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

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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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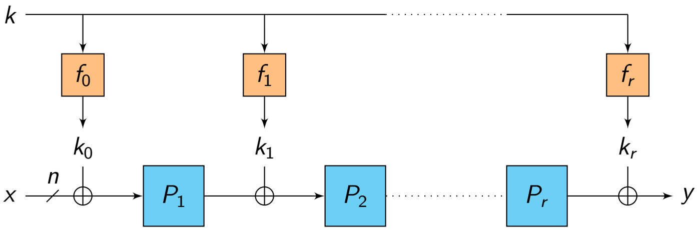
Key-Alternating Cipher (KAC): Definition



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 $\{0,1\}^n$
- the f_i's are key derivation functions mapping k to n-bit "round keys"
- examples: most SPNs (AES, SERPENT, PRESENT, LED, . . .)

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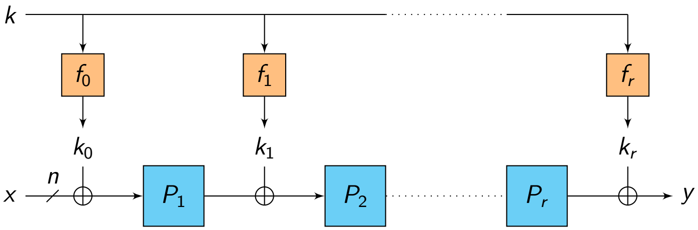

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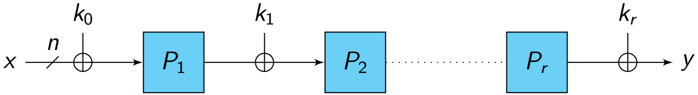

Round keys can be:

- 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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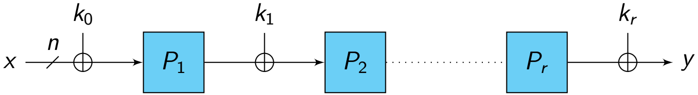

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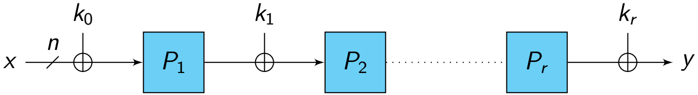

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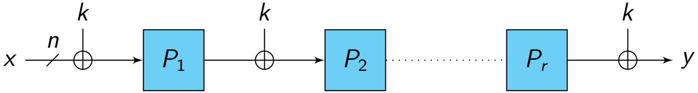

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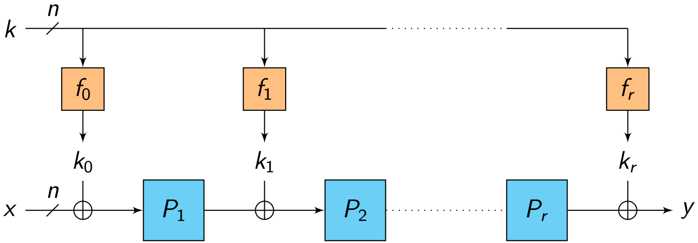

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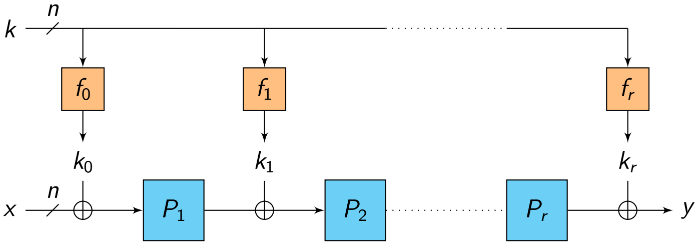

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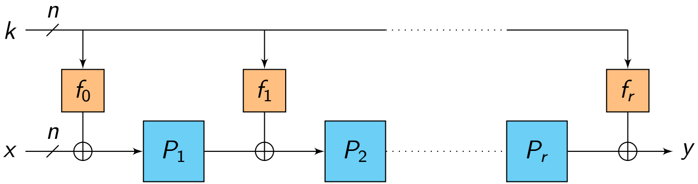

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How can we “prove” security?

