Survey of MPC- and ZK-friendly Symmetric Cryptography

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Symmetric Crypto for (MPC, ZK) Researchers and Practitioners

- This is about the art and science to create new hardness assumptions
- No unconditional proofs, no underlying hardness assumptions
- Proofs may rule out certain classes of attacks, but eventually this is (as almst all of cryptography anyhow) a cat-and-mouse game of attacks and defenses
- Symmetric Cryptography = Math + Mess
  (often more mess than elsewhere in crypto)

MPC, ZK, MPC+ZK, for Symmetric Cryptographers (1/2)

- "ZK": Checking integrity/Signing/Authenticating computation on data
  (instead of checking/signing/authenticating data)
- "MPC": Encrypting computation on data
  (instead of encrypting data)
- "MPC+ZK": question to the audience

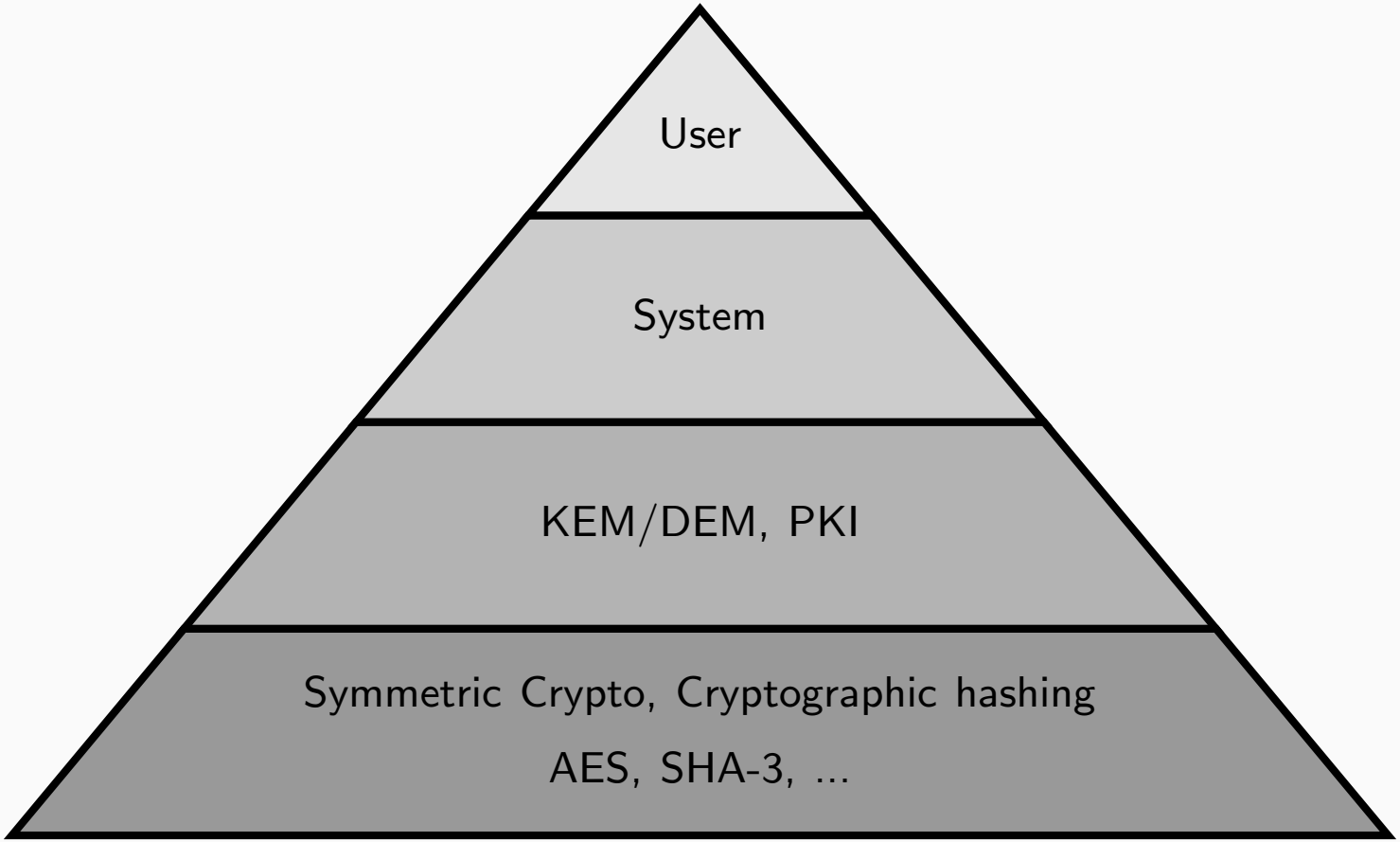
MPC, ZK, MPC+ZK, for Symmetric Cryptographers (2/2)

- Very fast moving field, esp. on practical aspects of "ZK" in the last 5 years.
- Work on practical aspects of "MPC" is also accelerating and finding larger and larger classes applications.
- The *combination* of both technologies is the most recent trend.
- Not all innovations are formally published! Blogs, HackMD pages, github repos are other relevant sources.

