Persistent Fault Model: Generalization, Cryptanalysis and Countermeasures

Viet-Sang Nguyen

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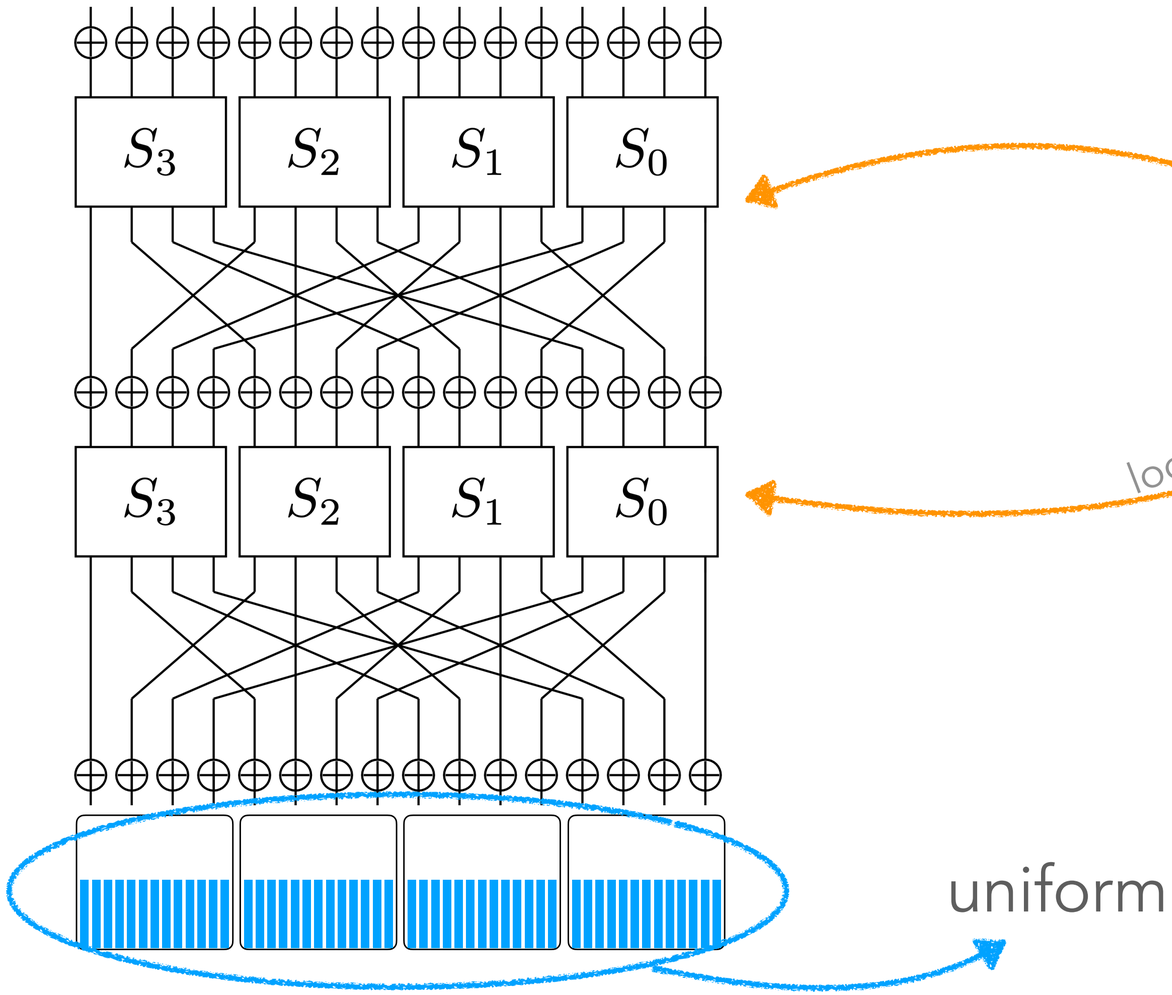
(joint work with Vincent Grosso and Pierre-Louis Cayrel)