- 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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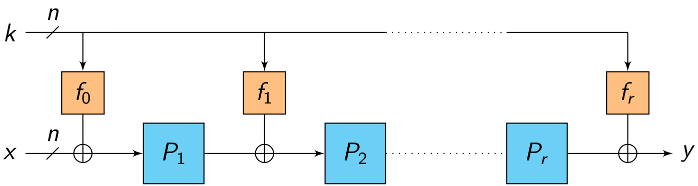

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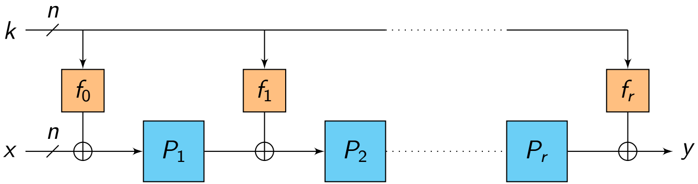

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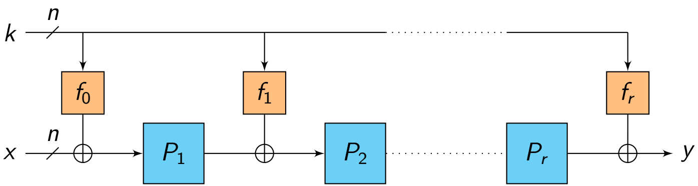

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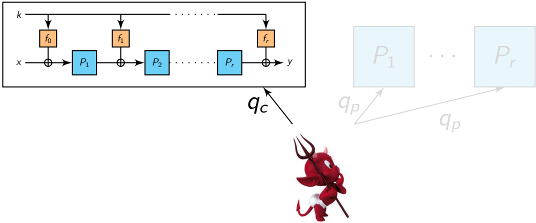

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- adversary cannot exploit any weakness of the P_i's ⇒ generic attacks
- trades complexity for randomness ($\simeq$ Random Oracle Model)
- complexity measure of the adversary:
  - $q_c = \#$ queries to the cipher = plaintext/ciphertext pairs (data D)
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  - but otherwise computationally unbounded
- ⇒ information-theoretic proof of security

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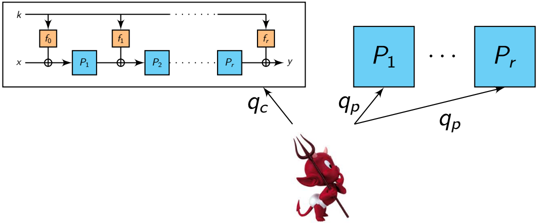

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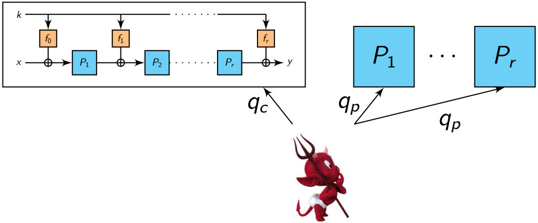

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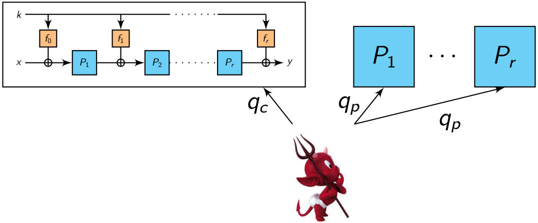

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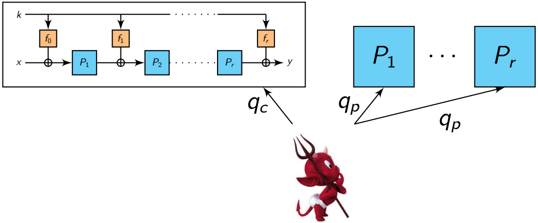

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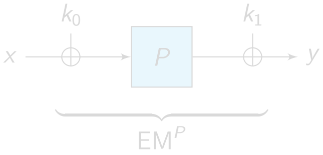
Analyzing KACs in the Random Permutation Model

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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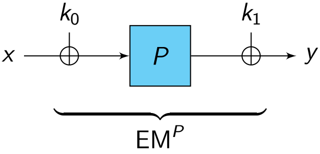

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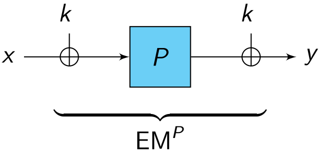

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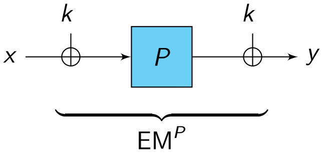

