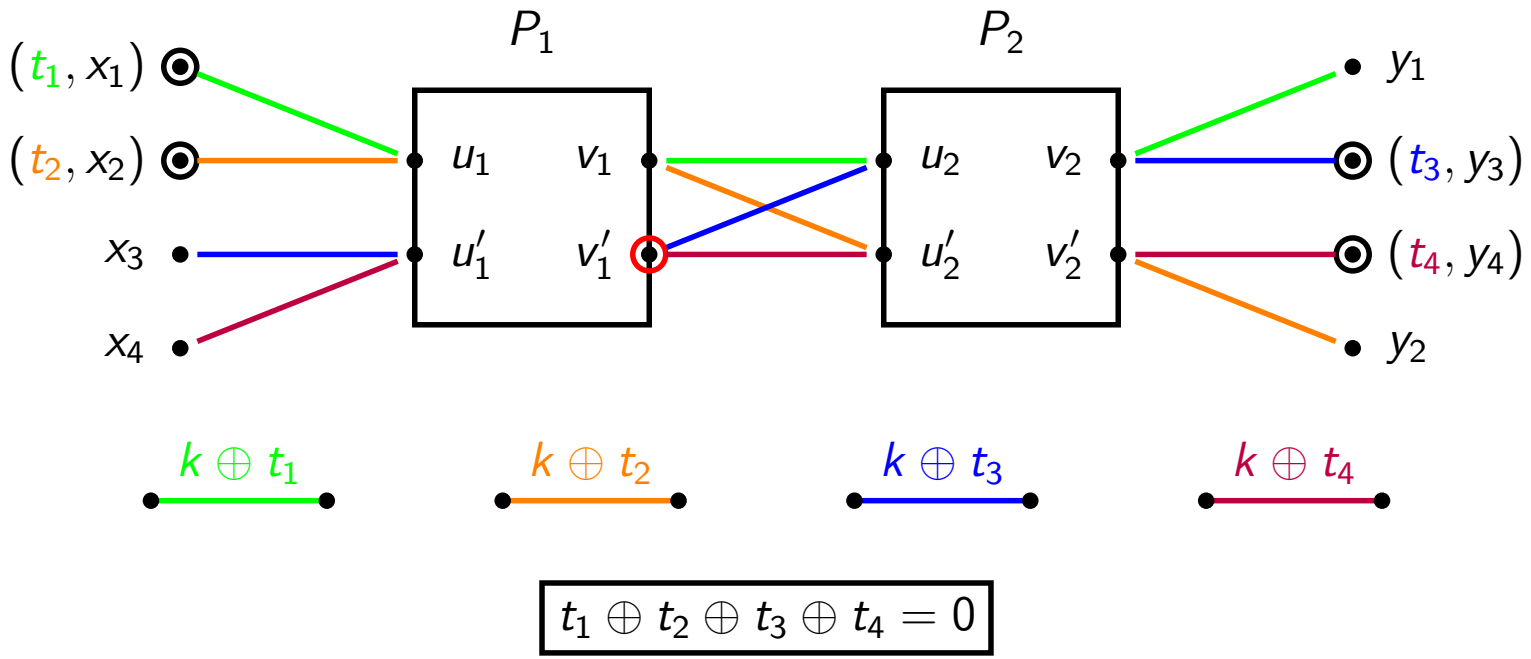

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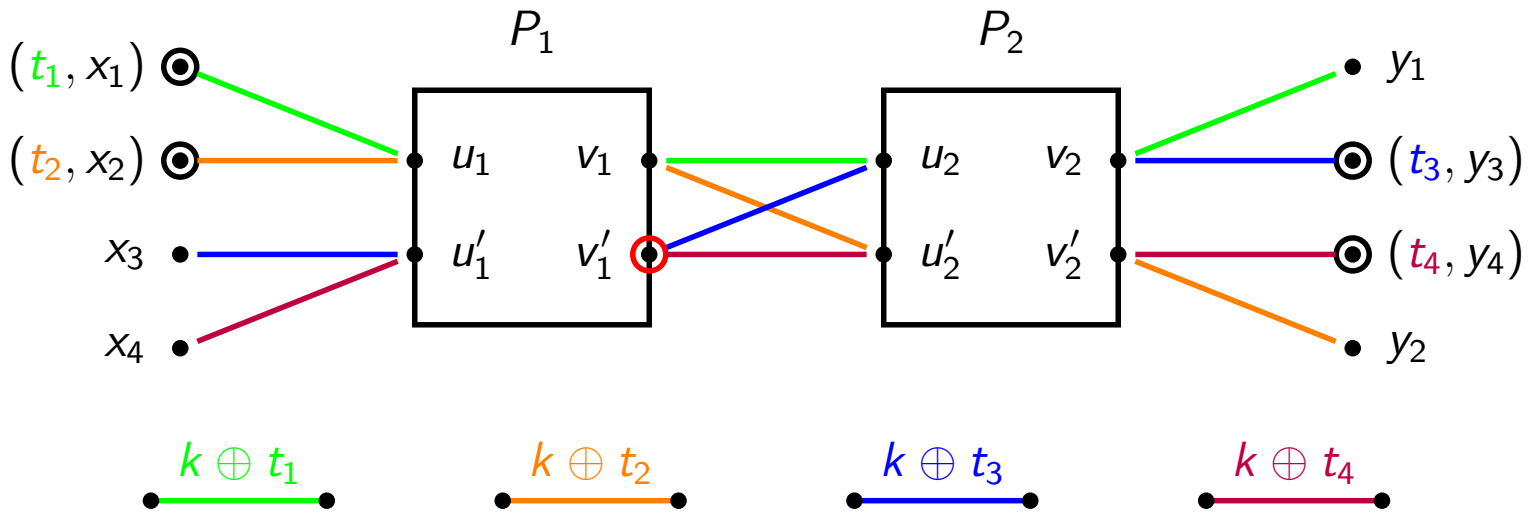

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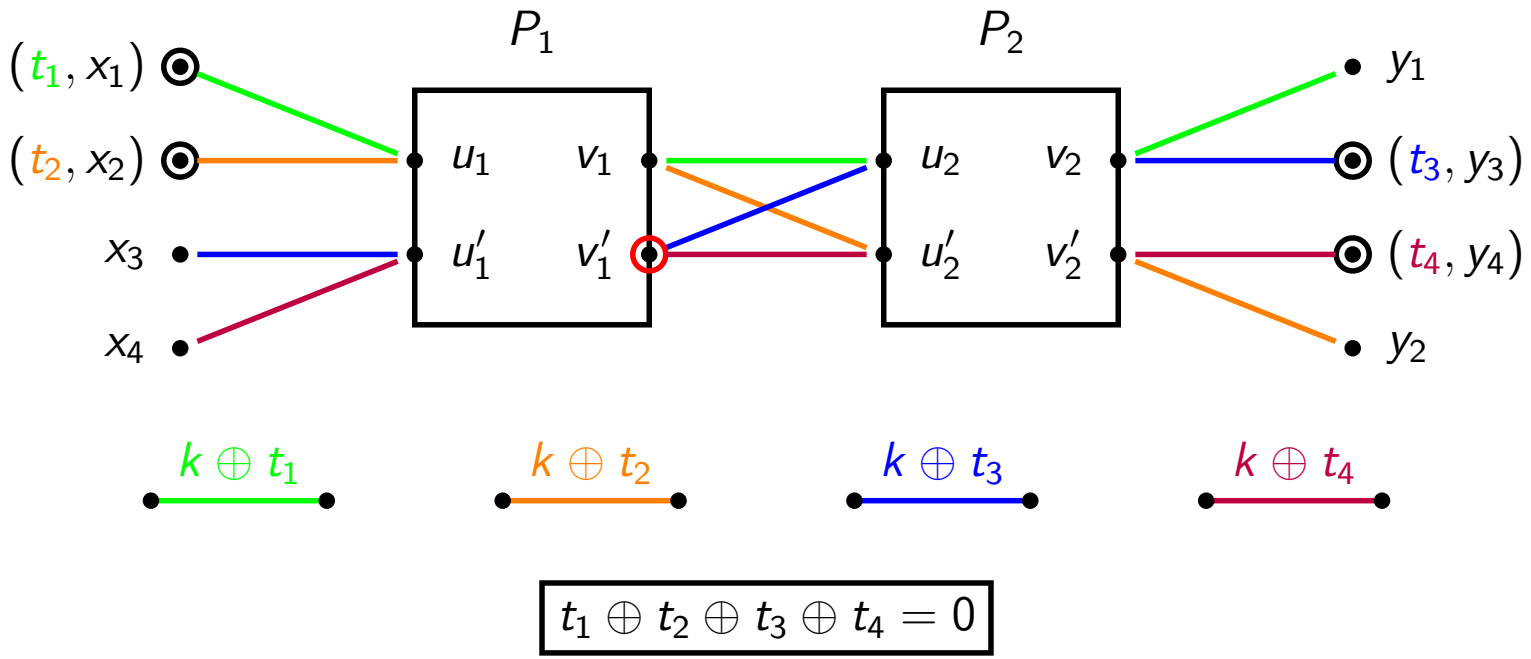

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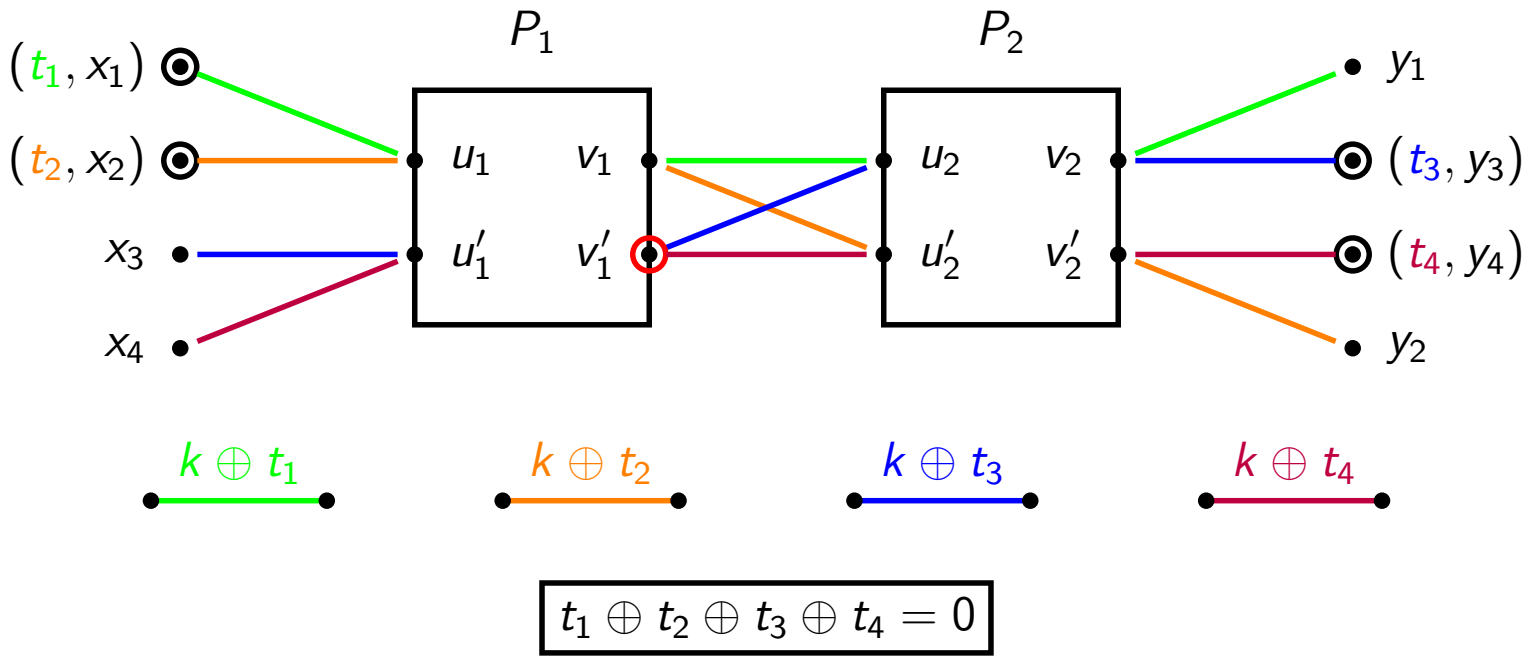

