On the Provable Security of the Iterated Even-Mansour Cipher against Related-Key and Chosen-Key Attacks

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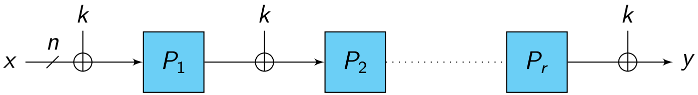
[2]ANSSI, France

April 16, 2015 — ENS Paris

One-Slide Digest



1 round: PRP

3 rounds: XOR-Related-Key-Attacks PRP

4 rounds: Chosen-Key-Attacks Resistance

12 rounds: Full indifferentiability from an ideal cipher

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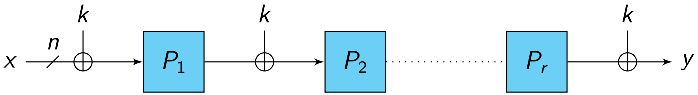

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Outline

Introduction: Key-Alternating Ciphers in the Random Permutation Model

Security Against Related-Key Attacks

Security Against Chosen-Key Attacks

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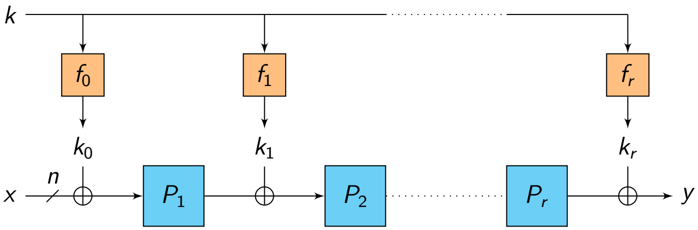
Key-Alternating Cipher (KAC): Definition



An r-round key-alternating cipher:

- plaintext $x \in \{0,1\}^n$, ciphertext $y \in \{0,1\}^n$
- master key $k \in \{0,1\}^\kappa$
- the P_i's are public permutations on $\{0,1\}^n$
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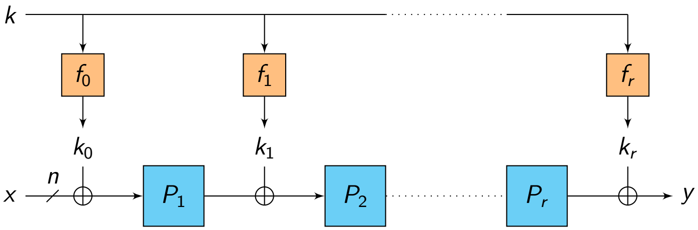

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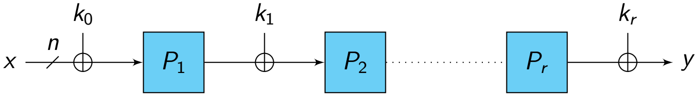
Various Key-Schedule Types



Round keys can be:

- independent (total key-length $\kappa = (r+1)n$)
- derived from an n-bit master key ($\kappa = n$), e.g.
  - trivial key-schedule: $(k, k, \ldots, k)$
  - more complex: $(f_0(k), f_1(k), \ldots, f_r(k))$
- anything else (e.g. $2n$-bit master key (k_0, k_1) and round keys $(k_0, k_1, k_0, k_1, \ldots)$ as in LED-128)

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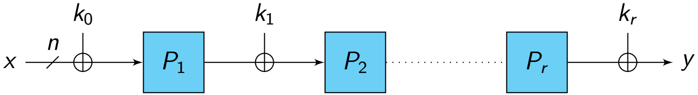

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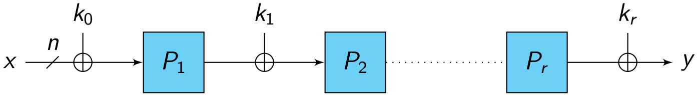

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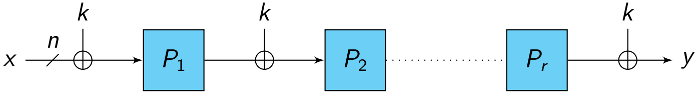

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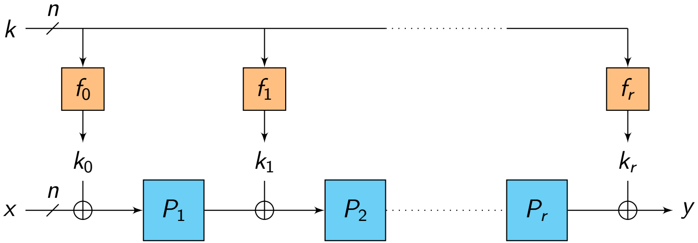

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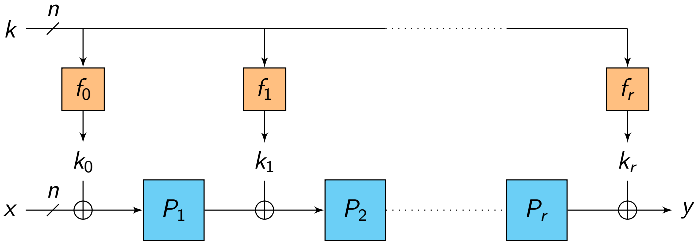

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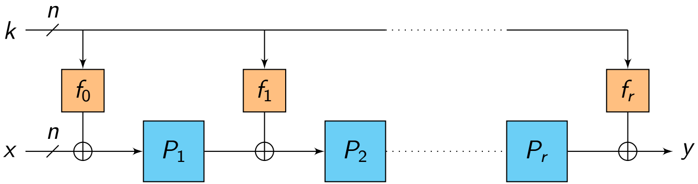

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How can we "prove" security?

- against a general adversary:
  ⇒ too hard (unconditional complexity lower bound!)
- against specific attacks (differential, linear. . .):
  ⇒ use specific design of $P_1, \ldots, P_r$ (count active S-boxes, etc.)
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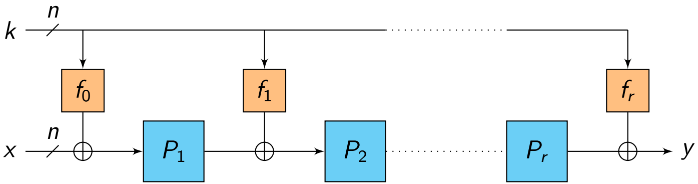

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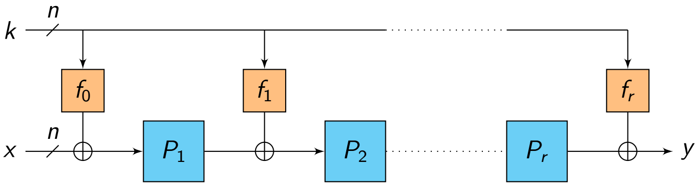

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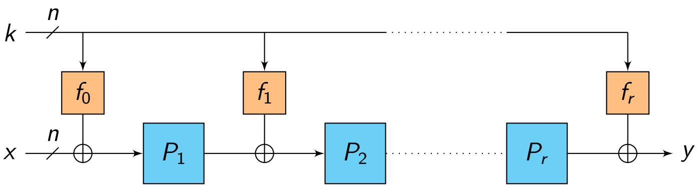

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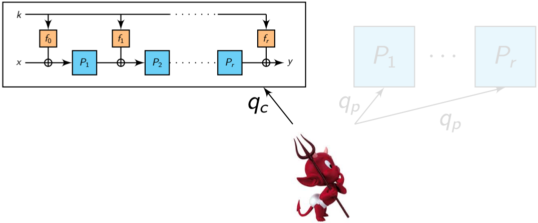
Analyzing KACs in the Random Permutation Model



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- trades complexity for randomness ($\simeq$ Random Oracle Model)
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  - $q_c = \#$ queries to the cipher = plaintext/ciphertext pairs (data D)
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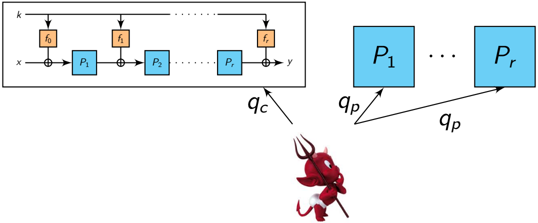

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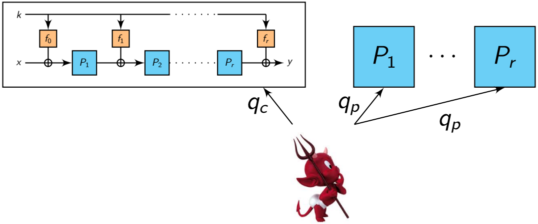

