The MD6 Hash Function

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- Cilk Arts
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Outline

- Design considerations
- Mode of Operation
- Compression Function
- Implementations
- Security

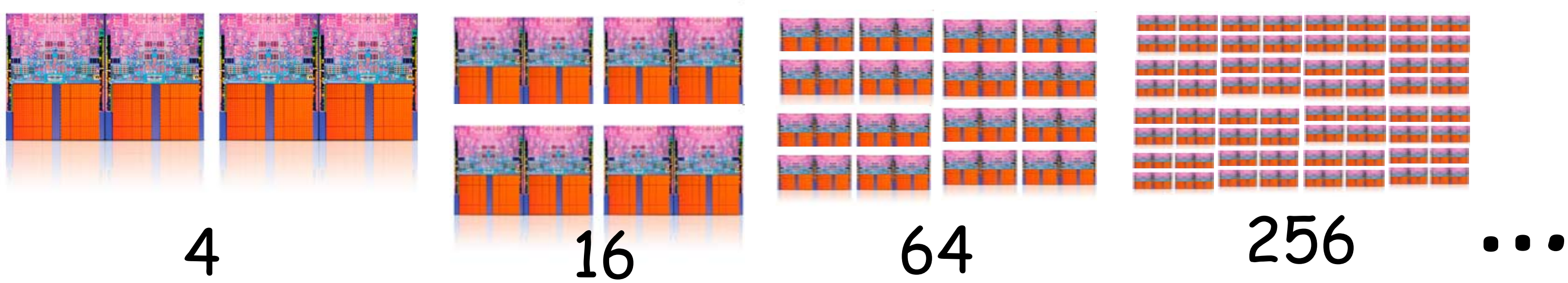
In response to recent attacks:

- (Differential attacks of Wang et al.)
- MD6 is *provably* resistant to standard differential attacks
- (SHA-3 should be, too!)

Design Considerations / Responses

Parallelism has arrived

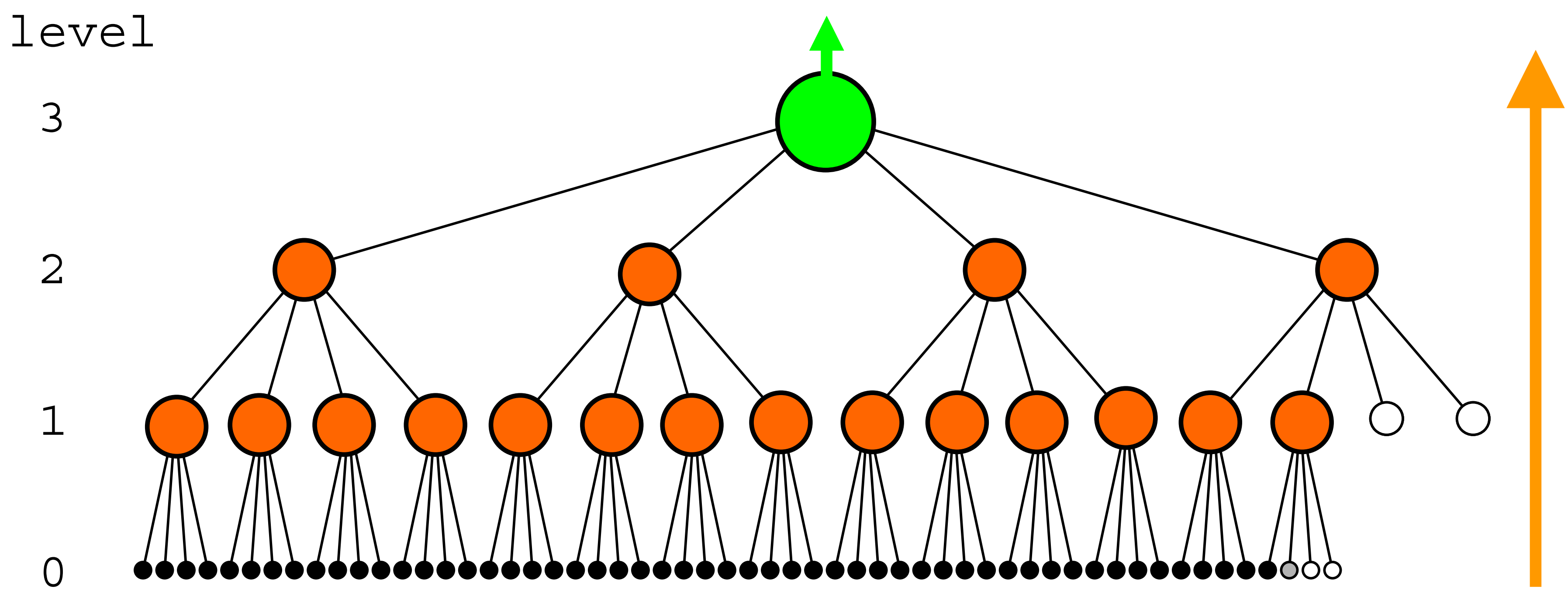
- Uniprocessors have “hit the wall”
  - – Clock rates have *plateaued*
- Hundreds of cores coming soon to a desktop near you!



- SHA-3 should be *parallelizable*!