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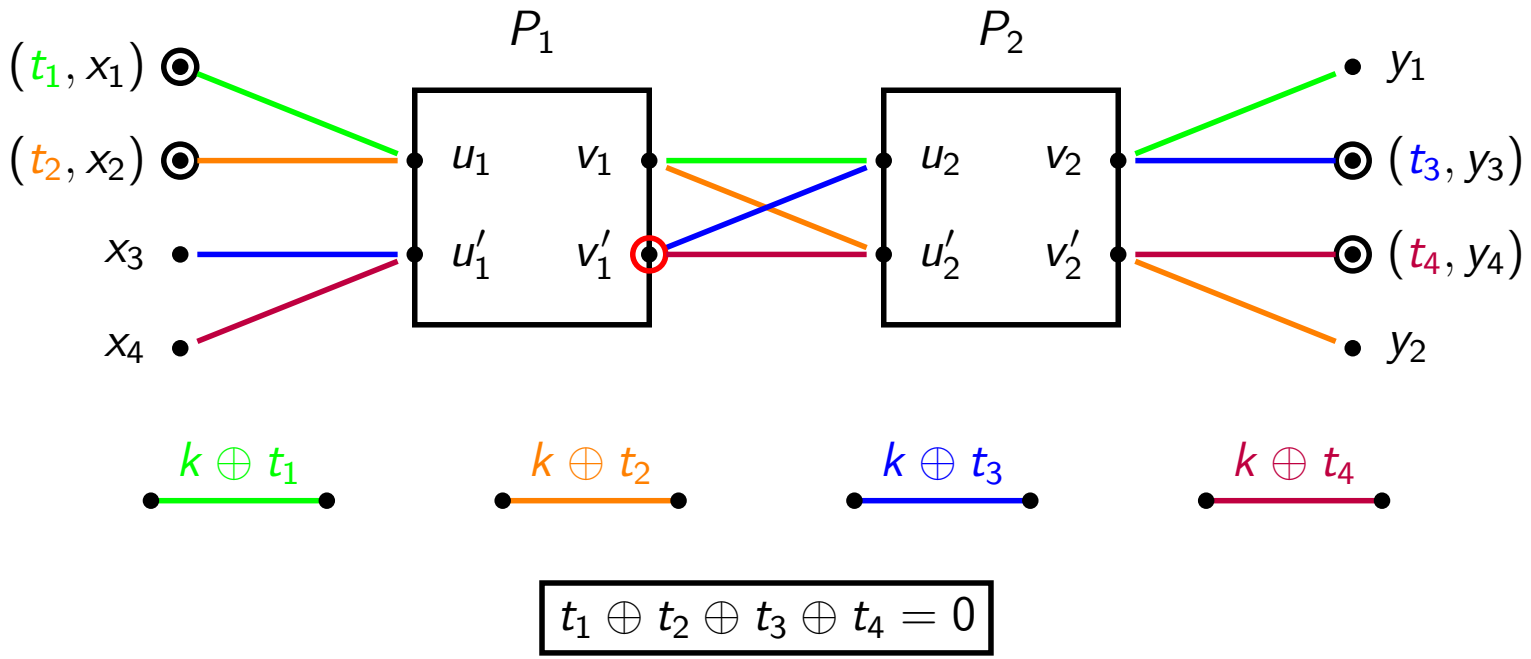

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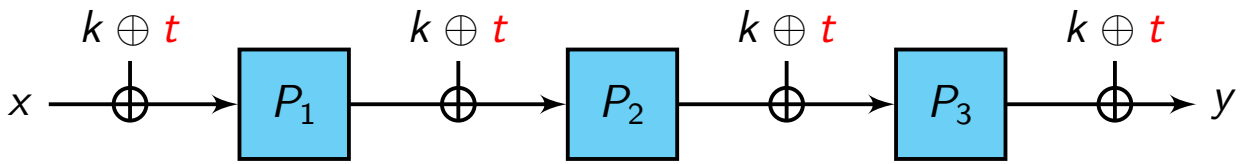
Security for Three Rounds



Theorem ([CS15, FP15])

The 3-round TEM with linear TKS is a strong tweakable PRP:

$$\mathbf{Adv}(q_c, q_p) \leq \frac{6q_c q_p}{2^n} + \frac{4q_c^2}{2^n}.$$

Proof sketch:

- adversary can create collisions at input of P_1 or output of P_3
- but proba. to create a collision at P_2 is $\lesssim q_c^2/2^n$
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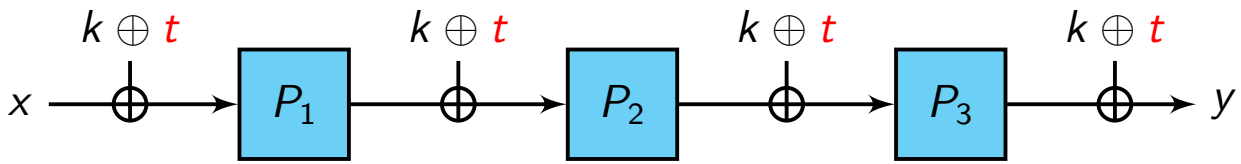

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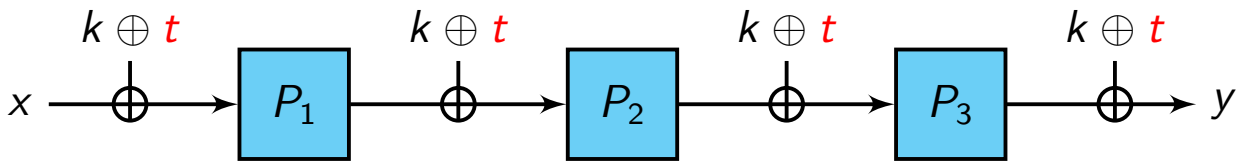

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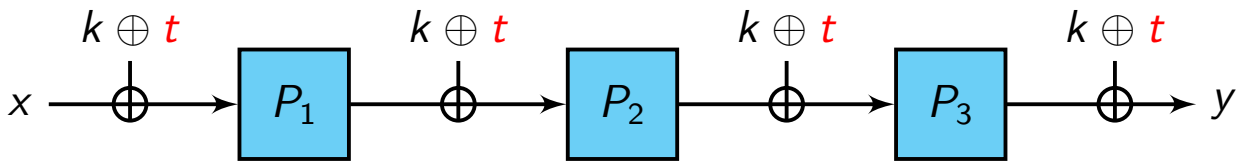

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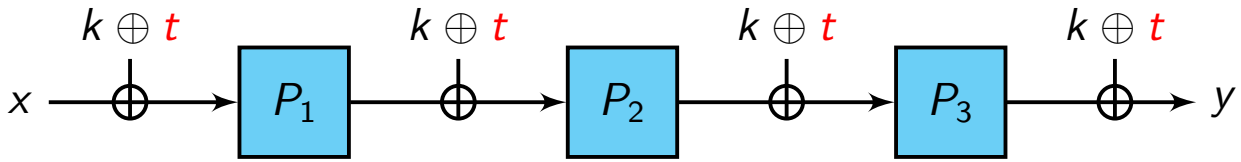
Tightness of the Bound



- can be written $\widetilde{E}(k, t, x) = E(k \oplus t, x)$ where E is the conventional 3-round EM cipher with trivial key-schedule
- $\Rightarrow$ secure up to $2^{n/2}$ queries *at best* by a simple collision attack:
  1. query $c_i = \widetilde{E}_{k^*}(t_i, 0) = E(k^* \oplus t_i, 0)$ for $2^{n/2}$ tweaks t_i
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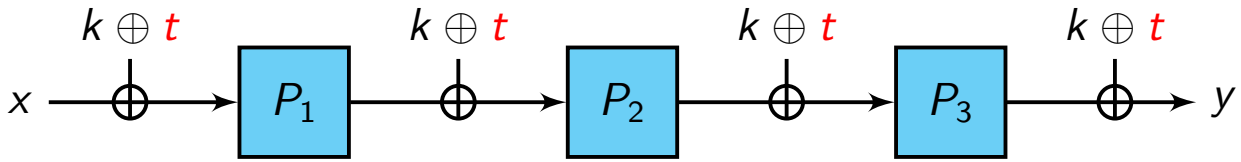

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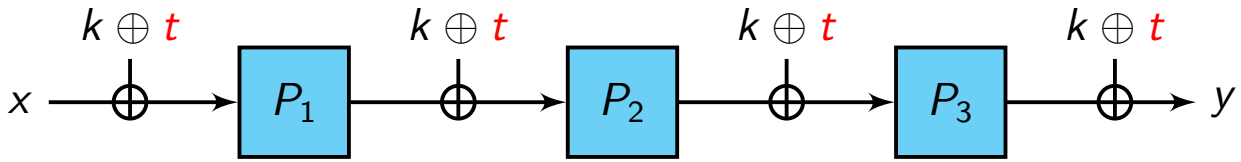

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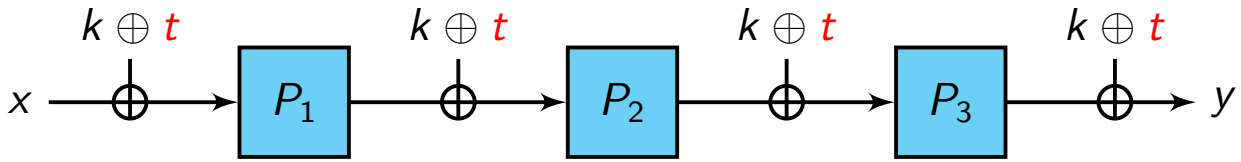

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Construction with less permutations?

Back to LRW

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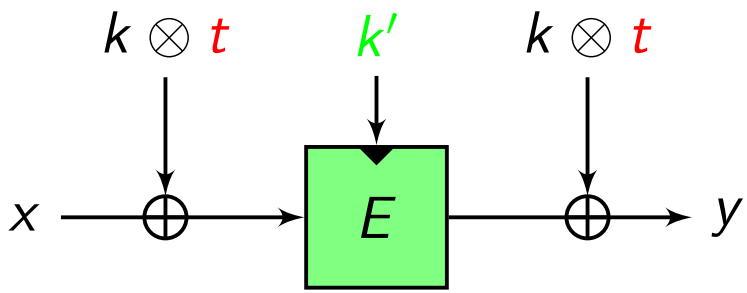

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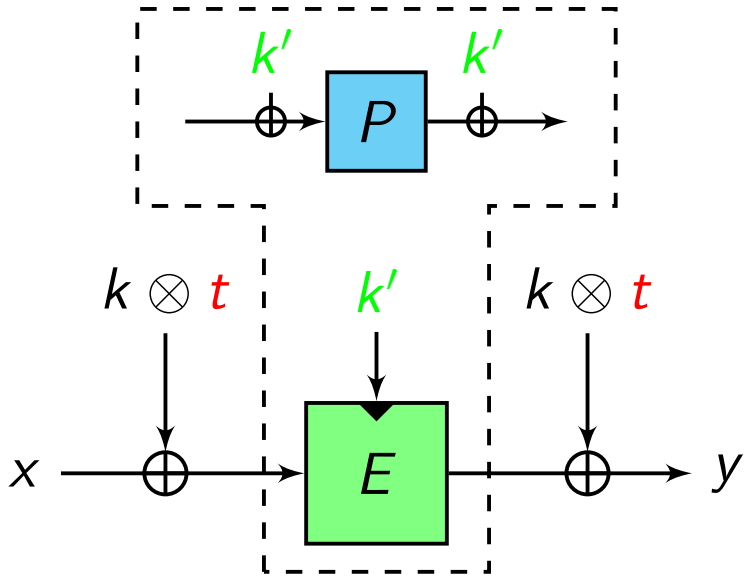

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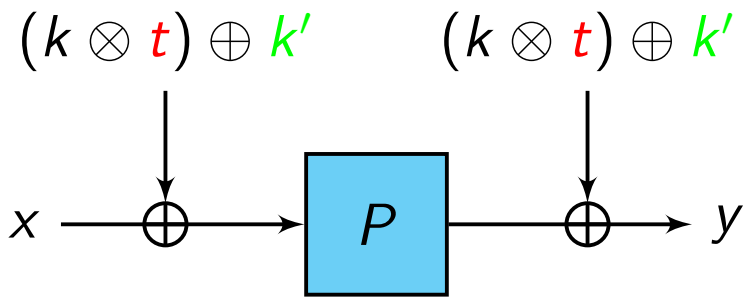