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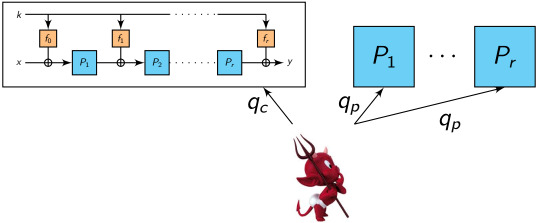

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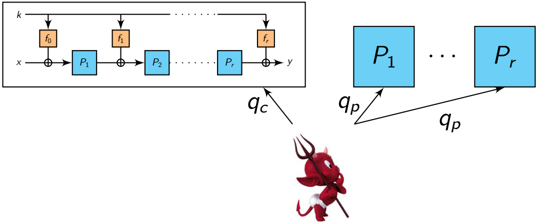

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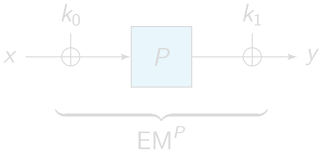
Even and Mansour seminal work:

- this model was first proposed by Even and Mansour at ASIACRYPT '91 for $r = 1$ round
- they showed that the simple cipher $k_1 \oplus P(k_0 \oplus x)$ is a secure PRP up to $\sim 2^{\frac{n}{2}}$ queries of the adversary to P and to the cipher
- similar result when $k_0 = k_1$ [KR01, DKS12]



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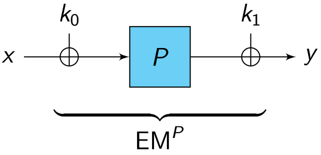

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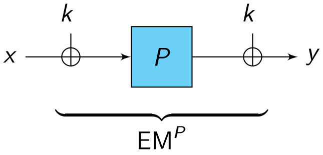

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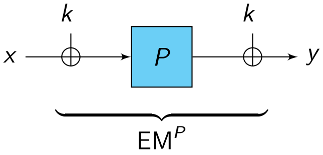

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A Word on Wording

"the" Iterated Even-Mansour (IEM) Cipher

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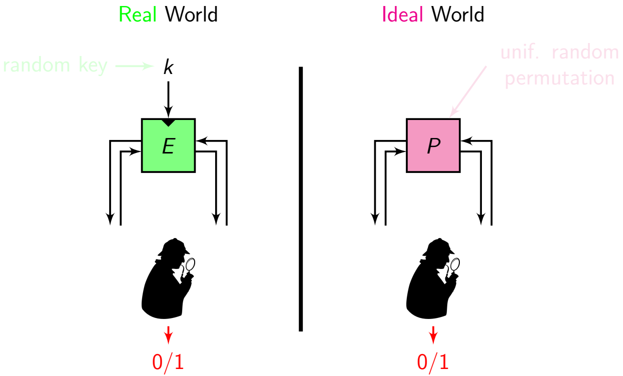
Formalizing Block Cipher Security: Pseudorandomness



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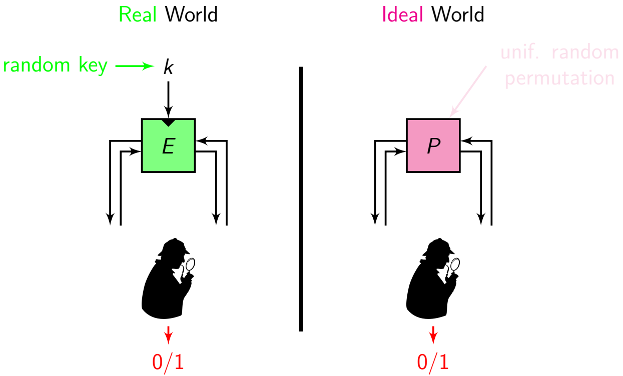

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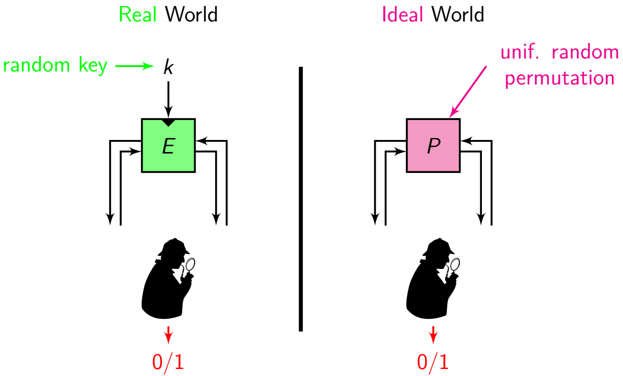

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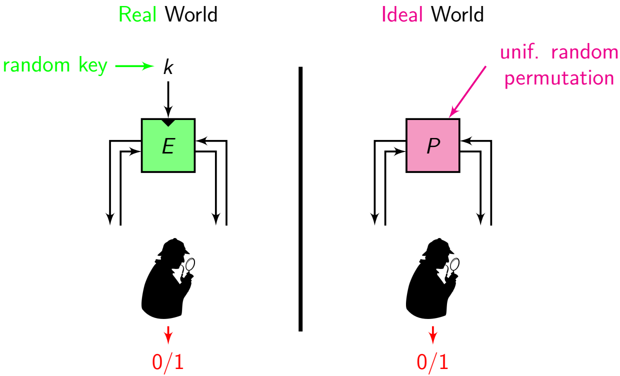

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Related-Key Attacks

The Related-Key Attack Model [BK03]:

- stronger adversarial model: the adversary can specify Related-Key Deriving (RKD) functions ϕ and receive $E_{\phi(k)}(x)$ and/or $E^{-1}_{\phi(k)}(y)$
- the block cipher should behave as an ideal cipher (an independent random permutation for each key)
- impossibility results for too "large" sets of RKDs
- positive results for limited sets of RKDs or using number-theoretic constructions
- we will consider XOR-RKAs: the set of RKD functions is

$$\{\phi_\Delta : k \mapsto k \oplus \Delta, \Delta \in \{0,1\}^\kappa\}$$

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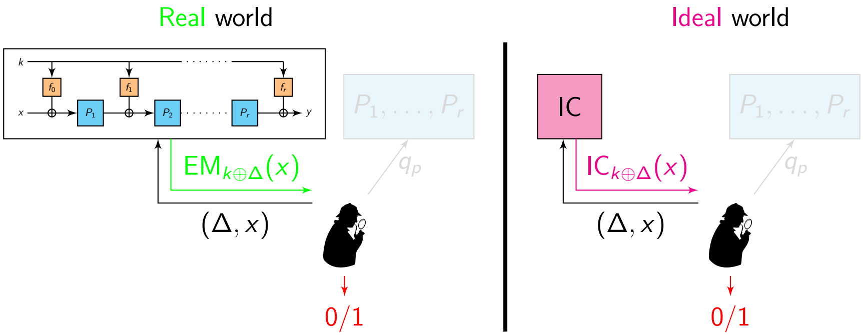

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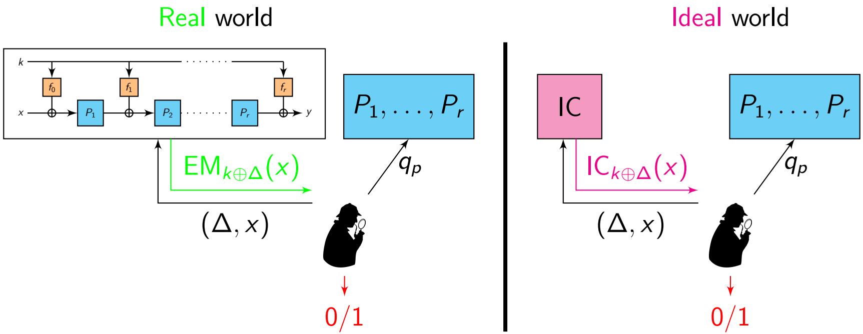

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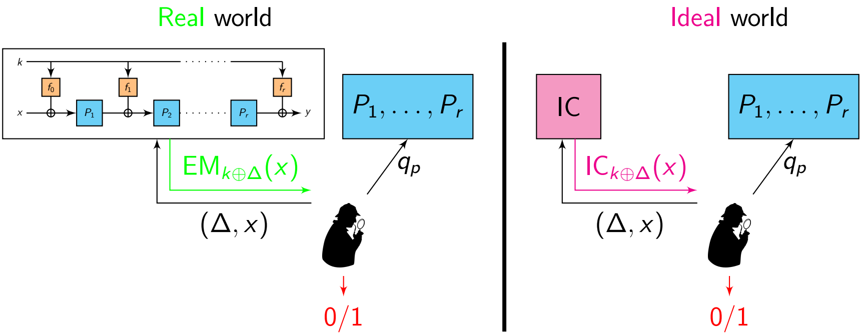
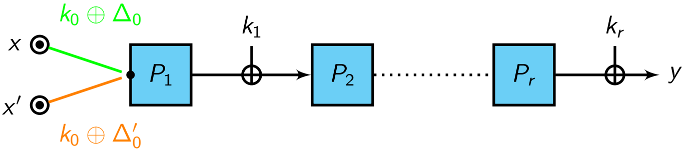
XOR-RKAs against the IEM Cipher: Formalization



- real world: IEM cipher with a random key $k \leftarrow_\$ \{0,1\}^\kappa$
- ideal world: ideal cipher IC independent from $P_1, \ldots, P_r$
- Rand. Perm. Model: $\mathcal{D}$ has oracle access to $P_1, \ldots, P_r$ in both worlds
- q_c queries to the IEM/IC and q_p queries to each inner perm.