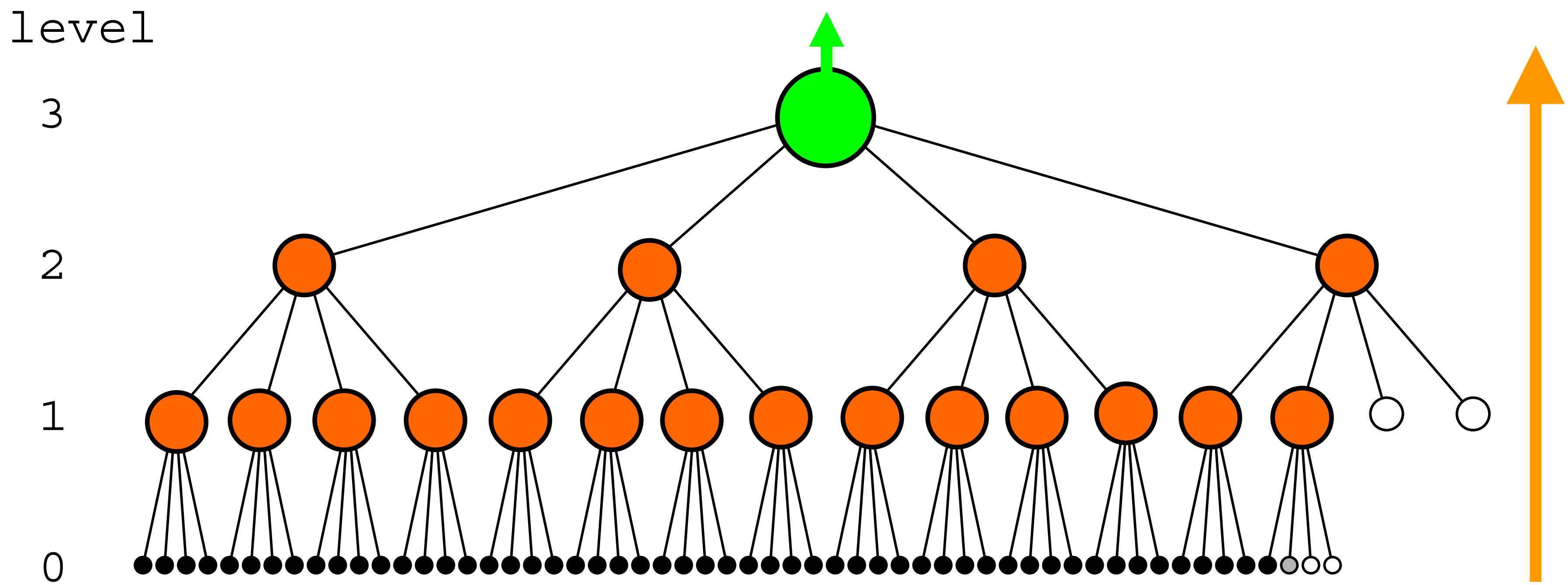
So… MD6 is tree-based

- Bottom-up tree-based mode of operation (like Merkle-tree)
- 4-to-1 compression ratio at each node



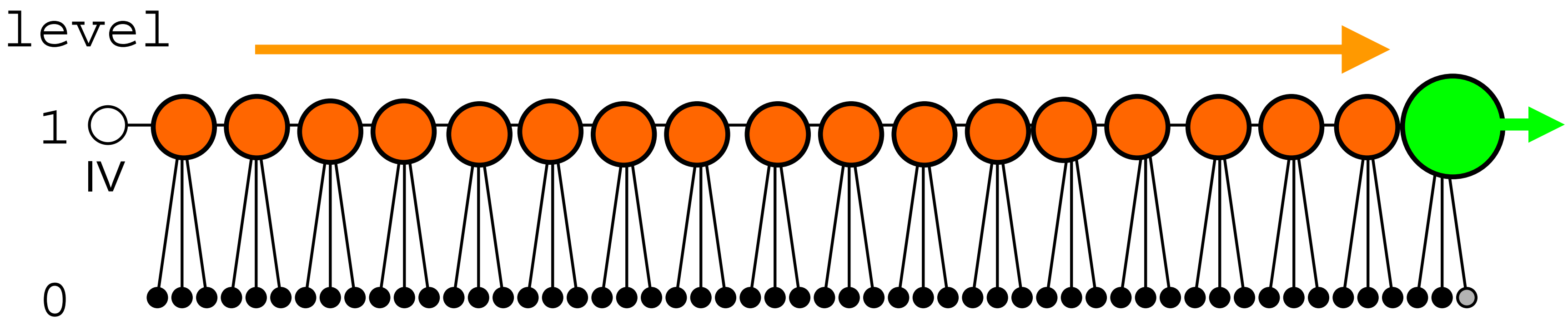
Which works very well in parallel

- Height is $\log_4$(number of nodes)