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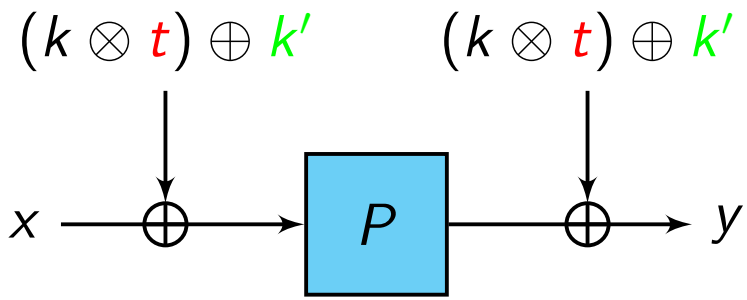

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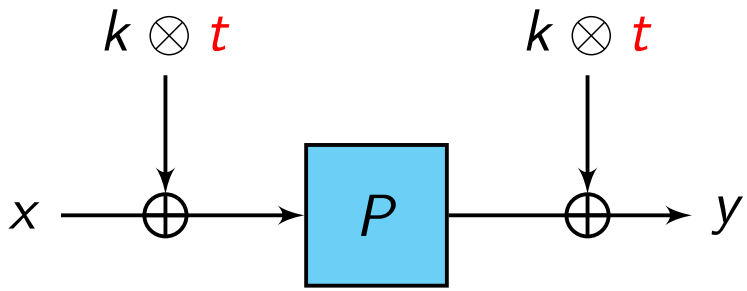

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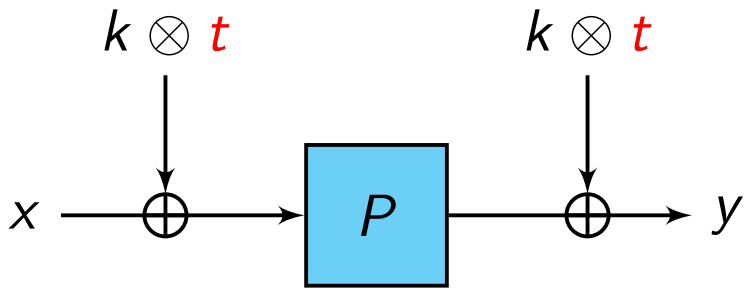
Non-Linear Tweakable Even-Mansour (NL-TEM) construction



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Birthday-Bound Security: Wrap-up

Two constructions provably secure up to the birthday bound:

1. linear TKS

2. nonlinear TKS

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Constructions secure beyond the birthday-bound?

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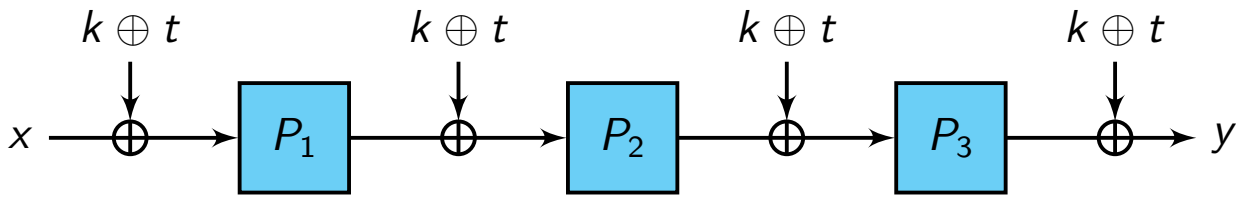

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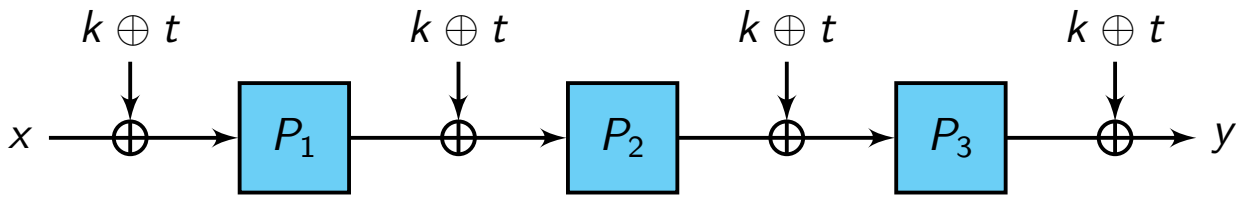

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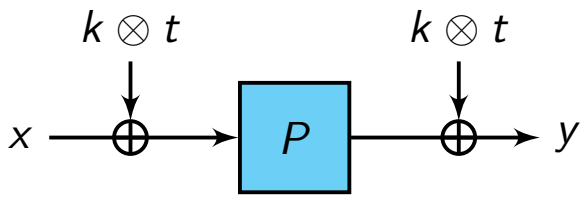

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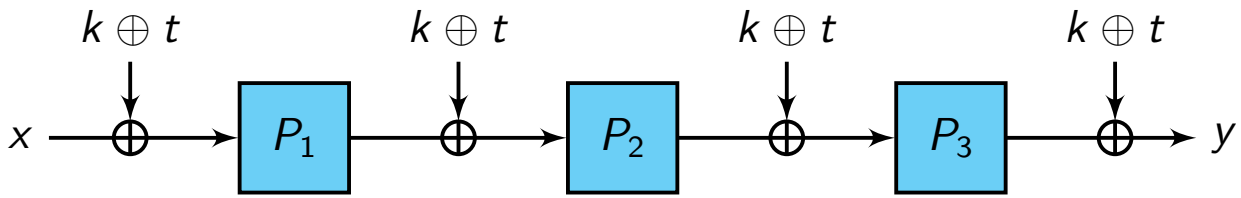

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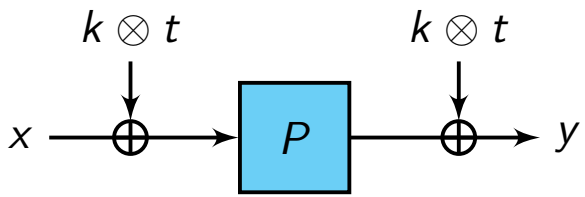

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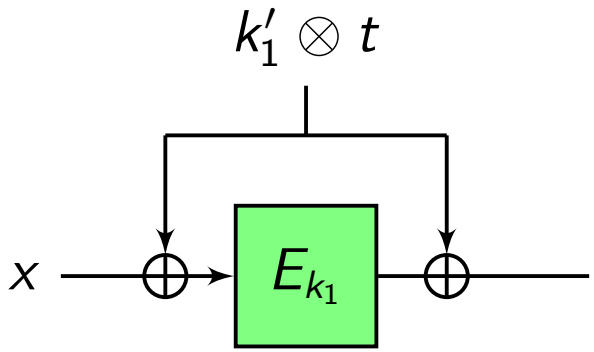
Outline

Cascading the LRW Construction



- $k_1, \ldots, k_r$ and $k_1', \ldots, k_r'$ independent keys
  $\Rightarrow$ total key-length $= r(\kappa + n)$
- 2 rounds: provably secure up to $\sim 2^{2n/3}$ queries [LST12]
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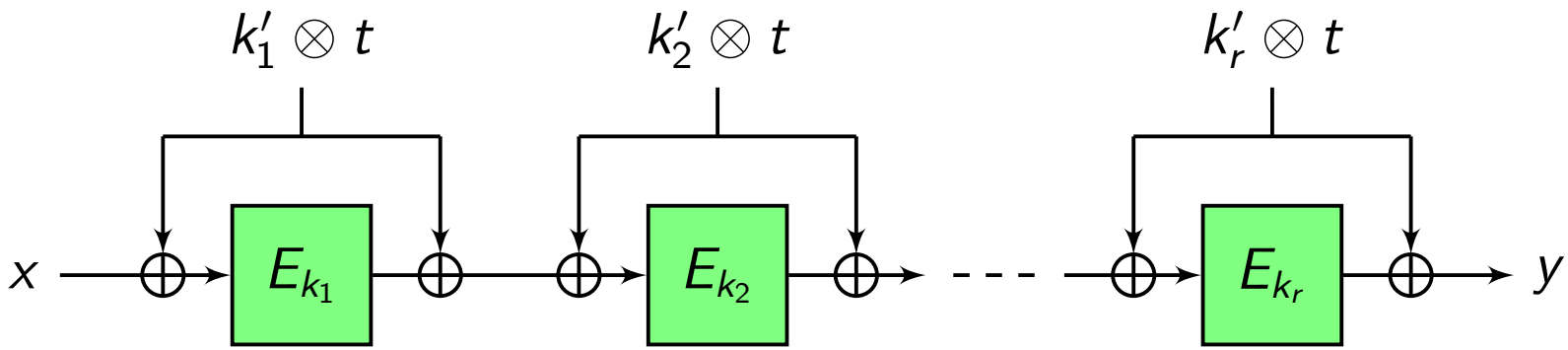

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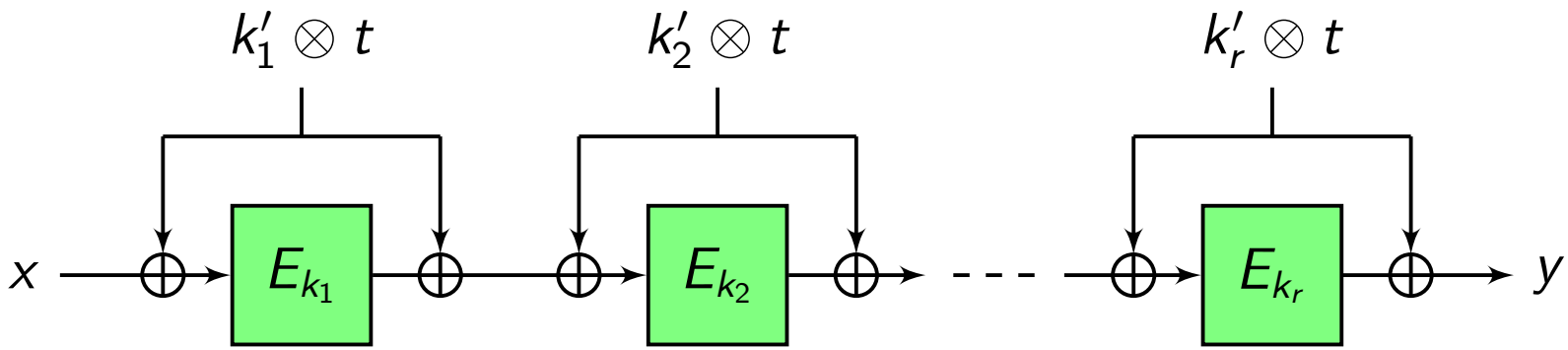

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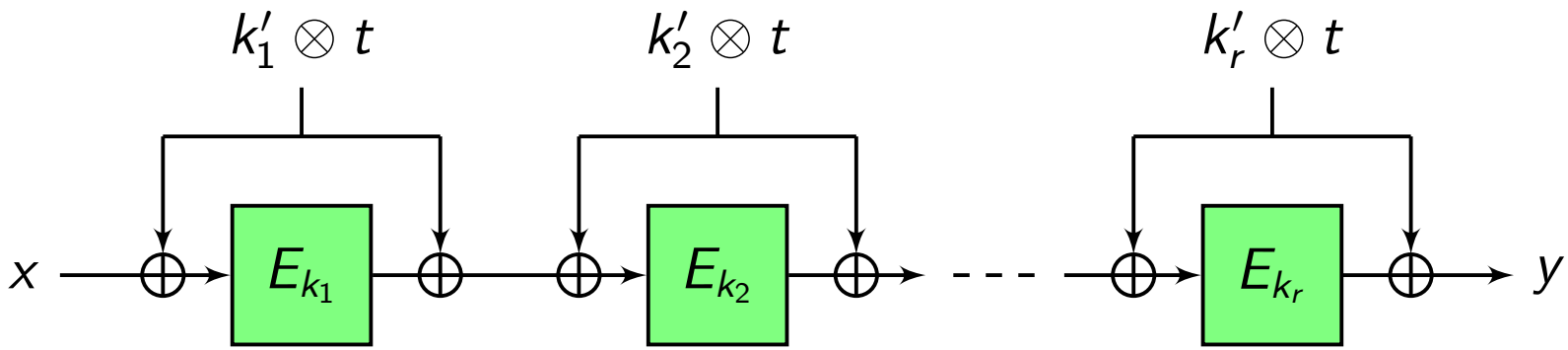