First Observation: Independent Round Keys Fails



RK Distinguisher for independent round keys:

- query $((\Delta_0, 0, \dots, 0), x)$ and $((\Delta_0', 0, \dots, 0), x')$ such that

$$x \oplus \Delta_0 = x' \oplus \Delta_0'$$

- check that the outputs are equal
- holds with proba. 1 for the IEM cipher
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- $\Rightarrow$ we will consider "dependent" round keys (in part. $(k, k, \dots, k)$)

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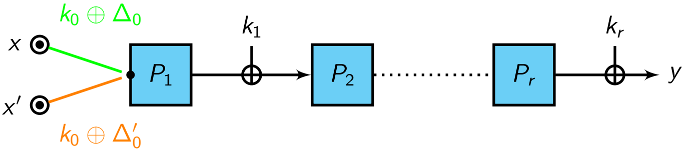

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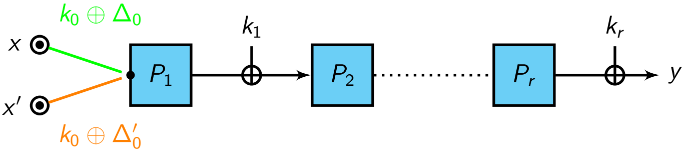

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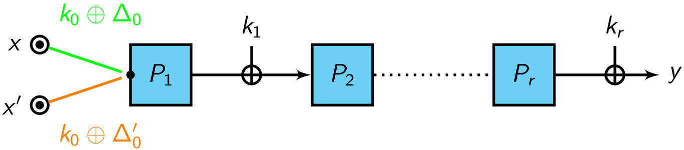

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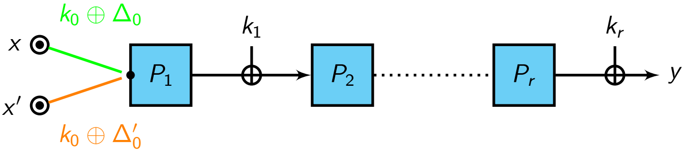

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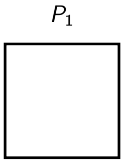

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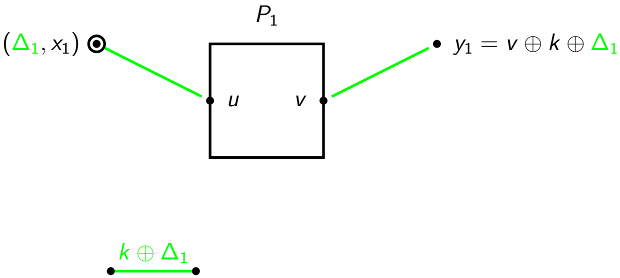

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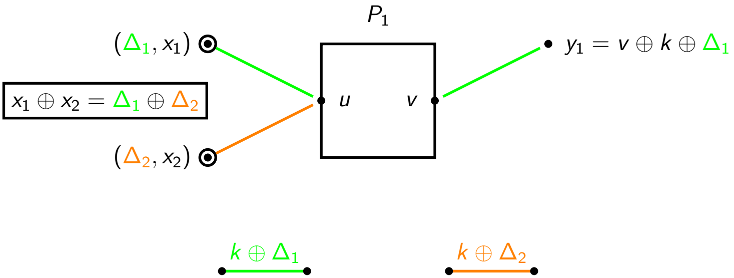

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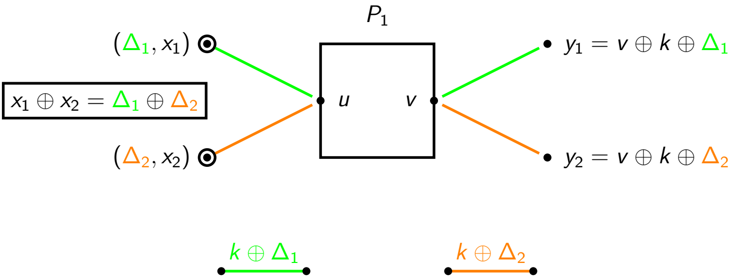
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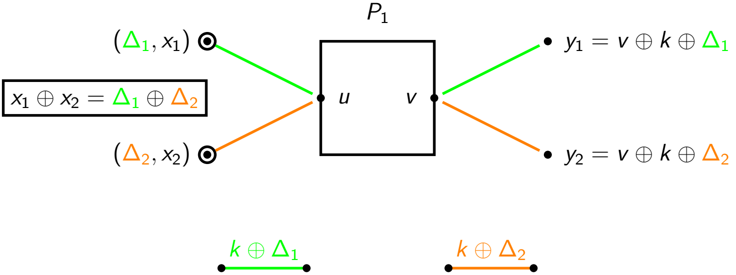
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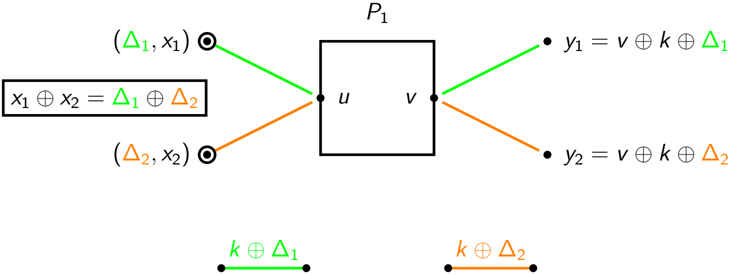
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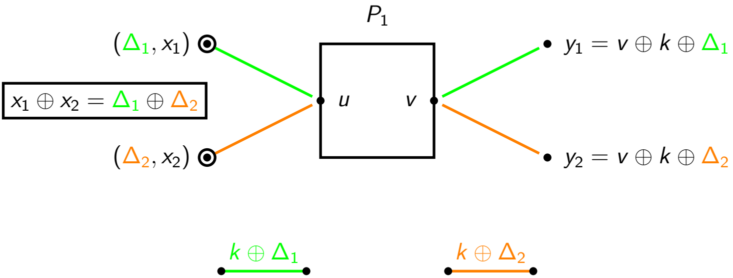
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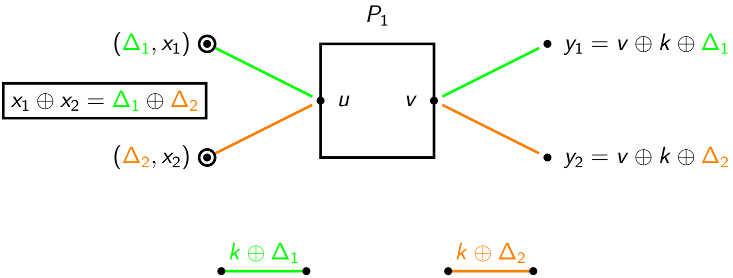
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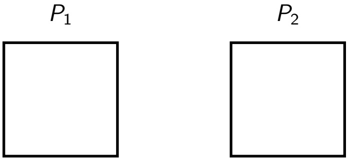

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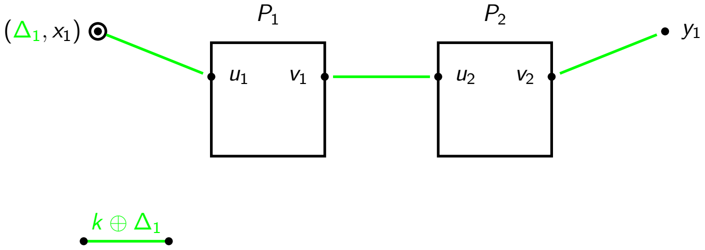

