SHA3
Past, Present, and Future

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CHES 2013

Overview

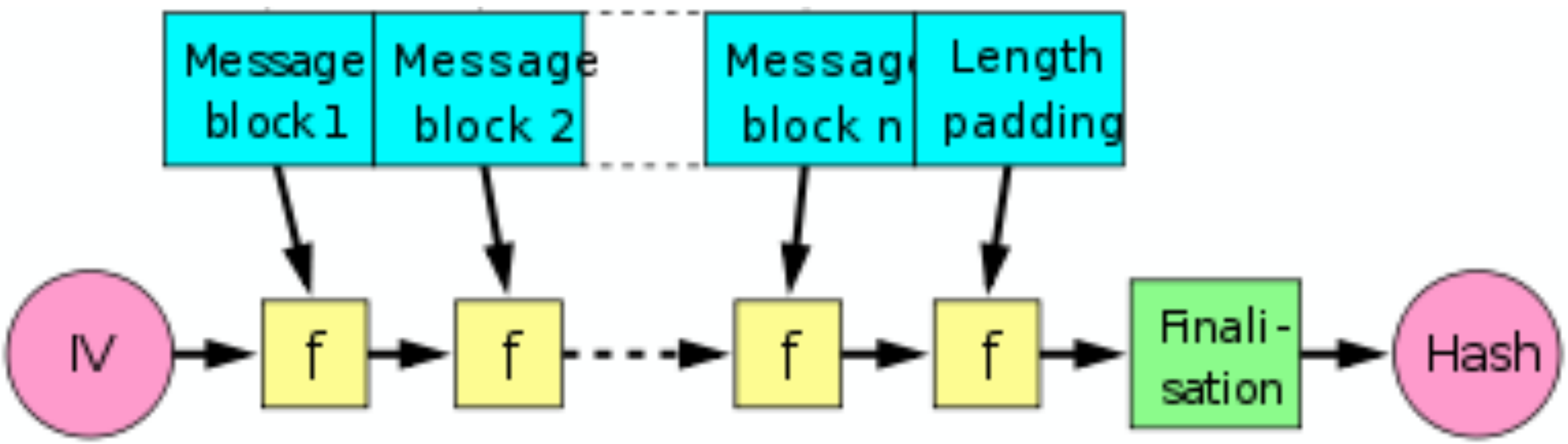
- Before the competition
- The competition
- Standardizing Keccak as SHA3
- What's next?

Before the Competition

Origins

- Hash functions appeared as an important idea at the dawn of modern public crypto.
- Many ideas floating around to build hash functions from block ciphers (DES) or mathematical problems.
- Ways to build hash functions from compression functions
  - Merkle-Damgaard
- Ways to build compression functions from block ciphers
  - Davies-Meyer, MMO, etc.

Merkle-Damgaard



- Used in all widespread hash functions before 2004
  - MD4, MD5, RIPE-MD, RIPE-MD160, SHA0, SHA1, SHA2

Image from Wikipedia

The MD4 Family

- Rivest published MD4 in 1990
- 128-bit output
- Built on 32-bit word operations
- Add, Rotate, XOR, bitwise logical operations
- Fast
- First widely used dedicated hash function
- 48 steps = 3 passes over msg

