Tweakable Block Cipher Based Cryptography

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Outline

1. **Introduction**
2. **Tweakable Block Ciphers Designs**
   - Block Cipher-Based TBC
   - Ad-hoc TBC Constructions
3. **Tweakable Block Ciphers for AE**
4. **Conclusion**

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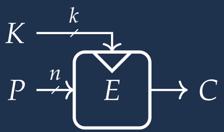
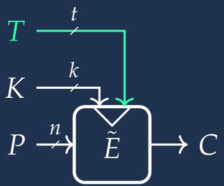
(Tweakable) Block Ciphers

A block cipher (BC) is a family of permutations parametrized by a secret key K



A tweakable block cipher (TBC) is a family of permutations parametrized by a secret key K and a public **tweak value** T



We denote

- P the n-bit plaintext
- C the n-bit ciphertext
- K the k-bit key
- T the t-bit tweak

(Tweakable) Block Ciphers

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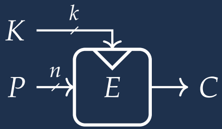

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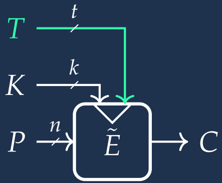
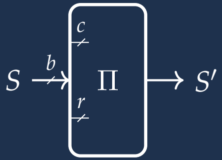


A permutation on $b = c + r$ bits, where c is the capacity and r is the rate (sponge framework [BDPV-07])



TBC History : Hasty Pudding Cipher

Some history : first tweakable block ciphers

Hasty Pudding Cipher from Schroeppel [Schroeppel-99]

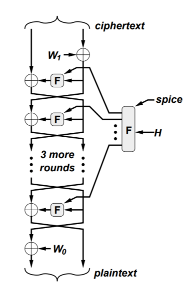
- AES competition candidate
- introduces a 512-bit "*spice*" as a "*secondary key, maybe completely or partially concealed, or completely open*" and notes that "*the spice can be changed very cheaply for each block encrypted*". It is "*expected to be changed often, perhaps for every encrypted block (allows the primary key to have a long lifetime)*"
- spice material is added to the cipher internal state every round
- **no claim against "*chosen spice attack*"**

TBC History : Mercy

Some history : first tweakable block ciphers

Mercy cipher from Crowley [Cro-FSE00]

- includes a 128-bit randomizer or "*spice*" (for disk sector encryption : sector number would be used as a tweak)
- *"The spice goes through a spice-scheduling procedure, analogous with key scheduling [...] this forms six 128-bit round spices"*
- claims about TBC security for encryption only
- broken [Flu-FSE01]



(picture from [Cro-FSE00])

TBC History : formalisation

Some history : first formalisation and generic constructions

Liskov et al. [LRW-C02] introduce first formalisation of TBC :

- *"we expect tweaks to be changed frequently, so a tweakable block cipher should have the property that changing the tweak should be efficient.* [...] *And, for any tweakable block cipher, changing the tweak should be less costly than changing the key."*.
- *"even if an adversary has control of the tweak input, we want the tweakable block cipher to remain secure"*
- introduces the two **first BC-based generic TBC constructions** `LRW1` and `LRW2`
- introduces new **TBC-based modes**, notably the **hash function** `TCH` (broken for certain instantiations [BCS-EC05]) and the **AE mode** `TAE`

Applications of TBCs

Some applications :

- many BC operating modes can be seen as TBC modes (using `XEX` construction). Ex : `PMAC`, `OCB` [Rog-AC04]
- `XTS` disk encryption mode = `XEX` + Ciphertext Stealing

Is that all ?

No, TBCs are very interesting primitives to provide **efficient**, **highly secure**, **simple** (to understand and to prove) **operating modes**, for most classical symmetric-key security notions.

Standardization effort :

- `XTS-AES` is IEEE P1619 standard (2007), NIST SP 800-38E (2010)
- `Deoxys` and `SKINNY` Committee Draft stage at ISO (18033-7)

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Building a TBC from a BC

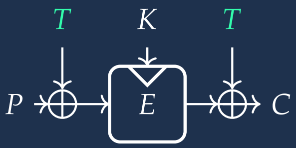
A first (bad) idea

Masking input/output with a tweak (DESX-like) :

$$\tilde{E}_K(T, P) = E_K(P \oplus T) \oplus T$$

$\rightarrow$ results in an undesirable property

$$\tilde{E}_K(T, P) \oplus \tilde{E}_K(T \oplus \delta, P \oplus \delta) = \delta$$