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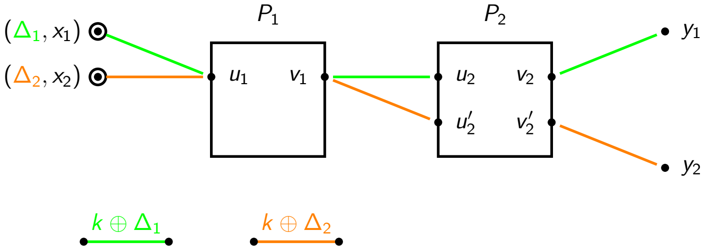

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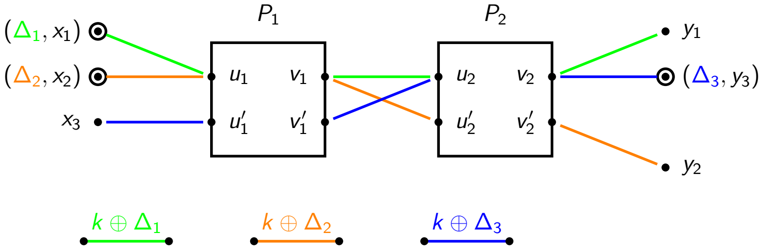

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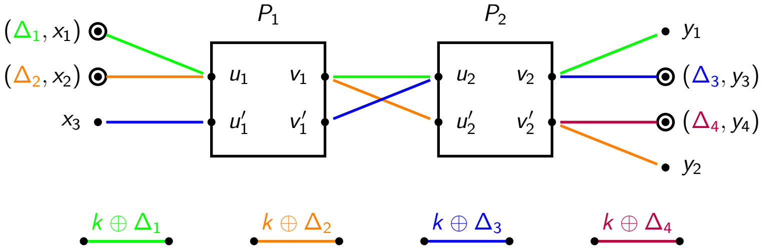

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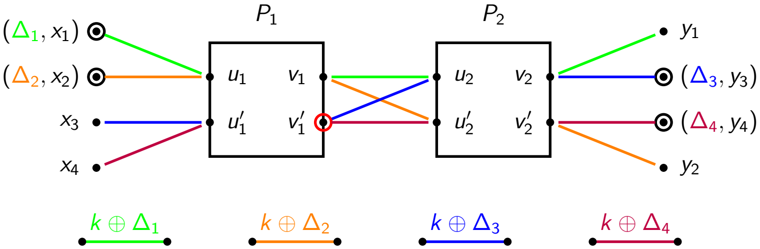

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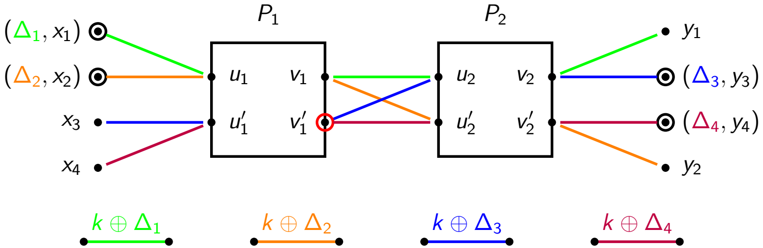

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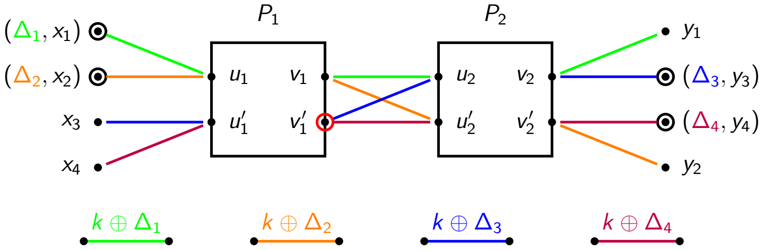

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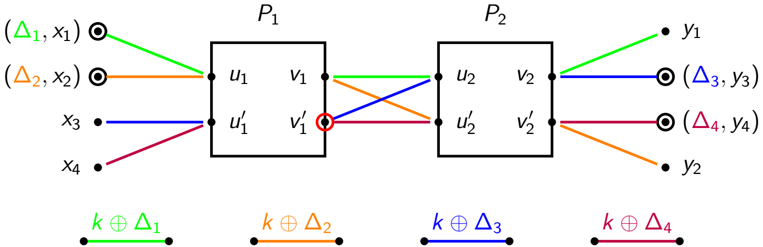

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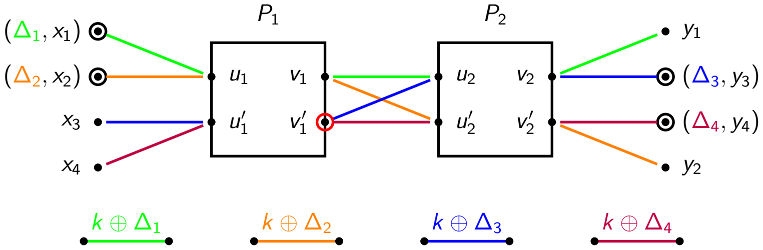

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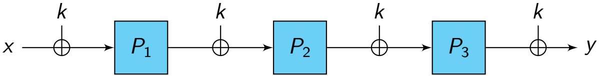

Theorem (Cogliati-Seurin [CS15])

For the 3-round IEM cipher with the trivial key-schedule:

$$\mathbf{Adv}^{\text{xor-rka}}_{\mathrm{EM}[n,3]}(q_c, q_p) \le \frac{6 q_c q_p}{2^n} + \frac{4 q_c^2}{2^n}.$$

Proof sketch:

- $\mathcal{D}$ can create forward collisions at P_1 or backward collisions at P_3
- but proba. to create a collision at P_2 is $\lesssim q_c^2/2^n$
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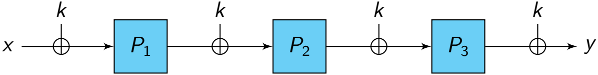

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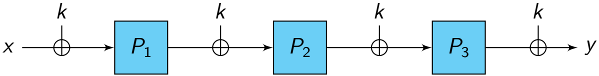

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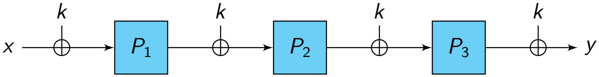

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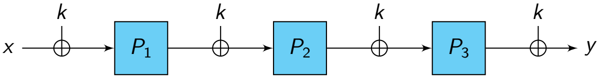

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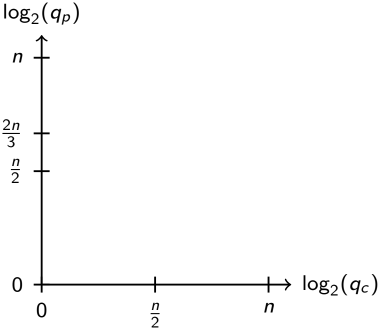

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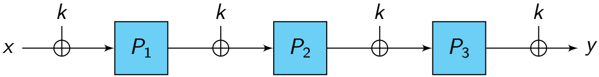

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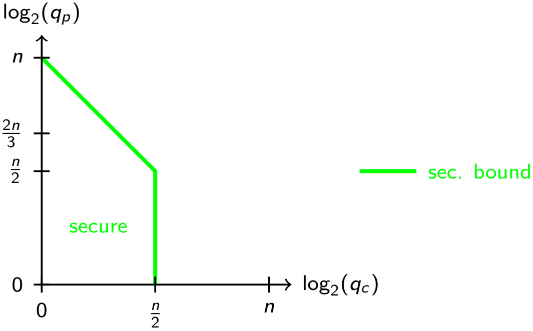

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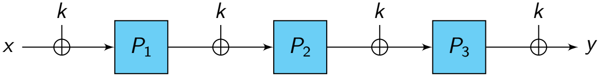

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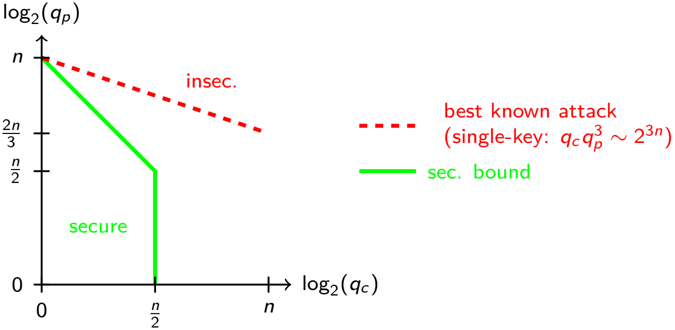