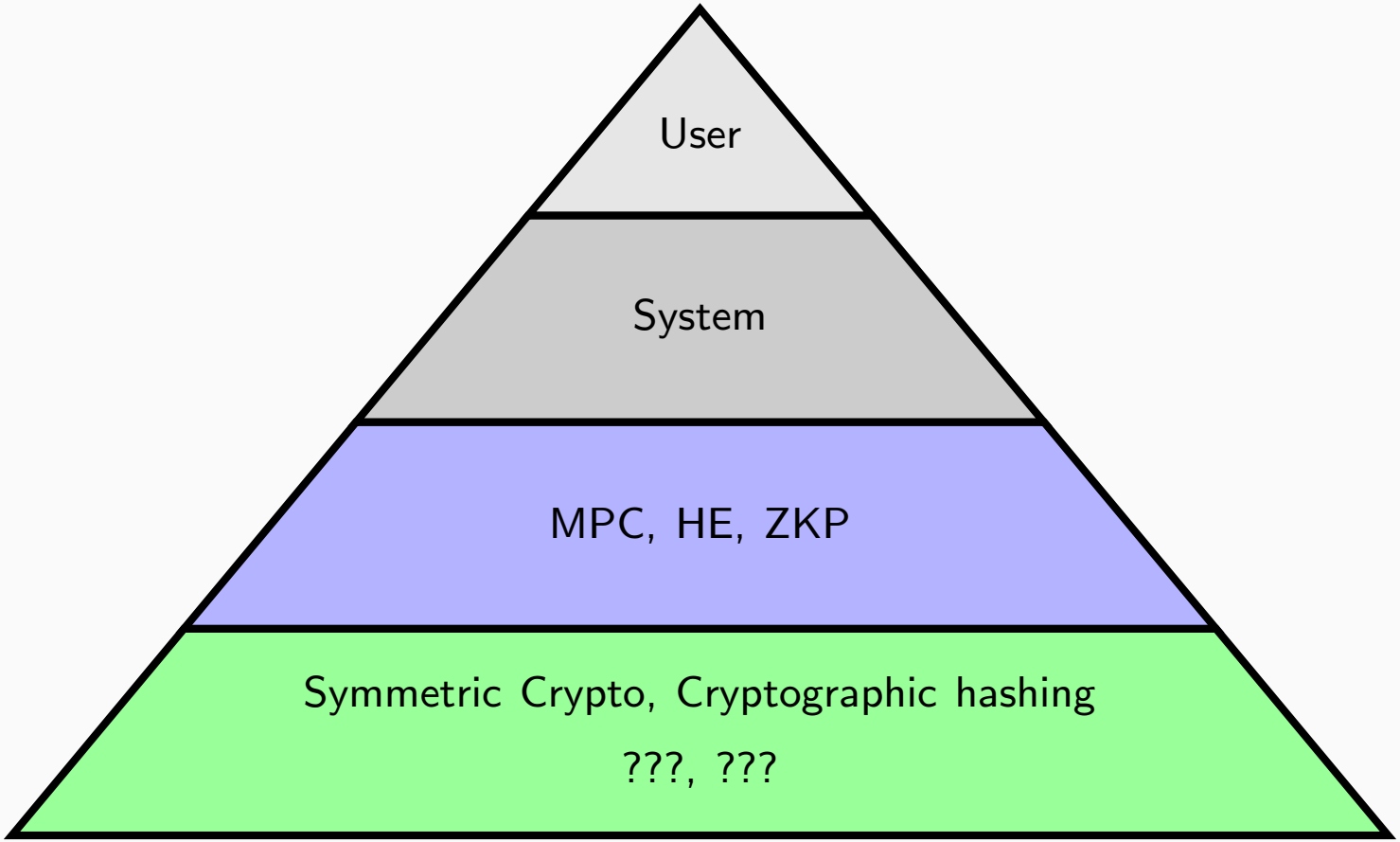
Wait, where is FHE in this?

- Technically, can be seen as an umbrella terms for a class of techniques to do MPC, next to others such as secret sharing, or garbled circuits
- sub-techniques: BGV/BFV, CKKS, TFHE all have distinct demands
- To keep things simpler, FHE-friendly and Garbled-circuit-friendly symmetric crypto and is out of scope for this talk

Role of symmetric-key crypto and hashing in systems



Role of symmetric-key crypto and hashing in systems



Implementation environments for symmetric cryptography

Efficiently provide confidentiality, authenticity, integrity

- until 1980s: dedicated machines, hardware implementing DES, LFSR-based approaches
- since 1990s: software implementations become more relevant in addition to hardware, see e.g. AES
- since 2010s: another boost for software-environments due to virtualization
- also since 2010s: programmable cryptography is becoming increasingly practical

New cryptographic functionalities are new applications of symmetric cryptography

- FHE: Reducing ciphertext expansion, OPRFs, ...
- MPC: Distributed databases, private set intersection, data analytics, OPRFs, public-key signature schemes
- ZKP: Use-cases of zero-knowledge proofs:
  - Set Membership Proofs ("I know a private key of one of the public keys of this Merkle tree")
  - Data Commitments ("Here is the Merkle tree of the execution trace of my program, I can open it at any point").
  - Outsourced Computation, "proof everything"