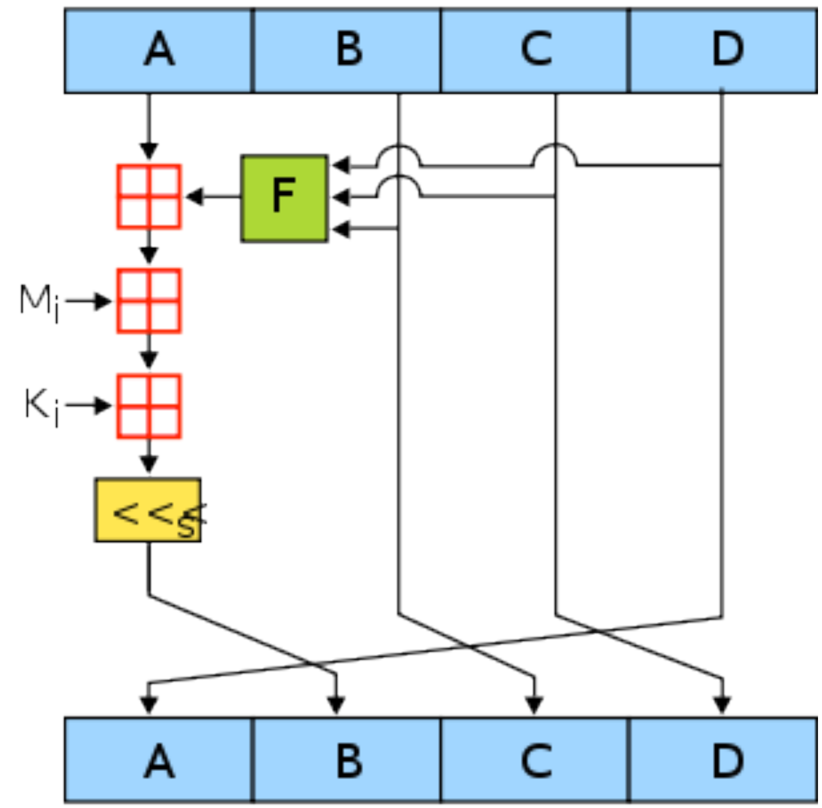


Image from Wikipedia MD4 Article

MD5

- Several researchers came up with attacks on weakened versions of MD4
- Rivest created stronger function in 1992
- Still very fast
- Same output size
- *Some attacks known*
  - *Den Boer/Bosselaers*
  - *Dobbertin*
- 64 steps = 4 passes over msg

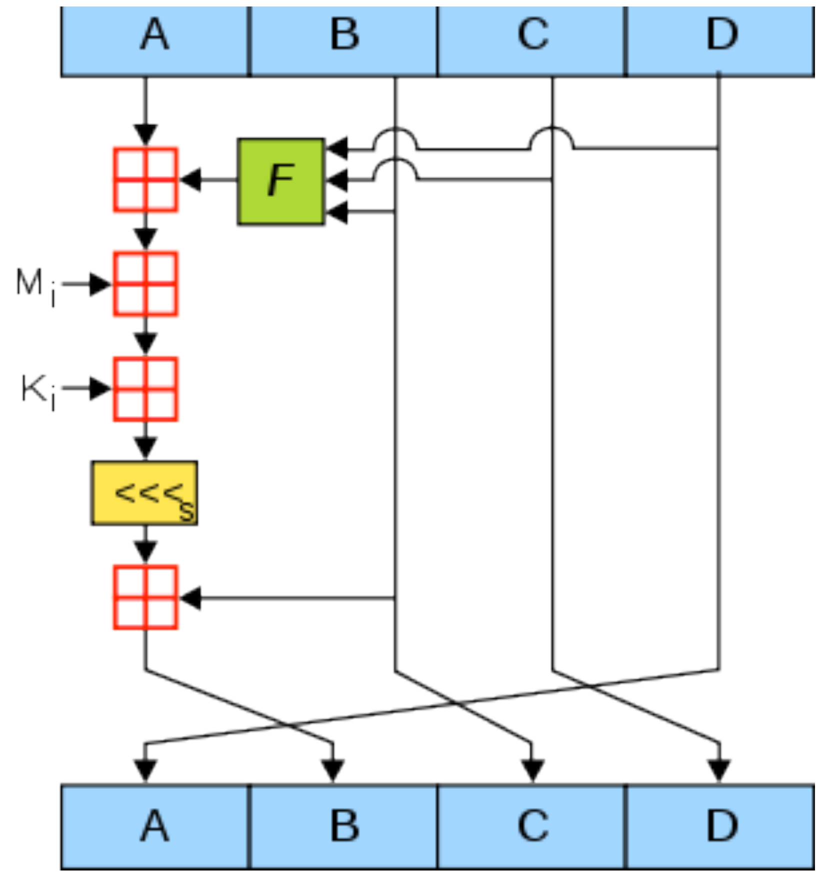


Image from Wikipedia MD5 Article

SHA-0 and SHA-1

- SHA-0 published in 1993
- 160-bit output
  - (80 bit security)
- NSA design
- Revised in 1995 to SHA-1
  - Round function (pictured) is same
  - Message schedule more complicated
- *Crypto '98 Chabaud/Joux attack on SHA-0*
- 80 steps = 5 passes over msg