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Related-Key Attacks

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

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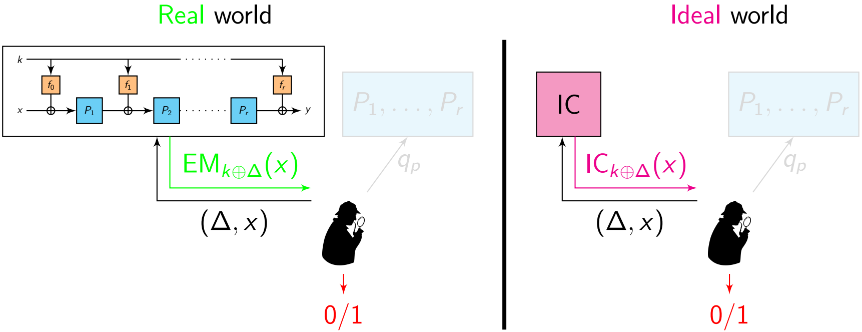
XOR-RKAs against the IEM Cipher: Formalization



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- 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
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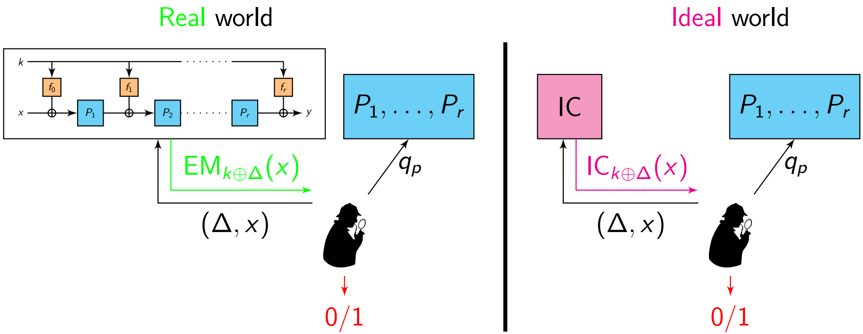

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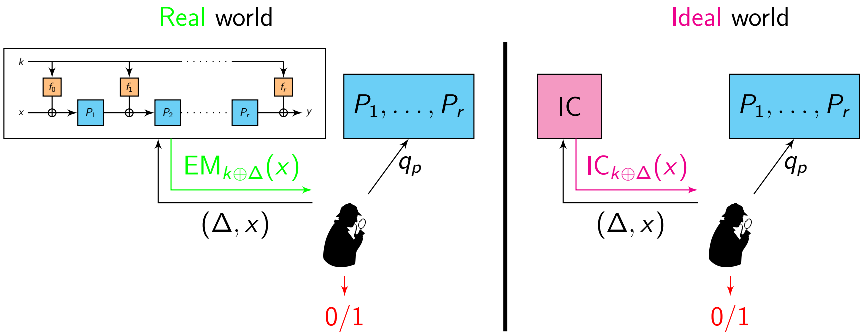

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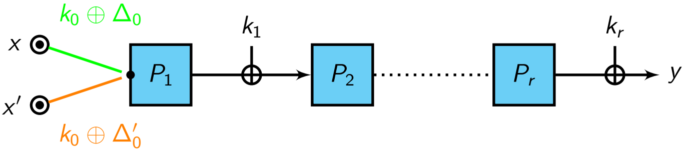

RK Distinguisher for independent round keys:

- query $((\Delta_0, 0, \ldots, 0), x)$ and $((\Delta'_0, 0, \ldots, 0), x')$ such that

$$x \oplus \Delta_0 = x' \oplus \Delta'_0$$

- check that the outputs are equal
- holds with proba. 1 for the IEM cipher
- holds with proba. 2^{-n} for an ideal cipher
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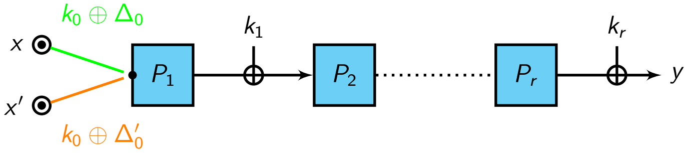

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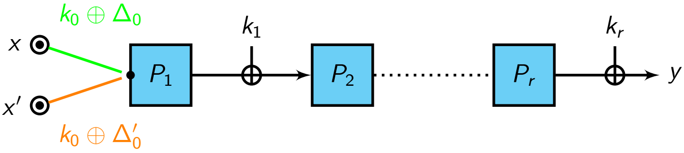