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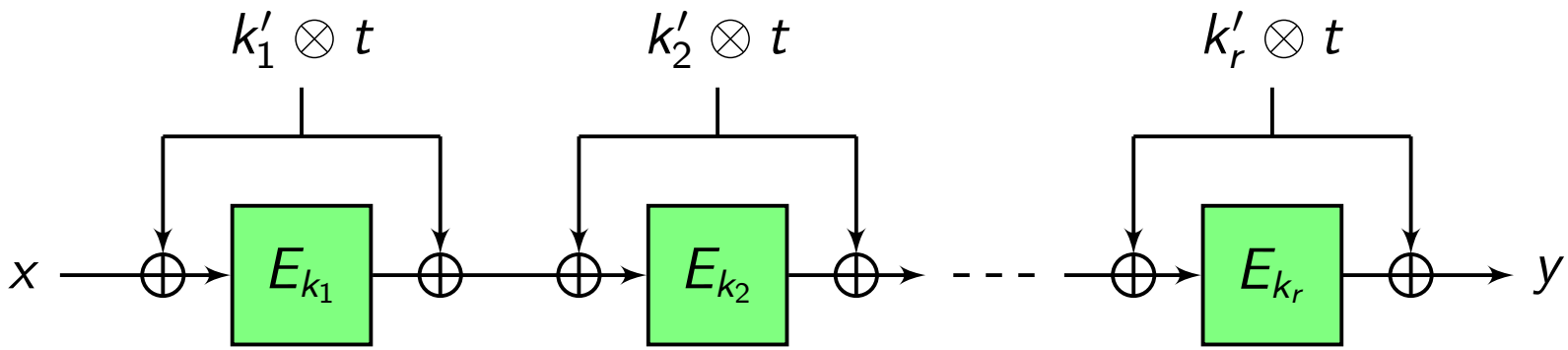

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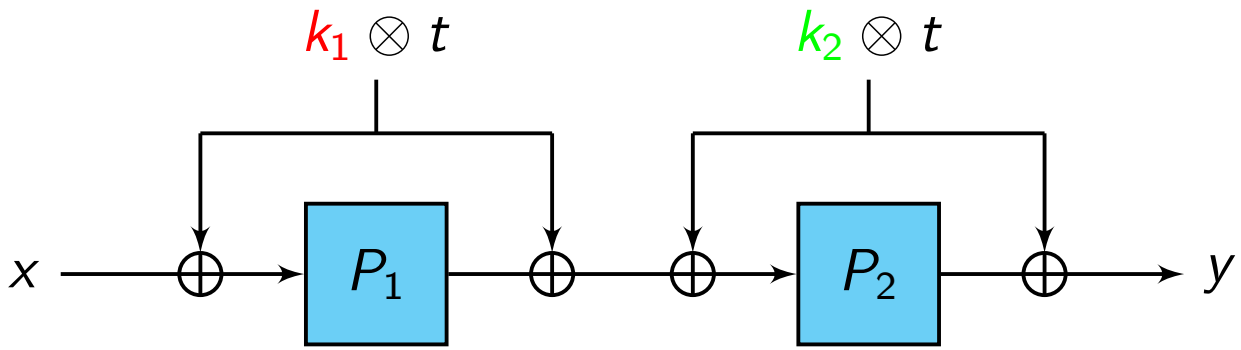

Theorem ([CLS15])

The 2-round NL-TEM construction is secure up to $\sim 2^{2n/3}$ queries in the RPM:

$$\mathbf{Adv}(q_c, q_p) \leq \frac{34 q_c^{3/2}}{2^n} + \frac{30\sqrt{q_c} q_p}{2^n}.$$

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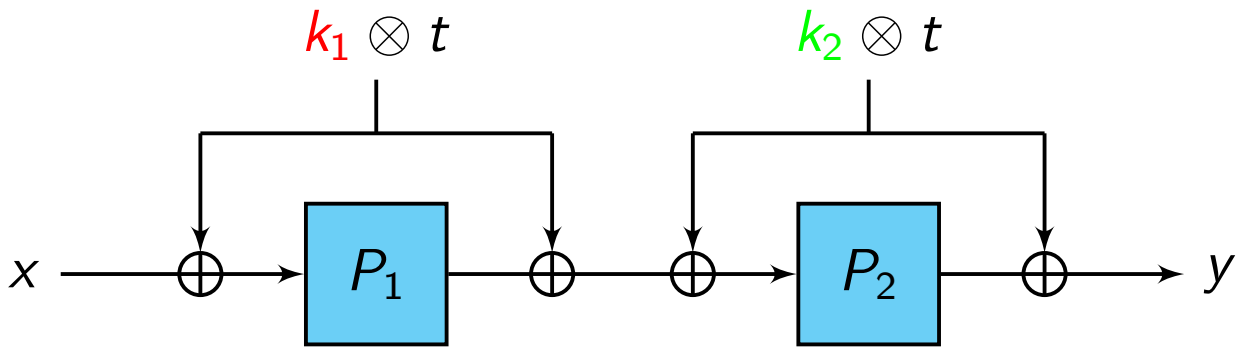

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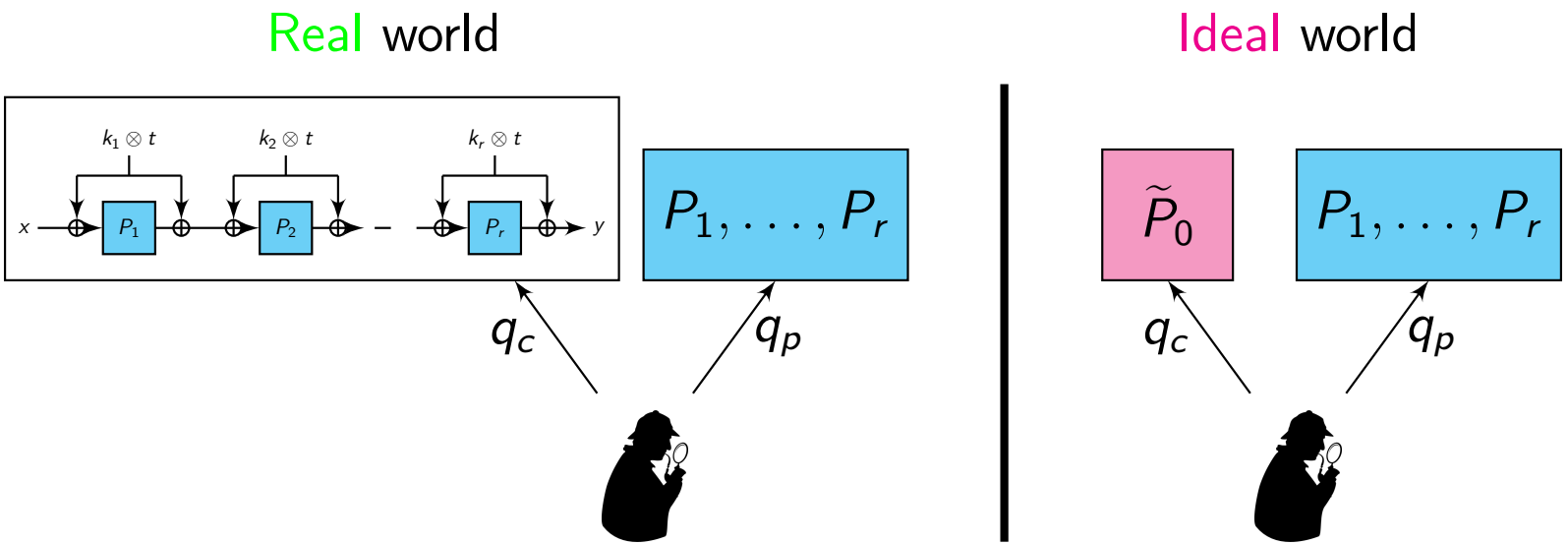

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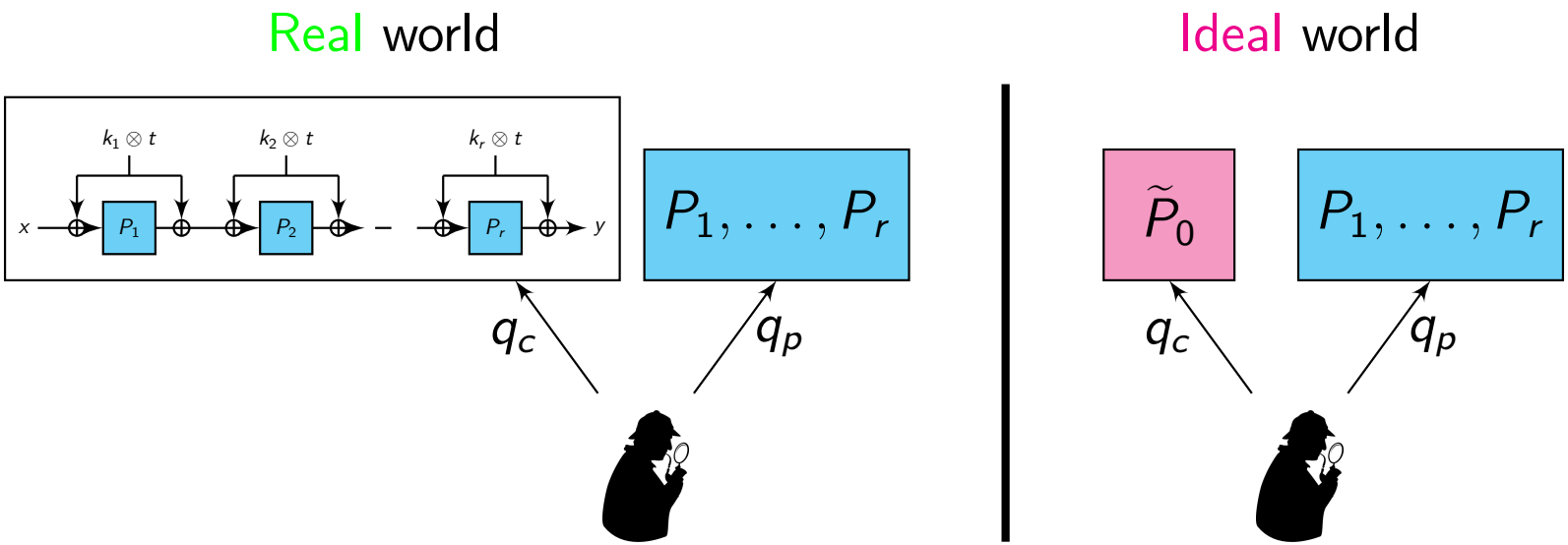

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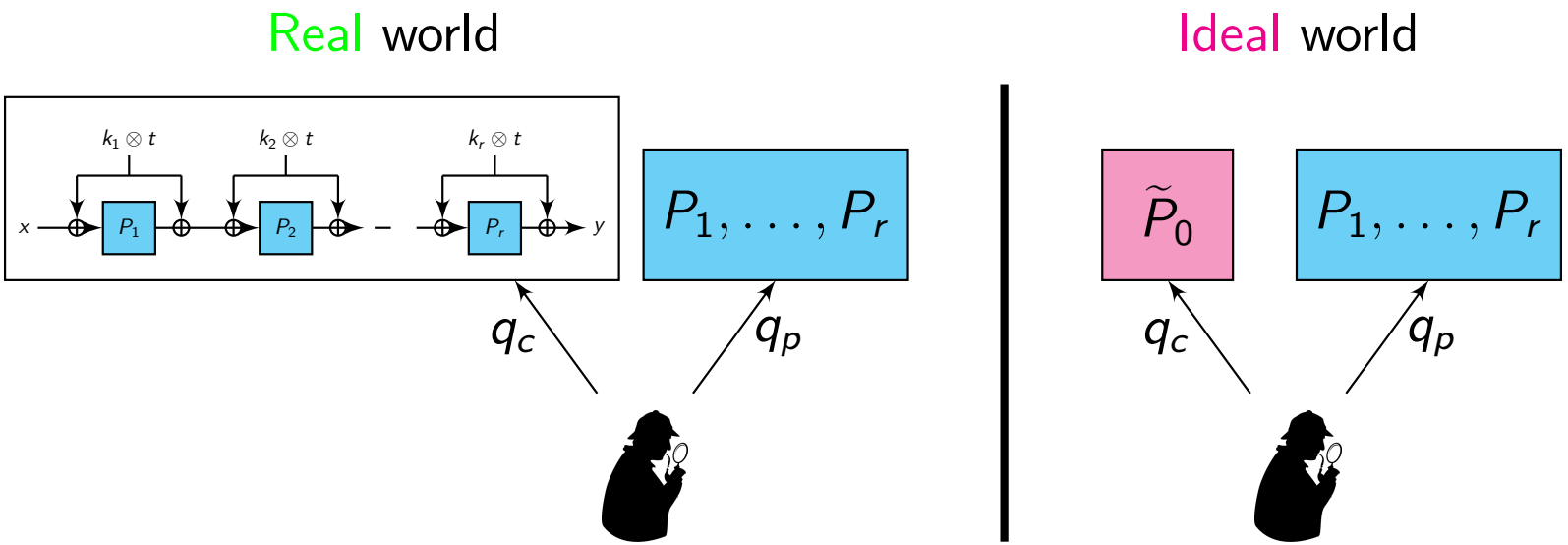

