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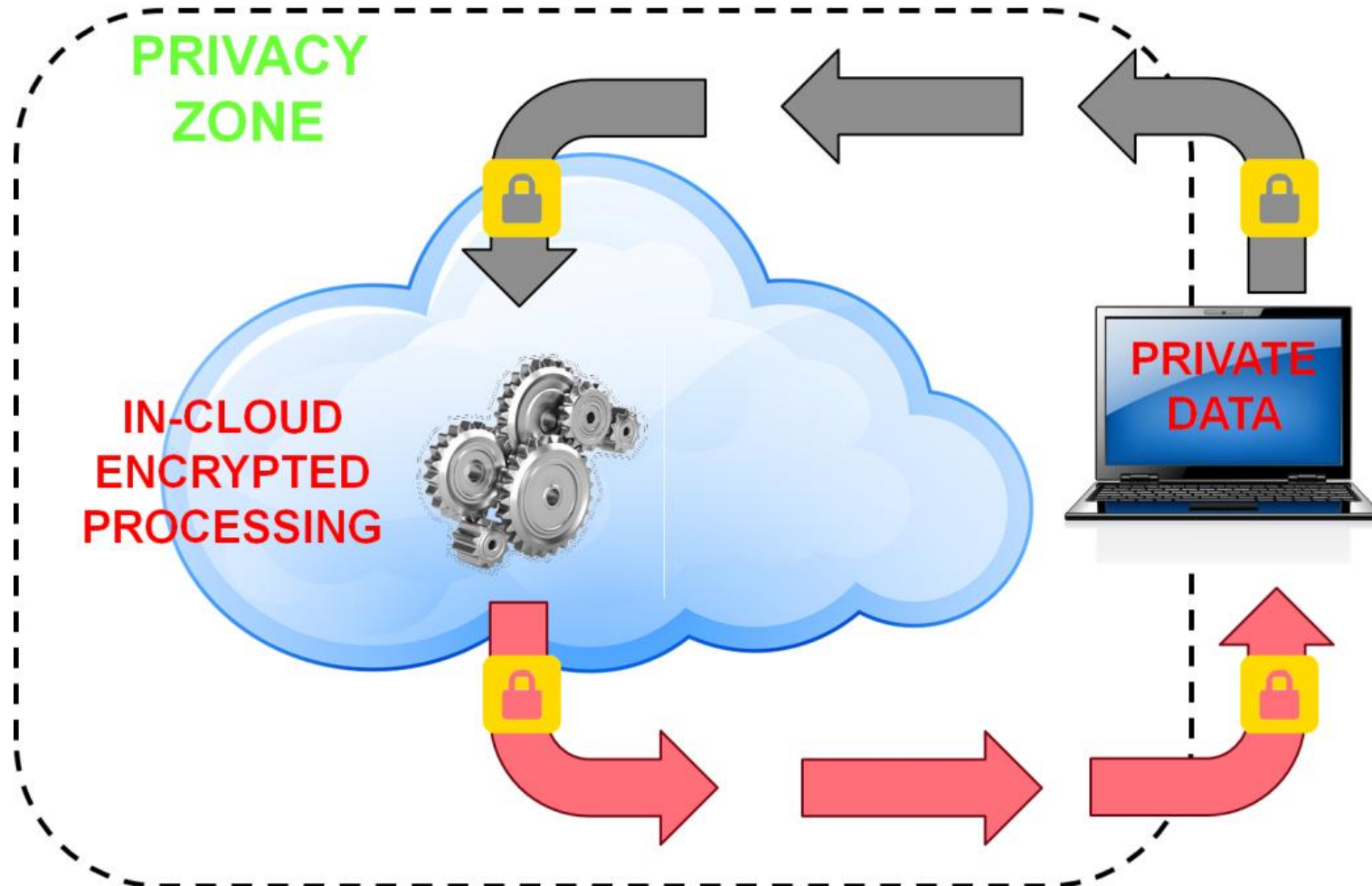
Stream ciphers: A Practical Solution for Efficient Homomorphic-Ciphertext Compression

**Anne Canteaut, Sergiu Carpov, Caroline Fontaine, Tancrede Lepoint,
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CryptoAction Symposium, Budapest, April 2016