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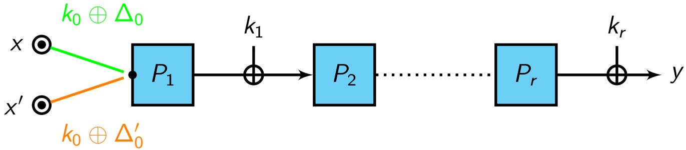

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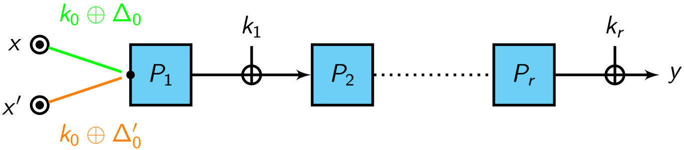

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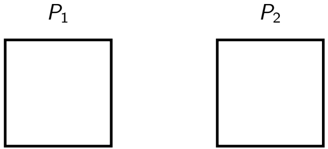
- query $((\Delta_0, 0, \dots, 0), x)$ and $((\Delta'_0, 0, \dots, 0), x')$ such that

$$x \oplus \Delta_0 = x' \oplus \Delta'_0$$

- check that the outputs are equal
- holds with proba. 1 for the IEM cipher
- holds with proba. 2^{-n} for an ideal cipher
- $\Rightarrow$ we will consider "dependent" round keys (in part. $(k, k, \dots, k)$)

An Attack for Two Rounds, Trivial Key-Schedule



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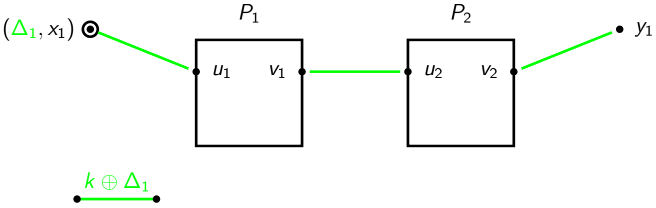

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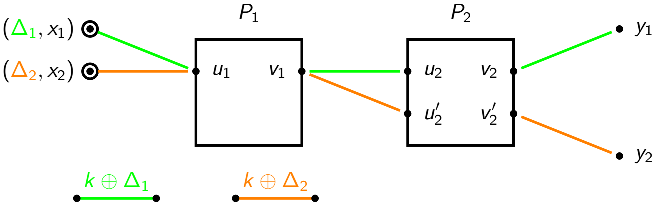

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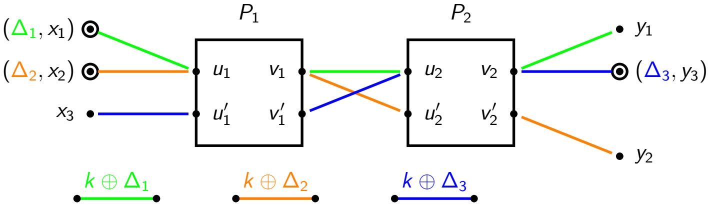

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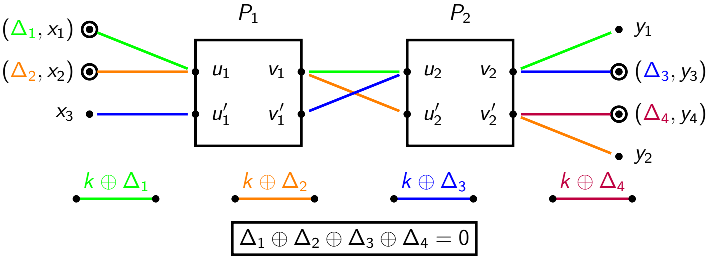

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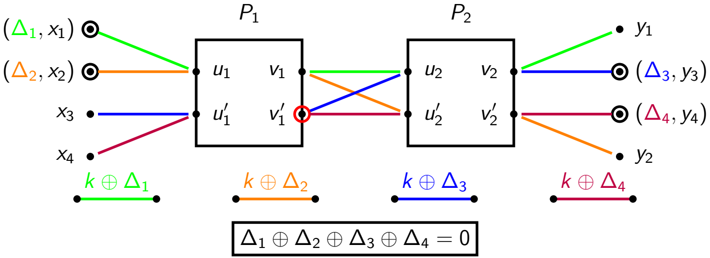