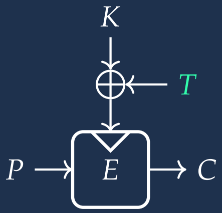
A second (bad) idea

XORing a tweak into the key input :

$$\tilde{E}_K(T, P) = E_{K \oplus T}(P)$$

$\rightarrow$ results in an undesirable property

$$\tilde{E}_K(T, P) = \tilde{E}_{K \oplus \delta}(T \oplus \delta, P)$$



BC-based TBC : LRW1 and LRW2

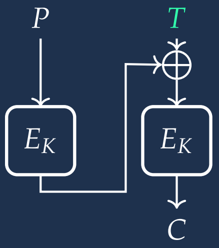
Block-cipher based TBC : LRW1 and LRW2

First BC-based constructions [LRW-C02], up to birthday bound, changing tweak hopefully cheaper than key : LRW1 and LRW2

LRW1

$$\tilde{E}_K(T, P) = E_K(T \oplus E_K(P))$$

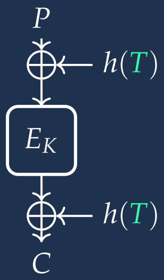
CBC-MAC



LRW2

$$\tilde{E}_{K,h}(T, P) = E_K(P \oplus h(T)) \oplus h(T)$$

h is $\oplus$-universal - part of the secret key



BC-based TBC : XE and XEX

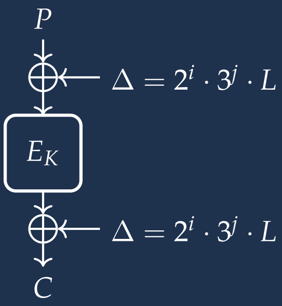
Block-cipher based TBC : XE and XEX

XOR Encrypt (XE) - XOR Encrypt XOR (XEX) [Rog-AC04]

Idea : mask input/(output) with a key and tweak-dependant value, s.t. it is efficient if sequential tweaks $T = T'||i||j$ are used :

$$\tilde{E}_K(T, P) = E_K(P \oplus \Delta) \oplus \Delta$$

with $\Delta = 2^i \cdot 3^j \cdot L$ and $L = E_K(T')$



PRP/SPRP up to **birthday bound** only :

▷ collision on $P \oplus \Delta \rightarrow P \oplus P' = C \oplus C'$

▷ recover the secret L, generate forgeries

Used in :

- ▷ XTS disk encryption mode
- ▷ PMAC, OCB, about a third of all CAESAR candidates, ...

Generic TBC constructions

More generic TBC constructions and advances

- more on XEX [CS-INS06] [Min-SAC06] [CS-IT08] [GJM+-EC16]
- birthday-bound TBC from a permutation :
  TEM [STA+-14] [CLS-C15] [CS-AC15] (XEX with a permutation)
  MEM [GJM+-EC16] (TEM with more efficient masking)
  XPX [Men-C16] (improved RK security guarantees)
- beyond birthday-bound TBC constructions from BC
  [Min-FSE09] [LST-C12] [LS-FSE13] [Men-FSE15] [WGZ+-AC16] [JLM+-LC17] [LL-AC18]
- XTX to extend tweak size [MI-IMA15]
- adding tweak in Luby-Rackoff ciphers [GHL+-AC07]
- building a larger BC out of a TBC (for BBB security)
  [CDMS-TCC10] [Min-FSE09] [MI-IMA11] [Min-DCC15] [NI-FSE20]

Very active field, many improvements every year ...

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Why ad-hoc TBC constructions ?

Why using ad-hoc TBC constructions ?

to get beyond birthday-bound security with improved efficiency !

Theoretical / ad-hoc constructions are not opposed !

We can see a lot of inspiration from ad-hoc TBCs to BC or permutation based ones and vice-versa. A lot of interplay !

How to build an ad-hoc TBC ?