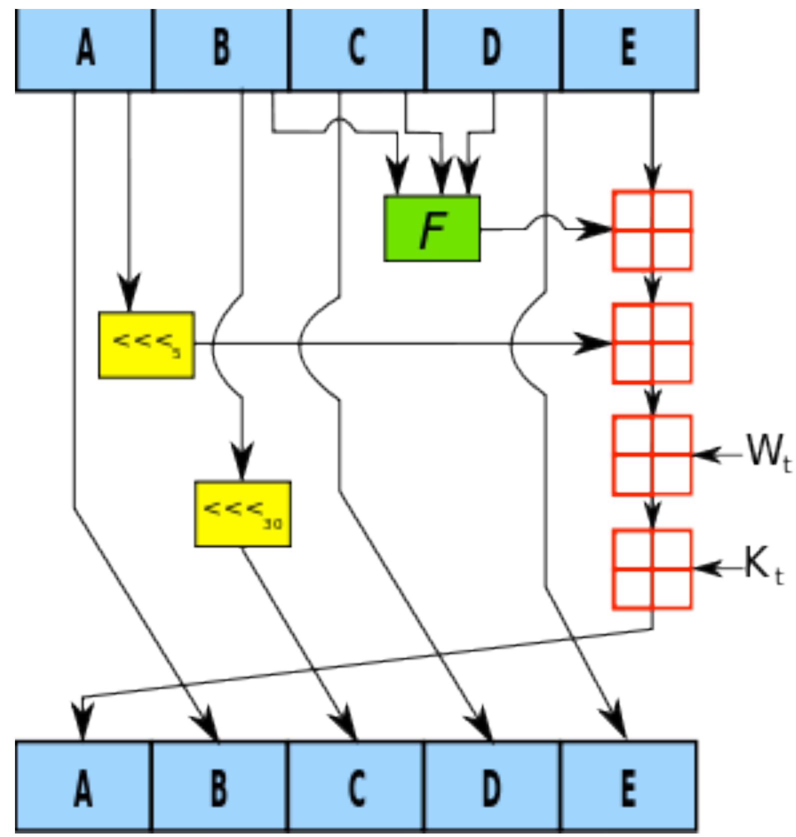


Image from Wikipedia SHA1 Article

SHA-2

- Published 2001
- Three output sizes
  - 256, 384, 512
  - 224 added in 2004
- Very different design
- Complicated message schedule

- *Still looks strong*

- 256 bit output: 64 steps = 4 passes
- 512 bit output: 80 steps = 5 passes

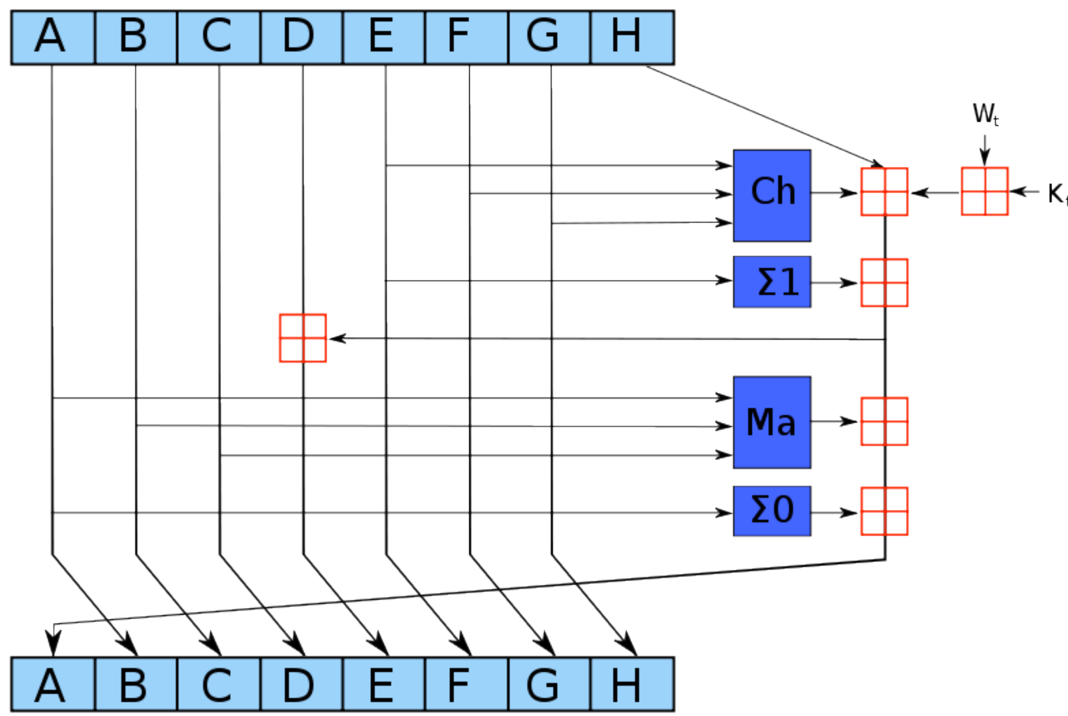


Image from Wikipedia SHA2 Article

As of 2004, we thought we knew what we were doing.

