SipHash: a fast short-input PRF

Jean-Philippe Aumasson, Daniel J. Bernstein

SipHash: a fast short-input MAC

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UMAC

(Black, Halevi, Krawczyk, Krovetz, Rogaway; 2000)

	43 bytes	256 bytes	1500 bytes	256 kbytes
UMAC32	**16.3**	**3.8**	**2.1**	**1.9**
UMAC-STD	52.9	12.3	3.8	1.9
UMAC16	**14.0**	**2.7**	**1.2**	**1.0**
UMAC-MMX	35.9	4.5	1.7	1.0

http://fastcrypto.org/umac/update.pdf

1 cycle/byte on a Pentium III !

$$\mathrm{UMAC}(m) = H(k1, m) \oplus \mathrm{AES}(k2, n)$$

UMAC’s universal hash

Polynomial-evaluation using 64-bit multipliers with Horner’s rule

$$\left(\sum_{i=1}^{\ell/2} ((m_{2i-1} + k_{2i-1}) \bmod 2^w) \cdot ((m_{2i} + k_{2i}) \bmod 2^w)\right) \bmod 2^{2w}$$

UMAC fast C implementation

2000+ LoC

(without AES)

Not portable

```c
int uhash(uhash_ctx_t ahc, char *msg, long len, char *res)
/* assumes that msg is in a writable buffer of length divisible by */
/* L1_PAD_BOUNDARY. Bytes beyond msg[len] may be zeroed.           */
{
    UINT8 nh_result[STREAMS*sizeof(UINT64)];
    UINT32 nh_len;
    int extra_zeroes_needed;

    /* If the message to be hashed is no longer than L1_HASH_LEN, we skip
     * the polyhash.
     */
    if (len <= L1_KEY_LEN) {
        if (len == 0)                  /* If zero length messages will not */
            nh_len = L1_PAD_BOUNDARY;  /* be seen, comment out this case   */
        else
            nh_len = ((len + (L1_PAD_BOUNDARY - 1)) & ~(L1_PAD_BOUNDARY - 1));
        extra_zeroes_needed = nh_len - len;
        zero_pad((UINT8 *)msg + len, extra_zeroes_needed);
        nh(&ahc->hash, (UINT8 *)msg, nh_len, len, nh_result);
        ip_short(ahc,nh_result, res);
    } else {
        /* Otherwise, we hash each L1_KEY_LEN chunk with NH, passing the NH
         * output to poly_hash().
         */
        do {
            nh(&ahc->hash, (UINT8 *)msg, L1_KEY_LEN, L1_KEY_LEN, nh_result);
            poly_hash(ahc,(UINT32 *)nh_result);
            len -= L1_KEY_LEN;
            msg += L1_KEY_LEN;
        } while (len >= L1_KEY_LEN);
```

```
* ------------------------------------------------------------------- */

/* ////////////////////// IMPORTANT NOTES /////////////////////////////////
 *
 * 1) This version does not work properly on messages larger than 16MB
 *
 * 2) If you set the switch to use SSE2, then all data must be 16-byte
 *    aligned
 *
 * 3) When calling the function umac(), it is assumed that msg is in
 * a writable buffer of length divisible by 32 bytes. The message itself
 * does not have to fill the entire buffer, but bytes beyond msg may be
 * zeroed.
 *
```

http://fastcrypto.org/umac/2004/src/umac.c

UMAC uses a PRG to expand the key to 33280 bits

Using a PRG, map Key to $K = K_1 K_2 \cdots K_{1024}$, with each K_i a 32-bit word, and to A, where $|A| = 512$.