Persistent Fault Attacks

S-box in ciphers



look-up

look-up

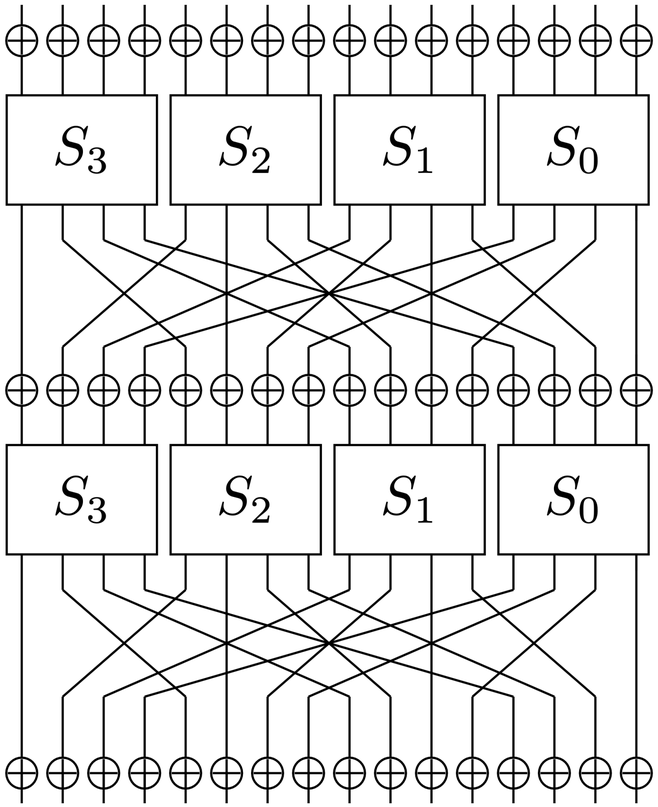
S-box

C	5	6	B	9	0	A	D
3	E	F	8	4	7	1	2

memory

uniform

Faulting S-box



look-up

look-up

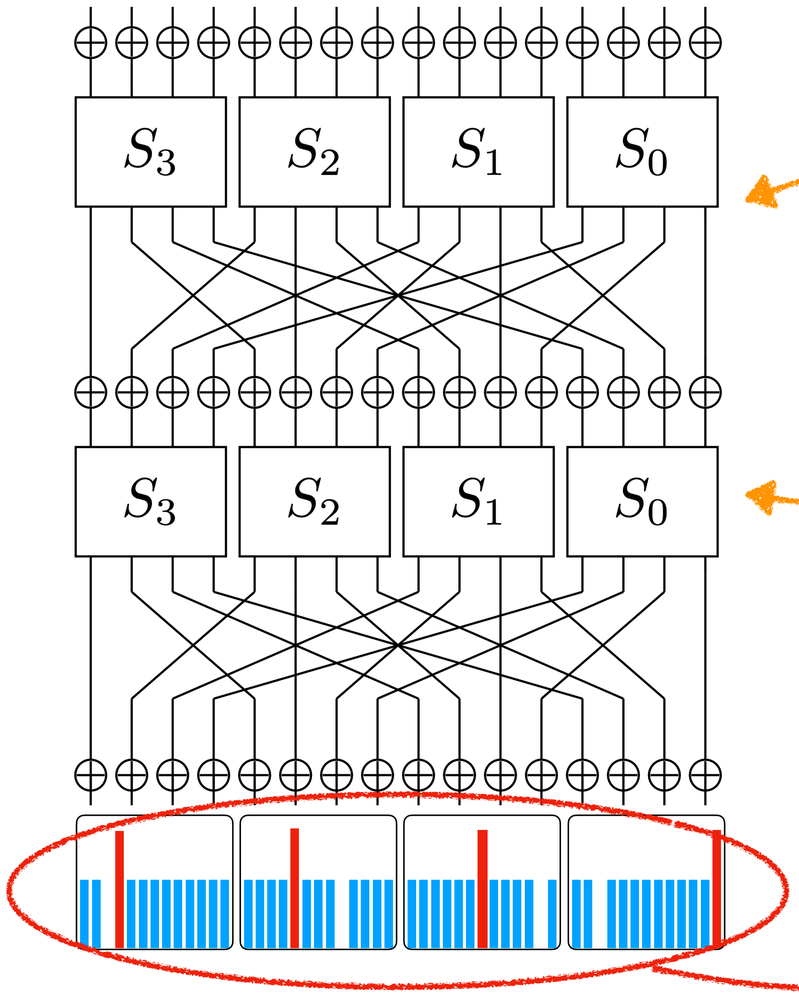
biased faulty S-box

5	5	6	B	9	0	A	D
3	E	F	8	4	7	1	2

memory

- Fault on first element: C → 5
  - C: disappears
  - 5: appears twice

Faulting S-box



look-up

look-up

biased faulty S-box

5	5	6	B	9	0	A	D
3	E	F	8	4	7	1	2

memory

recover key

non-uniform

- Fault on first element: C → 5
  - C: disappears
  - 5: appears twice

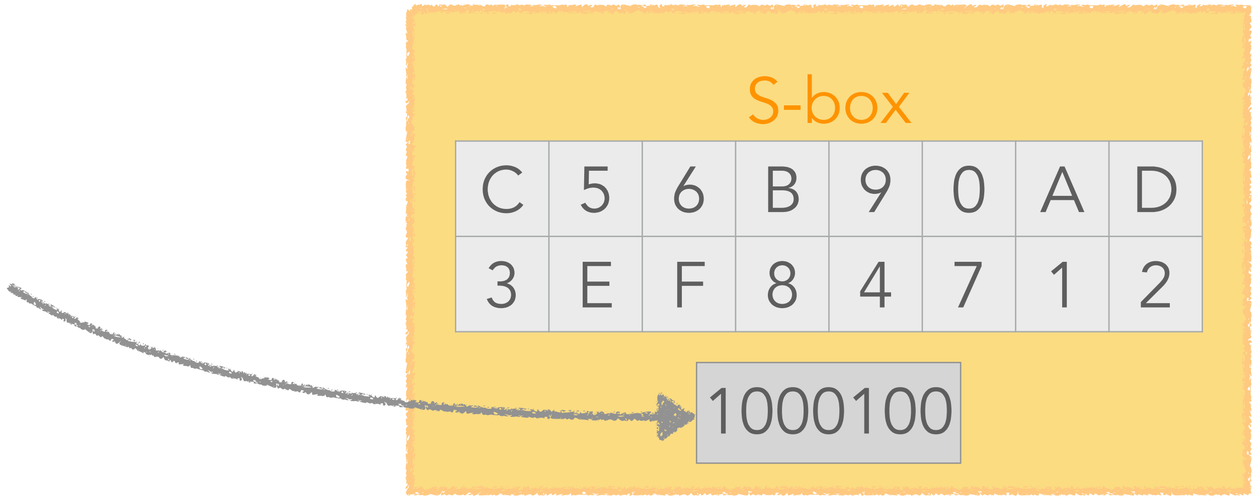
Many existing attacks

- [CGR20], [ESP20], [GPT19], [PZRB19], [SBHRBM22], [TL22], [XZYZHR21], [ZHFGTRZG23], [ZLZBHDQR18], [ZZJZBZLGR20]
  - Different techniques
  - Reduce #plaintext-ciphertext pairs

- All rely on biased faulty S-boxes

Countermeasures

- [SM12]: add check sum (CRC)



But wait… 🧐

- [SM12]: add check sum (CRC)

bypassed !!

S-box

C	5	6	B	9	0	A	D
3	E	F	8	4	7	1	2

1000100

What if we fault both S-box and checksum ?

S-box

C	5	6	B	9	2	A	D
3	E	F	8	4	7	1	2

0000100

Countermeasures

- [TGB23], [CM19]: detect the “bias”
  - #appearance (6): 1 ✅
  - #appearance (3): 1 ✅
  - #appearance (5): 2 ❌

⚡ biased faulty S-box

5	5	6	B	9	0	A	D
3	E	F	8	4	7	1	2

But wait… 🧐

- [TGB23], [CM19]: detect the "**bias**"
  - #appearance (6): 1 ✅
  - #appearance (3): 1 ✅
  - #appearance (5): 2 ❌

bypassed !!