The tweak schedule paradox : Tweak + Key = Tweakey

From [LRW-C02] :

- *"we expect tweaks to be changed frequently, so a tweakable block cipher should have the property that changing the tweak should be efficient. [...] And, for any tweakable block cipher, changing the tweak should be less costly than changing the key."*
- *"even if an adversary has control of the tweak input, we want the tweakable block cipher to remain secure"*

Ad-hoc TBC designer's perspective paradox :

- tweak schedule to be more efficient than the key schedule
- security requirements on the tweak *seem* somehow stronger than on the key : the attacker can fully control the former (even though tweak-recovery attacks are irrelevant)

The tweak schedule paradox : Tweak + Key = Tweakey

From [LRW-C02] :

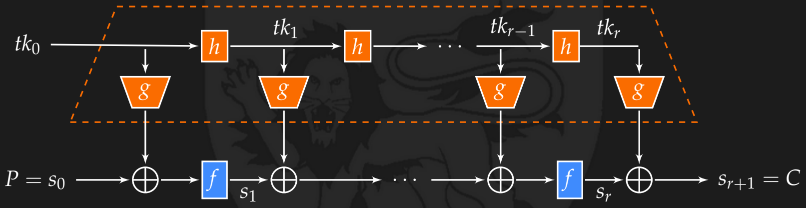
- *"we expect tweaks to be changed frequently, so a tweakable block cipher should have the property that changing the tweak should be efficient. [...] And, for any tweakable block cipher, changing the tweak should be less costly than changing the key."*
- *"even if an adversary has control of the tweak input, we want the tweakable block cipher to remain secure"*

From a designer's perspective, key and tweak should be considered as almost the same [JNP-AC14] :

Tweak + Key = Tweakey

The TWEAKEY framework

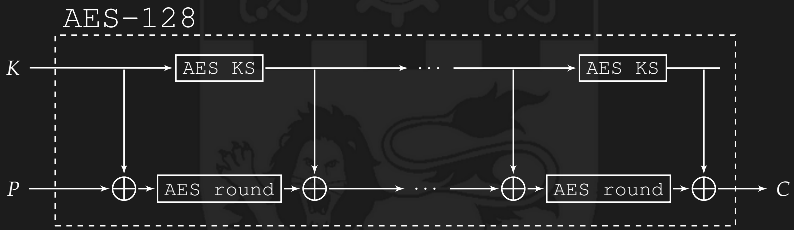
The TWEAKEY **framework rationale** [JNP-AC14] **:**
tweak and key should be treated the same way ⟶ tweakey



TWEAKEY **generalizes the class of key-alternating ciphers**

How to not tweak AES

A bad idea :
XOR 128-bit tweak value T to the internal state every round



$T =$

T_0	T_4	T_8	T_{12}
T_1	T_5	T_9	T_{13}
T_2	T_6	T_{10}	T_{14}
T_3	T_7	T_{11}	T_{15}

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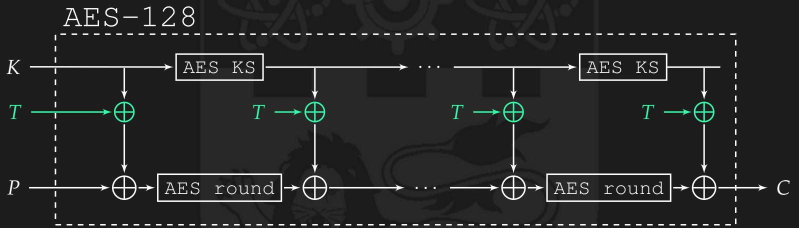

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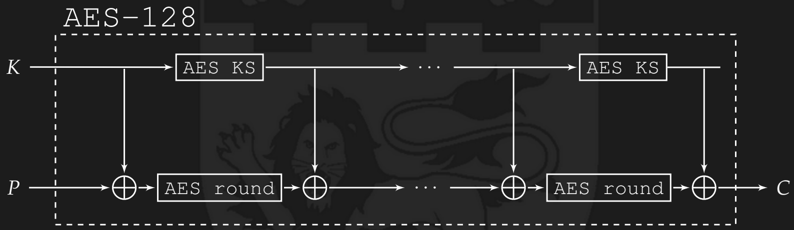
Related-tweak diff. paths with only 1 active Sbox per round

How to tweak AES : KIASU

KIASU [JNP-AC14]

Simply XORing 64-bit tweak T in the two first rows of AES internal state at every round leads to no good related-tweak differential paths



$T =$

T_0	T_2	T_4	T_6
T_1	T_3	T_5	T_7
0	0	0	0
0	0	0	0

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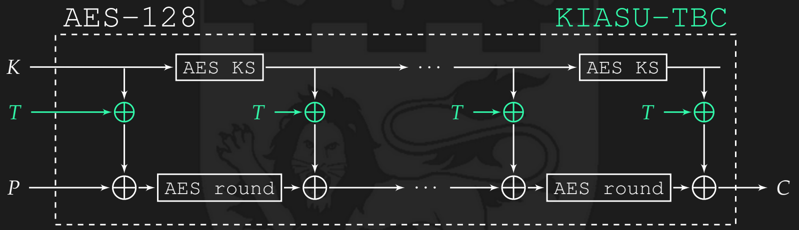