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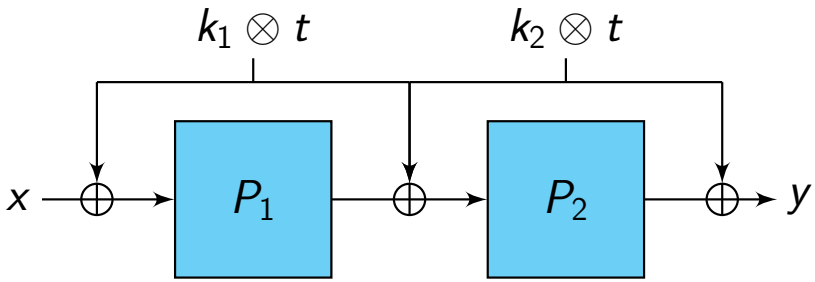

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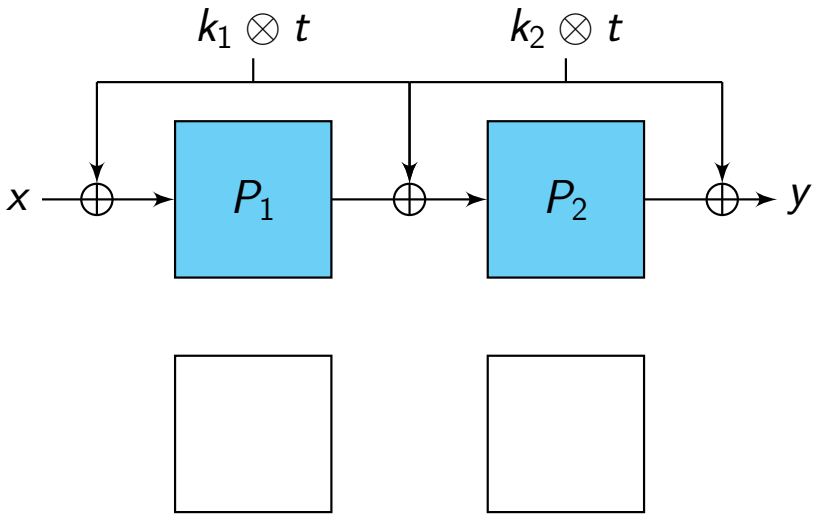

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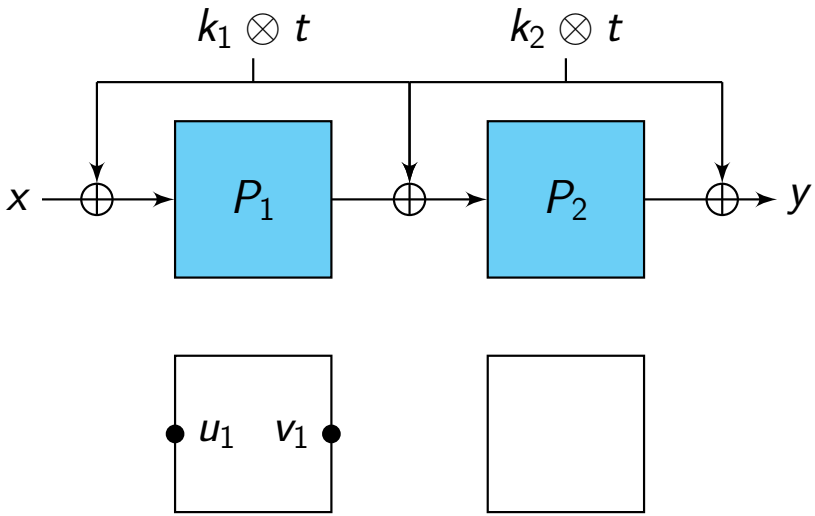

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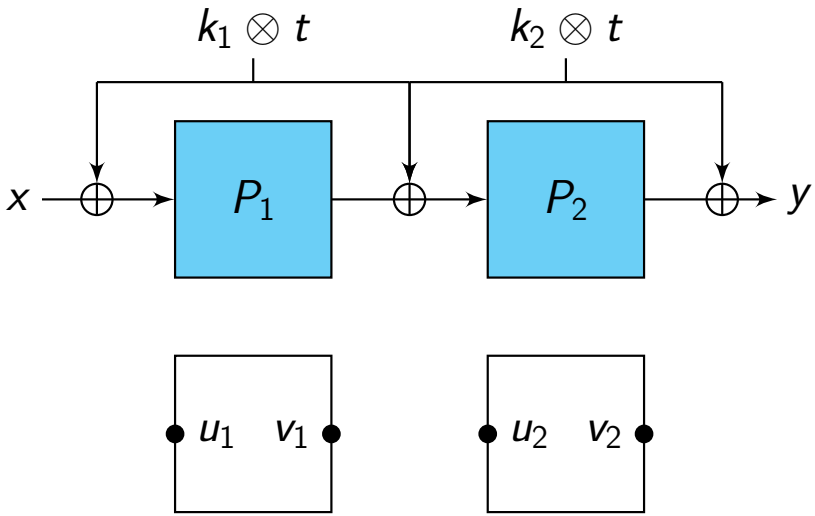

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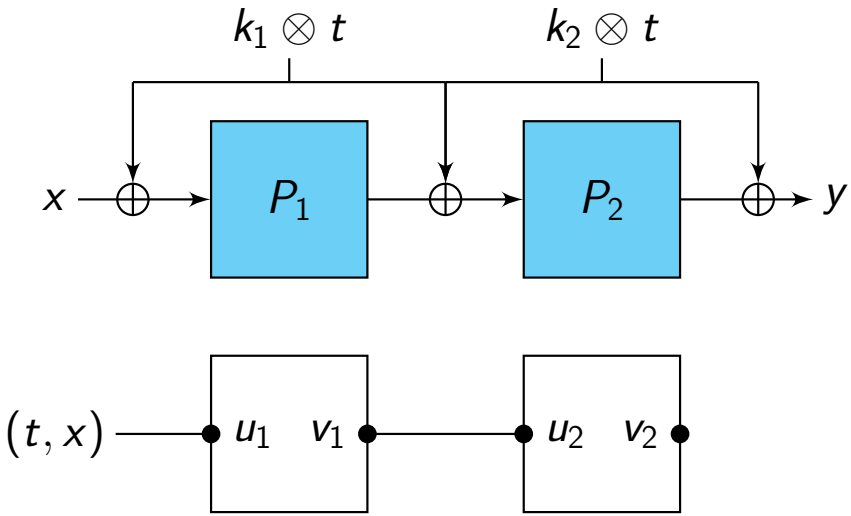

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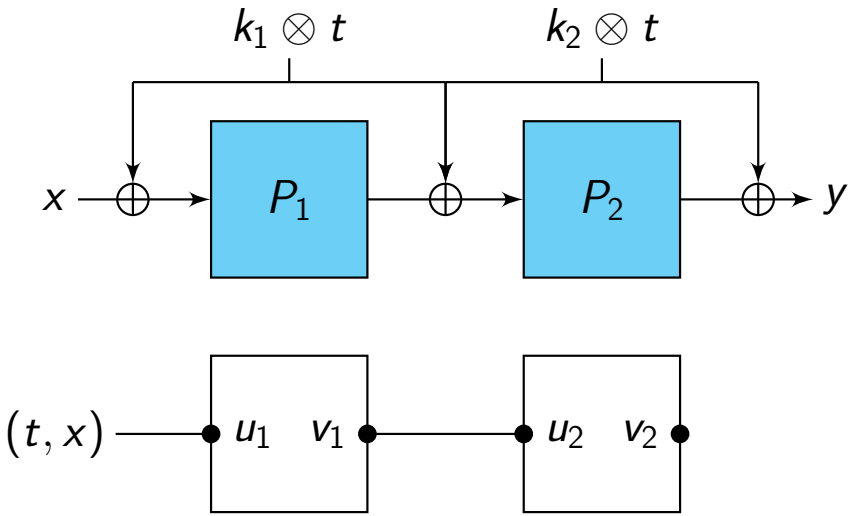

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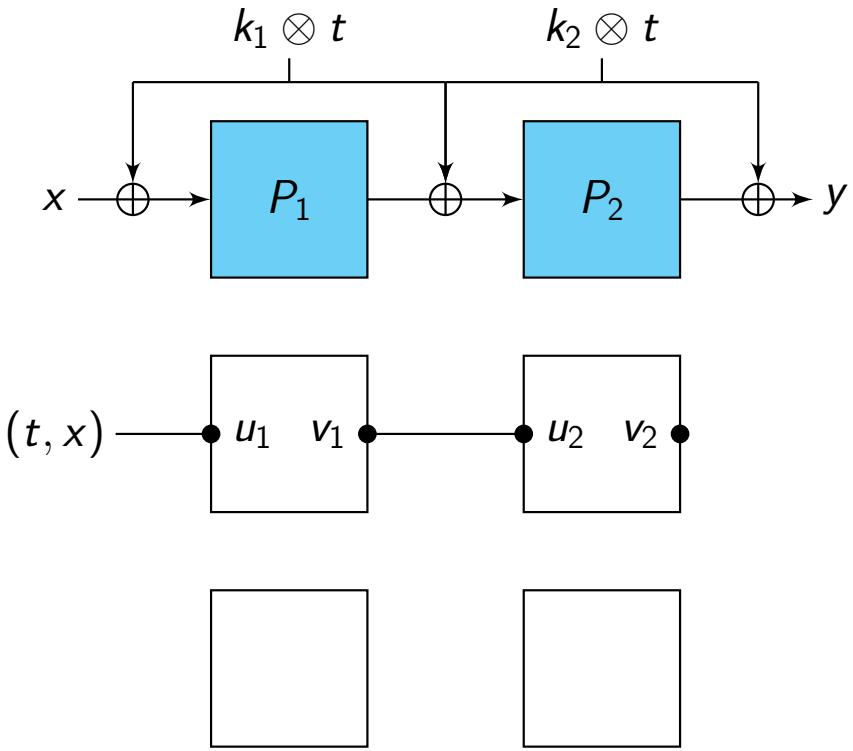

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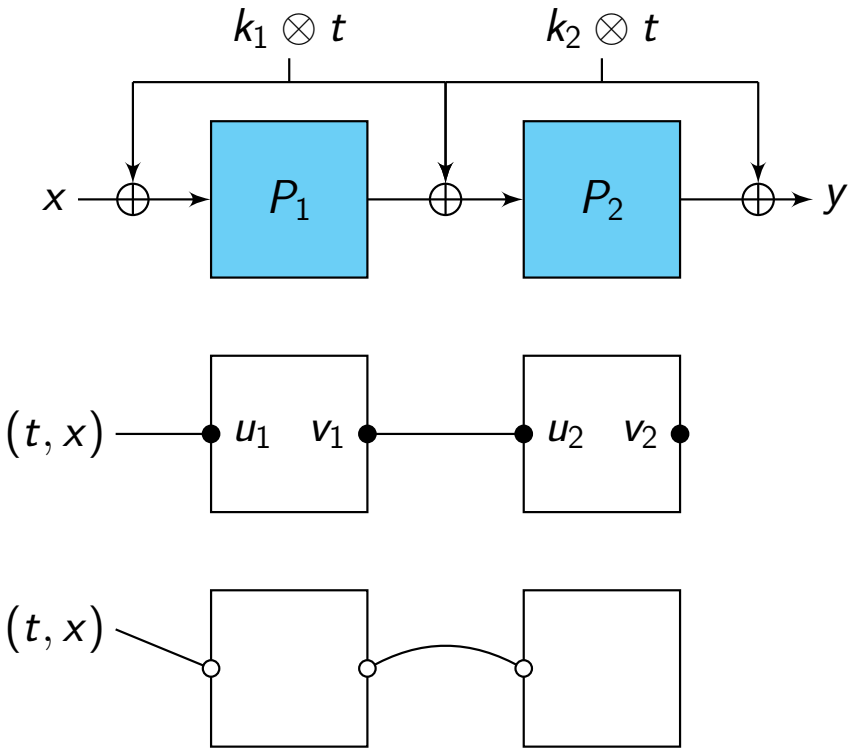