🤔

What if we swap 2 elements ?

biased faulty S-box

5	5	6	B	9	0	A	D
3	E	F	8	4	7	1	2

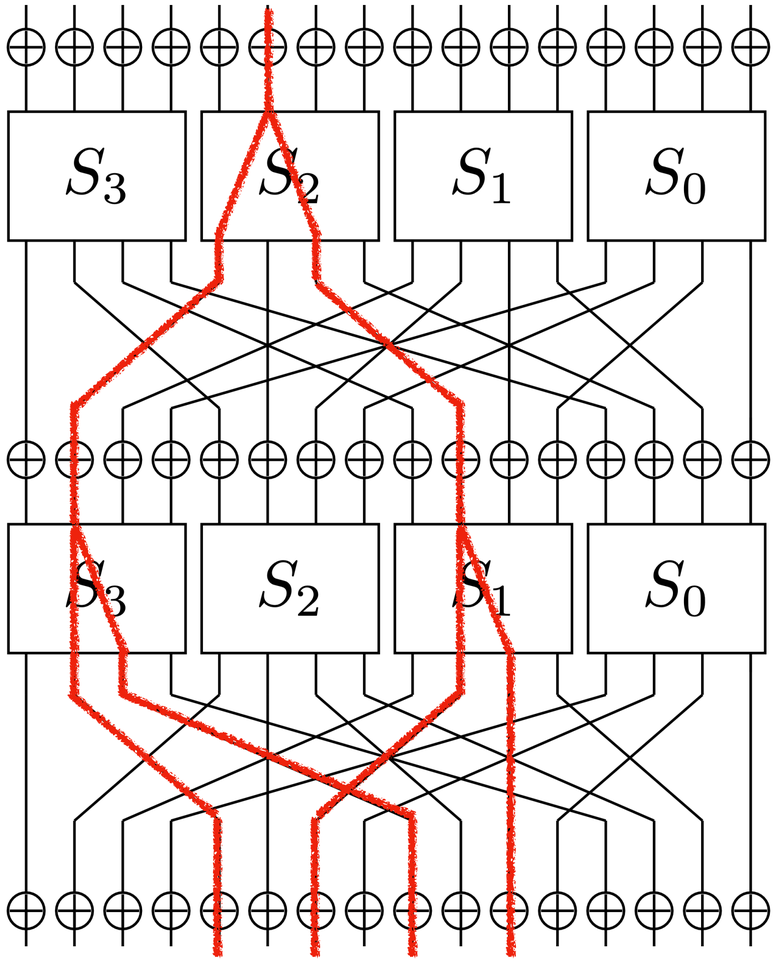
non-biased faulty S-box

C	5	6	B	9	0	A	D
3	F	E	8	4	7	1	2

After bypassing,
still possible to recover key

Classical linear attack

- [Matsui94] exploits weakness of S-box
  - Statistical analysis on many plaintext-ciphertext pairs
- We apply on PRESENT (80-bit key)
  - Recover a bits (advantage)
  - Brute-force $80 - a$ bits