RFC4418 replaces UMAC's PRG with an AES-based KDF...

```
3.2.1.  KDF Algorithm

   Input:
     K, string of length KEYLEN bytes.
     index, a non-negative integer less than 2^64.
     numbytes, a non-negative integer less than 2^64.
   Output:
     Y, string of length numbytes bytes.

   Compute Y using the following algorithm.

     //
     // Calculate number of block cipher iterations
     //
     n = ceil(numbytes / BLOCKLEN)
     Y = <empty string>

     //
     // Build Y using block cipher in a counter mode
     //
     for i = 1 to n do
       T = uint2str(index, BLOCKLEN-8) || uint2str(i, 8)
       T = ENCIPHER(K, T)
       Y = Y || T
     end for

     Y = Y[1...numbytes]

     Return Y
```

… and uses AES and this KDF in a “Pad-Derivation Function”

```
3.3.1.   PDF Algorithm

   Input:
     K, string of length KEYLEN bytes.
     Nonce, string of length 1 to BLOCKLEN bytes.
     taglen, the integer 4, 8, 12 or 16.
   Output:
     Y, string of length taglen bytes.

   Compute Y using the following algorithm.

      //
      // Extract and zero low bit(s) of Nonce if needed
      //
      if (taglen = 4 or taglen = 8)
        index = str2uint(Nonce) mod (BLOCKLEN/taglen)
        Nonce = Nonce xor uint2str(index, bytelength(Nonce))
      end if

      //
      // Make Nonce BLOCKLEN bytes by appending zeroes if needed
      //
      Nonce = Nonce || zeroes(BLOCKLEN - bytelength(Nonce))

      //
      // Generate subkey, encipher and extract indexed substring
      //
      K' = KDF(K, 0, KEYLEN)
      T = ENCIPHER(K', Nonce)
      if (taglen = 4 or taglen = 8)
        Y = T[1 + (index*taglen) ... taglen + (index*taglen)]
      else
        Y = T[1...taglen]
      end if

      Return Y
```

Not so simple

SipHash

Simple ARX round function

Simple JH-like message injection

No key expansion

No external primitive

No state between messages

SipHash initialization

256-bit state v0 v1 v2 v3

128-bit key k0 k1

$v0 = k0 \oplus 736f6d6570736575$

$v1 = k1 \oplus 646f72616e646f6d$

$v2 = k0 \oplus 6c7967656e657261$

$v3 = k1 \oplus 7465646279746573$

SipHash initialization

256-bit state v0 v1 v2 v3

128-bit key k0 k1

$v0 = k0 \oplus$ “somepseu”

$v1 = k1 \oplus$ “dorandom”

$v2 = k0 \oplus$ “lygenera”

$v3 = k1 \oplus$ “tedbytes”