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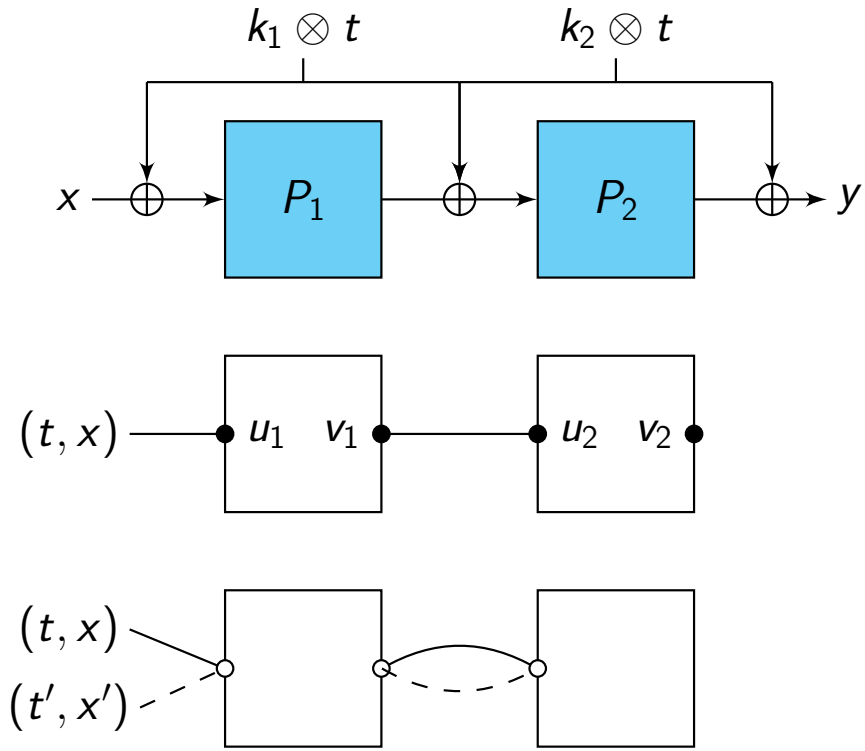

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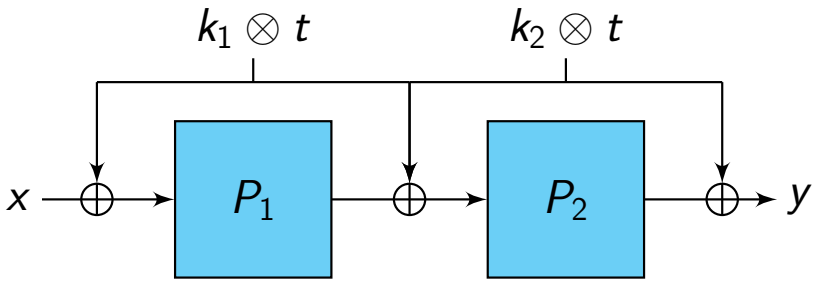

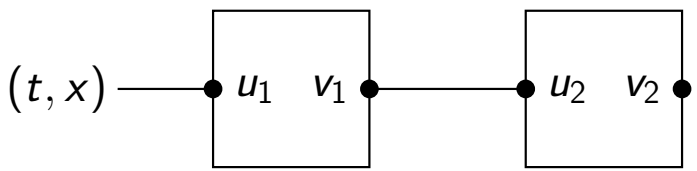

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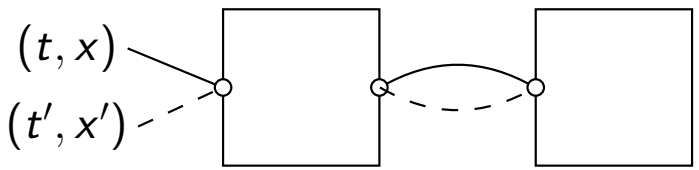

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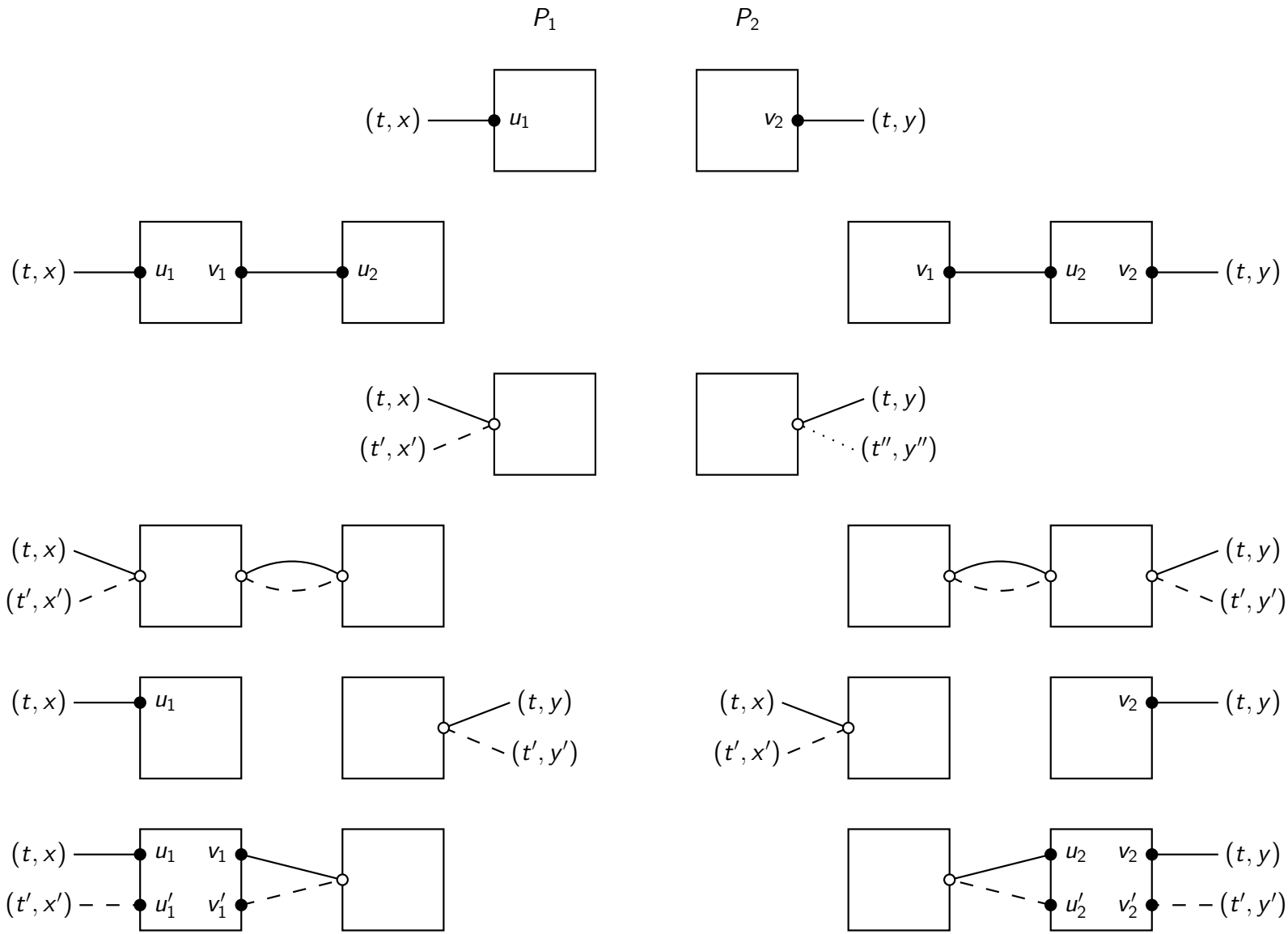

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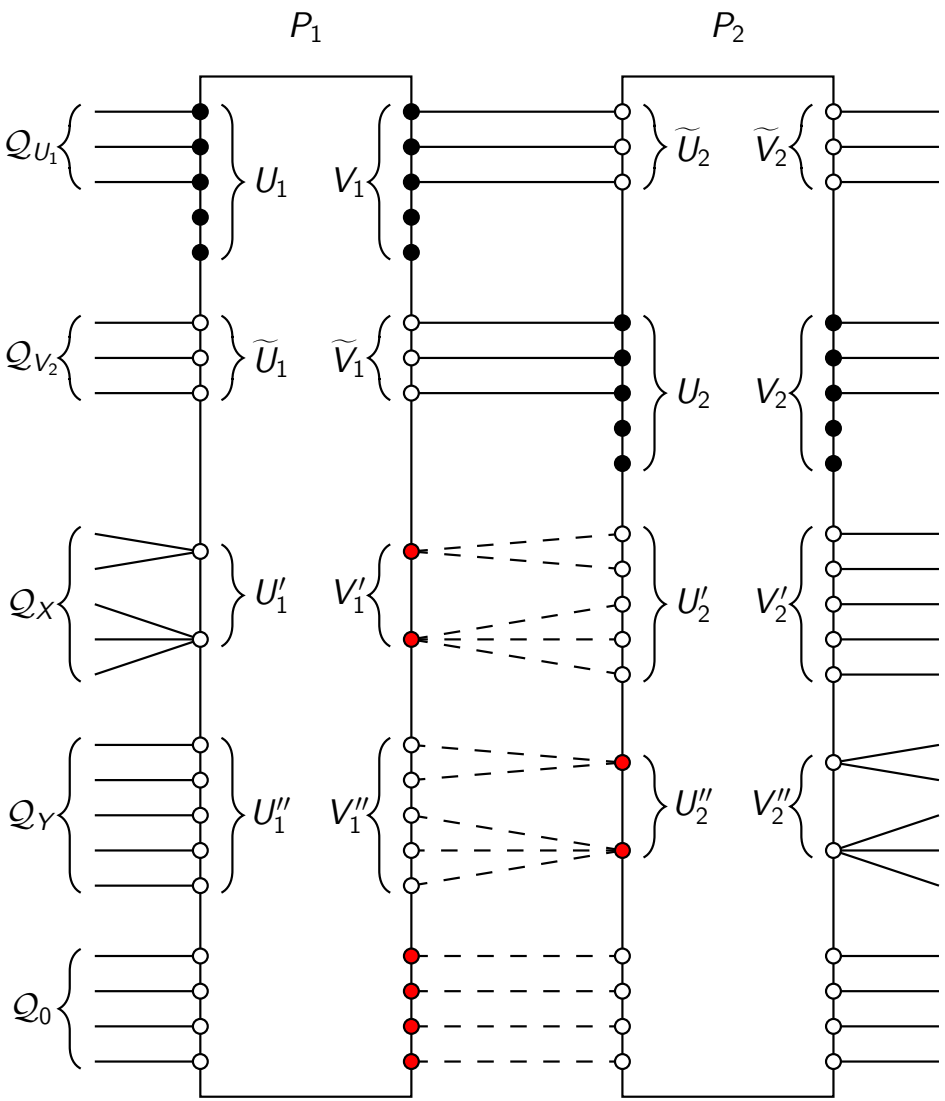