- MD4 was known to be broken by Dobbertin, but still saw occasional use
- MD5 was known to have theoretical weaknesses from Den Boer/Bosselaers and Dobbertin, but still in wide use.
- SHA-0 was known to have weaknesses and wasn't used.
- SHA-1 was thought to be very strong.
- SHA-2 looked like the future, with security up to 256 bits
- Merkle-Damgaard was normal way to build hashes

Crypto 2004: The Sky Falls

Crypto 2004

- Conference:
  - ▶Joux shows a surprising property in Merkle-Damgaard hashes
    - ▶ Multicollisions
    - ▶ Cascaded hashes don't help security much
  - ▶Biham/Chen attack SHA-0 (neutral bits)
- Rump Session:
  - ▶Joux shows attack on SHA-0
  - ▶Wang shows attacks on MD4, MD5, RIPEMD, some Haval variants, and SHA-0
    - ▶ Much better techniques used for these attacks

We found out we didn’t know much about hash functions

- Wang’s techniques quickly extended
  - Better attacks on MD5 by many people
  - Claimed attacks on SHA-1 (2005)

- Joux’s multicollisions extended and applied widely
  - Second preimages and herding
  - Multicollisions even for multiple passes of hash
  - Much more

What to do next?

- All widely used hash functions called into question
  - MD5 and SHA1 were very widespread
  - SHA-2 and RIPE-MD160, neither one attacked, were not widely used.
- At same time, NIST was pushing to move from 80- to 112-bit security level
  - Required switching from SHA-1 to SHA-2
- Questions about the existing crop of hash functions
  - SHA-1 was attacked, why not SHA-2?

Pressure for a Competition

- We started hearing from people who wanted a hash competition
- AES competition had happened a few years earlier, and had been a big success
- This would give us:
  - Lots of public research on hash functions
  - A new hash standard from the public crypto community
  - Everything done out in the open

Hash Workshops

- Gaithersburg 2005
- UCSB 2006

- Encouragement to have competition
- Lots of ideas/feedback about how competition should work.
- Somewhere in here, we decided to have a competition.

2007: Call for Proposals

- We spent a lot of time getting call for proposals nailed down:
  - Algorithm spec
  - Security arguments or proofs
  - Preliminary analysis
  - Tunable security parameter(s)

Security Requirements

- Drop-in replacement for SHA-2
  - or even SHA-1 or MD5 with truncation
- Security for N-bit Hash
  - N/2 bit collision resistance
  - *N bit preimage resistance*
  - N-K bit second preimage resistance
    - K = lg(target message length)
- Eliminate length-extension property!
- Tunable security/performance tradeoffs.

The Competition

Hash Competition Timetable

Date	*Event*	*Candidates Left*
11/2/2007	**Call for Proposals published, competition began**	
10/31/2008	**SHA3 submission deadline**	*64*
12/10/2008	***First-round candidates announced***	***51***
2/25/2009	**First SHA3 workshop in Leuven, Belgium**	**51**
7/24/2009	***Second-round candidates announced***	***14***
8/23/2010	**Second SHA3 workshop in Santa Barbara, CA**	**14**
12/9/2010	***SHA3 finalists announced***	***5***
3/22/2012	**Third SHA3 workshop in Washington, DC**	**5**
10/2/2012	***Keccak announced as the SHA3 winner***	*1*

64 → 51

- We started with 64 submissions (10/08)
- 51 were complete and fit our guidelines
- We published those 51 on December 2008
- Huge diversity of designs

51 → 14

- About a year and a half—published July 2009
- 2009 Hash Workshop in Leuven
- Many algorithms broken or seriously dented.
- AES competition had 15 submissions; we took a year to get down to 14.

BLAKE BMW Cubehash Echo Fugue **Grostl** Hamsi
JH **Keccak** Luffa SHABAL SHAVite SIMD **Skein**

14 → 5

- About a year and a half—announced Dec 2010
- Second SHA3 Workshop at Santa Barbara
- Much harder decisions
  - Cryptanalytic results were harder to interpret
  - Often distinguishers of no apparent relevance

BLAKE   Grostl   JH   *Keccak*   Skein

5 → 1

- About two years—final decision Oct 2012
- Third SHA3 Workshop in Washington, DC
- Very tough decisions
- Security, Performance, Complementing SHA3

Keccak

Security

- Nobody knocked out by cryptanalysis
- Different algorithms got different depth of cryptanalysis
- Keccak and Blake had best security margins
- Domain extenders (aka chaining modes) had security proofs
- Grostl had a very big tweak, Skein a significant one
- ARX vs non-ARX designs