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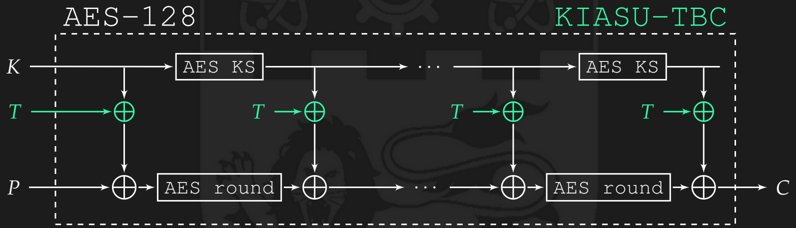


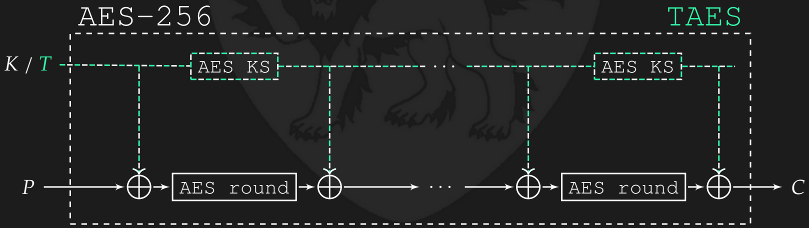
Interesting research topic :

- can an attacker leverage the freedom degrees from T ?
- what about more complex attacks ?
- so far 8 rounds can be attacked [DEM-ACNS16] [DL-CTRSA17]

Reusing existing long-key block ciphers

Idea : reuse existing long-key block ciphers

- what if we use a long-key block cipher and devote part of his key to be the tweak input? ⚠ related-key attacks!
- **Q :** is AES-256 with 128-bit key and 128-bit tweak a secure TBC? Basically TAES proposal [BGIM-FSE20]
- **A :** not in TWEAKEY framework (RK attacks [BK-AC09])!
- TAES assumes single-key scenario only, while AES-256 RK attacks require differences in both K and T



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- **A :** not in TWEAKEY framework (RK attacks [BK-AC09]) !
- `TAES` assumes single-key scenario only, while `AES-256` RK attacks require differences in both K and T

Interesting research topic :

Are there related-key differential paths for `AES-256` with only one 128-bit word active, so as to attack `TAES` in the single key model ?

Very short-tweak TBC

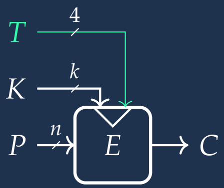
Elastic-Tweak construction for SPN ciphers [CDJ+19]

Very short-tweak TBC construction used in `ESTATE` and `LOTUS-AEAD/LOCUS-AEAD` of NIST LWC competition

Very short-tweak TBC Constructions

A very short tweak $t \ll n$ (like 4 or 8 bits) can be used :

- to simulate independent keys required by some operating modes : $E_{K_i}(P) \sim E_K(T_i, P)$
- for domain separation (full/partial block)
- not in TBC operating modes



Almost the same efficiency as the underlying BC, easy for designer because small tweak

How to build TBCs with large tweaks $t \gg n$?

How to build TBCs with large tweaks $t \gg n$?

Back to the good old problem of key schedule design

Tweakey scheduling design

Designing a tweakey scheduling is hard :

- many many ciphers got broken in the related-key model
- ... but we have a better understanding of how to build a (twea)key schedule since the `SHA-3` competition
- simplicity is an important criterion to make the analysis feasible (lack of security analysis is not allowed)
- recently automated tools (SAT, MILP, CP) are really helpful to analyse diff/linear properties of a cipher

Problem :

When t grows large, the SAT/MILP/CP problem instances becomes too large and the solvers can't handle them anymore.

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Problem :

When t grows large, the SAT/MILP/CP problem instances becomes too large and the solvers can't handle them anymore.