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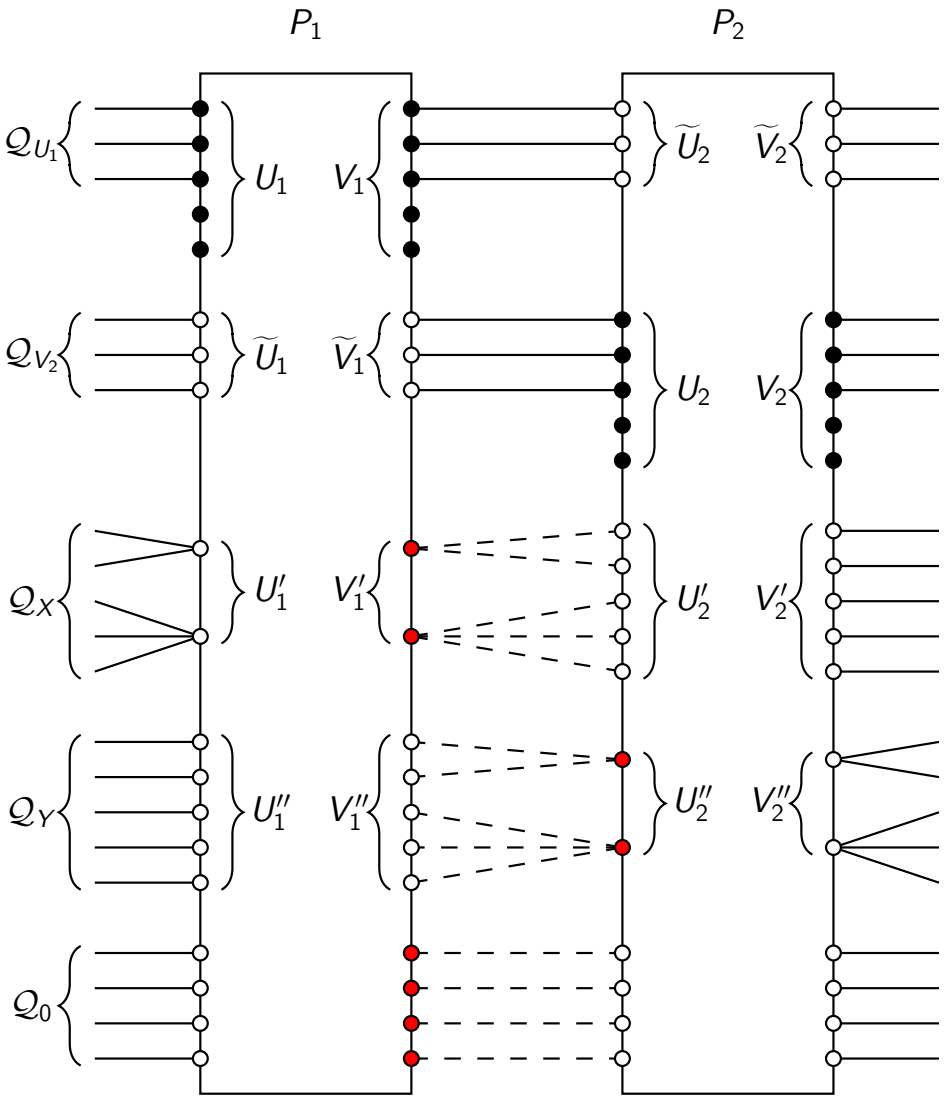

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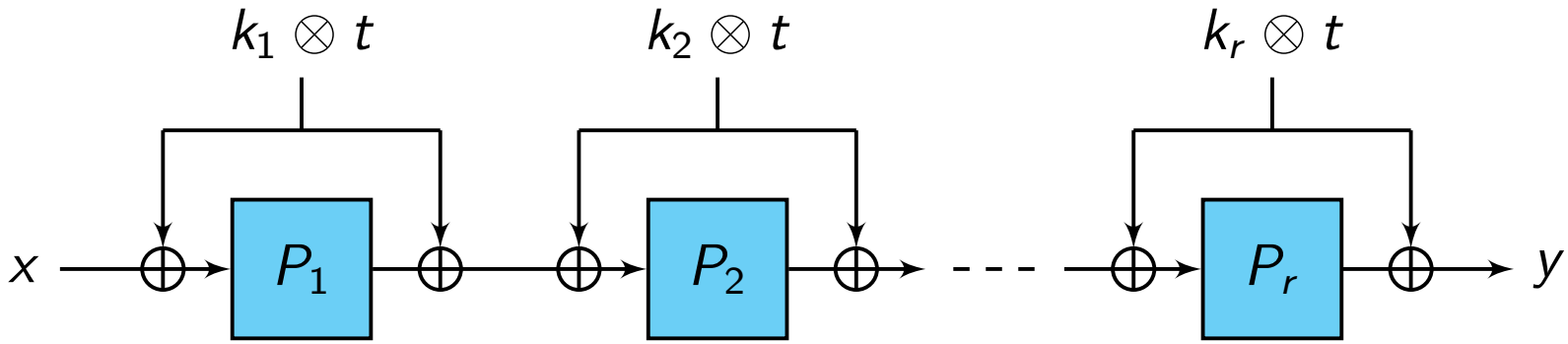

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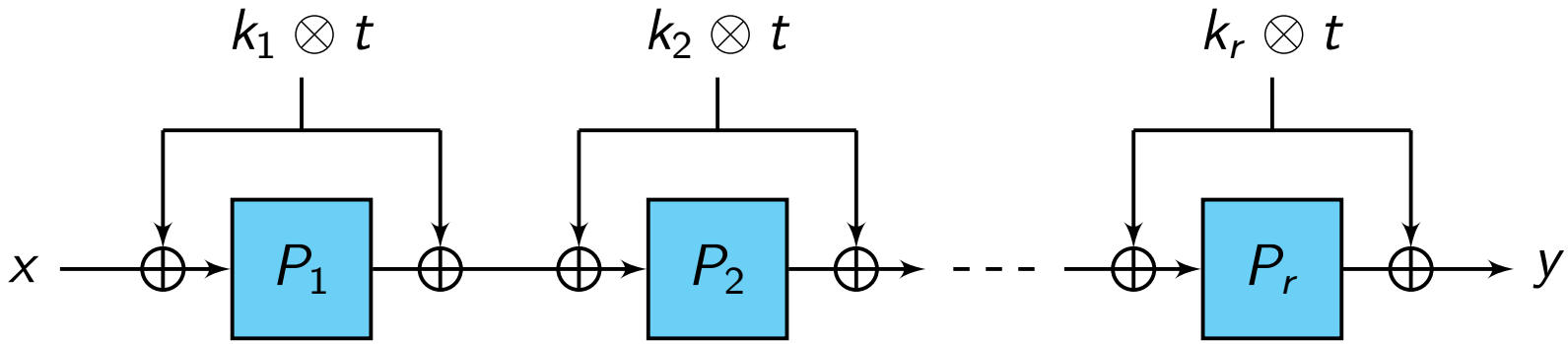

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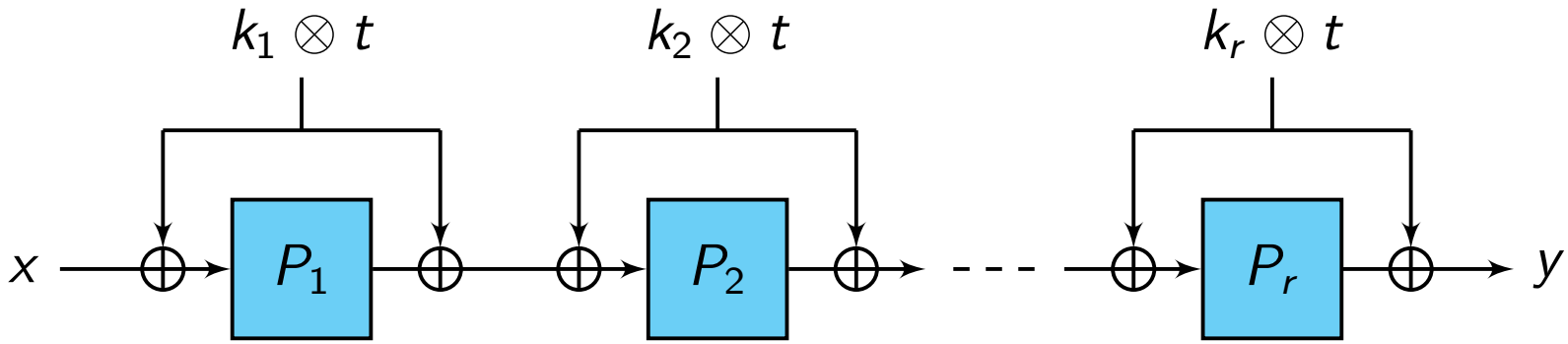

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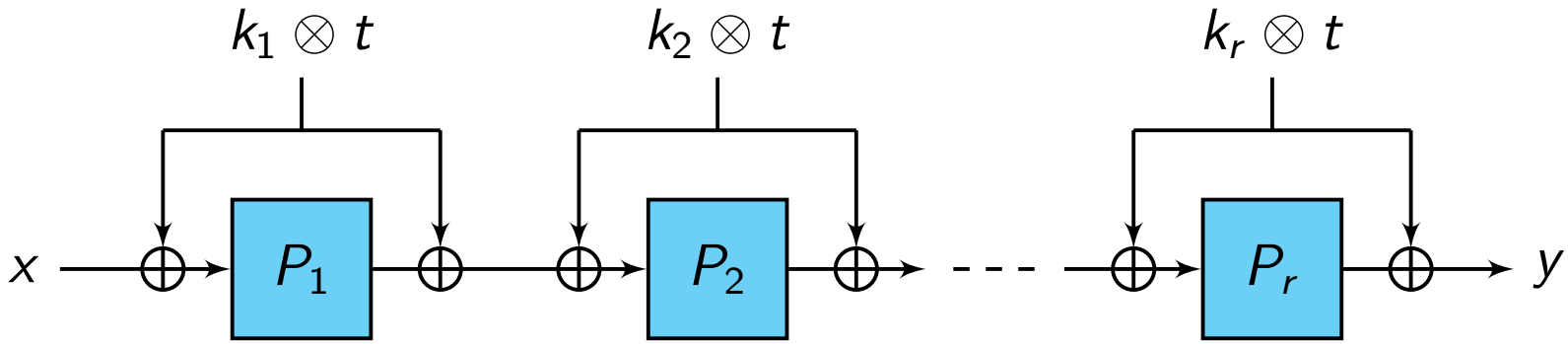

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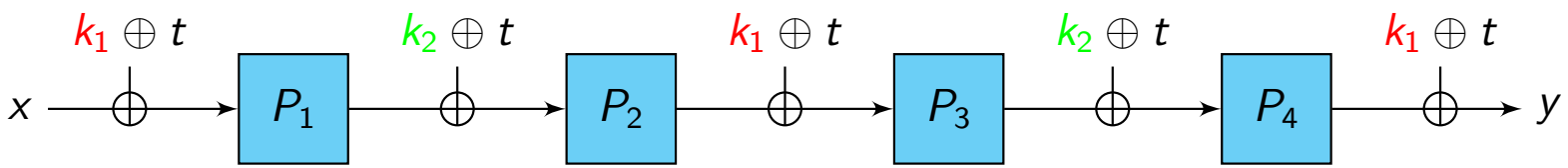

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The 4-round TEM with "alternating" linear TKS is secure up to $\sim 2^{2n/3}$ queries in the RPM.