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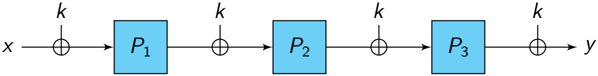

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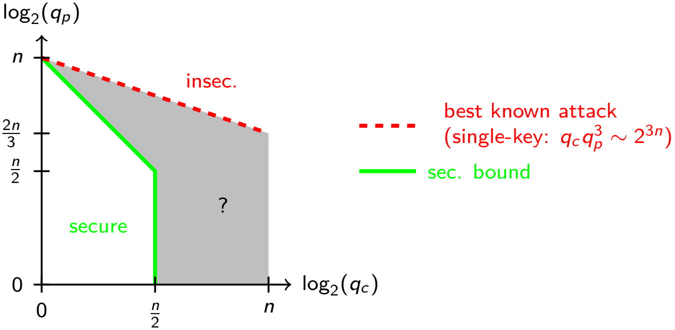
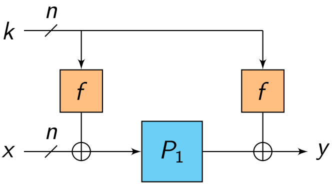


Security for One Round and a Nonlinear Key-Schedule



Theorem (Cogliati-Seurin [CS15])

For the 1-round EM cipher with key-schedule $f = (f_0, f_1)$:

$$\mathbf{Adv}^{\text{xor-rka}}_{\mathsf{EM}[n,1,f]}(q_c, q_p) \le \frac{2q_c q_p}{2^n} + \frac{\delta(f) q_c^2}{2^n},$$

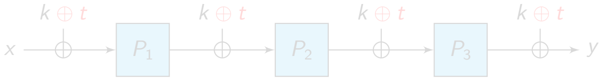
where $\delta(f) = \max_{a,b \in \{0,1\}^n, a \neq 0} |\{x \in \{0,1\}^n : f(x \oplus a) \oplus f(x) = b\}|$.
($\delta(f) = 2$ for an APN permutation.)

Some Observations

Application to tweakable block ciphers:

- from any XOR-RKA secure block cipher E, one can construct a tweakable block cipher [LRW02, BK03]

$$\widetilde{E}(k, t, x) \overset{\mathrm{def}}{=} E(k \oplus t, x)$$



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- 2 rounds: XOR-RKA security against chosen-plaintext attacks
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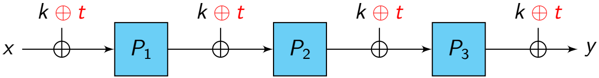

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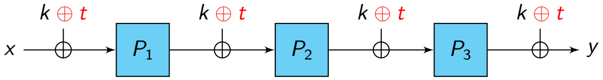

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Outline

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Security Against Related-Key Attacks

Security Against Chosen-Key Attacks

Formalizing Chosen-Key Attacks

- informal goal: find tuples of key/pt/ct (k_i, x_i, y_i) with a property which is hard to satisfy for an ideal cipher
- no formal definition for a single, completely instantiated block cipher E
- simply because, e.g., $E_0(0)$ has a specific, non-random value...
- OK this does not count
- but what counts as a chosen-key attack exactly?
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- e.g., IEM cipher based on a tuple of random permutations!

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An m-ary relation $\mathcal{R}$ is (q, ε)-evasive (w.r.t. an ideal cipher E) if any adversary $\mathcal{A}$ making at most q queries to E finds triples $(k_1, x_1, y_1), \ldots,$ (k_m, x_m, y_m) (with $E_{k_i}(x_i) = y_i$) satisfying $\mathcal{R}$ with probability at most ε.

Example

- consider E in Davies-Meyer mode $f(k, x) := E_k(x) \oplus x$
- finding a preimage of 0 for f is a unary $(q, \mathcal{O}(\frac{q}{2^n}))$-evasive relation for E [BRS02]
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Definition (Correlation Intractability)

A block cipher construction $\mathcal{C}^F$ based on some underlying primitive F is said to be (q, ε)-correlation intractable w.r.t. an m-ary relation $\mathcal{R}$ if any adversary $\mathcal{A}$ making at most q queries to F finds triples (k_1, x_1, y_1), . . . , (k_m, x_m, y_m) (with $\mathcal{C}^F_{k_i}(x_i) = y_i$) satisfying $\mathcal{R}$ with probability at most ε.

Definition (Resistance to Chosen-Key Attacks)

Informally, a block cipher construction $\mathcal{C}^F$ is said resistant to chosen-key attacks if for any (q, ε)-evasive relation $\mathcal{R}$, $\mathcal{C}^F$ is (q', ε')-correlation intractable w.r.t. $\mathcal{R}$ with $q' \simeq q$ and $\varepsilon' \simeq \varepsilon$.

Questions:

- How do we prove prove resistance to chosen-key attacks?
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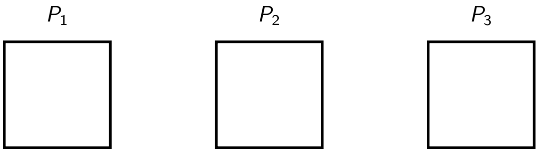

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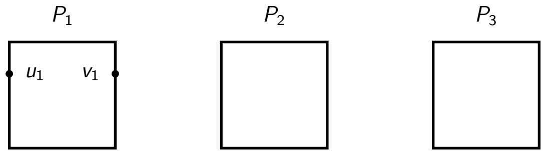

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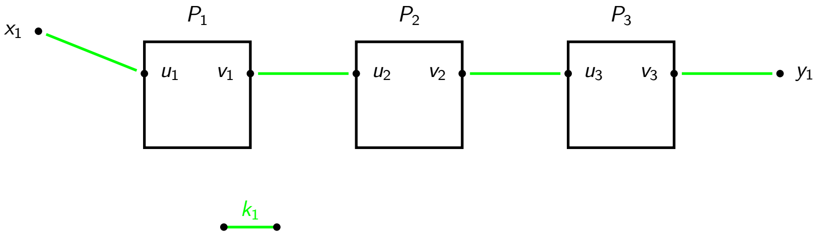

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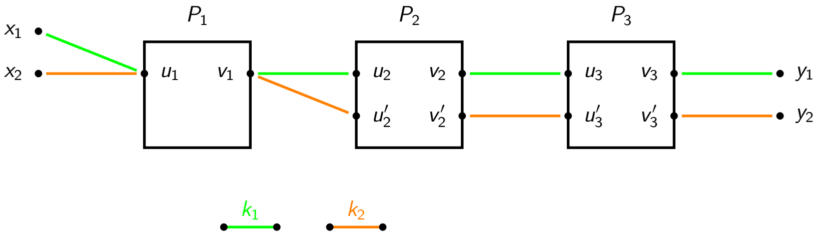

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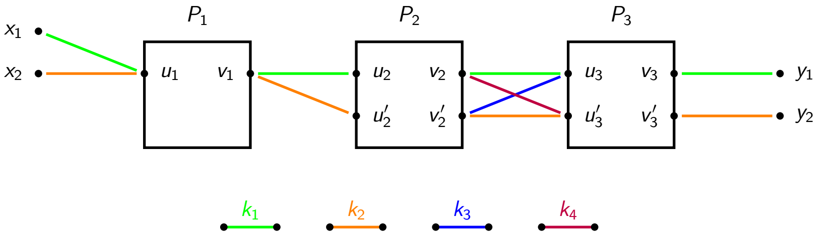

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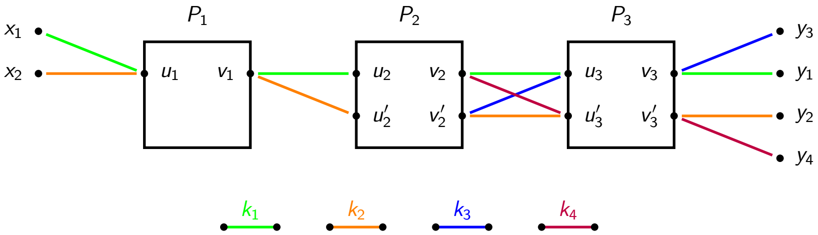