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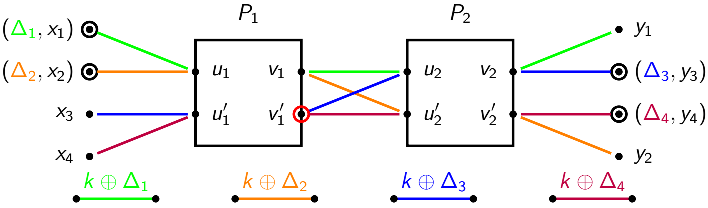

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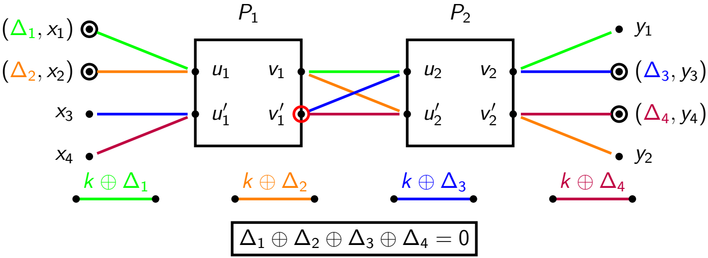

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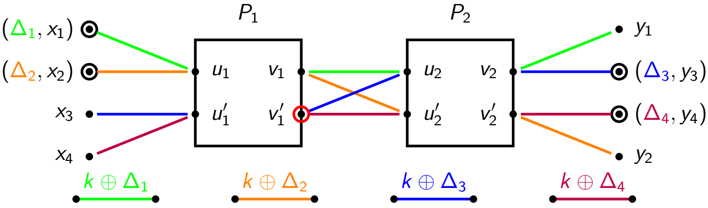

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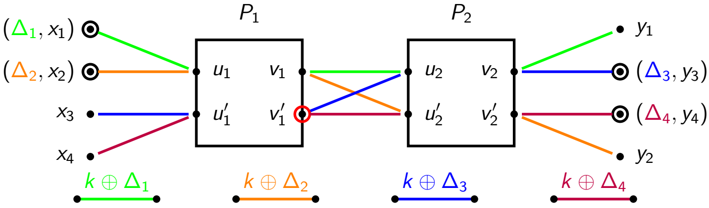

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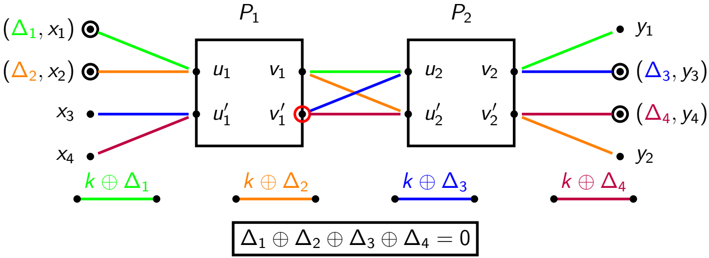

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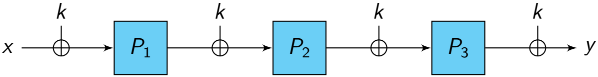

Theorem (Cogliati-Seurin [CS15])

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

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

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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  $\Rightarrow \sim$ single-key security of 1-round EM $\lesssim q_c q_p/2^n$

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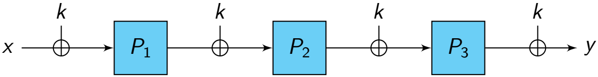

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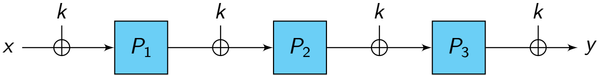

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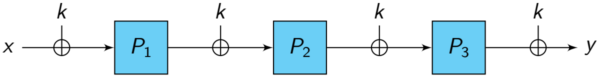

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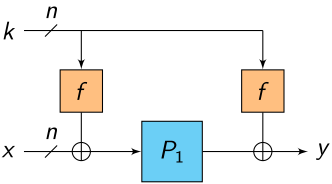
Security for One Round and a Nonlinear Key-Schedule



Theorem (Cogliati-Seurin [CS15])

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

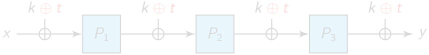
$$\mathbf{Adv}^{\text{xor-rka}}_{\text{EM}[n,1,f]}(q_c, q_p) \le \frac{2q_c q_p}{2^n} + \frac{\delta(f) q_c^2}{2^n},$$

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]



- Similar in spirit to the TWEAKEY framework from Jean et al [JNP14].