Motivation



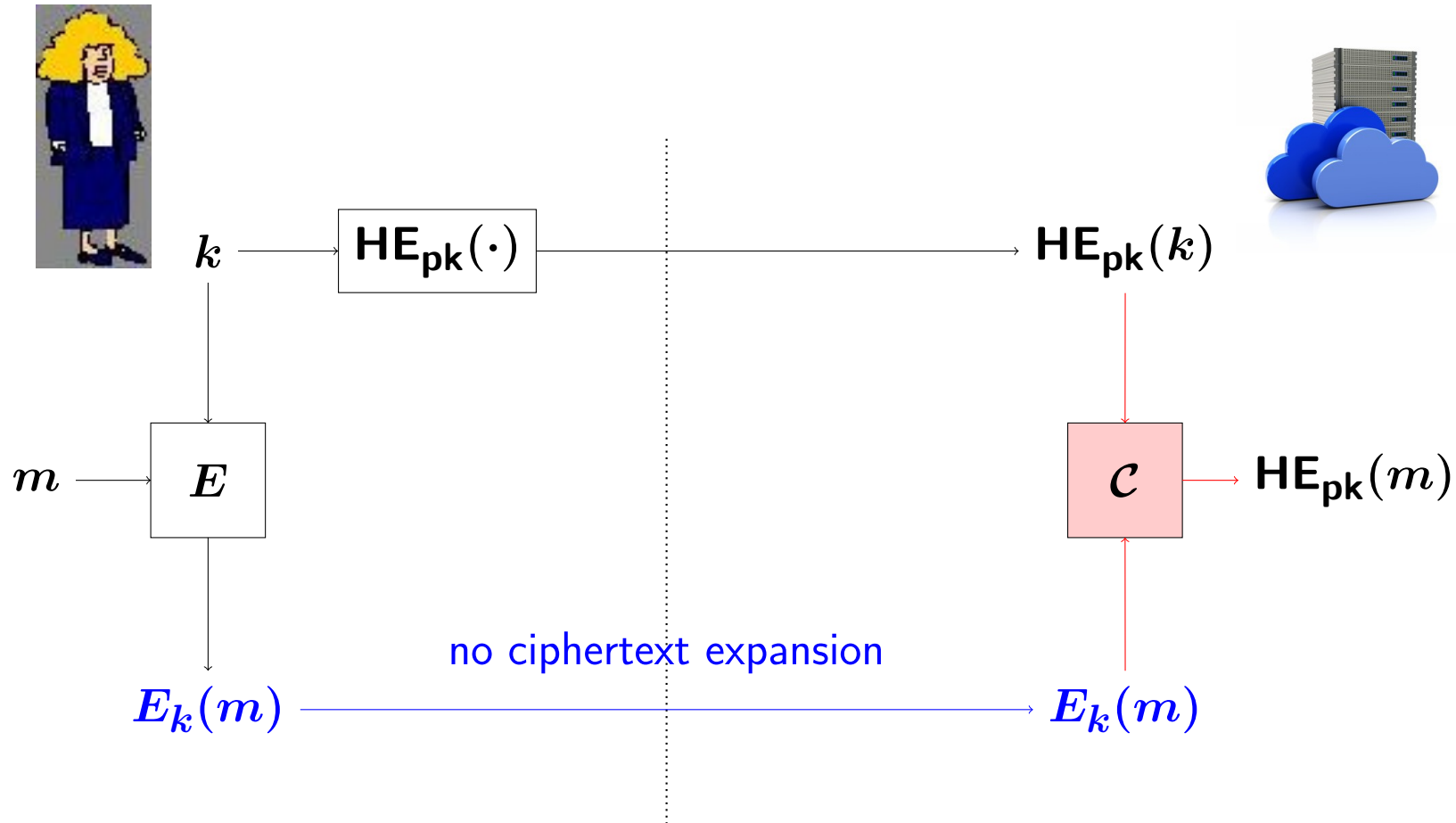
Homomorphic encryption



$$\text{HE}_{\text{pk}}(f(x)) = \text{HE.Eval}_f(\text{HE}_{\text{pk}}(x))$$

Typical ciphertext expansion: 200 kBytes for encrypting a single bit

Optimizing communication using symmetric encryption [Naehrig et al. 11]



$$C = \text{HE.Eval}_{E^{-1}}$$

Question: What kind of symmetric encryption is the most appropriate?