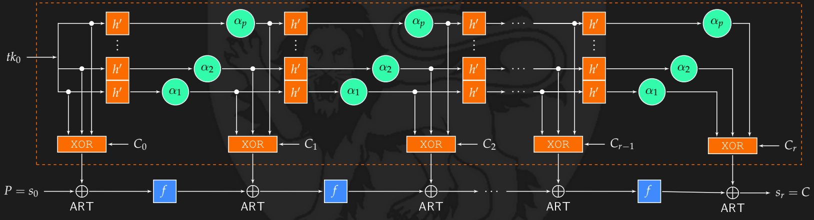
Solution :

Create a tweakey schedule that makes it easy for the solvers !

The Superposition Tweakey (STK) construction

We can solve this problem using the Superposition Tweakey (STK) construction [JNP-AC14] :
The search problem for the tweak part is now reduced from a t-bit to a n-bit problem with a few extra cancellation conditions.

STK Tweakey Schedule



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The search problem for the tweak part is now reduced from a t-bit to a n-bit problem with a few extra cancellation conditions.

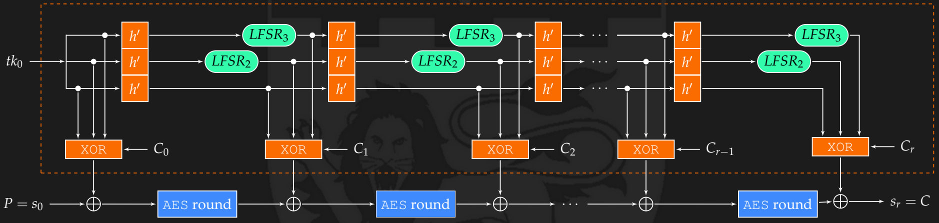
Now the goal is to find :
▷ cheap α_i transformations that minimize #cancellations
▷ best h' to maximize resistance against related-tweakey attacks

Interesting research topic :

▷ finding the α_i to minimize cancellations when t grows large
▷ maybe use an error correcting code on the tweak/key cells to generate all the successive subtweakeys ?

Deoxys-TBC

Deoxys-TBC applies this STK idea to the AES [JNP-AC14]



Comparing Deoxys-TBC and AES

Deoxys-TBC applies this STK idea to the AES [JNP-AC14]

Number of active Sboxes in single-key (SK) and related-key (RTK)

Cipher	Model	Rounds 1	2	3	4	5	6	7	8
Deoxys-TBC-256	SK	1	5	9	25	26	30	34	50
(14 rounds)	RTK	0	0	1	5	9	12	≥ 16	≥ 19
AES-256	SK	1	5	9	25	26	30	34	50
(14 rounds)	RTK	0	0	1	3	5	5	5	10

Comparison of security claims

Deoxys-TBC-256 provides a better resistance than AES-256 against plain related-key attacks, while being more efficient (no Sbox in key-schedule, just byte permutation and a few LFSRs)

Comparing Deoxys-TBC and AES

Deoxys-TBC applies this STK idea to the AES [JNP-AC14]

Number of active Sboxes in single-key (SK) and related-key (RTK)

Cipher	Model	Rounds							
		1	2	3	4	5	6	7	8
Deoxys-TBC-256	**SK**	1	5	9	25	26	30	34	50
(14 rounds)	**RTK**	0	0	1	5	9	12	≥ 16	≥ 19
AES-256	**SK**	1	5	9	25	26	30	34	50
(14 rounds)	**RTK**	0	0	1	3	5	5	5	10

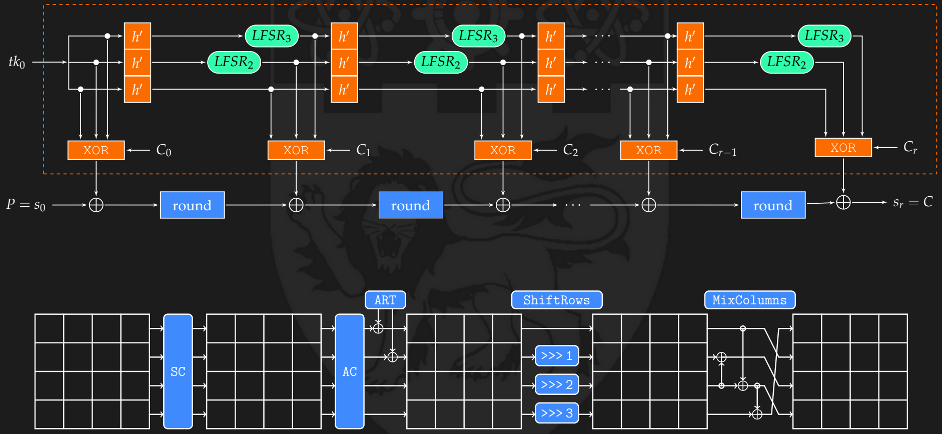
Interesting research topic :

▷ is it be possible to find a permutation that guarantees even more active Sboxes ? Or maybe a different tweakey schedule ?