For very tiny CPU's MD6 has…

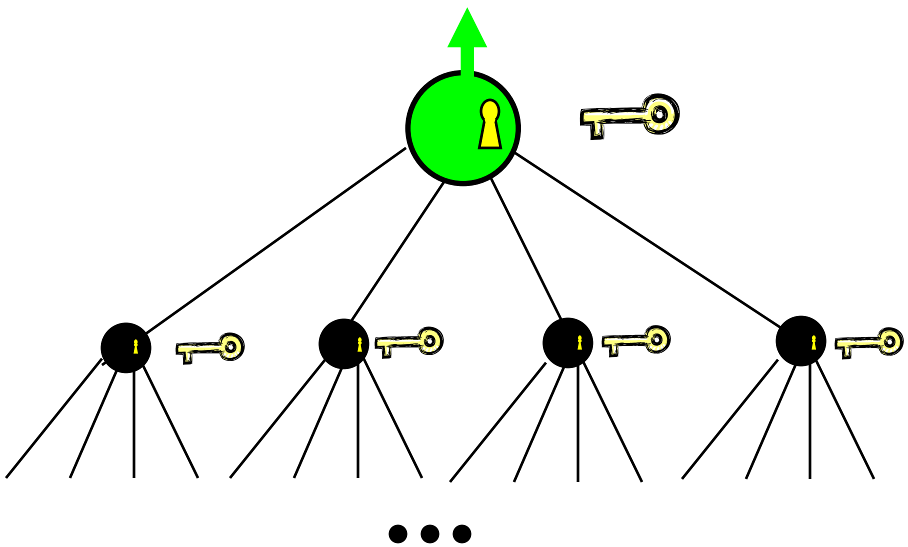
- Alternative sequential mode



- (Fits in 1KB RAM)

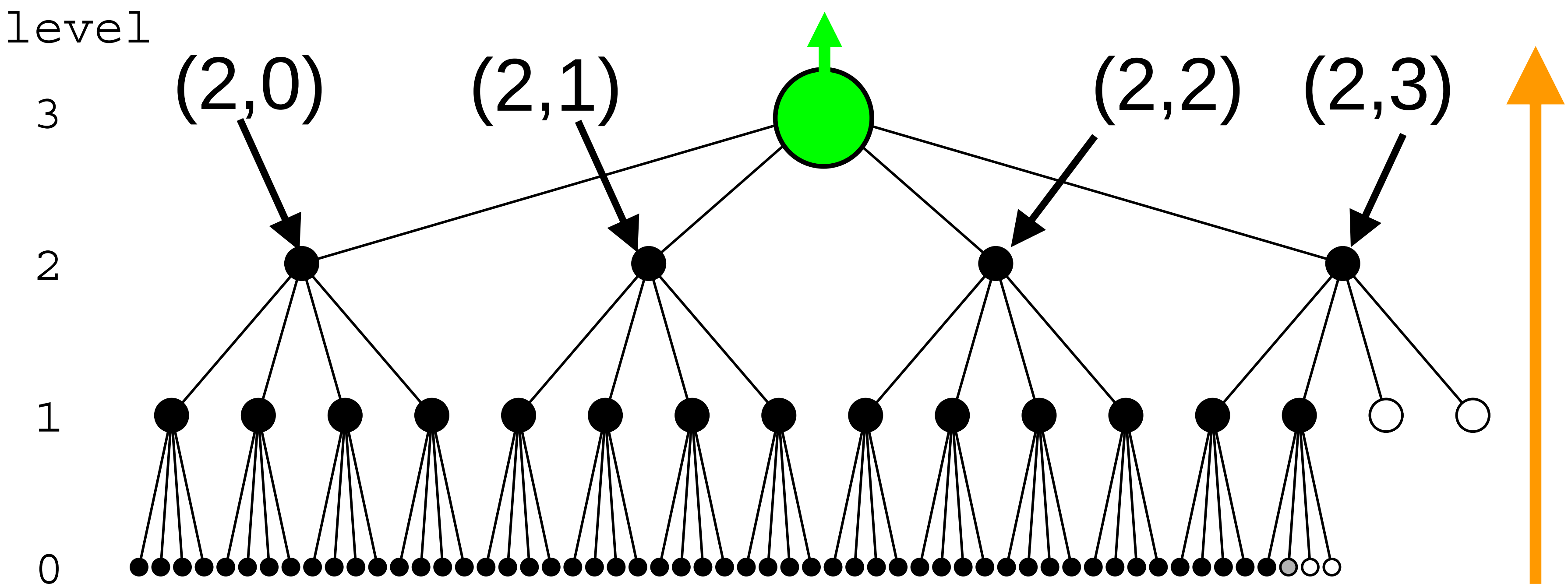
MD6 is *keyed*

- *(For salt, MAC key, etc.)*
- *Key input K* of up to 512 bits
- K input to every compression function