- *Keccak looks very strong, and had been analyzed in sufficient depth to give us confidence.*

Performance

- All five finalists have acceptable performance
- ARX designs (BLAKE and Skein) are excellent on high-end software implementations
- JH and Grostl fairly slow in software
- Keccak is very hardware friendly
  - High throughput per area

- *Keccak performs well everywhere, and very well in hardware.*

Complementing SHA2

- ▶SHA3 will be deployed into a world full of SHA2 implementations
- ▶SHA2 still looks strong
- ▶We expect the standards to coexist.
- ▶SHA3 should *complement* SHA2.
  - ▶ Good in different environments
  - ▶ Susceptible to different analytical insights

- *Keccak is fundamentally different from SHA2. Its performance properties and implementation tradeoffs have little in common with SHA2.*

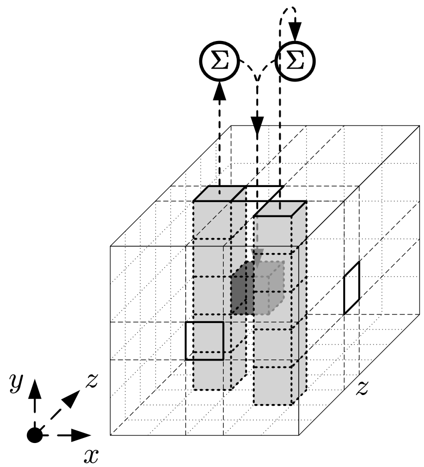
Wrapup on Selecting a Winner

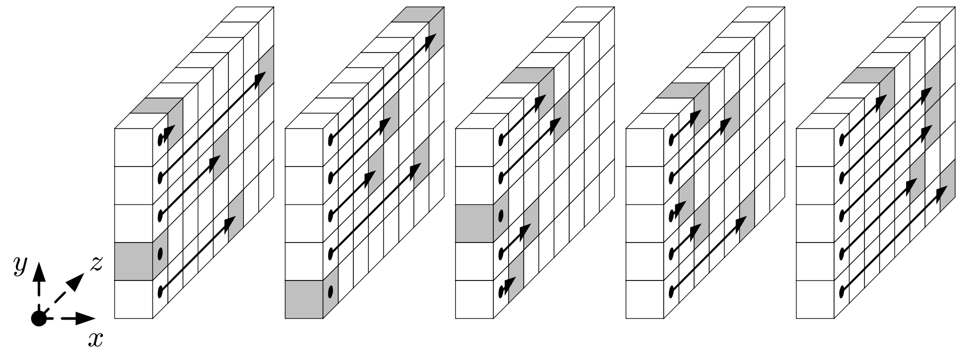
- Keccak won because of:
  - High security margin
  - High quality analysis
  - Elegant, clean design
  - Excellent hardware performance
  - Good overall performance
  - Design diversity from SHA2

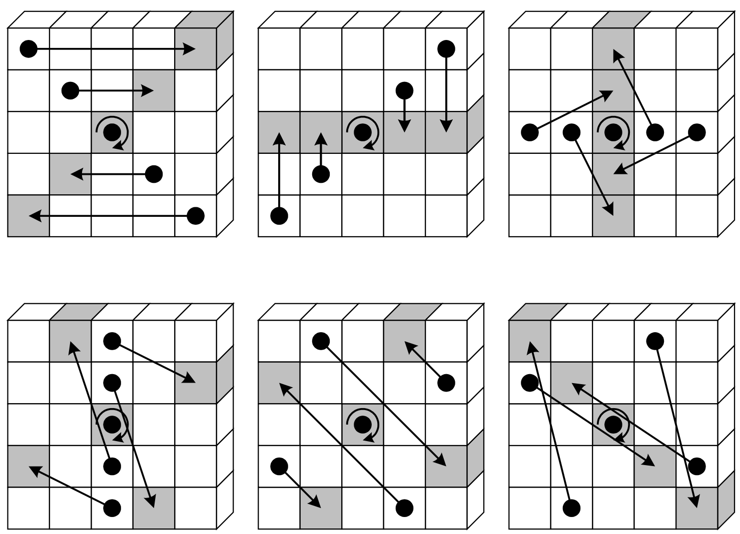
How Did It Work Out?