Classical linear attack

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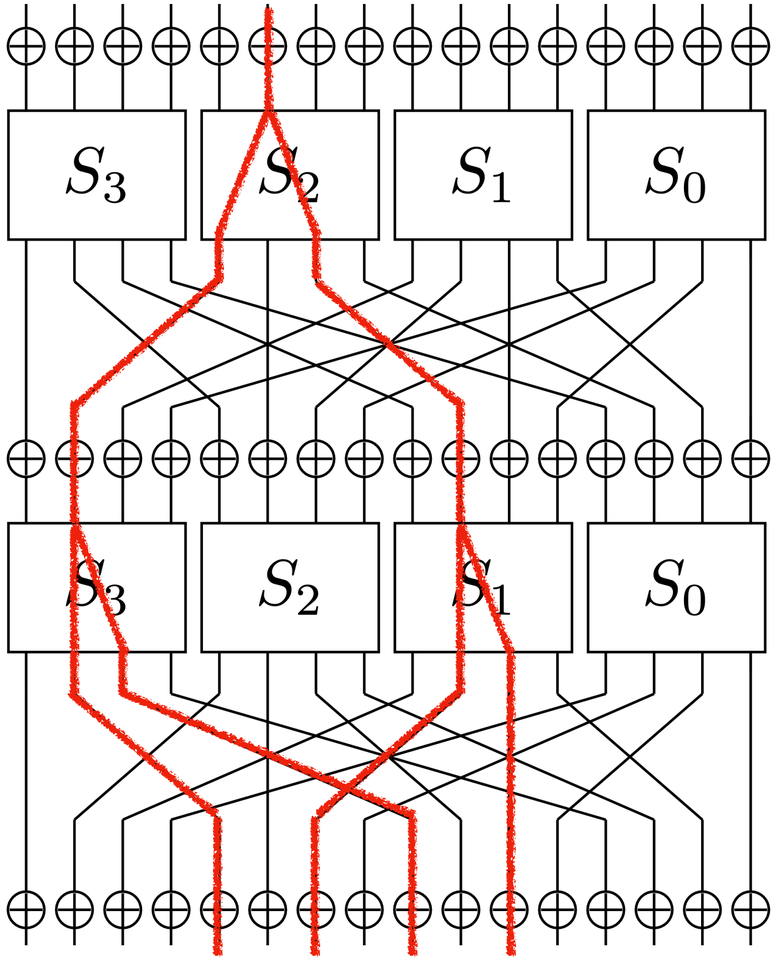
Data complexity N ?

Success probability P_S ?



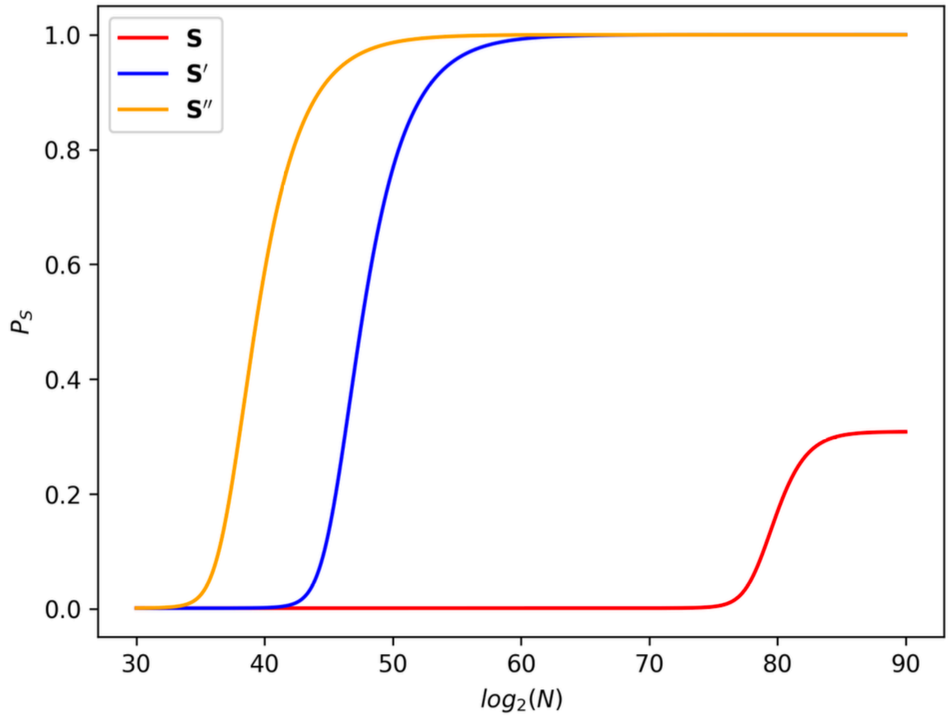
Linear attack with faulty S-boxes

	x	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
Orig.	**S'**(x)	C	5	6	B	9	0	A	D	3	E	F	8	4	7	1	2
2 swaps	**S'**(x)	C	5	6	B	9	0	A	3	D	E	F	8	4	7	1	2
3 swaps	**S"**(x)	C	5	8	B	9	0	A	D	3	6	F	E	4	7	1	2