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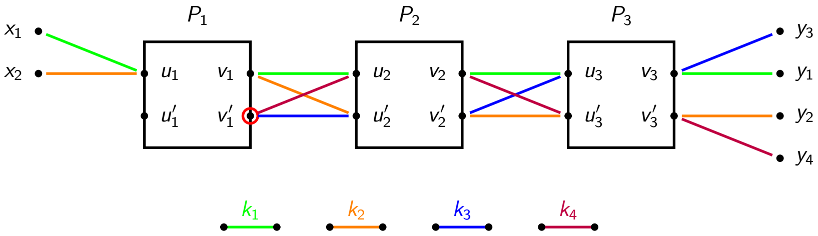

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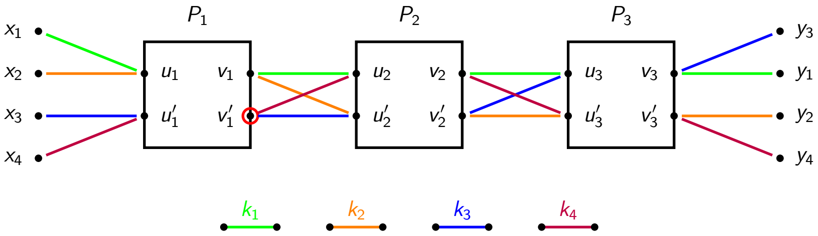

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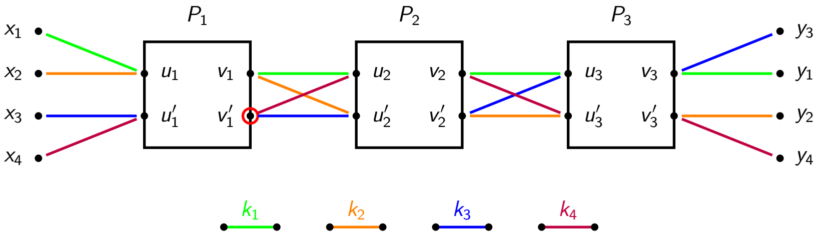

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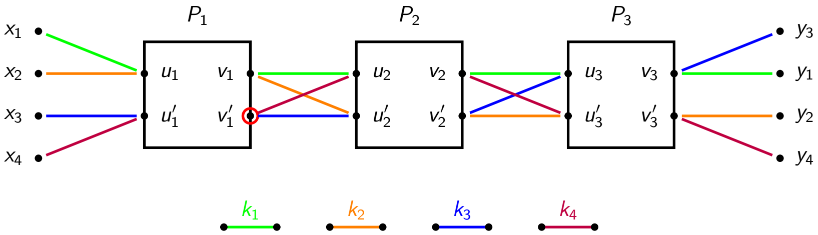

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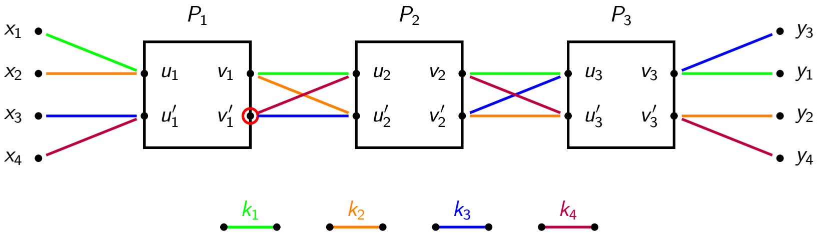

- tuples (k_1, x_1, y_1), (k_2, x_2, y_2), (k_3, x_3, y_3), (k_4, x_4, y_4) satisfy

$$\begin{cases} k_1 \oplus k_2 \oplus k_3 \oplus k_4 = 0 \\ x_1 \oplus x_2 \oplus x_3 \oplus x_4 = 0 \\ y_1 \oplus y_2 \oplus y_3 \oplus y_4 = 0 \ . \end{cases}$$

- this is a $\left(q, \mathcal{O}(\frac{q^4}{2^n})\right)$-evasive relation for an ideal cipher
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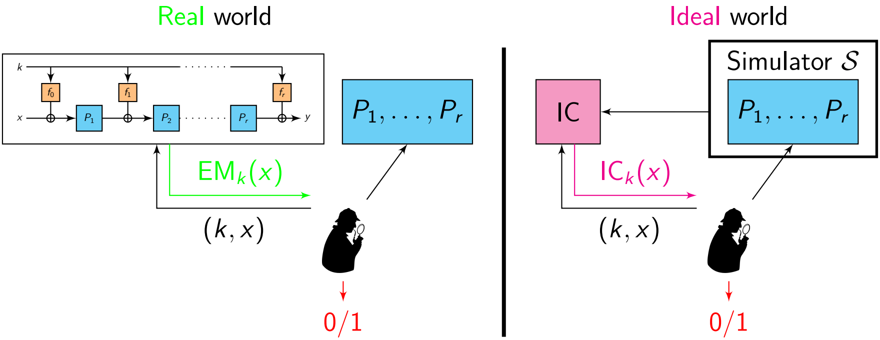
Proving CKA Resistance: Indifferentiability



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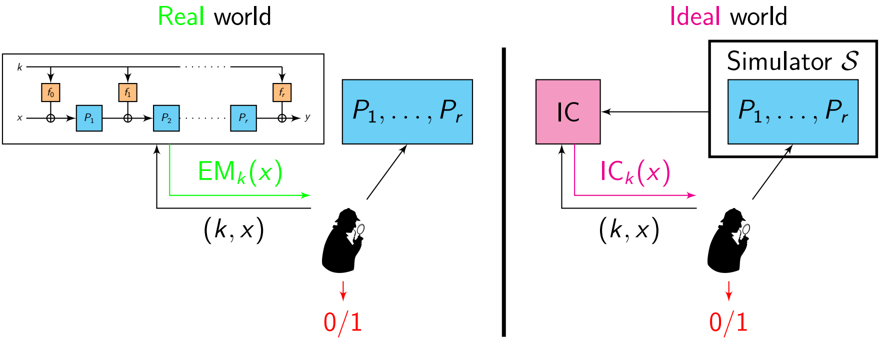

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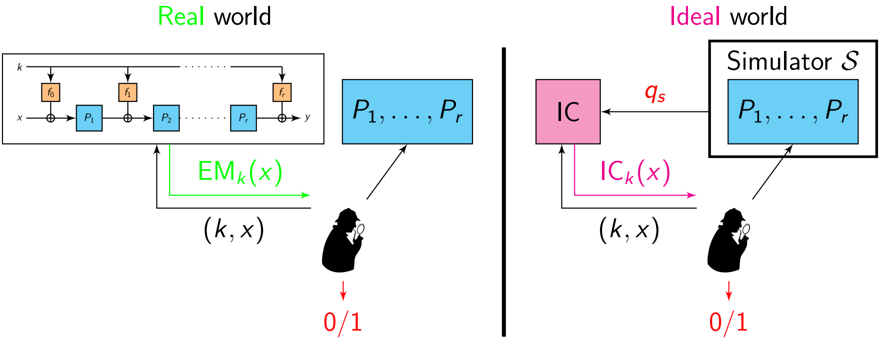
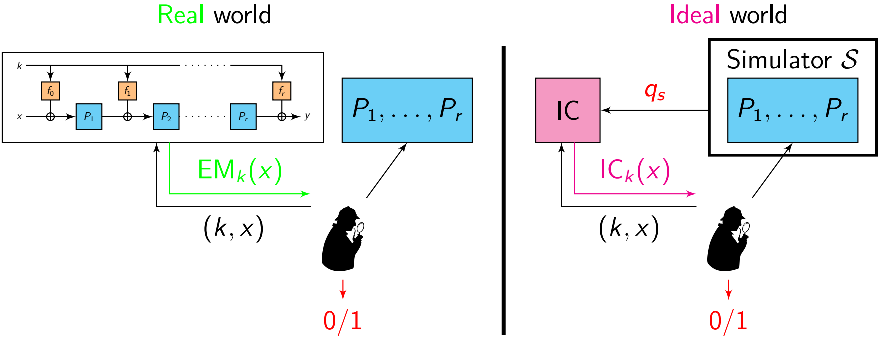


Definition (Indifferentiability [MRH04])

A block cipher construction is said (q_d, q_s, ε)-indifferentiable from an ideal cipher if there exists a simulator $\mathcal{S}$ such that for any distinguisher $\mathcal{D}$ making at most q_d queries in total, $\mathcal{S}$ makes at most q_s ideal cipher queries and $\mathcal{D}$ distinguishes the two worlds with adv. at most ε

Two Flavors of Indifferentiability



- full indifferentiability: $\mathcal{D}$ can queries its oracle as it wishes
- sequential indifferentiability: two query phases
  1. $\mathcal{D}$ first queries only P_i's/$\mathcal{S}$
  2. and then only EM/IC
- full indiff. $\Rightarrow$ sequential indiff.