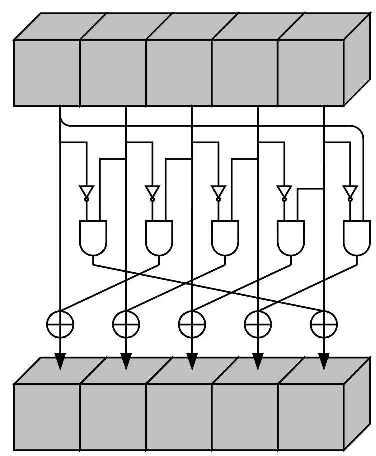
- The competition brought forth a huge amount of effort by people outside NIST
- The cryptographic community did the overwhelming majority of the work:
  - Submissions
  - Analysis
  - Proofs
  - Reviews of papers for conferences/journals
  - Performance benchmarks
  - Implementations
- NIST's main job was to understand that work and make decisions based on it.

Keccak looks nothing like MD4









Images from Keccak submission

Keccak as SHA3

What Will SHA3 Standardize?

- Hash functions (fixed output length)
  - **SHA3-224** **SHA3-256**
  - **SHA3-384** **SHA3-512**

- Sponge functions (variable output length)
  - **SHAKE256**
  - **SHAKE512**

SHA3 Fixed-Length Hash Functions

- Drop in replacements for SHA2
- SHA3-224, SHA3-256, SHA3-384, SHA3-512
- Different output lengths are unrelated

SHA3-224(X) = ABCDEFG
SHA3-256(X) = HIJKLMNO

Almost the same security claims as SHA2.

SHAKE256 and SHAKE512

- "Sponge functions"
- Variable length output
- SHA + Keccak
- *Different output lengths give related hashes*

$\text{SHAKE}256(\text{X}, 224)$ = ABCDEFG

$\text{SHAKE}256(\text{X}, 256)$ = ABCDEFGH

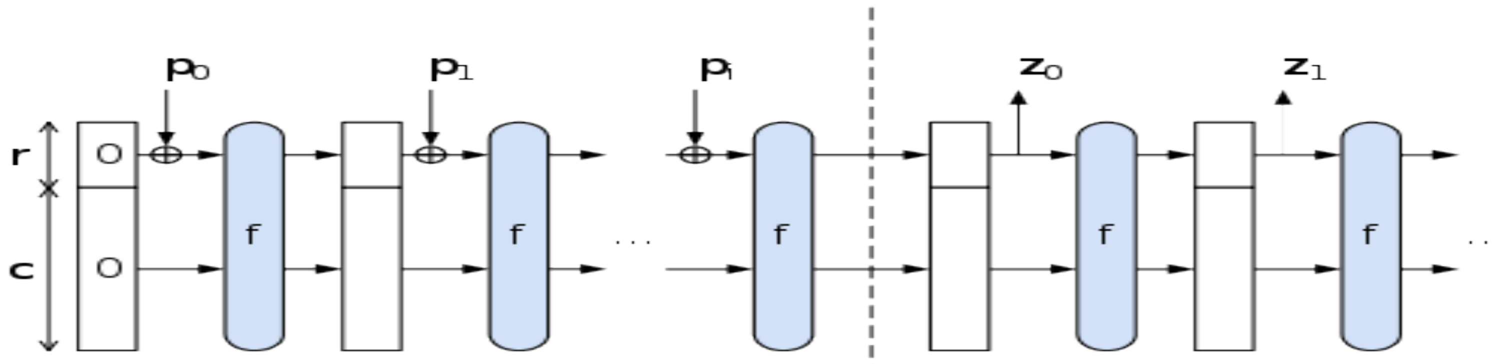
Variable-length output is useful

- Lots of protocols and applications need this
  - OAEP, most KDFs, Fix for Vaudenay's DSA attack
- Better to have it as part of hash definition
- But may be tricky to use correctly:
  - SHAKE256(X,112) = K1 K2
  - SHAKE256(X,168) = K1 K2 K3

SHAKE256 and SHAKE512

Image from Rene Peralta

Under the hood, they're all sponges



- Hash functions: (SHA3-x)
  - Restricted to fixed length
  - Padding: different outputs for different lengths
- Sponge functions: (SHAKE-c)
  - Variable length
  - We don't know output length till output's done