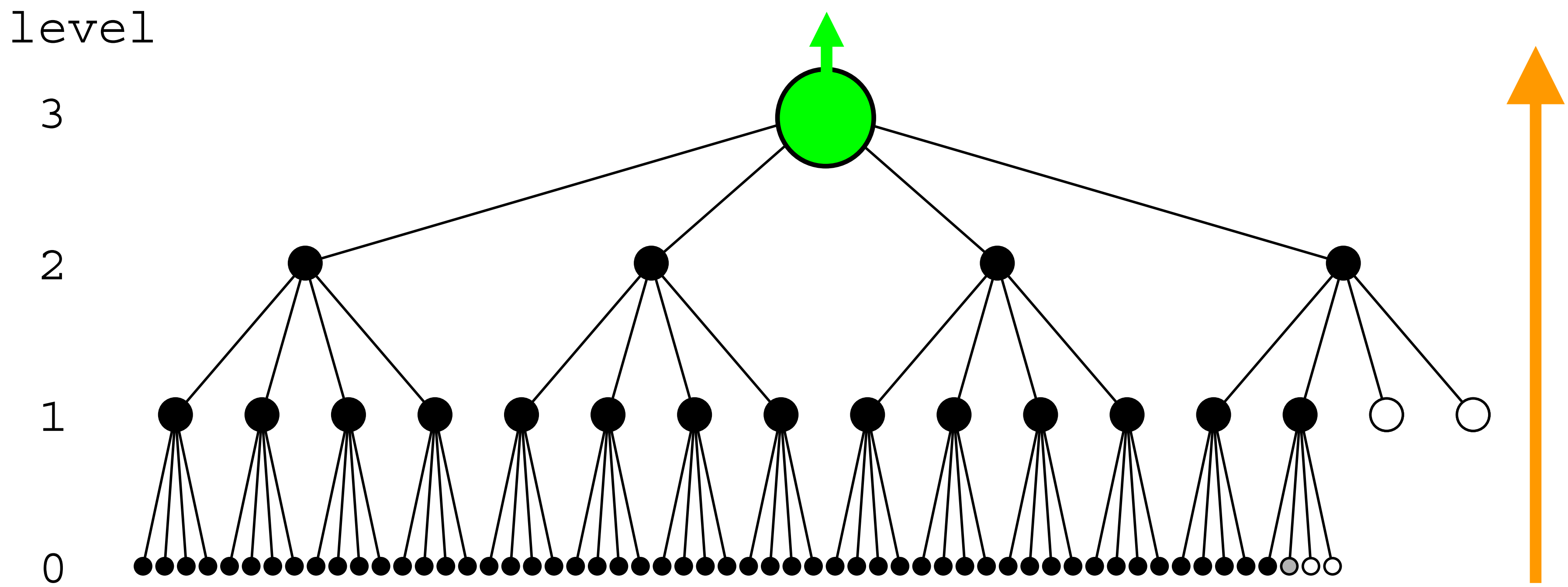
For “good hygiene” MD6 has:

- 1024-bit intermediate (chaining) values; root output chopped to desired length
- Location (level,index) input to each node



And the root is special!

- Compression function inputs “root bit” (z-bit or ``green bit”) which is True only at root:



MD6 Compression function

To prevent side-channel attacks:

- MD6 uses only the following *safe* operations, on 64-bit words:
  - XOR $\oplus$
  - AND $\wedge$
  - SHIFT by fixed amounts: >> <<

    $x >> r$

    $x << \ell$
- (All SHA-3 candidates should be required to submit timings for a *safe* implementation! No table lookups!)

MD6 has variable number r of rounds

- A round is 16 steps.
- For output digest size of d bits, default is

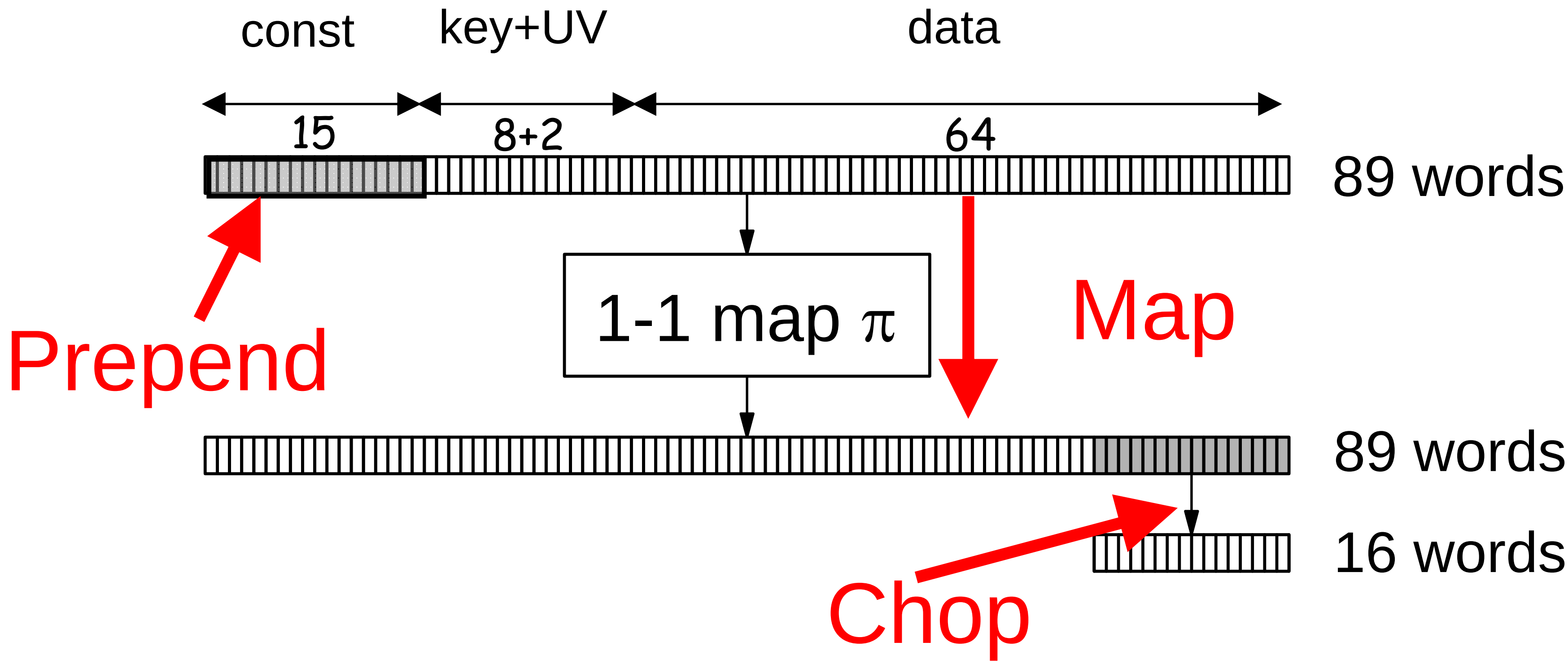
$$r = 40 + (d/4)$$

Digest size d	160	224	256	384	512
Rounds r	80	96	104	136	168

Compression function input

- 64 word (512 byte) data block
  - message, or up to 4 child chaining values
- 8 word (512 bit) key K
- 1 word location U = (level, index)
- 1 word metadata V:
  - Padding amount, key length, z-bit, max tree height, digest output size d, number r of rounds.
- 74 words total