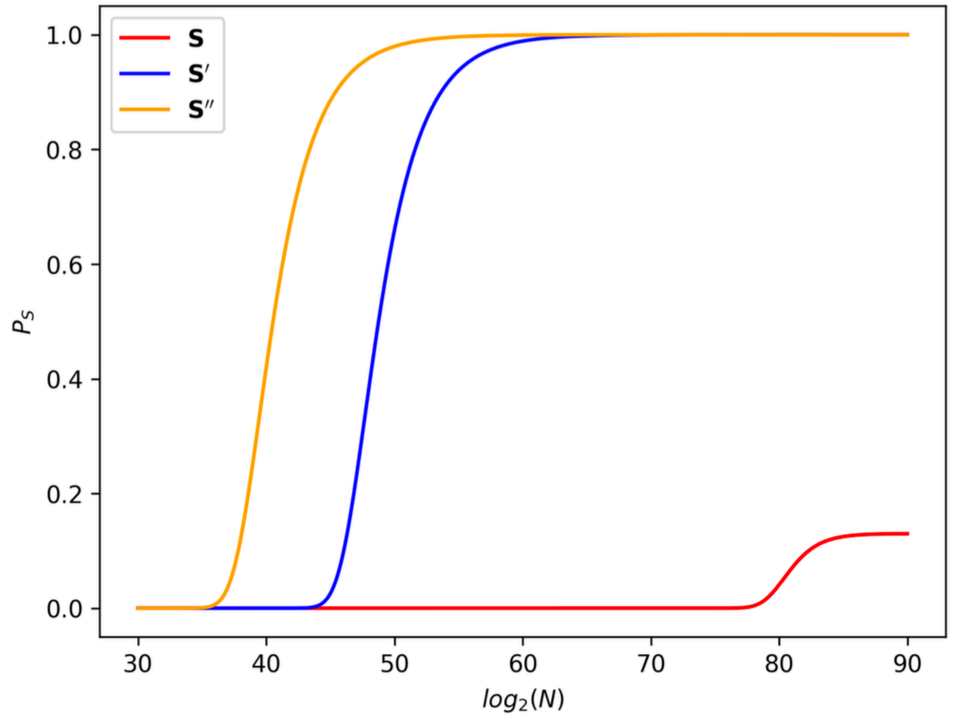
Linear attack with faulty S-boxes

	x	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
Orig.	**S**(x)	C	5	6	B	9	0	A	D	3	E	F	8	4	7	1	2
2 swaps	**S′**(x)	C	5	6	B	9	0	A	3	D	E	F	8	4	7	1	2
3 swaps	**S″**(x)	C	5	8	B	9	0	A	D	3	6	F	E	4	7	1	2