A Zoo of MPC/ZK-friendly concretely-efficient symmetric crypto

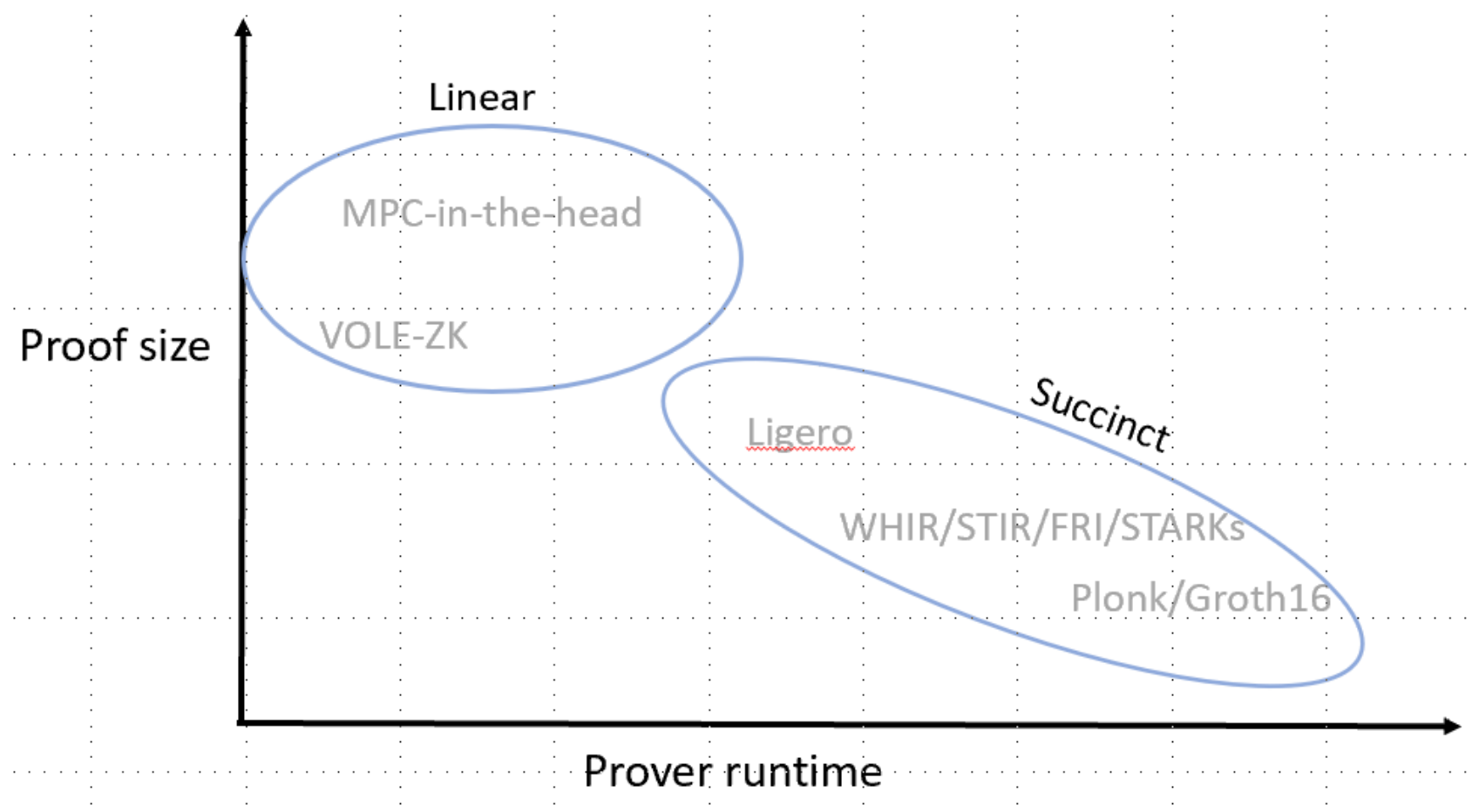
2015: 2	[Can+18; Alb+15]
2016: 2	[Gra+16; Alb+16]
2017: -	
2018: 2	[Bon+18; AD18]
2019: 4	[Alb+19; Aly+20; Gra+20; Gra+21]
2020: 1	[SAD20]
2021: 6	[Dob+21; Din+21; Sze21; Gra+22a; Dob+22; Gra+22b]
2022: 5	[Bou+23; AMT22; Gra+23b; Gra+23a; Ash+22]
2023: 6	[RST23; AKM23; Gra+24b; GKS23; Sze+23; Sal23]
2024: 3	[Ash+24; Gra+24a; AT24]
2025: 4	[Bal+25; Ha+25; Bou+25; Gra+26]

source: mostly IACR eprint, plus selection from IEEE Access, ToSC, arxiv

Included, but quite different: Signatures via MPC-in-the-head, VOLE-in-the-head

- 2017-2022: First NIST standardization process
  - Finalist Picnic based on MPCitH and LowMC
  - SPHINCS+ (hash based) was selected instead.
- since 2023: Additional signatures process at NIST
  - Lots of MPCitH-based submissions
  - Submission FAEST based on VOLEitH and AES (with Rain as a potential alternative OWF)

Families of ZK Proofs



The ZK-friendly Hash Function Zoo

Type 1

"low degree only"

- Low-degree

$$y = x^d$$

- Fast in Plain
- Many rounds
- Often more constraints
- MiMC(16), GMiMC (19), Poseidon (19), Neptune (21), Poseidon2 (23), Poseidon2b(25)

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Type 2

"non-procedural", "fluid"

- Low-degree equiv.