Proof idea:

- exclude bad events related to P_1 and P_4
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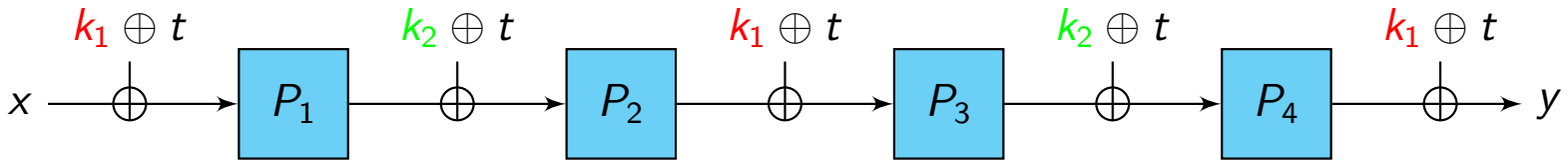

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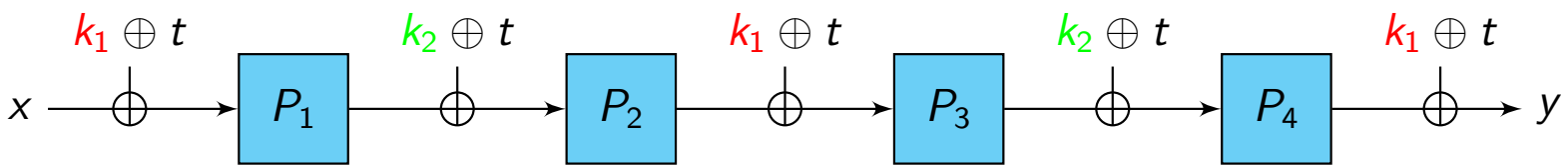

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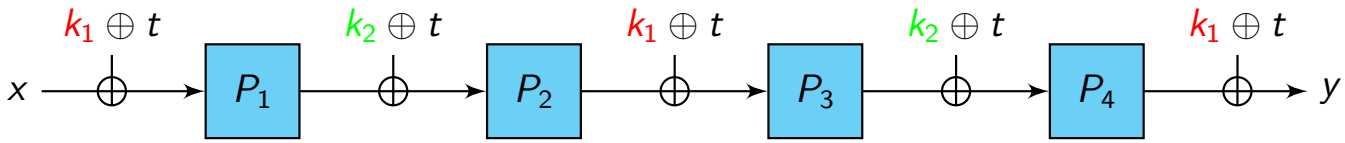

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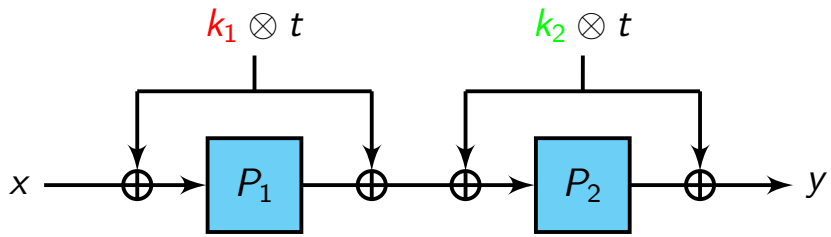

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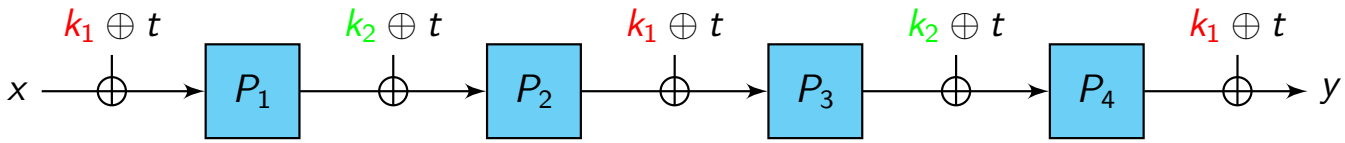

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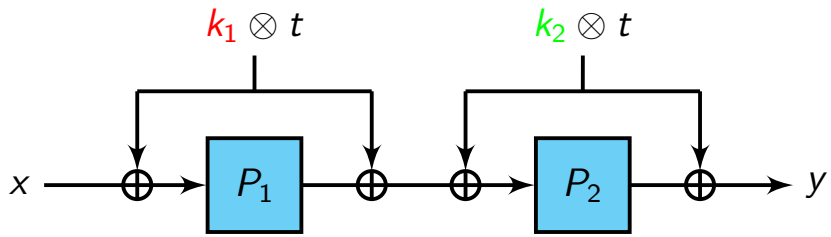

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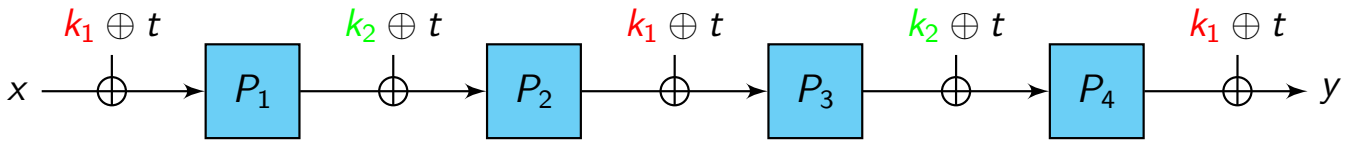

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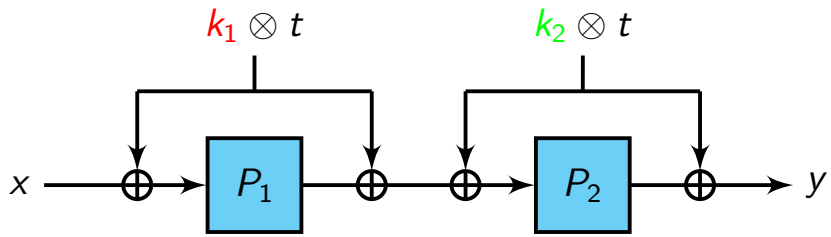

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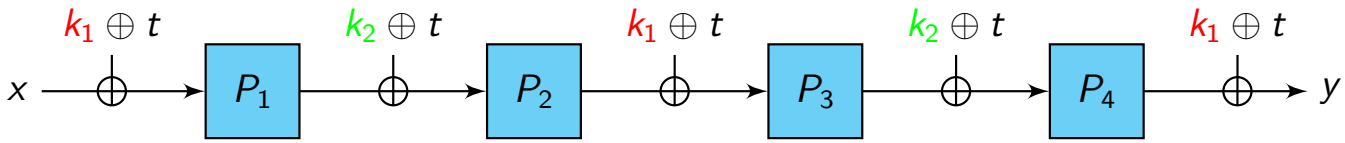

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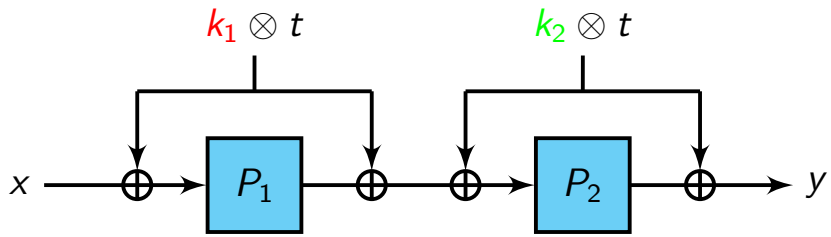

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Link with the TWEAKEY Framework

- proposed by Jean, Nikolić, and Peyrin [JNP14]
- Superposition TWEAKEY (STK) constructions:

- sufficient conditions on f and g to have provable beyond-birthday-bound security in the RPM?
- NB: $f = g$ linear does not work since $\widetilde{E}(k, t, x) = E(k \oplus t, x)$

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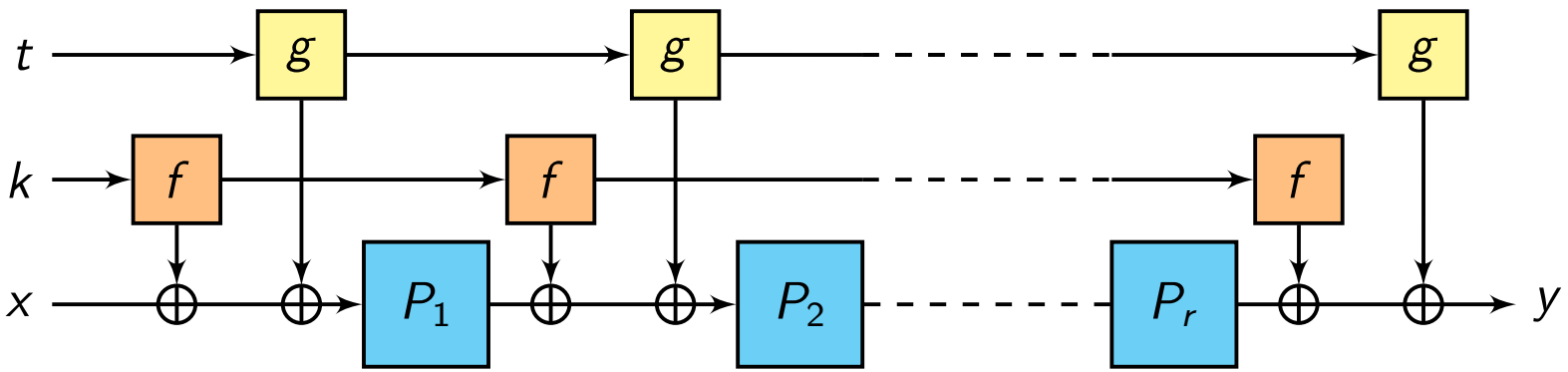

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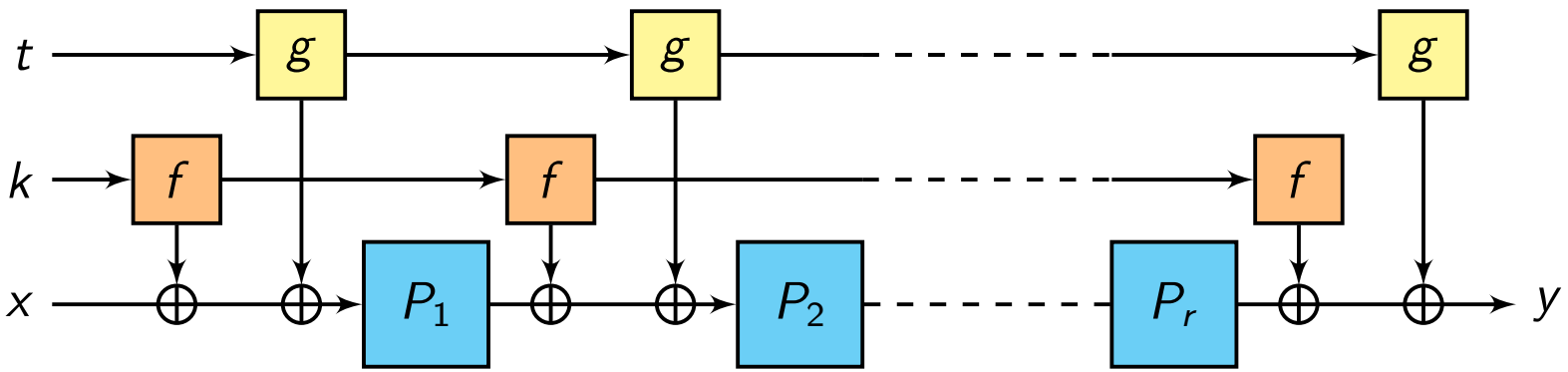

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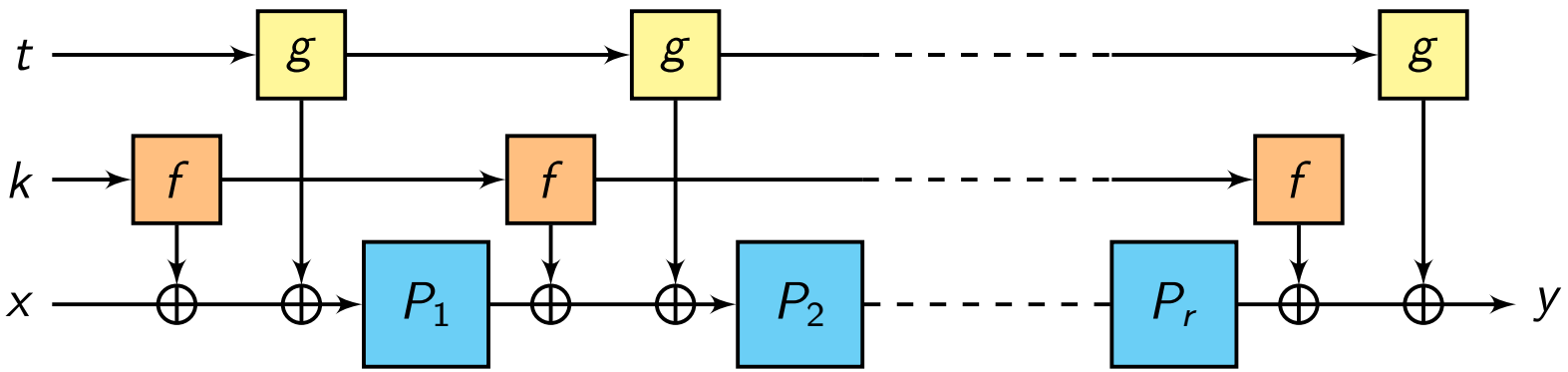

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The end...

Thanks for your attention!

Comments or questions?

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