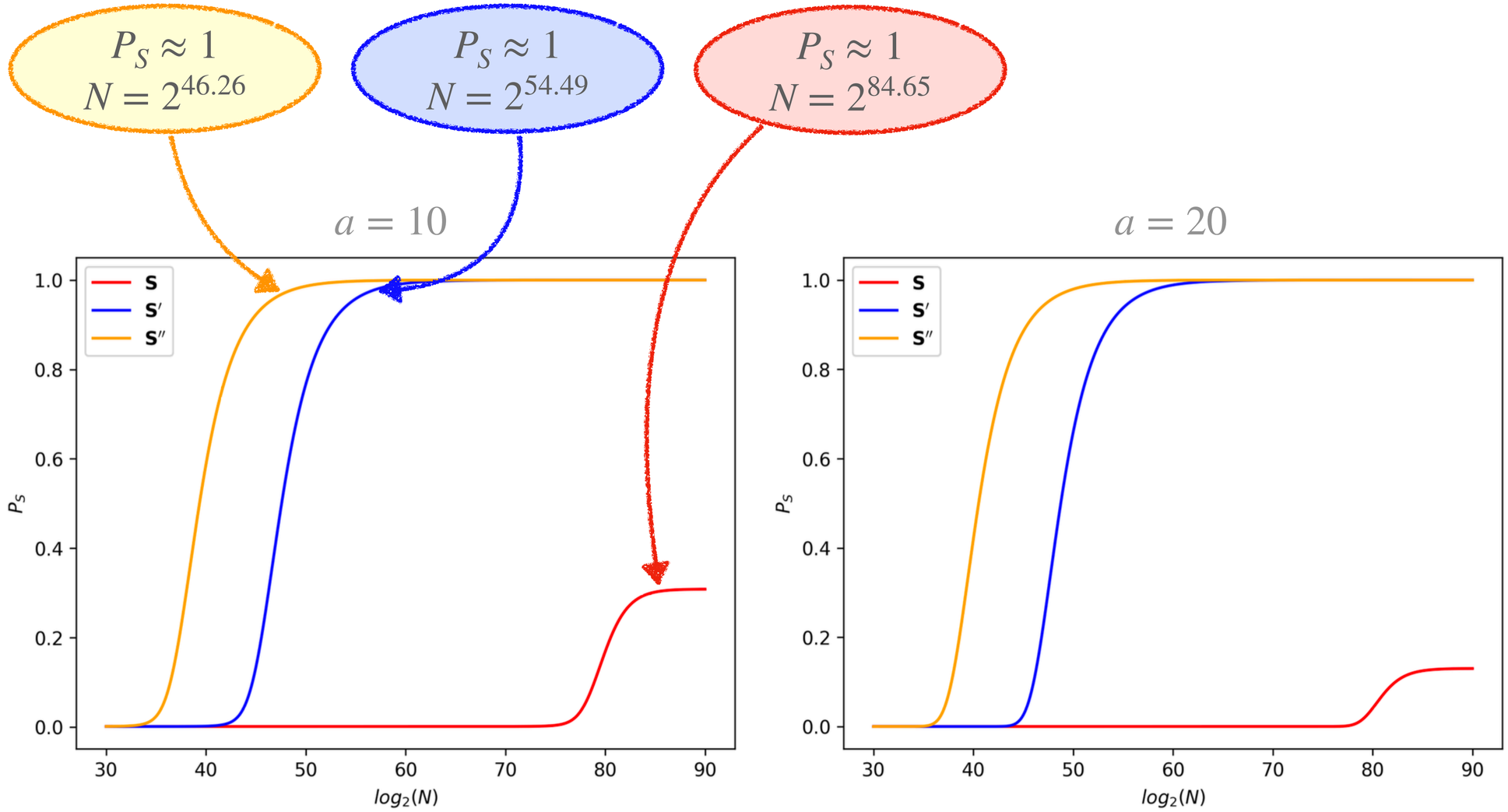
$a = 10$



$a = 20$



Linear attack with faulty S-boxes



Comparison with advanced attacks

Rounds	S-box	Data	Time	Memory	P_S	Source
27	$\mathbf{S}$	$2^{63.8}$	2^{77}	2^{70}	0.95	[ZZ15]
27	$\mathbf{S}$	$2^{63.8}$	$2^{77.5}$	2^{48}	0.95	[BTV18]
27	$\mathbf{S}$	$2^{63.4}$	2^{72}	2^{44}	0.95	[FN20]
28	$\mathbf{S}$	2^{64}	-	2^{89}	0.95	[FN20]
31	$\mathbf{S}'$	$2^{54.49}$	2^{70}	2^{24}	0.95	This work
31	$\mathbf{S}''$	$2^{46.26}$	2^{70}	2^{24}	0.95	This work

Generalize a Strong Model

Our proposed model

	Previous models	Our model
Biased faulty S-box	✅	✅
Non-biased faulty S-box	❌	✅
Key schedule	❌	✅
Implementations without look-up tables for S-box	❌	✅
Faulting checksum for countermeasure	❌	✅