$$y = x^{1/d} \Rightarrow x = y^d$$

- Slow in Plain
- Fewer rounds
- Fewer constraints
- Friday(18), Vision(19), *Rescue* (19), Grendel(21), Rain(21), AIM(22), Griffin (22), Anemoi (22), Arion(23)

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Type 3

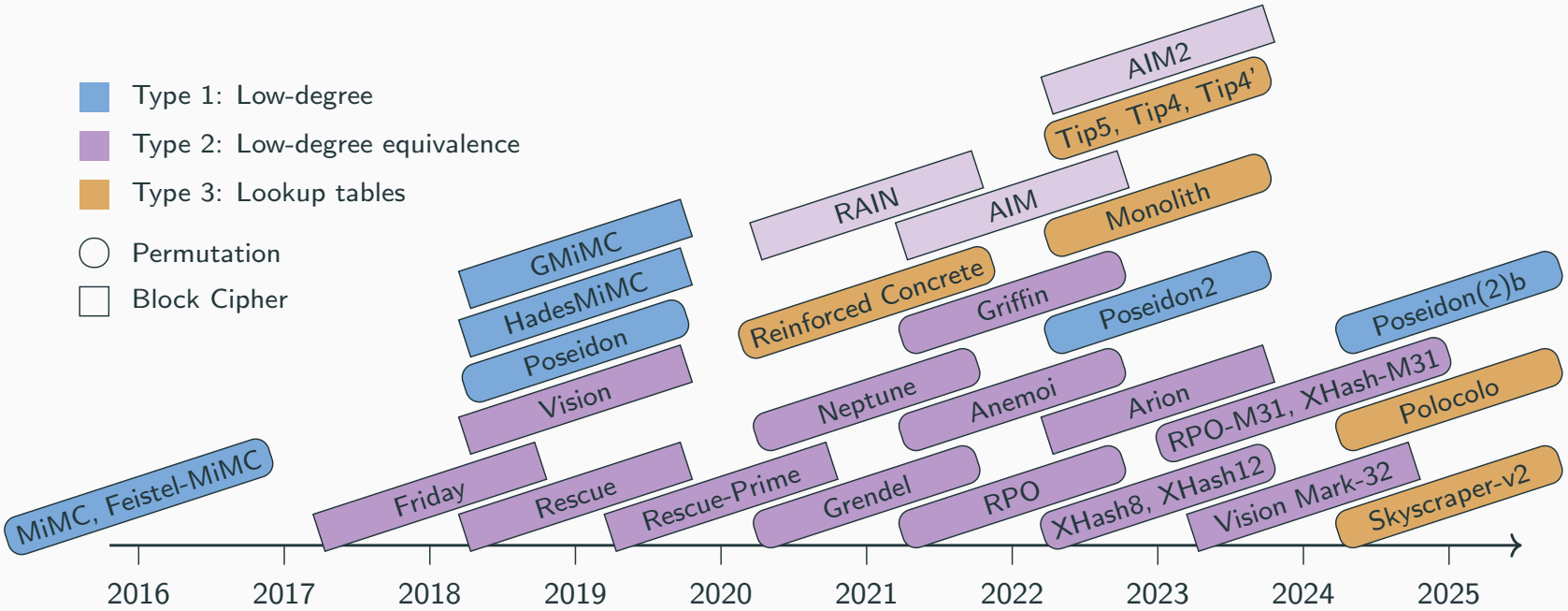
"lookups"

- Lookup tables

$$y = T[x]$$

- Very fast in Plain
- Even fewer rounds
- Constraints depend on proof system
- `Reinforced Concrete` (21), Tip5/Tip4 (23), `Monolith` (23), Skyscraper-v2(25), Polocolo (25)