Prior HE-friendly ciphers

Aim:

Minimize the **multiplicative depth** of the decryption function.

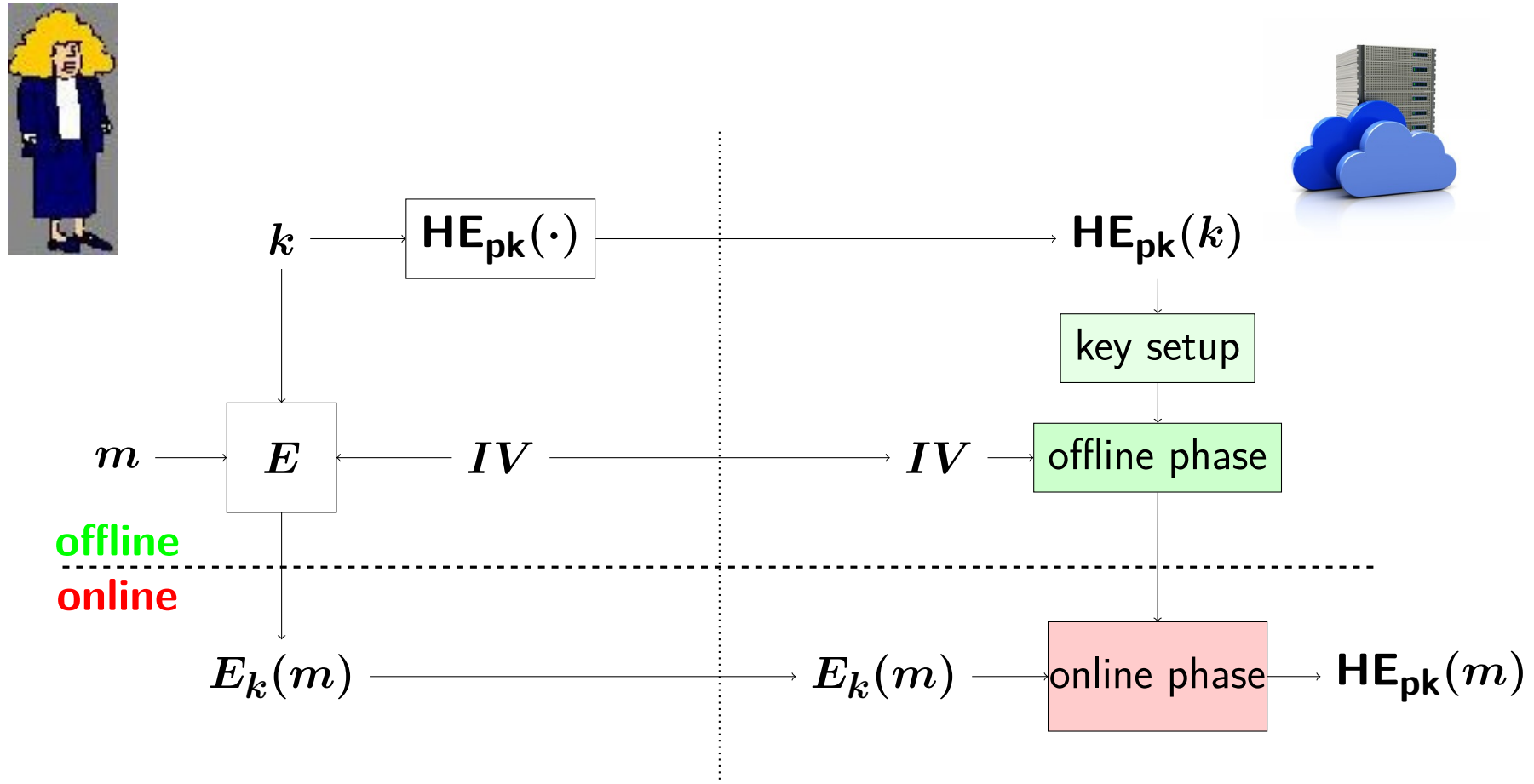
Concrete proposals:

- Optimized implementations of AES [Gentry Halevi Smart 12][Cheon et al. 13]
[Döröz Hu Sunar 14]
- Lightweight block ciphers: SIMON [Lepoint Naehrig 14], PRINCE [Döröz et al.14]
- Dedicated block cipher: Low-MC [Albrecht et al. 15]

Outline

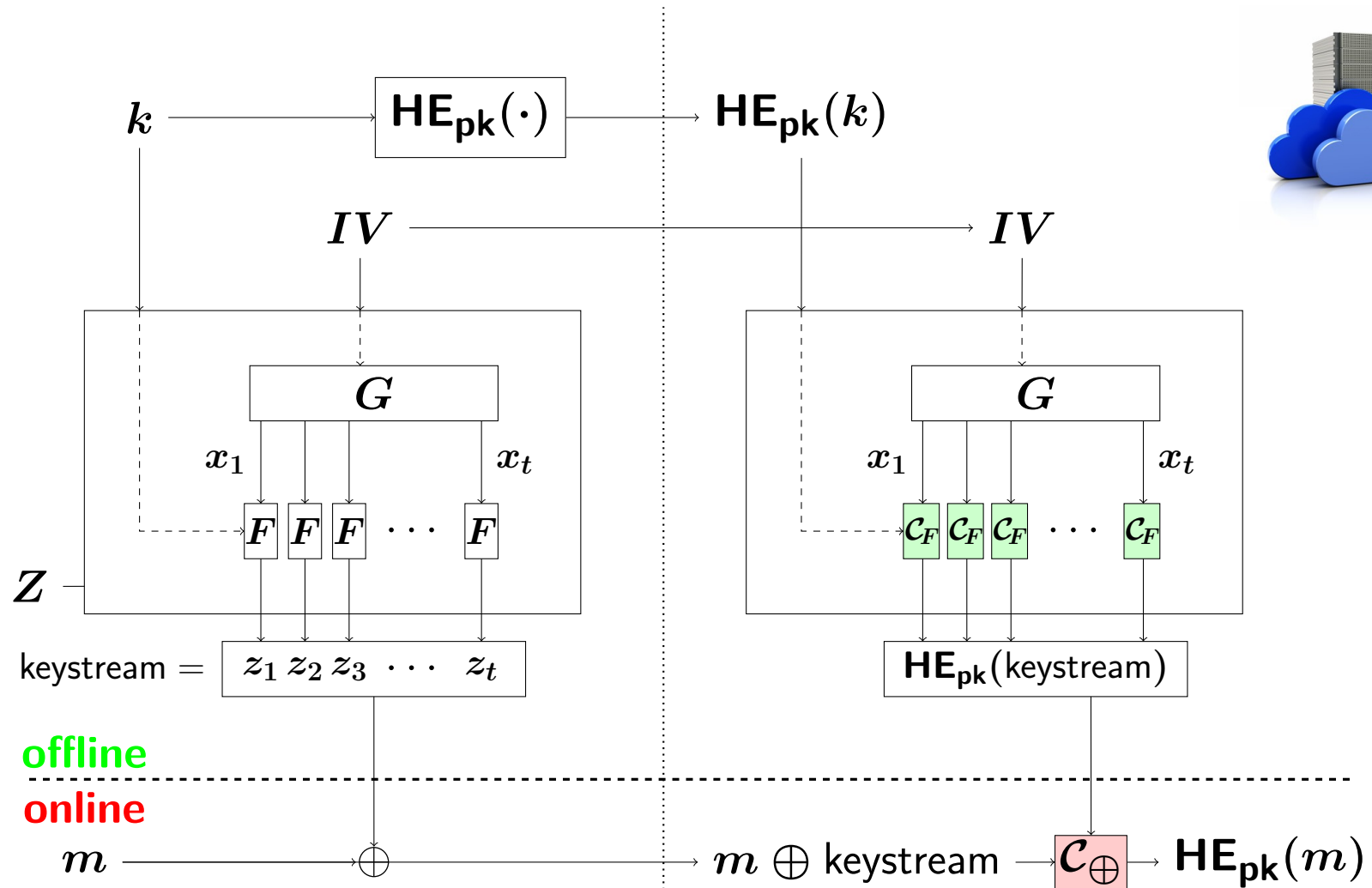
1. Revisiting the whole encryption scheme
2. Trivium and Kreyvium in the HE setting
3. Experimental results

Ciphertext decompression with IV-based encryption



→ Reduce the online phase to a minimum.