▷ can an attacker exploit the freedom degrees for more advanced attacks

SKINNY

SKINNY applies this STK idea to lightweight crypto [BJK+-C16]



Ad-hoc TBCs zoo

Many other ad-hoc TBCs

Threefish [FLS+-08]
KIASU-TBC, Deoxys-TBC and Joltik-TBC [JNP-AC14]
Minalpher [STA+-14]
Scream and iScream [GLS+-14]
Skinny and Mantis [BJK+-C16]
QARMA [Ava-FSE17]
Clyde-128 [BBB+-19]
Lilliput [ABC+-19]
CRAFT [BLM+-FSE19]
T-Twine [SMS+-I19]
Pholkos [BLLS+-eP20]
...

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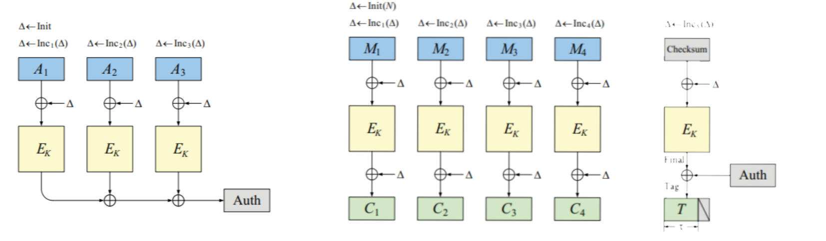
Beyond birthday-bound security

Classical BC-based AE modes
only provide birthday security

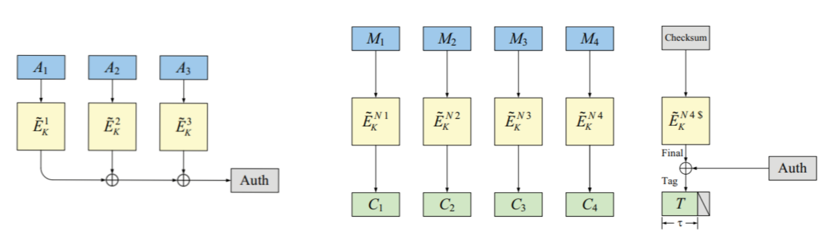


(picture from [KR-FSE11])

Reason : internal collisions on a n-bit value gets you a $q^2/2^n$ term in your security proofs. May lead to birthday complexity attacks. Complex proof.
Ex : OCB3 [KR-FSE11]

Beyond birthday-bound security

TBC-based AE modes can easily provide beyond birthday-bound (BBB) security



(picture from [KR-FSE11])

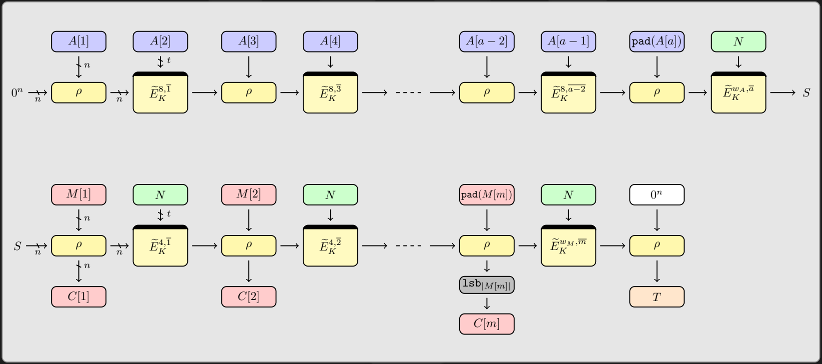
Use tweak input with nonce and counter to always ensure a new TBC instance is called. Easier to understand, better bounds, simpler proofs. priv. bound is 0.

Ex : ΘCB3 [KR-FSE11]

Romulus-N : a lightweight AE mode

Romulus-N [IKMP-19] :
lightweight BBB nonce-respecting AEAD

trades parallelism for small area



(Lightweight) AE modes

Designing an AE mode :

what internal primitive to use ?

BC ?

Permutation ?

TBC ?

(Lightweight) AE modes

Designing an AE mode :

what internal primitive to use ?