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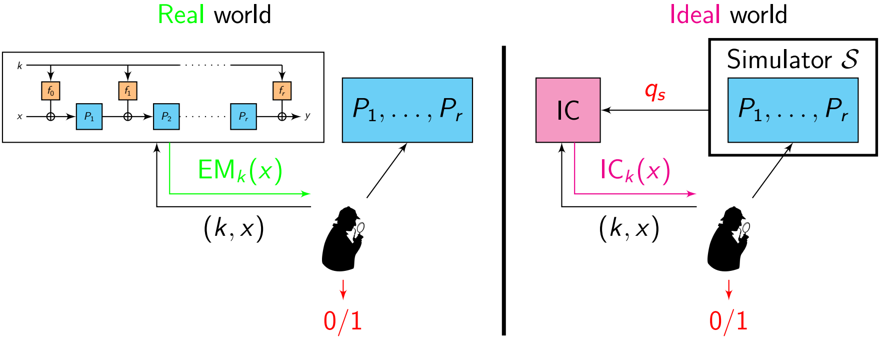

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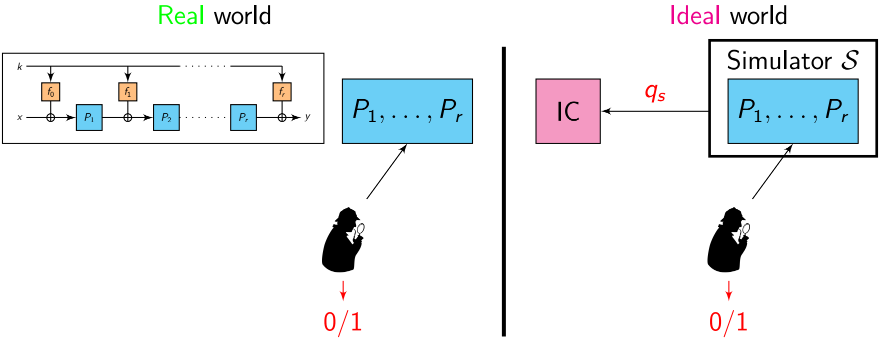

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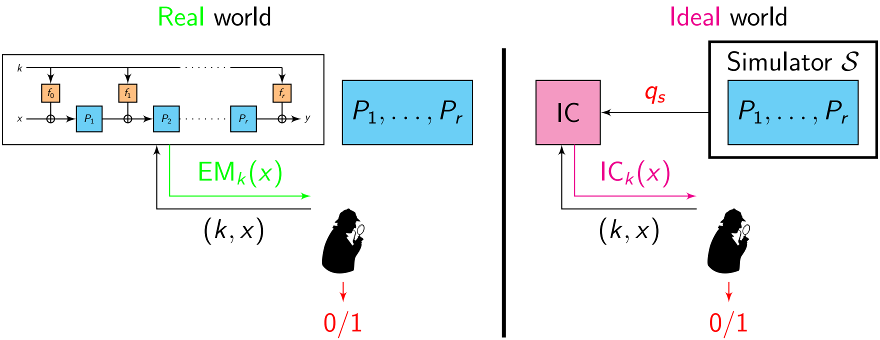

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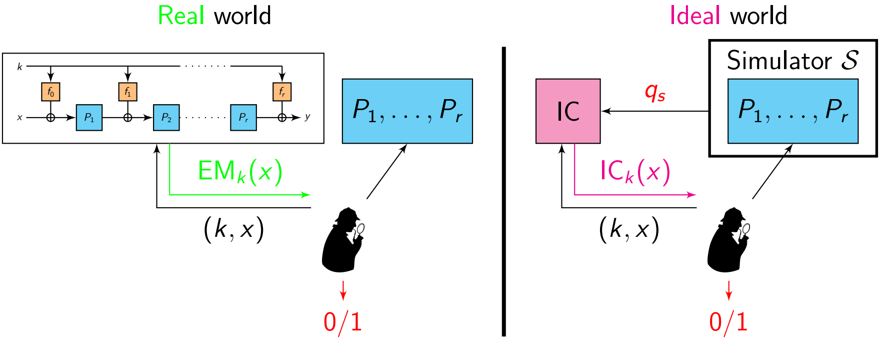

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Composition Theorems

Theorem (Composition for full indiff. [MRH04])

Informally, if a block cipher construction $\mathcal{C}^F$ is full-indifferentiable from an ideal cipher, then any cryptosystem proven secure with an ideal cipher remains provably secure when used with $\mathcal{C}^F$ (for cryptosystems whose security is defined by a single-stage game [RSS11]).

Theorem (Composition for seq. indiff. [MPS12, CS15])

If a block cipher construction $\mathcal{C}^F$ is (q_d, q_s, ε)-seq-indiff. from an ideal cipher, and if a relation $\mathcal{R}$ is $(q_s, \varepsilon_{\mathrm{ic}})$-evasive for an ideal cipher, then $\mathcal{C}^F$ is $(q_d, \varepsilon_{\mathrm{ic}} + \varepsilon)$-correlation intractable w.r.t. $\mathcal{R}$.

	IC		$\mathcal{C}^F$
queries	q_s	$\xrightarrow{(q_d, q_s, \varepsilon)\text{-seq-indiff.}}$	q_d
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Indifferentiability Results for the IEM Cipher

Theorem (Andreeva *et al.* [ABD+13])

The 5-round IEM cipher with a key-schedule modeled as a random oracle is fully indifferentiable from an ideal cipher.

NB: strong assumption on the key-schedule (often invertible in real BCs)

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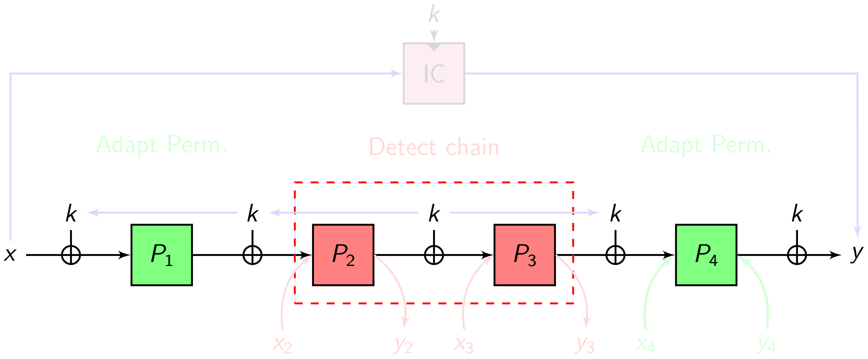
Seq-indifferentiability for 4 Rounds: Simulator



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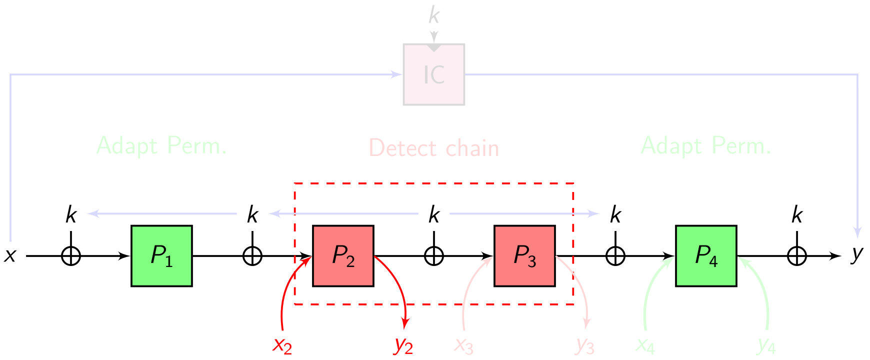

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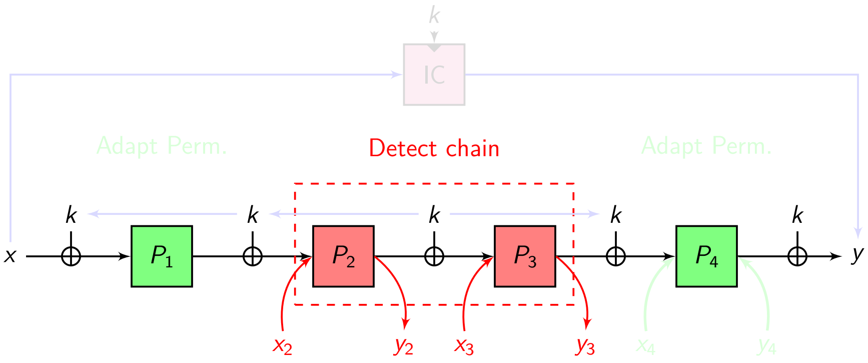