SipHash compression

Message parsed as 64-bit words **m0**, **m1**, …

v3 $\oplus$= **m0**

c iterations of SipRound

v0 $\oplus$= **m0**

SipHash compression

Message parsed as 64-bit words **m0**, **m1**, …

v3 $\oplus$= **m1**

c iterations of SipRound

v0 $\oplus$= **m1**

SipHash compression

Message parsed as 64-bit words **m0**, **m1**, …

v3 $\oplus$= **m2**

c iterations of SipRound

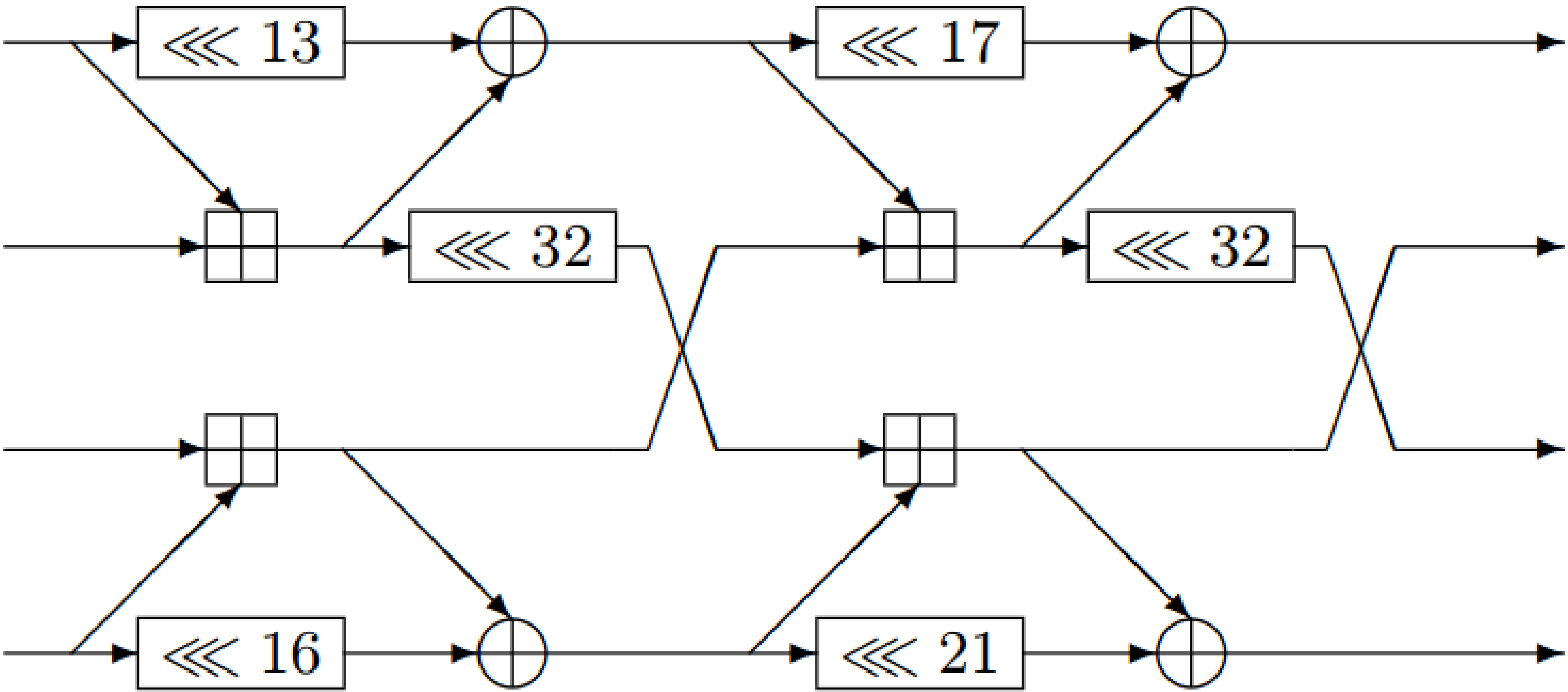
v0 $\oplus$= **m2**

SipHash compression

Message parsed as 64-bit words **m0**, **m1**, …

Etc.