From Keccak to SHA3: Preliminaries

Collision and Preimage Resistance

- Collision:
  - Find X, Y so that

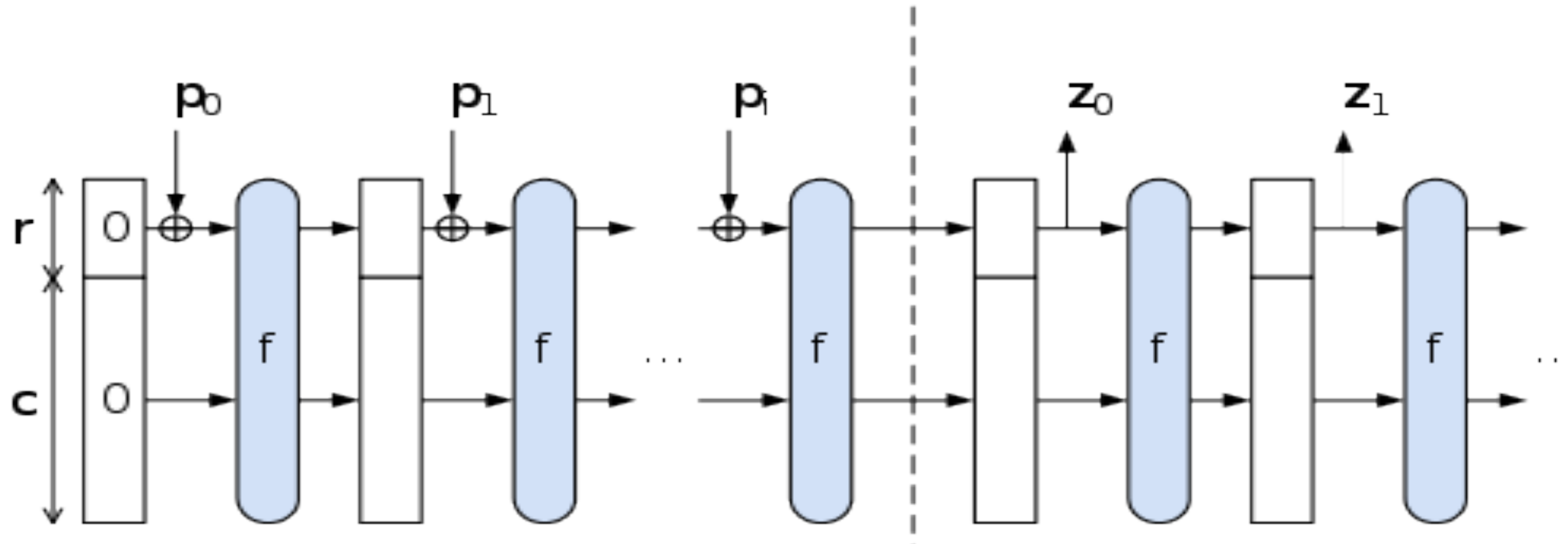
    hash(X) == hash(Y)
  - n-bit output → collisions with $2^{n/2}$ work
- Preimage:
  - Given Y, find X so that

    hash(X) == Y
  - n-bit output → preimages with 2^{n} work

Security Levels

- Convenient to assign each algorithm a security level
- Algorithm with 128-bit security level promises to resist attacks up to about 2^{128} computations.
- SHA256: 128-bit security level
  - But claims no preimages up to 2^{256} work!
  - Natural—that's the limit for n-bit hash functions

Capacity and Security



- A sponge has collision and preimage resistance of C/2 bits.
- Finding a collision or preimage is equally hard
- Bigger C = slower hashing

Sponges vs Merkle-Damgaard

- Most MD hashes: n bit output means
  - n bits preimage resistance
  - n/2 bits collision resistance
- Sponges: C bit capacity means
  - C/2 bit security level
  - Variable output size