Strong Countermeasure

S-box in ciphers

- Store correct plaintext-ciphertext pairs
- Check encryption's correctness

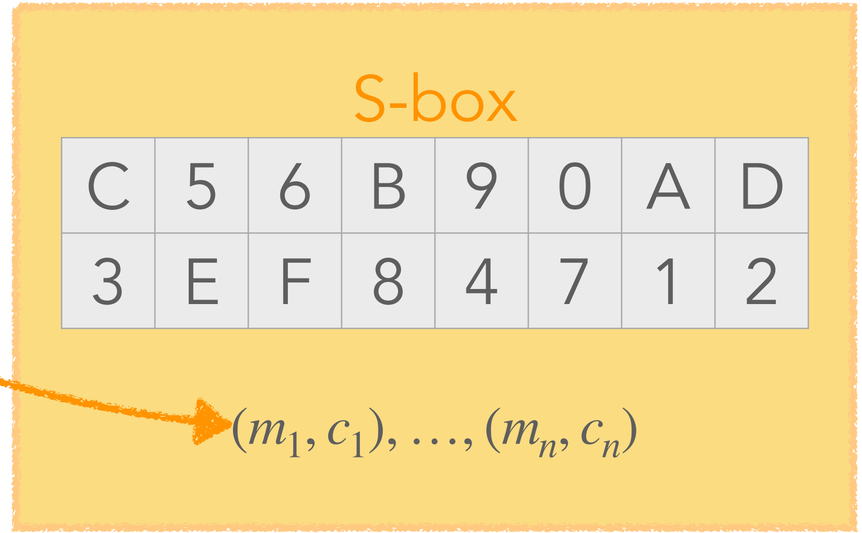
S-box

C	5	6	B	9	0	A	D
3	E	F	8	4	7	1	2

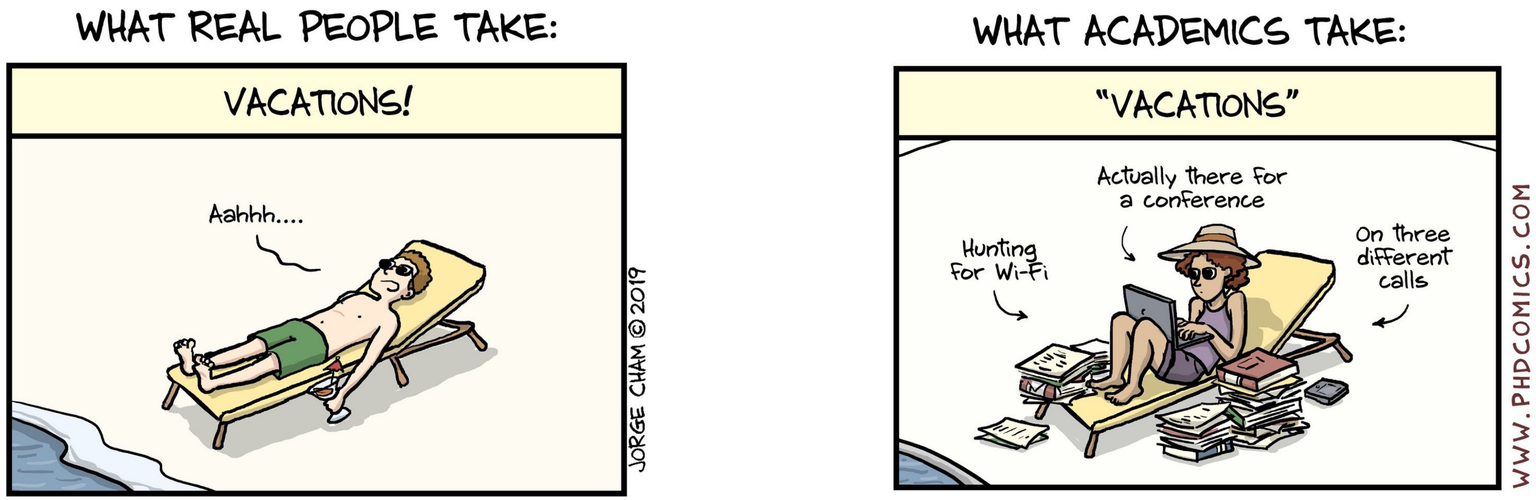
$(m_1, c_1), \ldots, (m_n, c_n)$

S-box in ciphers

- Store correct plaintext-ciphertext pairs
- Check encryption's correctness



	Resistent
Biased faulty S-box	✅
Non-biased faulty S-box	✅
Faults in implementations without look-up tables	✅
Faulting checksum for countermeasure	✅



Thank you! 🙏

Any questions? 🤔

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