Prepend Constant + Map + Chop



Simple compression function:

Input: A[0 .. 88] of A[0 .. 16r + 88]

for i = 89 **to** 16 r + 88 :

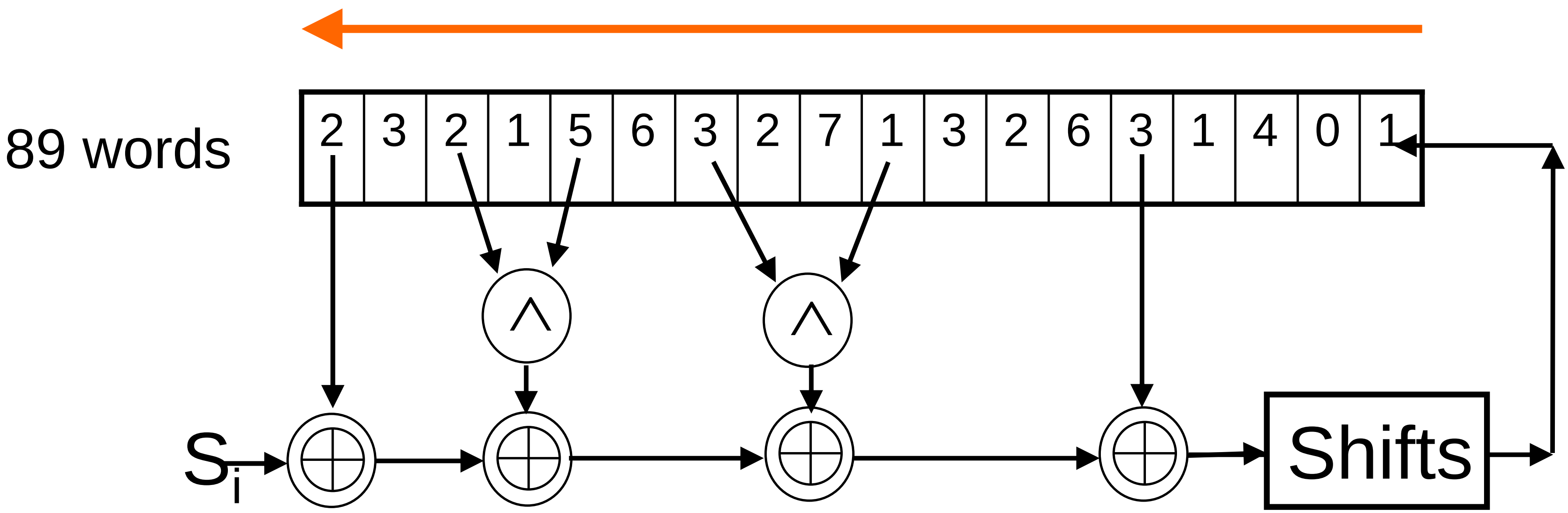
$x = S_i \oplus A[i-17] \oplus A[i-89]$
$\quad \oplus (A[i-18] \wedge A[i-21])$
$\quad \oplus (A[i-31] \wedge A[i-67])$

$x = x \oplus (x >> r_i)$

$A[i] = x \oplus (x << \ell_i)$

return A[16r + 73 .. 16r + 88]