With an additive stream cipher



→ Minimize the multiplicative depth of F .

Instantiation with a counter

Expansion function G :

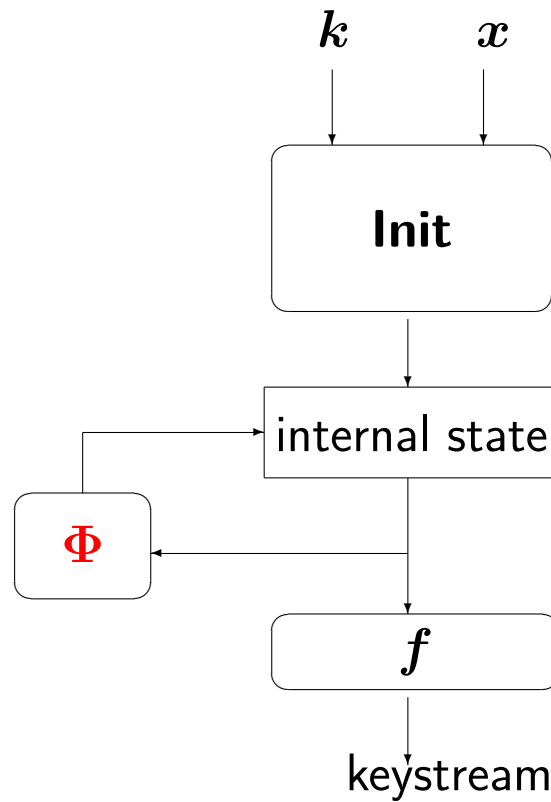
$$G(IV) = (IV, IV \boxplus 1, IV \boxplus 2, \dots, IV \boxplus (t - 1))$$

Why not use for F a block cipher?

security limited to $2^{n/2}$ where n is the block size.

→ strong limitation for lightweight ciphers with $n = 64$ or 32 .

Low-depth keystream generator



- We need a transition function Φ with a low multiplicative depth.
- No strong limitation of the size of the internal state.