SipRound



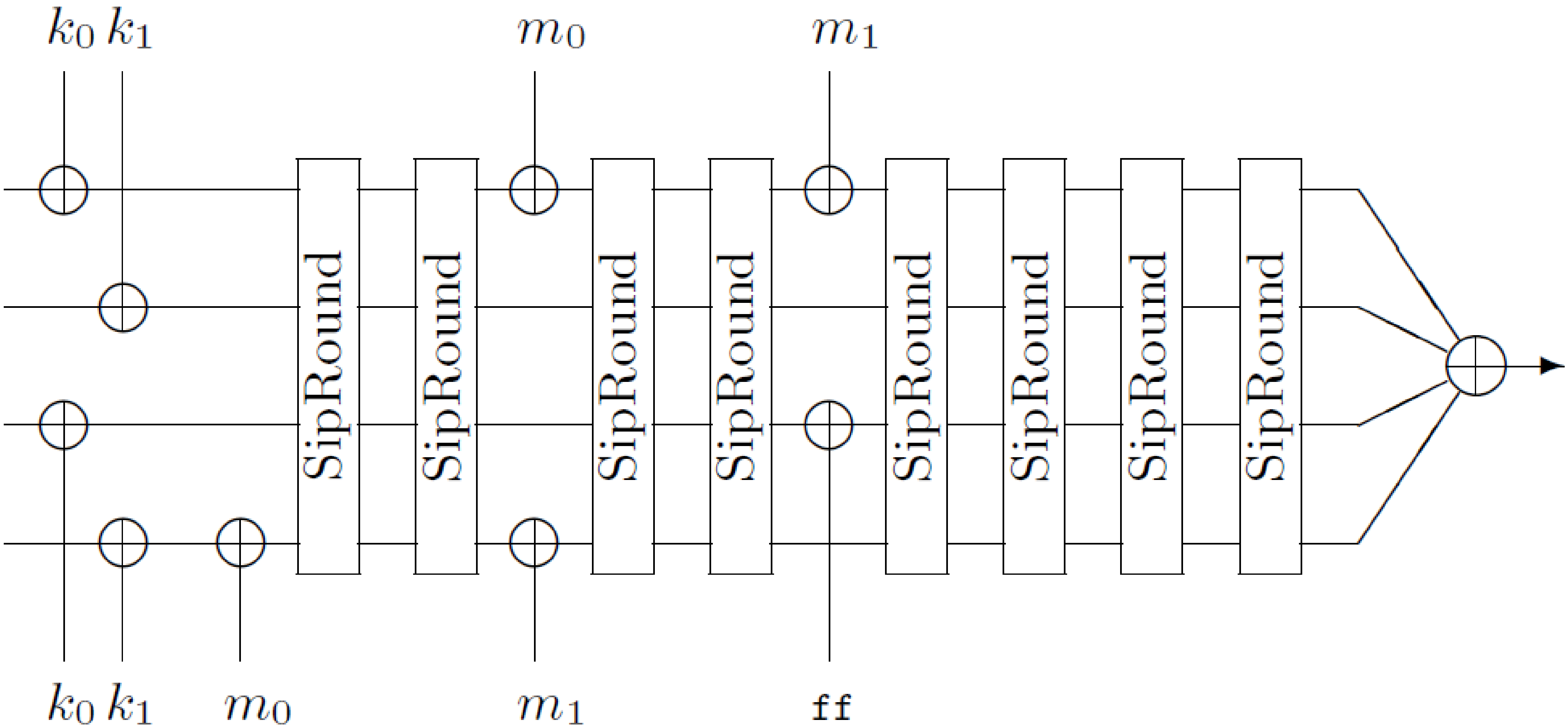
SipHash finalization

$v2 \oplus= 255$

d iterations of SipRound

Return $v0 \oplus v1 \oplus v2 \oplus v3$

SipHash-2-4 hashing 15 bytes