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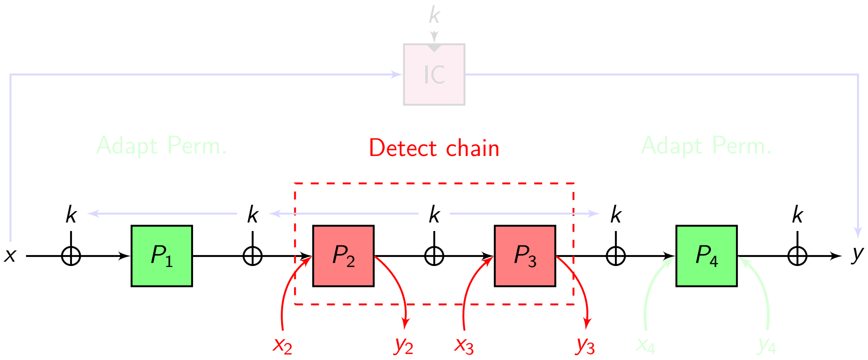

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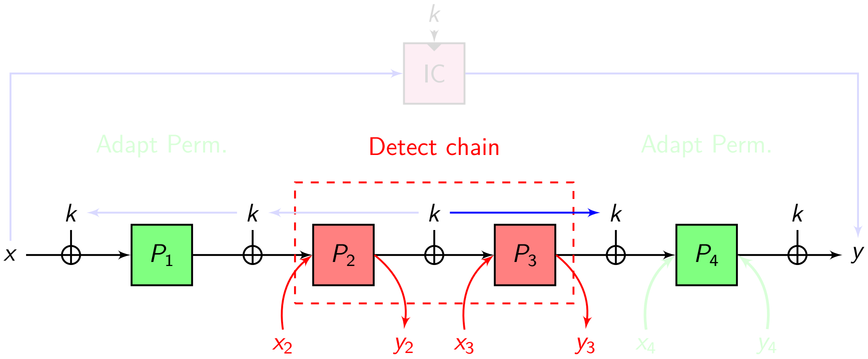

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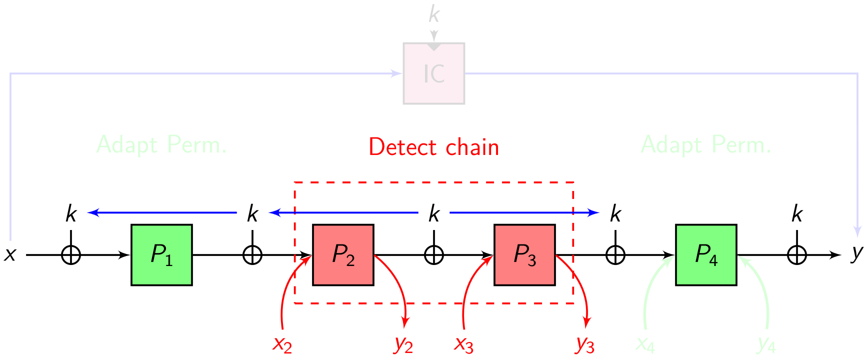

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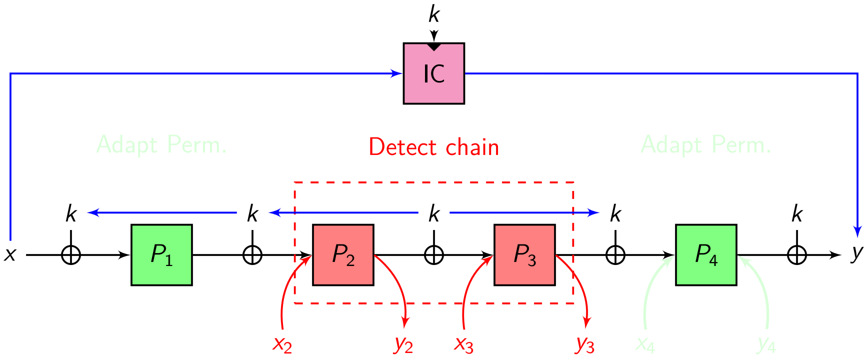

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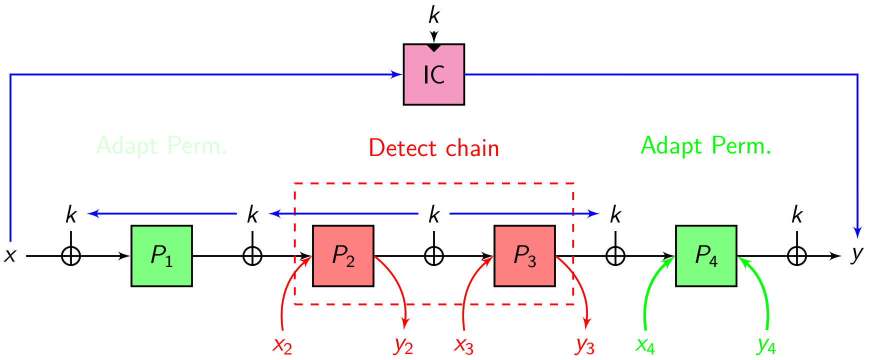

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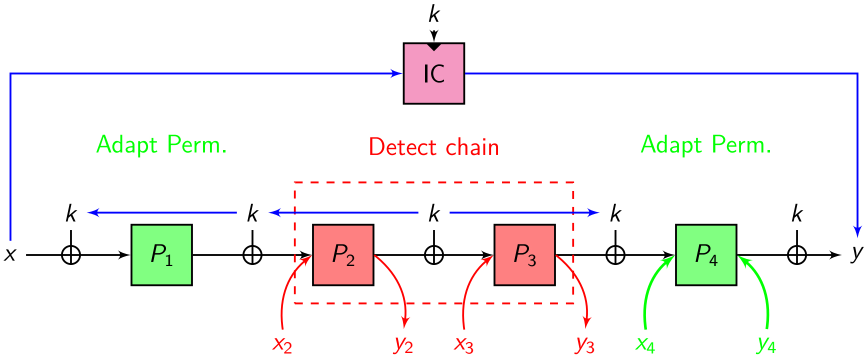

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By the composition theorem “seq-indiff. ⇒ correlation-intractability”:

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Let $\mathcal{R}$ be a $(q^2, \varepsilon_{\mathrm{ic}})$-evasive relation w.r.t. an ideal cipher. Then the 4-round IEM with the trivial key-schedule is $\left(q, \varepsilon_{\mathrm{ic}} + \mathcal{O}(\frac{q^4}{2^n})\right)$ correlation intractable w.r.t. $\mathcal{R}$.

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Consider f = 4-round IEM cipher in Davies-Meyer mode. Then

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- idealized models can be fruitful
- practical meaning of the results is debatable:
  - the high-level structure of SPNs is sound (and may even yield something close to an ideal cipher)
  - says little about concrete block ciphers (inner permutations of, say, AES are too simple)

Open problems:

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- seq-indifferentiability: find a construction with linear simulator complexity and small distinguishing advantage ($\sim q_d/2^n$)

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Summary of Known Results

Security notion	# of rounds	Key schedule	Security bound	Simul. (q_S/t_S)	Ref.
Single-key	$r \geq 1$	independent	$2^{\frac{rn}{r+1}}$	—	[CS14]
	1	trivial	$2^{\frac{n}{2}}$	—	[EM97, DKS12]
	2	trivial	$2^{\frac{2n}{3}}$	—	[CLL$^+$14]
XOR RKA	3	trivial	$2^{\frac{n}{2}}$	—	[CS15, FP15]
	1	nonlinear	$2^{\frac{n}{2}}$	—	[CS15]
CKA (Seq-ind.)	4	trivial	$2^{\frac{n}{4}}$	q^2 / q^2	[CS15]
Full indiff.	5	rand. oracle	$2^{\frac{n}{10}}$	q^2 / q^3	[ABD$^+$13]
	12	trivial	$2^{\frac{n}{12}}$	q^4 / q^6	[LS13]

The End. . .

Thanks for your attention!

Comments or questions?

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