712 byte shift-reg implementation

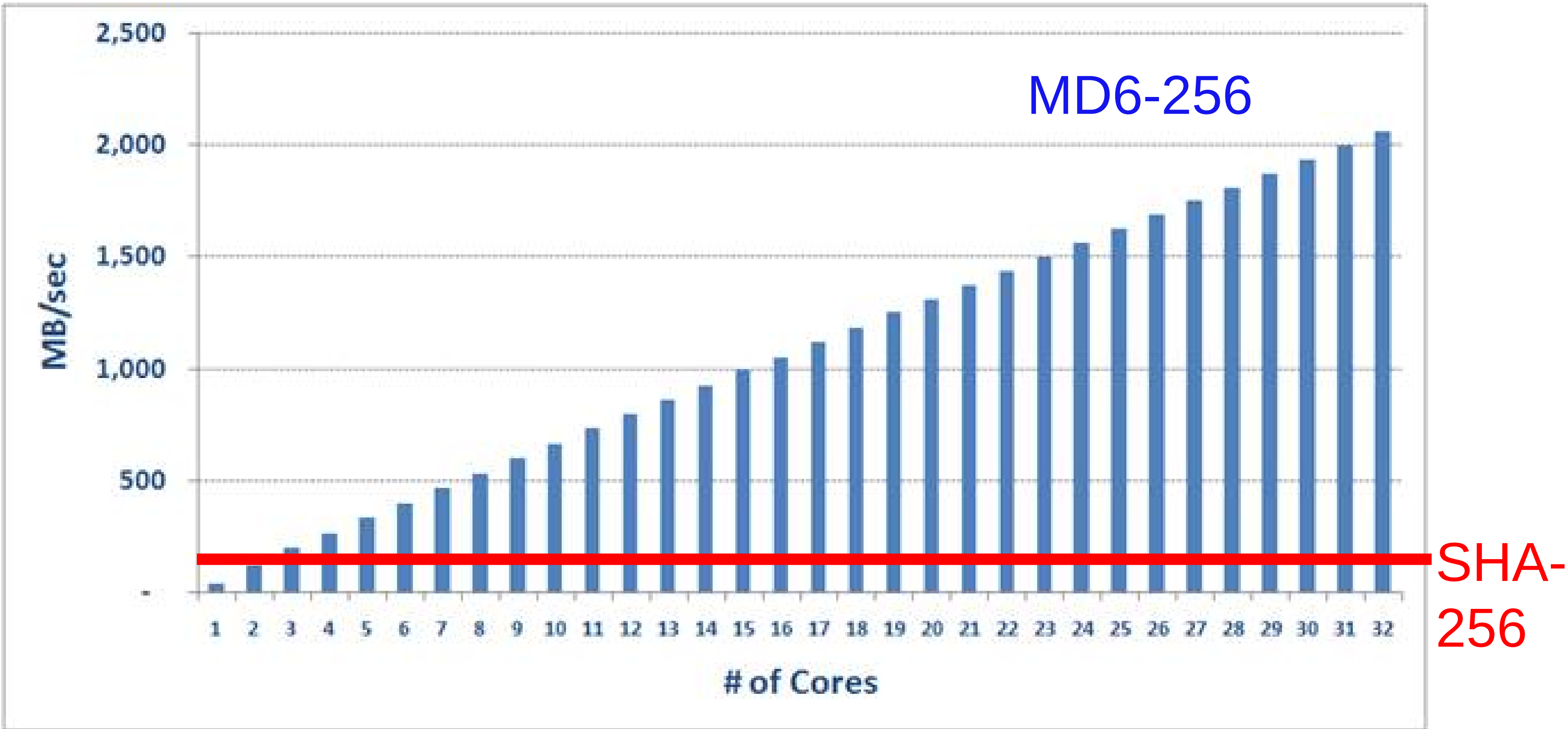


Implementations

NIST SHA-3 Reference Platforms

	32-bit	**64-bit**
MD6-160	54 cpb	24 cpb
MD6-224	63 cpb	29 cpb
MD6-256	68 cpb	31 cpb
MD6-384	87 cpb	40 cpb
MD6-512	106 cpb	48 cpb
SHA-512	63 cpb	13 cpb

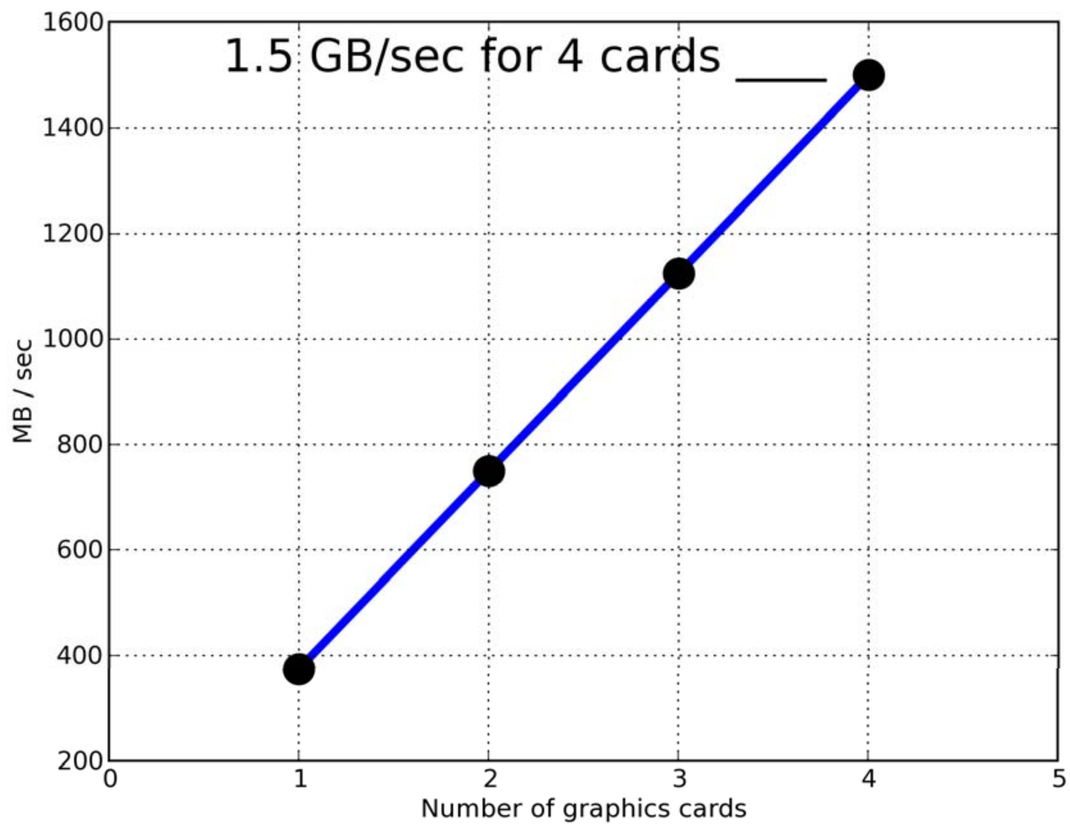
Multicore efficiency > 2GB/sec !