First we need to get an estimation

of what is the rate of a BC/TBC/Permutation

Permutation ?

TBC ?

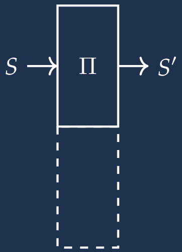
Cost of scaling increasing internal primitives size

We define **rate** according to output size only

Is it justified ?

On scaling costs

Q : assume a n-bit permutation costs x **bitwise operations**, how many do we need to build a $2n$-bit permutation ?



A : at least $\times 2$ and probably a bit more :

- Keccak : about $\times 2.2 \sim 2.32$
- PHOTON : about $\times 2$
- SPONGENT : about $\times 4$

Cost of scaling increasing internal primitives size

We define **rate** according to output size only

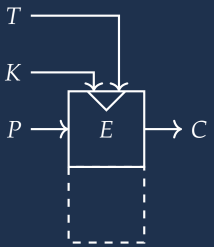
Is it justified ?

On scaling costs

Q : assume a n-bit TBC with t-bit tweakey costs x **bitwise operations**, how many do we need to build a $2n$-bit TBC with t-bit tweakey ?

A : at least $\times 2$ and probably a bit more :

- `SKINNY` : about $\times 2.22$
- `GIFT` : about $\times 2.84$
- `SIMON` and `SPECK` : about $\times 3.16$ and $\times 2.37$



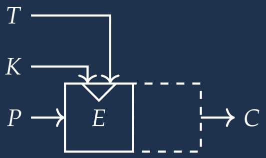
Cost of scaling increasing internal primitives size

We define **rate** according to output size only

Is it justified ?

On scaling costs

Q : assume a n-bit TBC with t-bit tweakey costs x **bitwise operations**, how many do we need to build a n-bit TBC with $2t$-bit tweakey ?



A : much less than $\times 2$:

- SKINNY : about $\times 1.1 \sim 1.2$
- Deoxys : about $\times 1.3$
- AES (key) : about $\times 1.4$
- SIMON and SPECK (key) : about $\times 1.06$

Cost of scaling increasing internal primitives size

Conclusion :

- increasing block/permutation size costs a lot !
- increasing tweakey size doesn't cost much
- rate should be defined according to the output size

Try to use an internal primitive with the smallest output size as possible for a given security level !

Use case 1 : minimal area

Use case 1 : minimal area

In this scenario, we don't care if the ciphering process is really slow, we just want to minimize area
(typically bit-serial or word-serial implementation)

- We will cipher m-bit at a time (m is small)
- We want at least n-bit security, with a n-bit key

Use case 2 : low energy consumption and lightweight

Use case 2 : low energy consumption and lightweight

In this scenario, we want a small area and good throughput performances (typically round-based implementation)
Efficiency = state size/rate (the lowest the better, basically estimates the inverse of throughput-to-area ratio)

- We will cipher about n-bit at a time
- We want at least n-bit security, with a n-bit key

Use case 3 : fast MAC/encryption

Use case 3 : fast MAC/encryption

In this scenario, we want good throughput performances (high rate)

- We can cipher more than n-bit at a time, if needed
- We want at least n-bit security, with a n-bit key

	Min State Size (S)	Max Rate (R)		Best efficiency (S/R)	
		enc.	auth.	enc.	auth.
BC	$4n$ ($\longrightarrow 3n$)	1	1	$4n$	$4n$
Sponge	$2n$	$1/2$ ($\longrightarrow 1$)	1	$4n$	$2n$
TBC	$3n$ ($\longrightarrow 2n$)	1	$1 + t/n$	$3n$	$n < \cdot \leq 1.75n$

Use cases

- **Use case 1 : min. state** with sponges (TBC can also do $2n$)
- **Use case 2 :** best **efficiency** with TBC (reached at lightest point)
- **Use case 3 :** best **rate** with TBC (for auth.)