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- similar result for 3 rounds (slightly worse bound, game-based proof)
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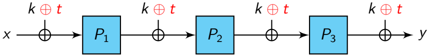

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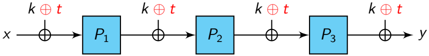

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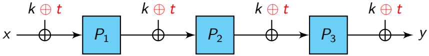

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Outline

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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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Definition (Evasive relation)

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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- for BC-based hashing, most hash function security notions can be recast as evasive relations for the underlying BC

Formalizing Chosen-Key Attacks

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 $(k_1, x_1, y_1), \ldots,$ (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 $\varepsilon' \simeq \varepsilon$.

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For any relation $\mathcal{R}$, finding triplets $(\mathsf{k_i}, \mathsf{x_i}, \mathsf{y_i})$ satisfying $\mathcal{R}$ should be "almost as hard" for the construction $\mathcal{C}^F$ as for an ideal cipher.

Formalizing Chosen-Key Attacks

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

- we use a weaker variant of indifferentiability called sequential indifferentiability
- 12 rounds provide full indifferentiability [LS13] which implies sequential indifferentiability
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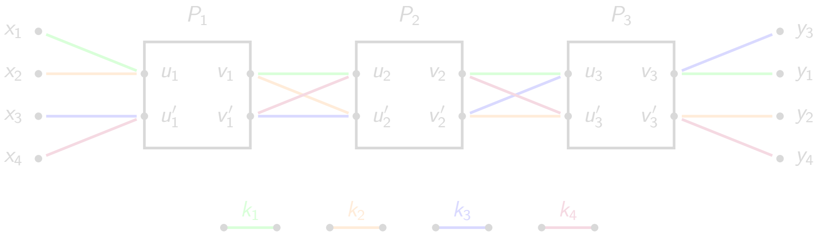

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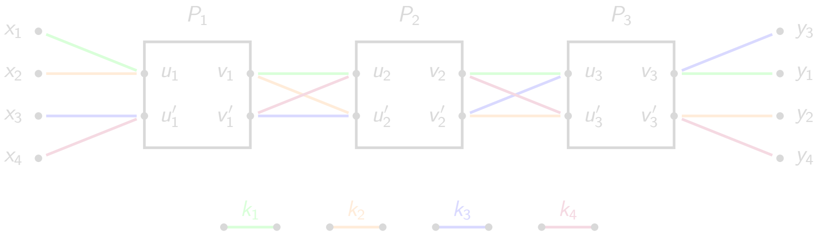

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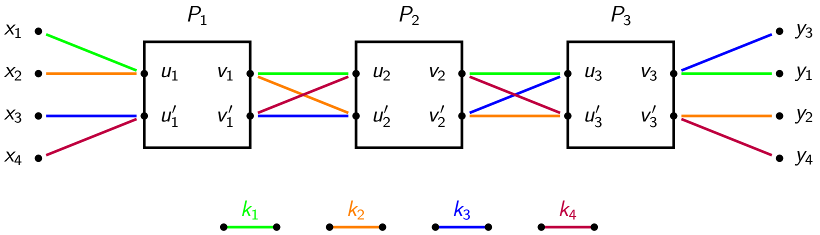

CKA Resistance for the 4-Round IEM Cipher

Theorem

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. $\mathcal{R}$.

Example

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

- f is $\left(q, \mathcal{O}(\frac{q^4}{2^n})\right)$-preimage resistant
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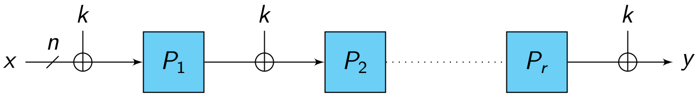

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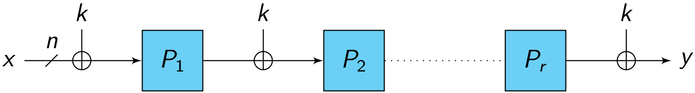

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Morality:

- 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:

- RKA security beyond the birthday bound (4 rounds → $2^{\frac{2n}{3}}$-security?)
- a matching $\mathrm{xor\text{-}rka}$ in $\mathcal{O}(2^{\frac{n}{2}})$ queries against 3 rounds

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The End. . .

Thanks for your attention!

Comments or questions?

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