This is real data, courtesy of *Cilk Arts*!

Efficiency on a GPU

- Standard $100 NVidia GPU
- 375 MB/sec on one card



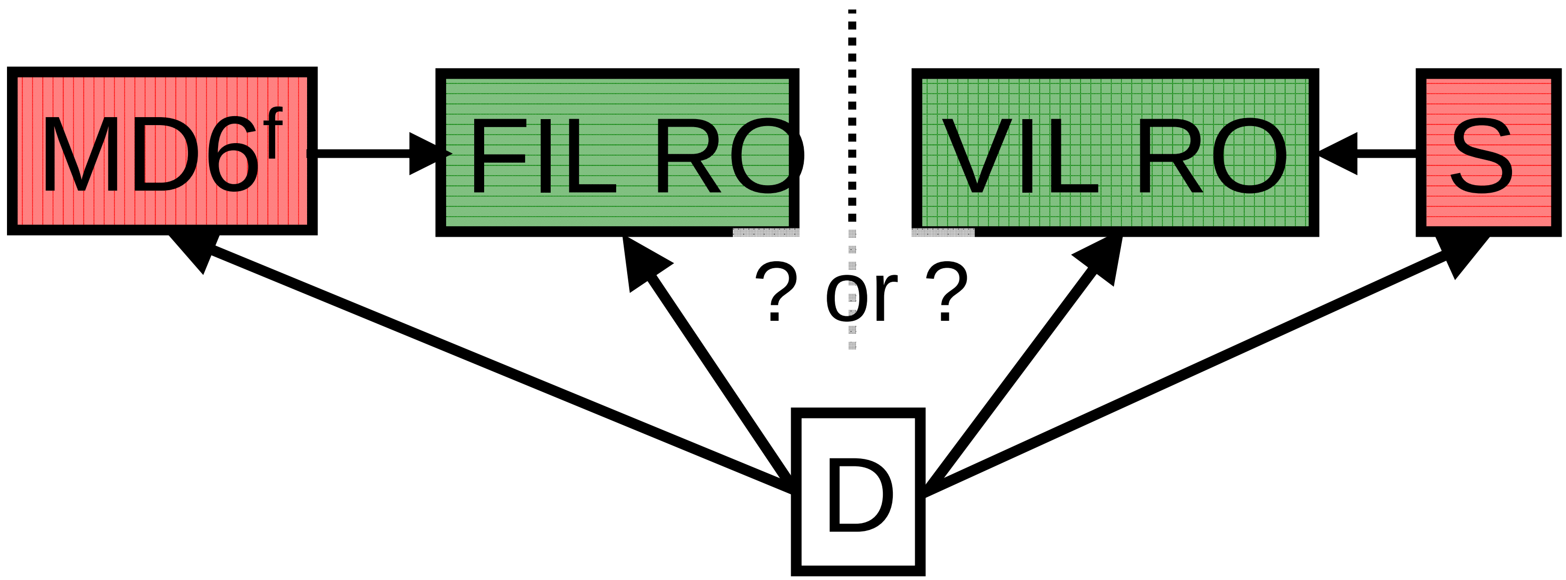
Security

Property-Preservations

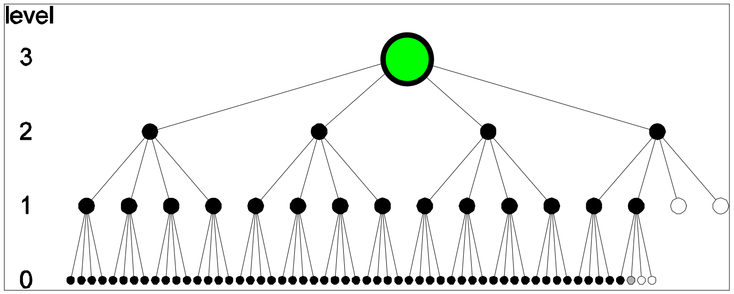
- **Theorem.** If f is collision-resistant, then $MD6^f$ is collision-resistant.
- **Theorem.** If f is preimage-resistant, then $MD6^f$ is preimage-resistant.
- **Theorem.** If f is a FIL-PRF, then $MD6^f$ is a VIL-PRF.
- **Theorem.** If f is a FIL-MAC and root node effectively uses distinct random key (due to z-bit), then $MD6^f$ is a VIL-MAC.
- (See thesis by Crutchfield.)

Indifferentiability (Maurer et al. '04)

- Variant notion of indistinguishability appropriate when distinguisher has access to inner component (e.g. mode of operation $MD6^f$ / comp. fn f).

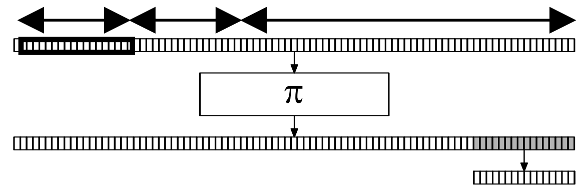


Indifferentiability (I)



- **Theorem.** The MD6 mode of operation is indifferentiable from a random oracle.
- **Proof:** Construct simulator for compression function that makes it consistent with any VIL RO and MD6 mode of operation…
- (All SHA-3 candidates should have such a result known for them!)