Comments

- **efficiency of sponge is worse than TBC** in theory because one needs a permutation larger than n (effect reduced with a non-hermetic sponge)
- **TBC :** it seems we can increase the auth rate indefinitely by using a bigger tweak (true in practice ... but only up to a certain level)

128-bit security

Scheme	State Size (S)	Rate (R)		Efficiency (S/R)	
		enc.	auth.	enc.	auth.
Romulus-N1	$3.5n$	1	2	$3.5n$	$1.75n$
Romulus-N3	$3n$	1	7/4	$3n$	$1.71n$
ΘCB3	$4.5n$	1	1	$4.5n$	$4.5n$
COFB	$4n$	1	1	$4n$	$4n$
DUPLEX ($r \ll n$)	$\longrightarrow 2n$	$\longrightarrow 0$	1	$\longrightarrow \infty$	$\longrightarrow 2n$
DUPLEX ($r = n$)	$3n$	1/3	1	$9n$	$3n$
DUPLEX ($r = 2n$)	$4n$	1/2	1	$8n$	$4n$
DUPLEX ($r \gg 2n$)	$\longrightarrow \infty$	$\longrightarrow 1$	1	$\longrightarrow \infty$	$\longrightarrow \infty$
BEETLE	$2.1n$	1/2	1/2	$4.2n$	$4.2n$
ASCON-128	$3.5n$	1/5	1/5	$17.5n$	$17.5n$
Ascon-128a	$3.5n$	2/5	2/5	$8.75n$	$8.75n$

TBC for AE!

Flexibility of the TBC

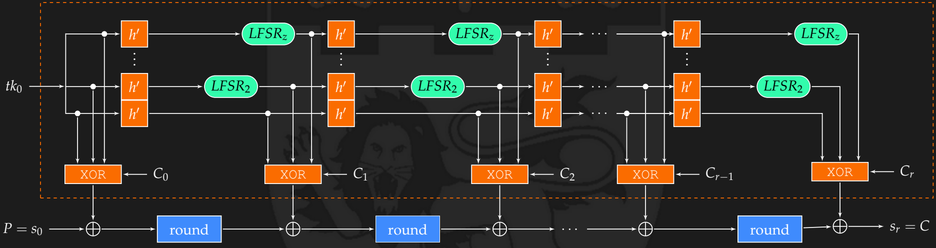
AE mode design process :
fix the **output size** of the TBC according to your security need, then play with the tweak size to get the proper rate and state size according to your constraints.

Don't use a large output size internal primitive if you only want a security of n bits!

Infinitweak

Idea :

Since auth. rate increases with the size of tweak, why not trying constructions with huge tweaks for crazy auth. efficiency ?

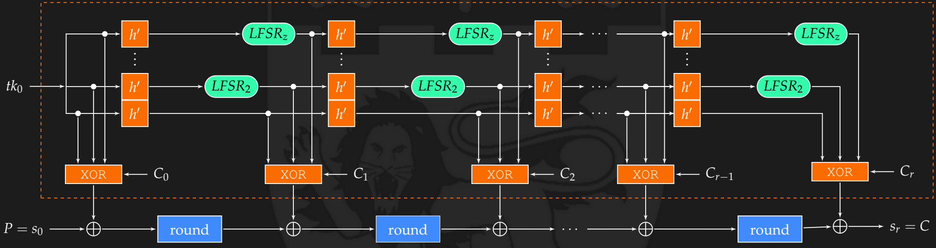


- ▷ rate will eventually reach a limit, but where ?
- ▷ Deoxys-128/1024 or Skinny-128/1024 variants would theoretically provide 50% $\sim$ 100% speed-up (ongoing work)

Infinitweak

Idea :

Since auth. rate increases with the size of tweak, why not trying constructions with huge tweaks for crazy auth. efficiency ?



Interesting research topic :

- How can we design such a very large tweak TBC ?
- What tweakey construction to minimize cancellations ?

Outline

1. Introduction
2. Tweakable Block Ciphers Designs
   - Block Cipher-Based TBC
   - Ad-hoc TBC Constructions
3. Tweakable Block Ciphers for AE
4. **Conclusion**

Future Works

TBCs are promising primitives

- many more applications :
  - side-channels resistance (modes and implementations)
  - Forkcipher for small messages [ALP+-AC19]
  - easy misuse-resistance/RUP, for example with Romulus-M [IKMP-19]
  - Multi-users security (ongoing work with B. Cogliati) : put separately counter, nonce and key in the tweak input of the TBC !
  - Hashing/XOF for example with Naito's MDPH [N-LC19] construction used for Romulus-H. Ongoing work : **blazing fast** Deoxys-TBC**-based hash function** with speed similar to `KangarooTwelve` [BDP+-ACNS18]
  - backdoor ciphers (MALICIOUS framework [PW-C20]) can use TBC with XOF-based tweak schedule
- many open problems, many interesting research topics for TBCs, both in cryptanalysis and design

We're hiring!

Looking for a PhD/postdoc position to work on anything related to cryptography?

Contact me!

Thank you !