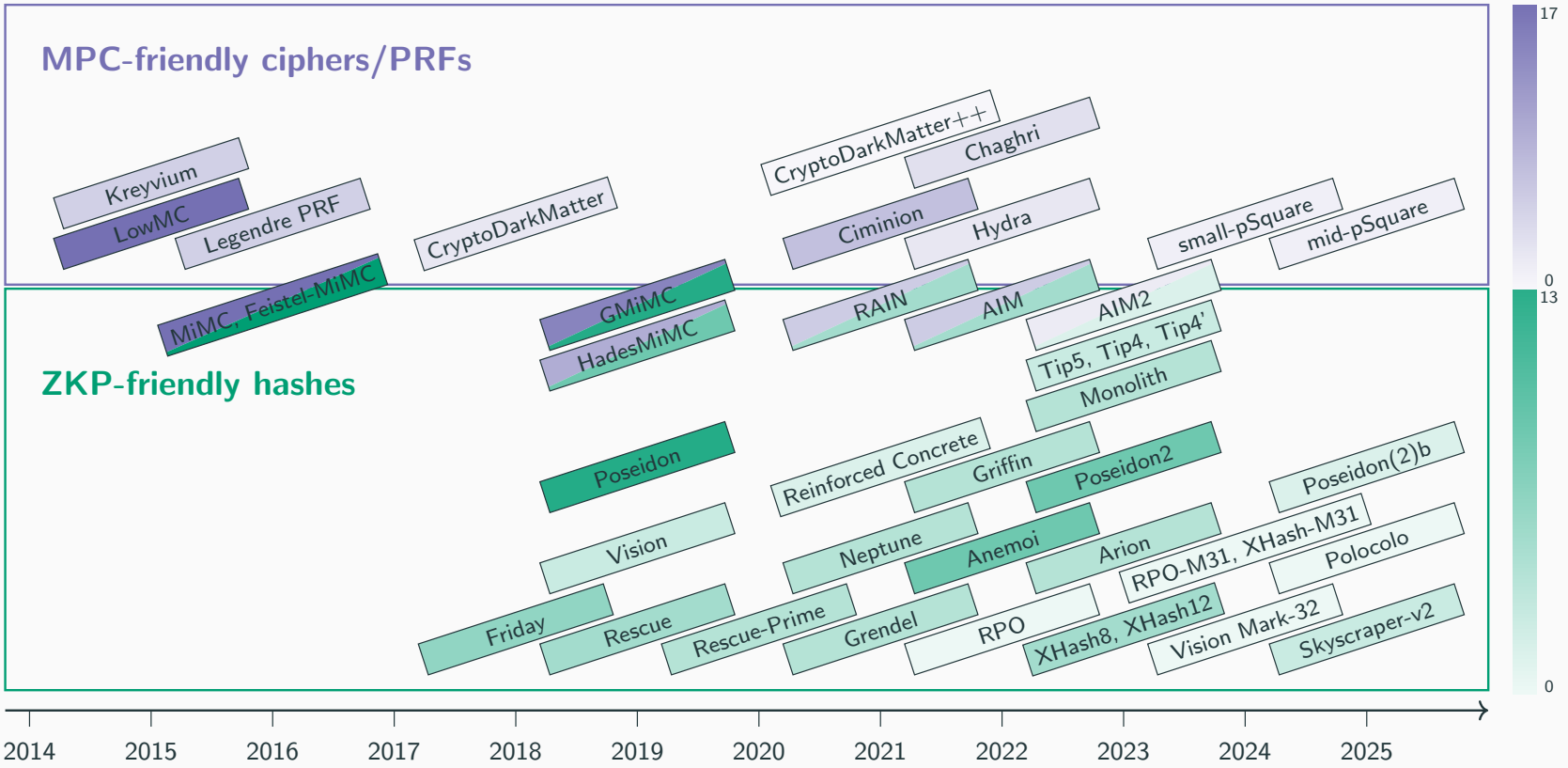
The ZK-friendly Hash Function Zoo



The MPC/Sharing-friendly Symmetric Crypto Zoo

- 2015: LowMC
- 2016: MiMC, LegendrePRF
- 2018: CryptoDarkMatter
- 2019: GMiMC
- 2020: HadesMiMC
- 2021: Ciminion, "CryptoDarkMatter++"
- 2022: Rain, AIM
- 2023: Hydra
- ongoing: GenLowMC (new: lookup aligned, dynamic generation of MPC circuit)