Indifferentiability (II)



- **Theorem.** MD6 compression function f^{π} is indifferentiable from a FIL random oracle (with respect to random permutation π).
- **Proof:** Construct simulator S for π and π^{-1} that makes it consistent with FIL RO and comp. fn. construction.

Differential attacks don’t work

- **Theorem.** *Any s*tandard differential attack has less chance of finding collision than standard birthday attack.

Differential attacks (cont.)

- Compare birthday bound BB with our lower bound LB on work for any standard differential attack.
- (Gives adversary fifteen rounds for message modification, etc.)
- These bounds can be improved…

d	r	BB	LB
160	80	2^{80}	2^{104}
224	96	2^{112}	2^{130}
256	104	2^{128}	2^{150}
384	136	2^{192}	2^{208}
512	168	2^{256}	2^{260}

Attacks

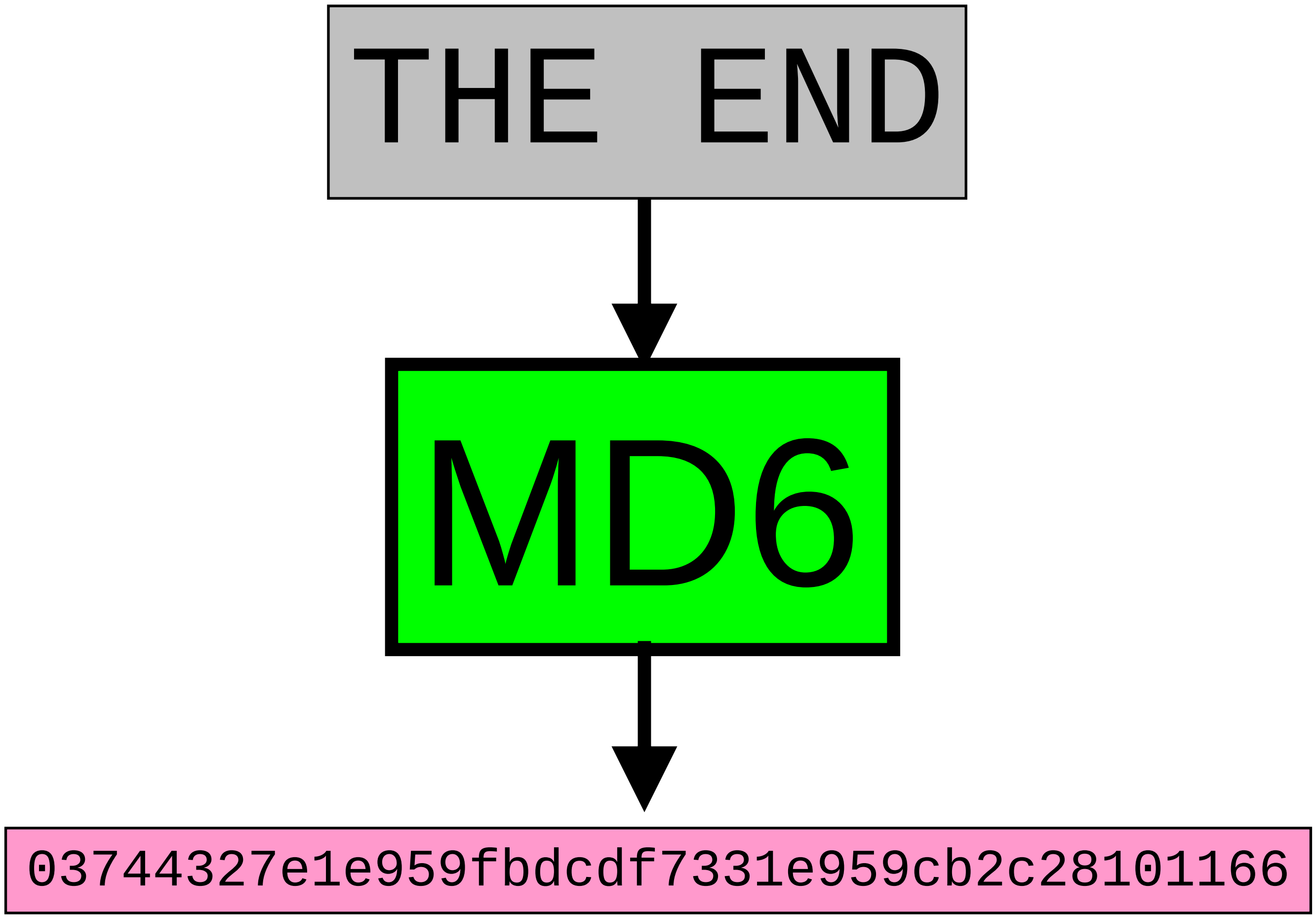
- Collision known for 16 rounds [Khazaei]
- Distinguishable from RO for 18 rounds [Aumasson et al.]
- Key recovery for 14 rounds [Aumasson et al.]
- Fixing Q=0, can distinguish up to 33 rounds [Khovratovich]
- Fixing S=0, can distinguish up to 66 rounds [Aumasson et al.]

Choosing number of rounds

- For digest sizes 224 … 512 , MD6 has 80 … 168 rounds; these defaults are conservative (intentionally);
  MD6 may well be secure at 40 rounds (which gives 12 cpb for 64-bit platform).
- Default allows *proof* of resistance to differential cryptanalysis; these proofs may get better!

Summary

- MD6 is:
  - Arguably secure against known attacks (including differential attacks)
  - Relatively simple
  - Highly parallelizable
  - Reasonably efficient


THE END
MD6
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