Trivium and Kreyvium

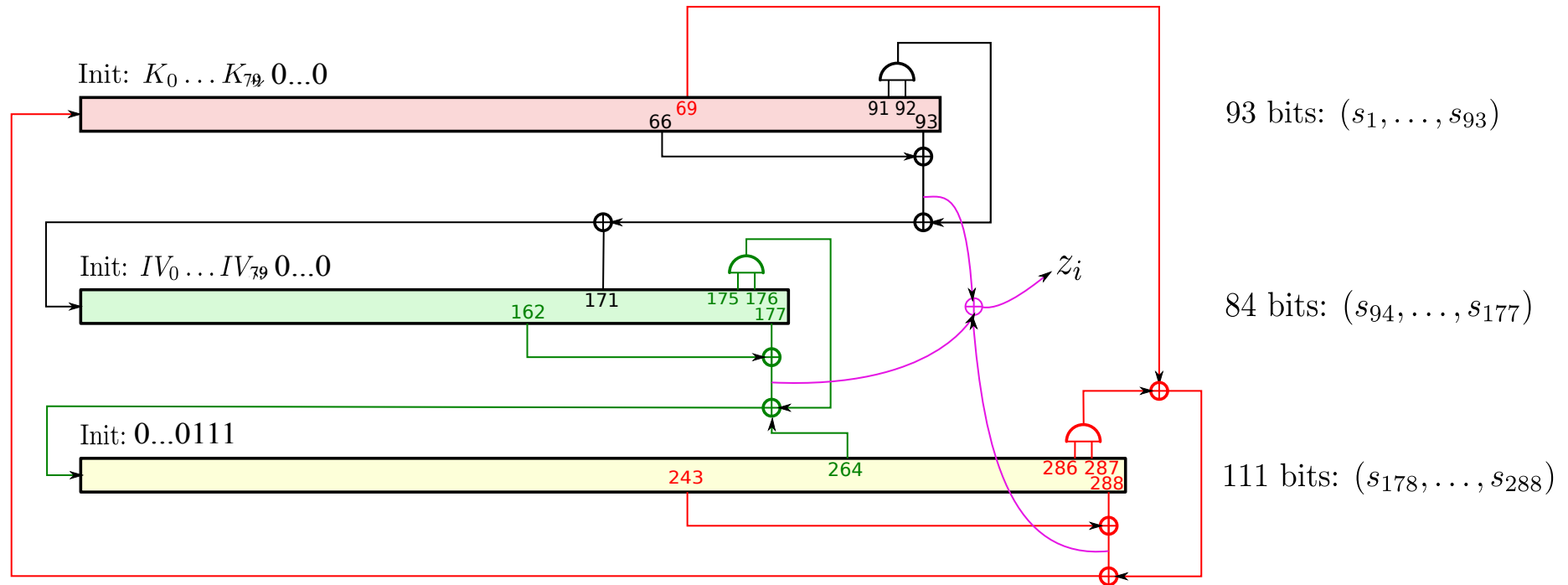
two low-depth stream ciphers

Trivium [De Cannière Preneel 08]

recommended by the eSTREAM project

- transition function with degree 2
- key size = 80 bits
- IV size = 80 bits
- initialization = 1152 blank rounds

Trivium [De Cannière Preneel 08]



Multiplicative depth of Trivium

The keystream length which can be produced with a circuit of depth d , $d \geq 4$, is

$$282 \times \left\lfloor \frac{d}{3} \right\rfloor + \begin{cases} 81 & \text{if } d \equiv 0 \pmod{3} \\ 160 & \text{if } d \equiv 1 \pmod{3} \\ 269 & \text{if } d \equiv 2 \pmod{3} \end{cases}$$

- At depth 12, 57 bits
- At depth 13, 136 bits

Kreyvium, a 128-bit version of Trivium

key size = IV size = 128 bits

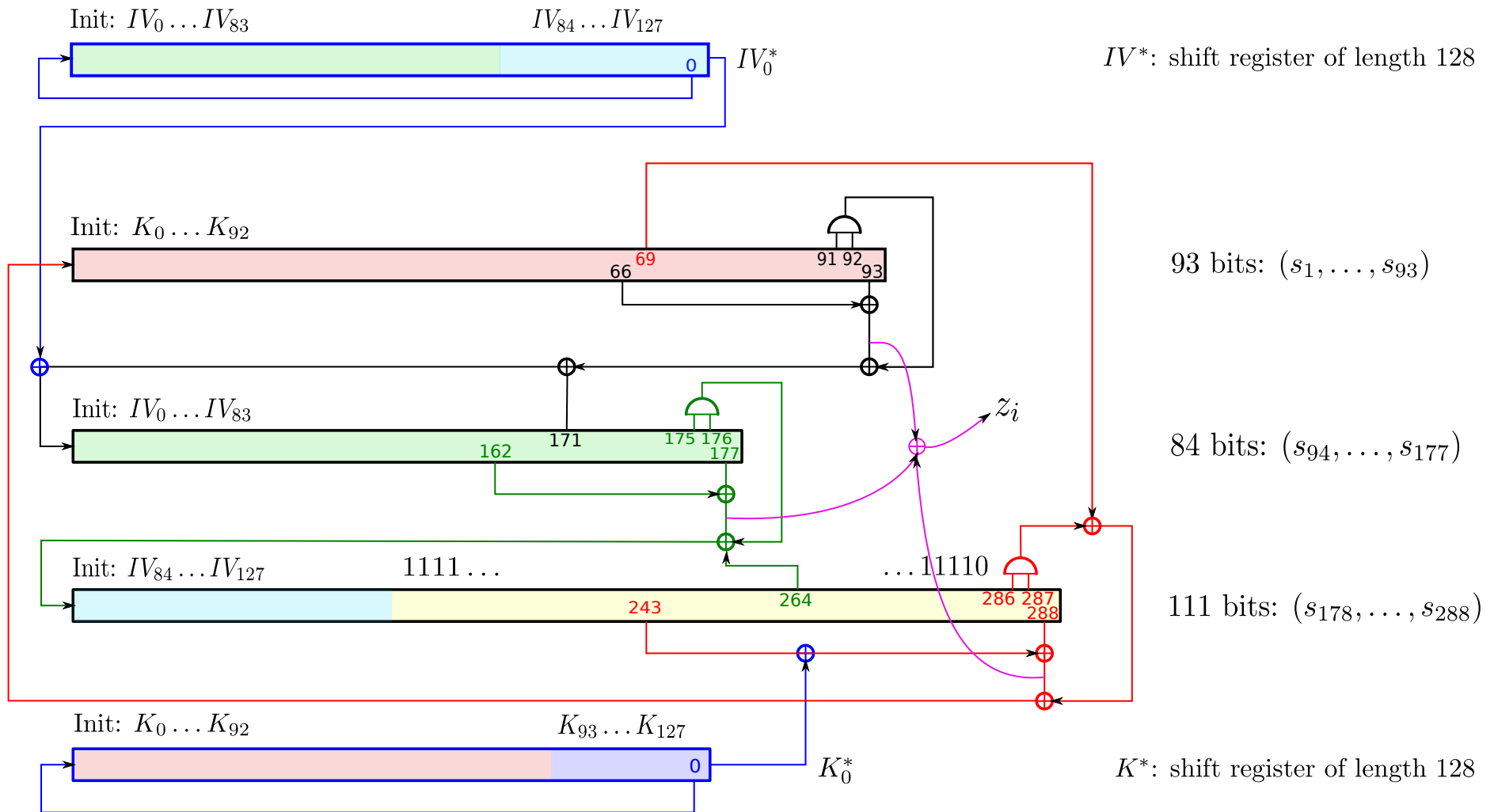
Increasing the size of the internal state.

