# Sponge functions

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# Outline

The SHA-3 competition

Sponge functions

KECCAK and SHA-3

# The SHA-3 competition

# Towards the SHA-3 competition

- 2005-2006: MD5 and SHA-1 crisis
  - actual collisions for MD5
  - theoretical collision attacks for SHA-1
  - attacks on Merkle-Damgård with higher success probability than believed up to that point
- SHA-2 based on same principles, so NIST got nervous
- 2007: NIST announces plans to have open SHA-3 competition
  - goal: find a worthy successor for SHA-2
  - similar process as AES competition
- 2008: NIST publishes SHA-3 requirements
  - *more efficient than SHA-2*
  - output lengths: 224, 256, 384, 512 bits
  - security: collision and (2nd) pre-image resistance strengths
  - specs, code, design rationale and preliminary analysis
  - patent waiver

# The SHA-3 competition

- Started in 2008
- Three-round public process
  - round 1: 64 submissions, 51 accepted
  - round 2: 14 semi-finalists
  - round 3: 5 finalists
- All selections done by NIST but based on public evaluation by crypto community
- October 2012: NIST announces the SHA-3 winner
- The winner: KECCAK by Guido Bertoni, Joan Daemen, Michaël Peeters and Gilles Van Assche
  - something completely different than MD5/SHA-1/SHA-2
  - ...and completely different than Rijndael/AES
- August 2015: NIST finally publishes the SHA-3 standard: FIPS 202

# Sponge functions

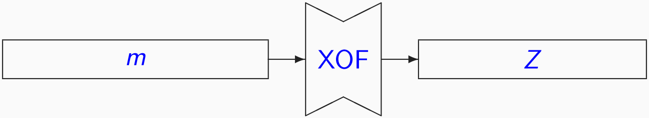
# The idea: permutation-based hashing

KECCAK uses a construction called *sponge*, where did that come from?

- Our goal: find a hashing mode that is sound and simple
  - with birthday-bound $\mathcal{RO}$-differentiating advantage
  - calling a primitive that we know how to design
  - nice to have: support for arbitrary output length
- Block cipher as a primitive
  - round function design: several good approaches known
  - key schedule: not so clear how to do design good one
- But do we really need a block cipher?
  - no need for separation between data path and key schedule
  - let us merge them: *an (iterative) permutation*
- Result: *the sponge construction*

  [Bertoni, Daemen, Peeters, Van Assche (KECCAK team) 2007]

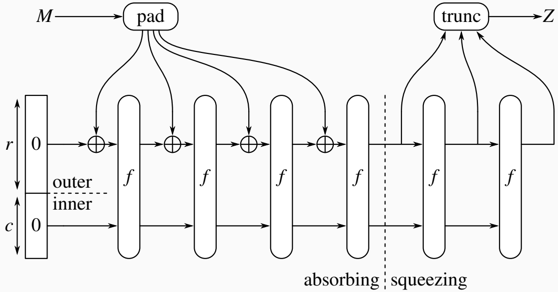
# Modern hashing: Extendable Output Function (XOF)




$$Z = \mathrm{XOF}(m, n)$$

- Many use cases of hashing require outputs longer or shorter than some nominal digest length
- XOF:
  - user specifies output length $n$ when calling the function
  - name introduced in SHA-3 standard [FIPS 202]
- *Secure if it behaves as a* $\mathcal{RO}$
- Strength specified in terms of (internal) parameter *capacity* $c$

# The sponge construction

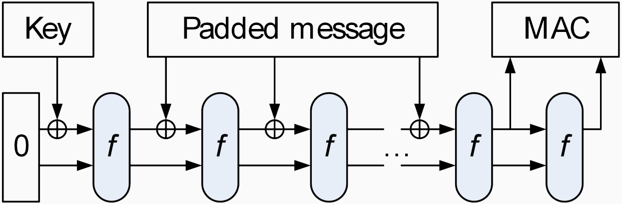



- Builds a XOF from a $b$-bit **permutation** $f$, with $b = r + c$
  - $r$ bits of *rate*
  - $c$ bits of *capacity* (security parameter)
- $\mathcal{RO}$-differentiating advantage $= N^2 2^{-(c+1)}$ [Keccak team, 2008]
  - due to collisions in $c$-bit inner part
  - super-tight: it is the birthday bound in $c$

# Implications of the $\mathcal{RO}$-differentiating bound

- *Random sponge*: sponge construction with a random permutation $\mathcal{P}$
- Success probability of attack on random sponge upper bound by
  - success probability of that attack on $\mathcal{RO}$, plus
  - differentiating advantage of random sponge from $\mathcal{RO}$
- Classical attacks on random sponge with output truncated to $n$ bits:
  - collision: $N^2 2^{-(n+1)} + N^2 2^{-(c+1)}$
  - (first) pre-image: $N 2^{-n} + N^2 2^{-(c+1)}$
  - 2nd pre-image resistance: $N 2^{-n} + N^2 2^{-(c+1)}$
- Security strength of random sponge truncated to $n$ bits
  - collision-resistance: $\min(c/2, n/2)$
  - 1st or 2nd pre-image resistance: $\min(c/2, n)$
- But in reality we have to construct a concrete permutation $f$
  - above bounds are for *generic attacks*: those that do not exploit specific properties of $f$
- Once we fix $f$, we are again in the *world of cryptanalysis*