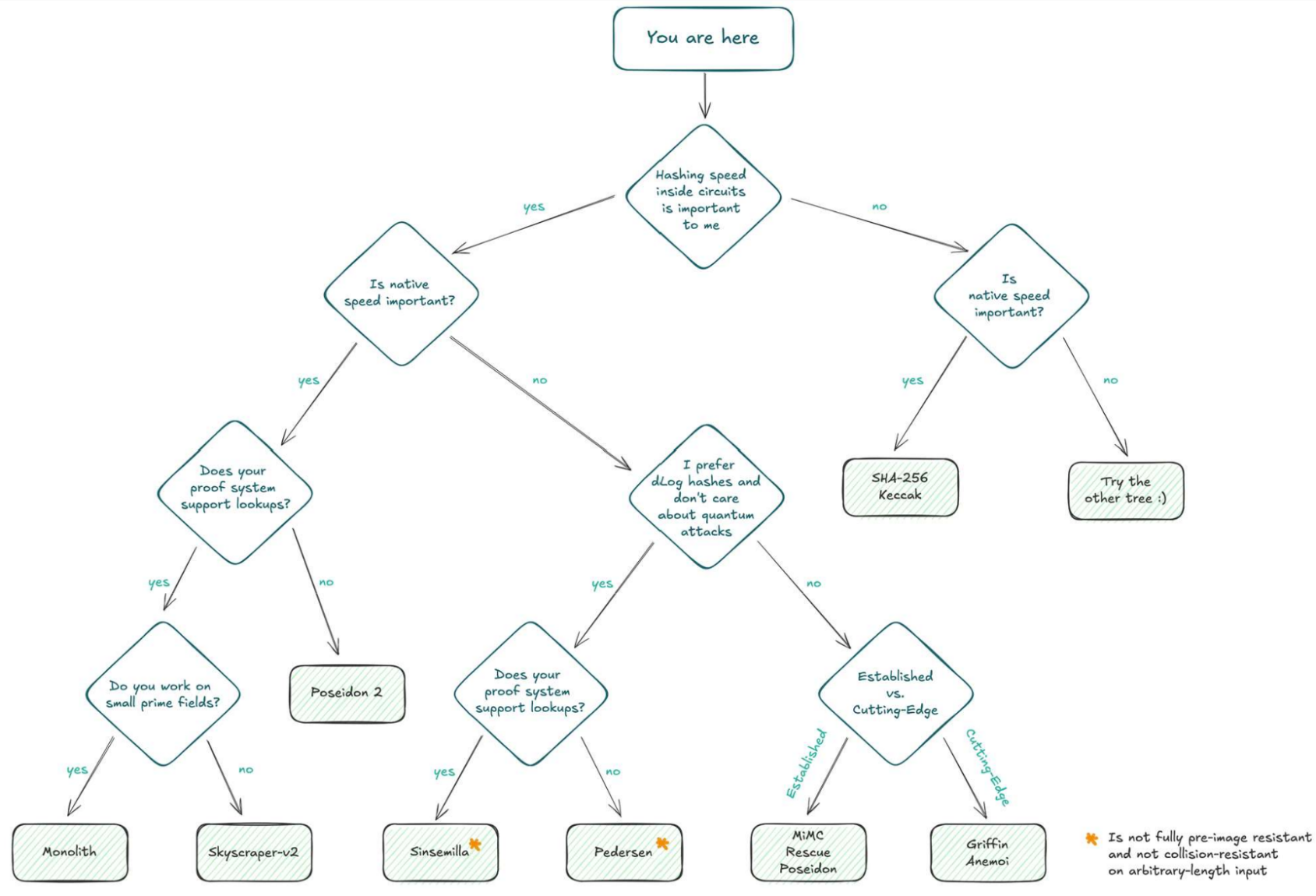
Cryptanalysis



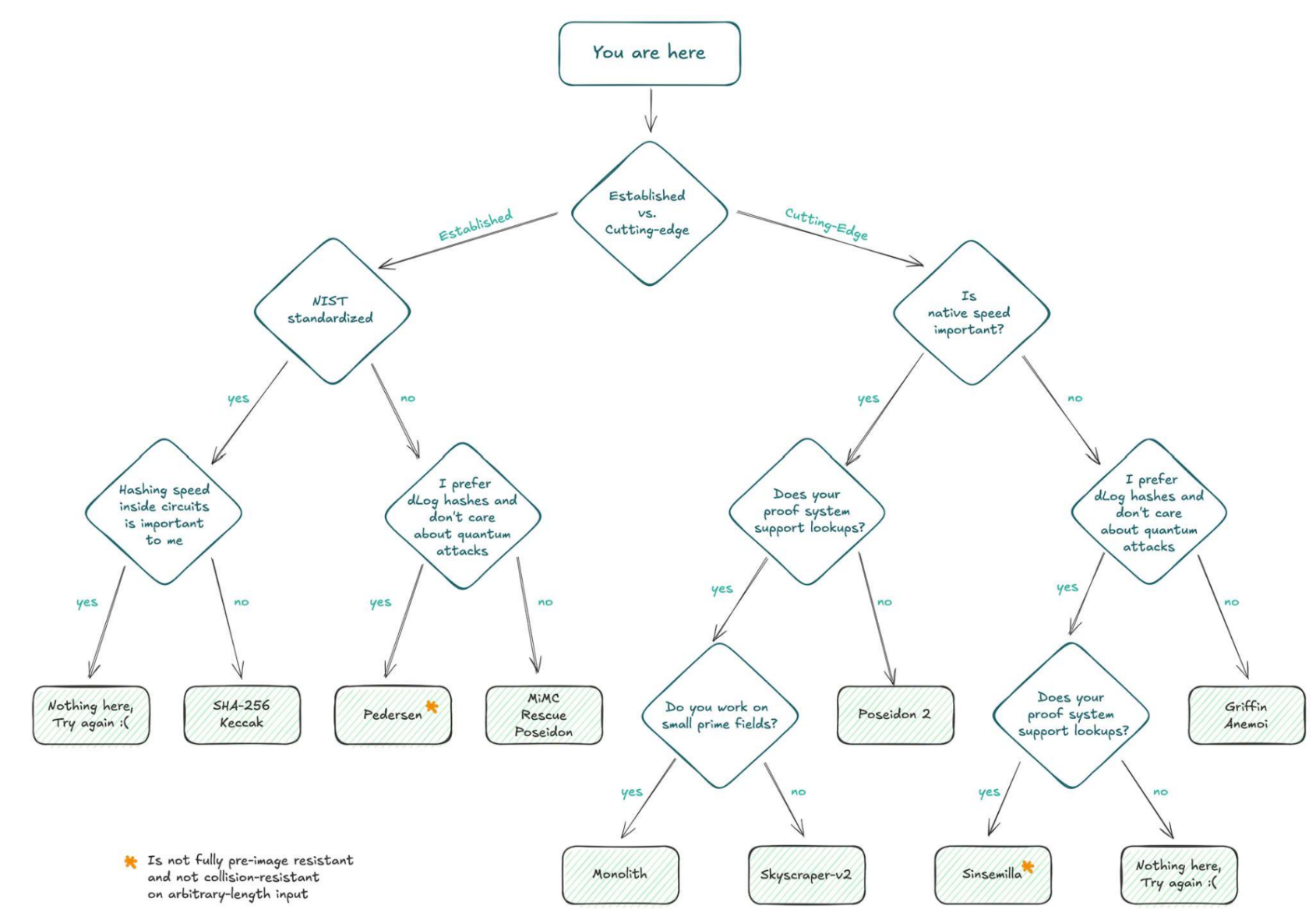
Cryptanalysis bounties/challenges/...