- no cost if the additional part is updated linearly
- better resistance to TMDTO attacks and to algebraic attacks if the additional part contains some secret material

→ the 128-bit key and the 128-bit IV are added to the internal state

Size of the internal state = 544 bits (416 are unknown)

Kreyvium



Multiplicative depth of Kreyvium

The keystream length which can be produced with a circuit of depth d , $d \geq 4$, is

$$282 \times \left\lfloor \frac{d}{3} \right\rfloor + \begin{cases} 70 & \text{if } d \equiv 0 \pmod{3} \\ 149 & \text{if } d \equiv 1 \pmod{3} \\ 258 & \text{if } d \equiv 2 \pmod{3} \end{cases}$$

→ 11 bits less than with Trivium

- At depth 12, 46 bits
- At depth 13, 125 bits

Some security arguments

Internal state collision:

the number of keystream bits generated from the same key/IV pair must be less than 2^{144} .

Algebraic attacks [Maximov Biryukov 07]:

every relation corresponding to a keystream bit introduces a new unknown in the system.

Cube testers [Dinur Shamir 09][Aumasson et al. 09][Fouque Vannet 13]:

two additional XORs per round → better mixing of the variables

Conditional differential cryptanalysis [Knellwolf et al. 11]

even in the weak-key setting, 64 bits can never be set to 0

Experimental results

Using HElib (on one core of a server with 4 x AMD Opteron 6172 processors)

	security level	N	used depth	#slots	latency (sec.)	throughput (bits/min)
Trivium-13	80	136	13	600	3650	1341
			20	720	11380	516
Kreyvium-13	128	125	13	682	3987	1272
			20	480	12451	287
LowMC-128	$? \leq 118$	256	13	682	3369	3109
			20	480	9977	739

Using the Fan-Vercauteren scheme on a 48-core server

	security level	N	used depth	throughput (bits/min)		Speed gain
				1 core	48 cores	
Trivium-13	80	136	13	9.2	240	× 26.2
			20	3.4	106	× 31.0
Kreyvium-13	128	125	13	5.7	151	× 26.5
			20	2.2	77	× 34.0
LowMC-128	$? \leq 118$	256	14	10.0	90	× 9.0
			21	4.6	47	× 10.2

Conclusions

- **IV-based stream ciphers** are the most appropriate ciphers.
- Good performances can be obtained with firmly-established symmetric ciphers.

Open question.

How many **multiplicative levels are necessary** to achieve a reasonable security level?
→ (impractical) approach based on discrete-log achieving a multiplicative depth of $(\lceil \log \kappa \rceil + 1)$ for κ -bit security.