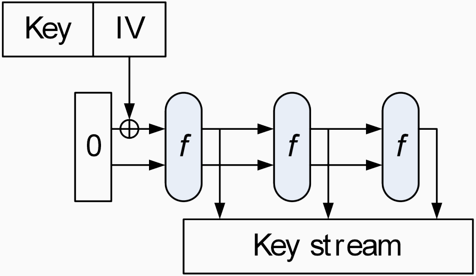
# Using sponge for MAC (and key derivation)




- $\mathrm{MAC}_K(m) = \mathrm{XOF}(K \| m, n)$
- $\mathrm{KDF}_K(D) = \mathrm{XOF}(K \| D, n)$

No need for patches à la HMAC as sponge is basically sound

# Stream cipher mode




- Many output blocks per $D$: similar to OFB
- 1 output block per $D$: similar to counter mode

Note: figure indicates diversifier by $IV$

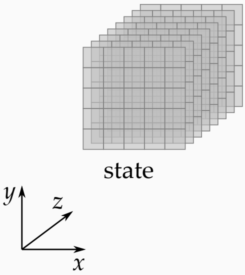
# Required primitive: a cryptographic permutation

- A permutation that *should not have exploitable properties*
- Like a block cipher
  - sequence of identical rounds
  - round function is sequence of simple step mappings
- ...but not quite
  - no key schedule
  - round constants instead of round keys
  - inverse permutation need not be efficient

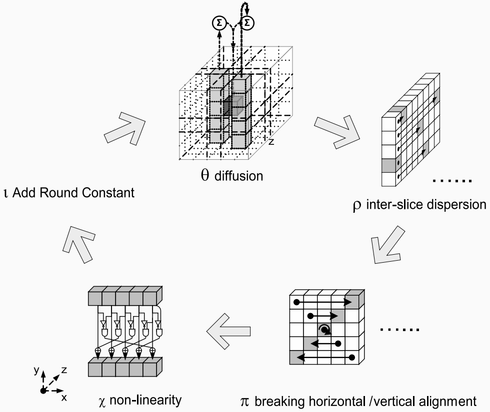
# Keccak and SHA-3

# Keccak and Keccak-$f$

- KECCAK is a sponge function using permutation KECCAK-$f$
- KECCAK-$f$ operates on 3-dimensional state:
  - $5 \times 5$ *lanes*, each containing $2^\ell$ bits (1, 2, 4, 8, 16, 32 or 64)
  - $(5 \times 5)$-bit *slices*, $2^\ell$ of them



# Keccak-$f$: the steps of the round function




bit-oriented highly-symmetric *wide-trail* design

# Keccak[$r$, $c$]

- Sponge function using the permutation KECCAK-$f$
  - 7 permutations: $b \in \{25, 50, 100, 200, 400, 800, 1600\}$

    ... from toy over lightweight to high-speed ...
- SHA-3 instance SHAKE128: $r = 1344$ and $c = 256$
  - permutation width: 1600
  - security strength 128
- Lightweight instance: $r = 40$ and $c = 160$
  - permutation width: 200
  - security strength 80: what SHA-1 should have offered
- Security status:
  - best attack on hash function covers 6-round version
  - # rounds ranges from 18 for $b = 200$ to 24 for $b = 1600$

See [The KECCAK reference] at `keccak.team` for details

# The XOFs and hash functions in FIPS 202

- Four drop-in replacements for SHA-2 and two XOFs
- All use KECCAK-$f$ with $b = 1600$
- Domain-separated from each other:
  - padding rule ensures separation between different capacities $c$
  - XOF inputs end in **11**, drop-in inputs end in **01**
  - XOF Tree-hashing ready: SAKURA encoding [ePrint 2013/231]

| **XOF** | **SHA-2 drop-in replacements** |
|---|---|
| KECCAK$[c = 256](m\|\|11\|\|\mathbf{11})$ | |
| | first 224 bits of KECCAK$[c = 448](m\|\|\mathbf{01})$ |
| KECCAK$[c = 512](m\|\|11\|\|\mathbf{11})$ | |
| | first 256 bits of KECCAK$[c = 512](m\|\|\mathbf{01})$ |
| | first 384 bits of KECCAK$[c = 768](m\|\|\mathbf{01})$ |
| | first 512 bits of KECCAK$[c = 1024](m\|\|\mathbf{01})$ |
| **SHAKE128** and **SHAKE256** | **SHA3-224** to **SHA3-512** |

# Conclusions

# Conclusions

- Modern hashing is based on permutations
- SHA-3 is based on KECCAK
- Sponge construction: up to $c/2$ bits of security strength
- XOFs SHAKE128 and SHAKE256 can simplify usage
- no more need for HMAC or MGF1!
- All symmetric crypto can be based on permutations: **symmetric crypto 2.0**