- Picnic/LowMC: Three rounds of challenges since 2020-2023:
  - winners: Subhadeep Banik, Khashayar Barooti, Serge Vaudenay, Hailun Yan, F. Betül Durak, Itai Dinur
  - `https://lowmcchallenge.github.io/`
- ZKProofs-friendly hashes, 2021-2022:
  - winners: Augustin Bariant, Clémence Bouvier, Gaëtan Leurent, Léo Perrin
  - `https://www.zkhashbounties.info/`
- Ongoing: Poseidon cryptanalysis initiative (2024-2026)
  - winners (so far): Aurelien Boeuf, Antoine Bak, Augustin Bariant, Maël Hostettler, Guilhem Jazeron, Giuseppe Vitto, William Borgeaud, Ziyu Zhao, Jintai Ding, Simon-Philipp Merz, À̀lex Rodríguez
  - `https://www.poseidon-initiative.info/`
  - New challenges to be announced very soon (TM). Total sum around 1M.

How to choose? (1/2)



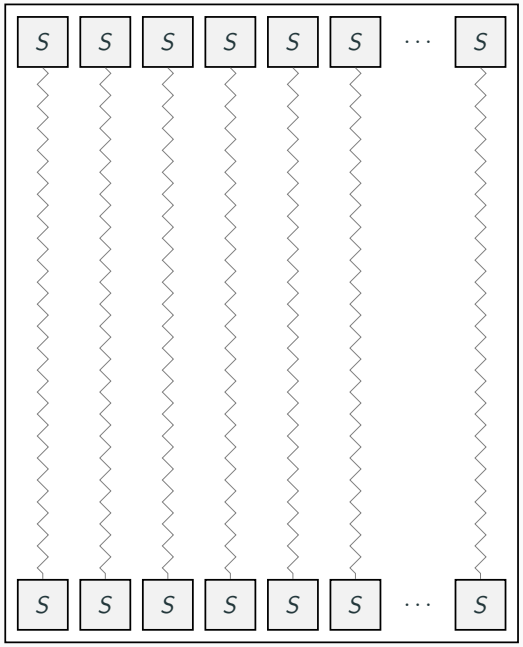
How to choose? (2/2)



S-Box sizes, over time. A selection

- mid 1970s, 6to4-bit: DES S-box just fits on a Chip
- mid 1990s, 8to8-bit: e.g. Rijndael/AES, attractive for good performance in both HW and SW
- since 2000, smaller, more "lightweight" S-boxes
  - 3to3-bit (e.g. Printcipher, LowMC)
  - 4to4-bit (e.g. Noekeon, Present, Klein, Prince)
  - 5to5-bit (e.g. Keccak, Ascon)
- since 2015, big and huge "S-boxes"
  - n to n-bit, elements in GF(2^n)
    - for n from 100 to 1000 (e.g. MiMC, Rain)
  - n to n-bit, elements in GF(p)
    - for n from 128 to $\geq$1000 (e.g. MiMC)
    - for n from 17 to 63 (e.g. Pasta)
    - for n from 8 to 256 (most in the ZK-friendly Zoo)

How to arrange the S-Boxes? SPNs with Partial Nonlinear Layers



SPN
(e.g., SHARK in
1996)

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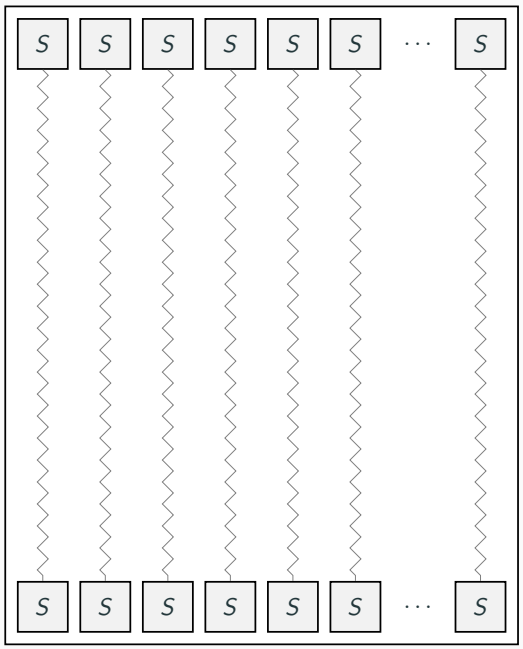

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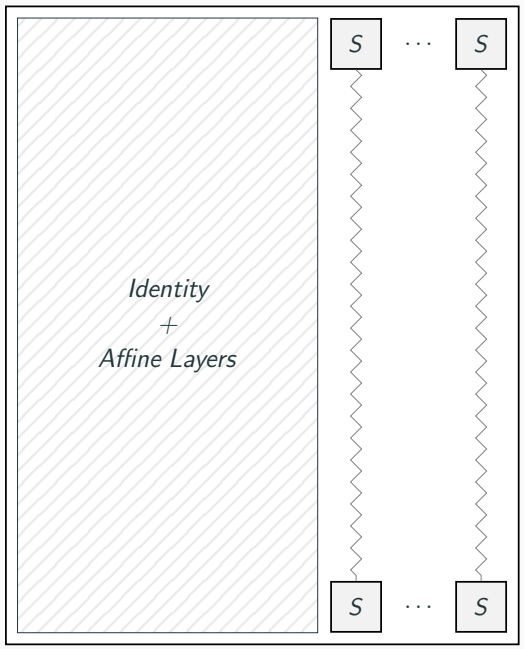