From Keccak to SHA3

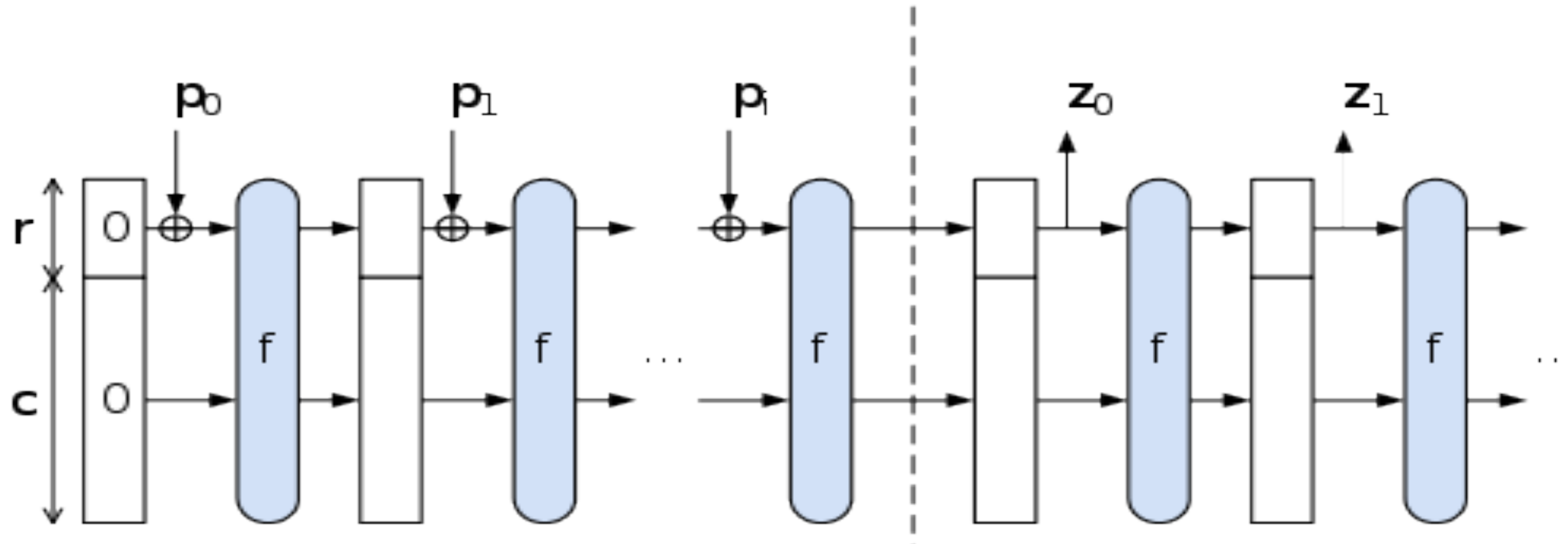
Keccak SHA3 Submission

- Had four versions, each with a different capacity
  - Keccak-224, -256, -384, -512
  - Hard to see why we needed four
- Guaranteed n-bit preimage resistance by making capacity huge.
- Suffered big performance hit to get this preimage resistance.
  - Hard to see why this made sense.

One security level for each function
Only two capacities in SHA3

• **SHA3-224***	}	**128** bits of security
• **SHA3-256**	}	against everything
• **SHAKE256**	}	(C = 256)
• **SHA3-384***	}	**256** bits of security
• **SHA3-512**	}	against everything
• **SHAKE512**	}	(C = 512)

Capacity and Security



- A sponge has collision and preimage resistance of C/2 bits.
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Security level determined by hash function internals, not output size

- 128-bit security level
  - SHA3-224
  - SHA3-256
  - SHAKE256

- 256-bit security level
  - SHA3-384
  - SHA3-512
  - SHAKE512

Summary of Keccak → SHA3 Changes

- Changed padding scheme
  - Sakura scheme from Keccak designers
  - Supports fixed-length hashes and sponges
  - Supports tree hashing
- Only two capacities (256 and 512)
- Preimage strength = collision strength
  - Using tunable parameter to make performance/ security tradeoff
  - But this is a pretty big change from the submission

What next?

Getting the FIPS Out

- This should be FIPS 202
- Draft for public comment around end of October 2013.
- The FIPS process can be slow

  …and a lot of it is outside our control

  – The final FIPS document goes to the Secretary of Commerce for approval

Authenticated Encryption

- Keccak specified a duplex mode for authenticated encryption
- We plan to standardize this in a special publication
- Hope to have draft for public comment next year

PRF

- Keccak specifies a dedicated PRF
  - Can be used in place of HMAC
  - Perhaps also for randomized hashing
- We also plan to standardize this in a special publication.
- Hope to have a draft out next year.

Tree Hashing

- We are also working on a standard for tree hashing
  - Will incorporate Keccak team's Sakura padding scheme where possible
  - Will support tree-hashing with SHA3 and SHA2
- Hope to have a draft out next year.

Random Number Generation

- Keccak Duplex mode can be used for cryptographic random number generation
- We are considering adding another DRBG for SP 800-90A based on SHA3 in duplex mode
- No timetable or commitment to this yet

Further in the Future

- We are interested in analysis of Keccak with smaller permutation sizes
  - Could be really nice for constrained devices
  - Currently not a lot of published analysis
- What else can be done with sponge functions?
- What else can be done with duplex mode?

2014 NIST Hash Workshop

- Colocated with Crypto 2014
  - Friday and Saturday
- Workshop on all things SHA2 and SHA3
  - Keccak with smaller permutations
  - Cryptanalysis and differential/linear trail bounds
  - Tree hashing
  - Generic hash-based authenticated encryption
  - Clever applications for sponges or duplex mode

http://csrc.nist.gov/groups/ST/hash/sha-3/Aug2014/index.html

Thank You!

- This whole thing would have been impossible without the help of the community
- The amount of work done for free to choose a new SHA3 was incredible
- We really appreciate it

- Questions?