P-SPN since 2010
(e.g., ARMADILLO, Zorro, LowMC)

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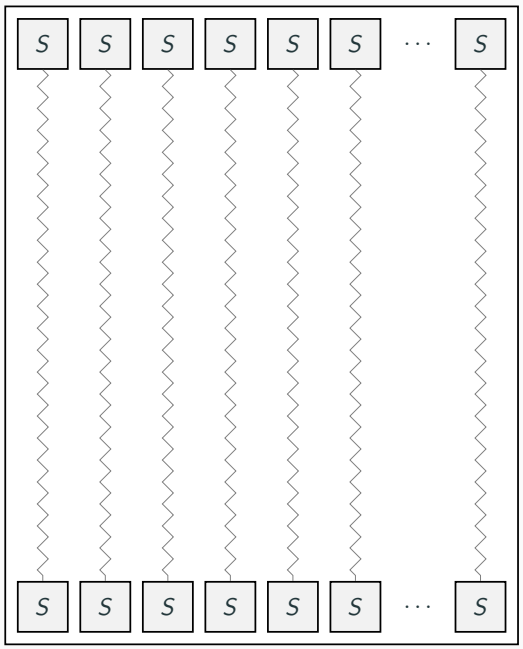

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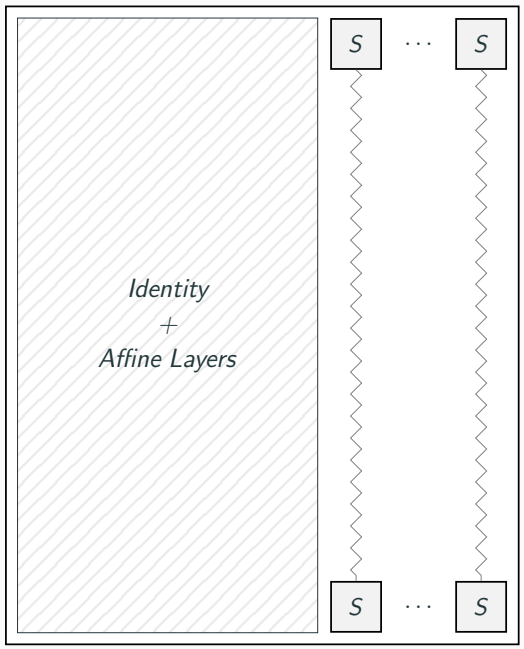

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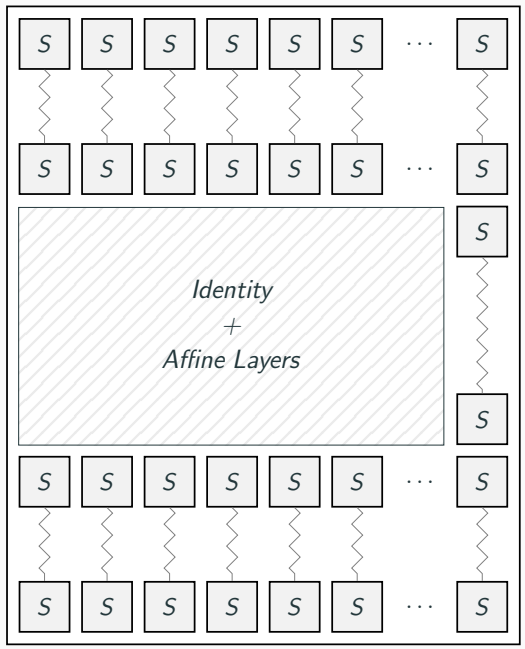

Hades
(e.g., HadesMiMC, Poseidon)

Thoughts on "Theory" vs. "Practice"

- Provable Security?
  - Modes of operation: do proofs carry over from F_2 to F_p?
  - SPN vs. Partial-SPN: First positive results by Guo, Standaert, Wang, Wang, Yu (FSE 22)
    - Stronger model, like indifferentiability?
  - "ZK-friendly" compression? New work by Andreeva, Bhattacharyya, Roy, Trevisani (CSF 24)
- "Asymptotic analysis" / "asymptotic designs".
  - Input: blocksize, security level
  - Output: concrete design with security claim
  - Some designs allow for it, e.g. HPC, LowMC, MiMC, Poseidon, ...
  - Pros: Flexibility
  - Cons: Less focused cryptanalysis.

Wanted

1) Consolidate spezialization tree of candidate hashes
2) A concretely efficient primitive for *Low-depth hashing*
   - ZK-friendly and simultaneously MPC-friendly
3) Generalization of results to non-binary/arbitrary fields
   - Proofs
   - Cryptanalysis techniques
4) Rings as underlying object instead of fields?

Standardization and Investments

NIST is organizing a Threshold Cryptography Process (two workshops in the last 2 years)
ZKproof.org community standard

- Large investments by governments
  - US DARPA, 100Ms of USD
  - EU Framework Programs
  - Asia?
- Even larger private investments
  - closer to 1B, early focus mostly on "ZK", now more activity in MPC incl. FHE

Conclusions

- Lots of exciting new developments in "high functionality cryptography" - some are likely here to stay
- Industry interest is growing
- Demand for standards to support interoperability and increase trust
- Lots of exciting research for design and analysis of symmetric crypto and hashing
- Even if you don't care about use-cases, super nice excuse to do new math, new symmetric crypto

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