Family SipHash-**c**-**d**

Fast proposal: SipHash-**2**-**4**

Conservative proposal: SipHash-**4**-**8**

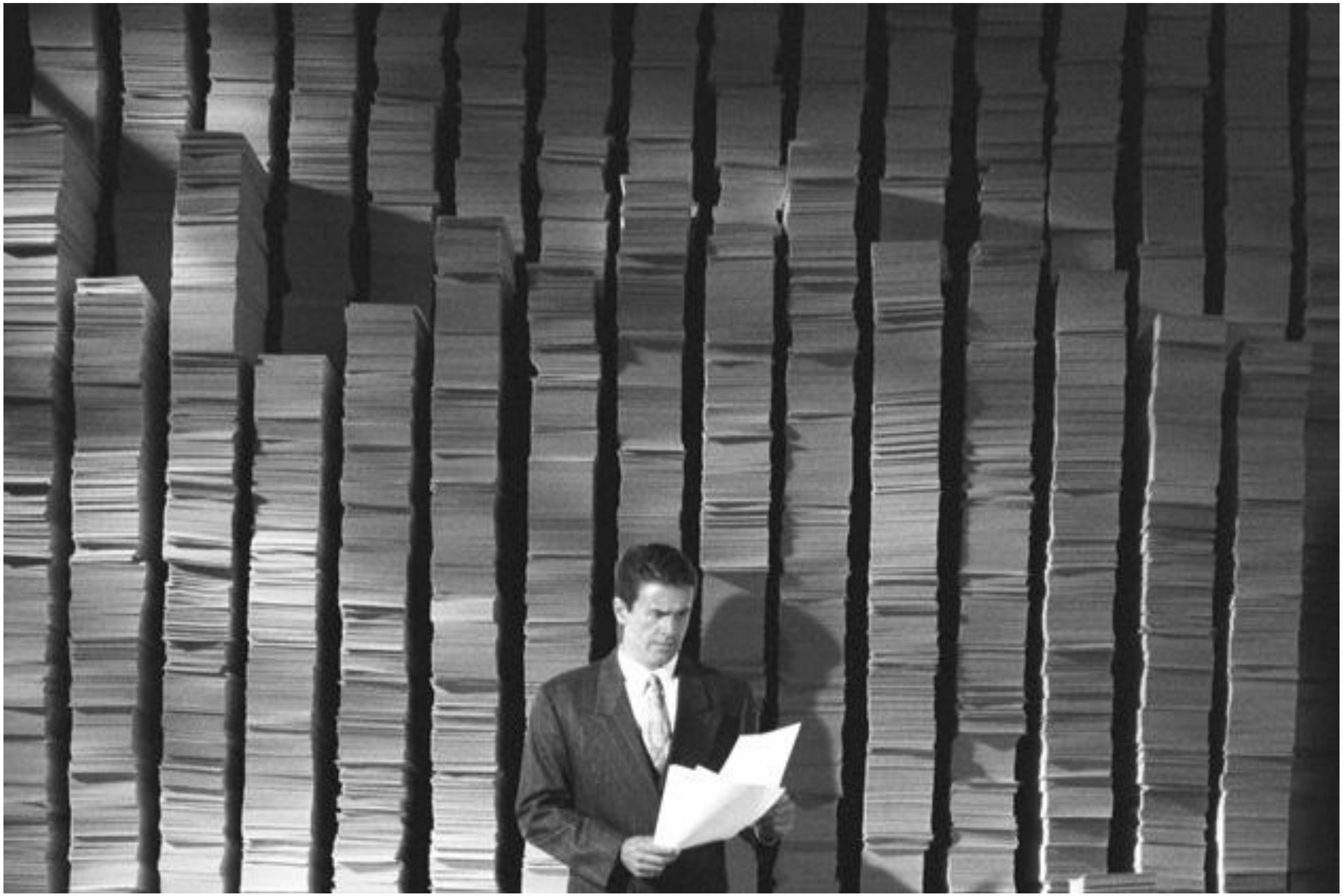
Weaker versions for cryptanalysis:

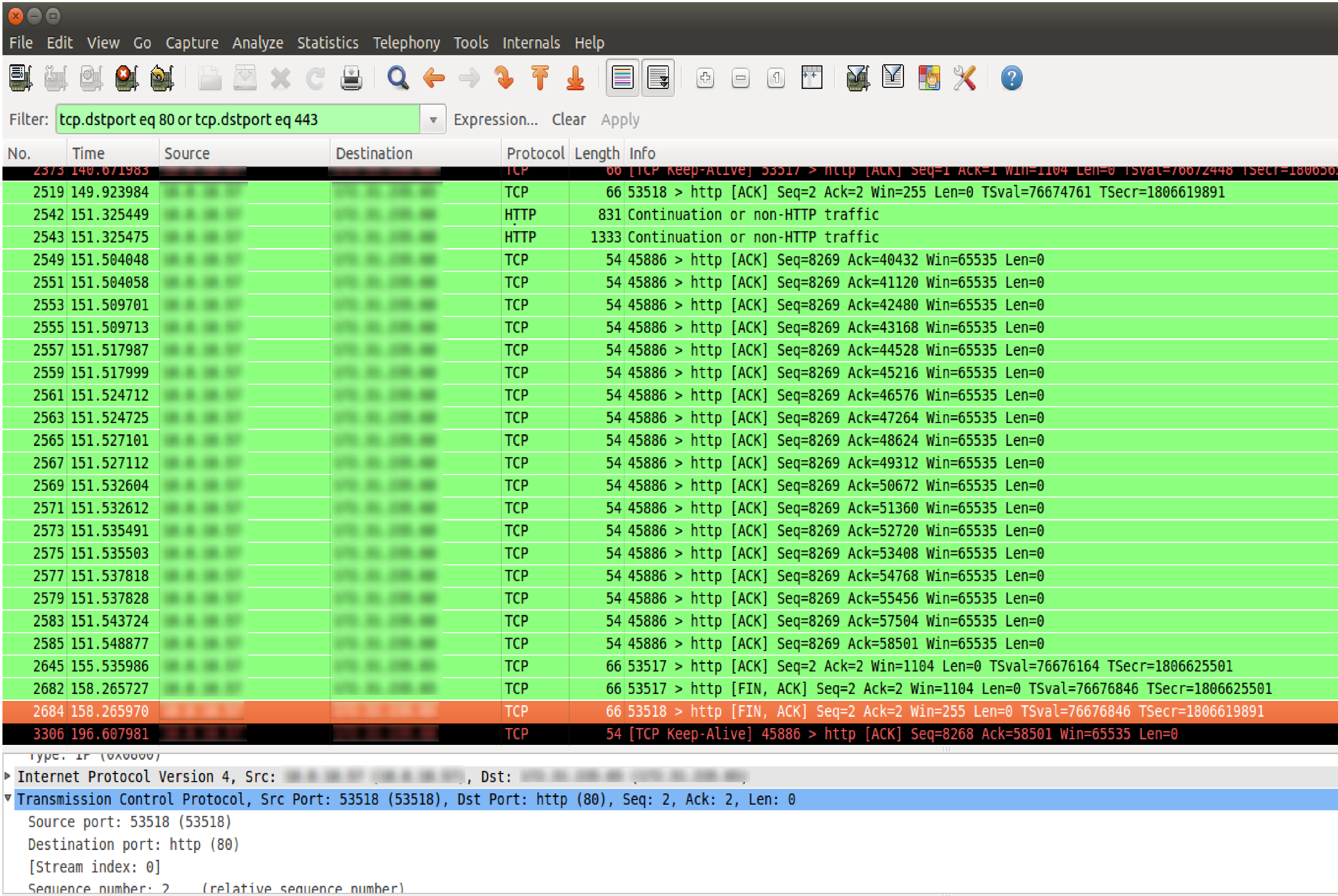
SipHash-1-0, SipHash-2-0, etc.

SipHash-1-1, SipHash-2-1, etc.

Etc.

(Many) short inputs?




File Edit View Go Capture Analyze Statistics Telephony Tools Internals Help
Filter: tcp.dstport eq 80 or tcp.dstport eq 443
Expression... Clear Apply
No. Time Source Destination Protocol Length Info
2519 149.923984 TCP 66 53518 > http [ACK] Seq=2 Ack=2 Win=255 Len=0 TSval=76674761 TSecr=1806619891
2542 151.325449 HTTP 831 Continuation or non-HTTP traffic
2543 151.325475 HTTP 1333 Continuation or non-HTTP traffic
2549 151.504048 TCP 54 45886 > http [ACK] Seq=8269 Ack=40432 Win=65535 Len=0
2551 151.504058 TCP 54 45886 > http [ACK] Seq=8269 Ack=41120 Win=65535 Len=0
2553 151.509701 TCP 54 45886 > http [ACK] Seq=8269 Ack=42480 Win=65535 Len=0
2555 151.509713 TCP 54 45886 > http [ACK] Seq=8269 Ack=43168 Win=65535 Len=0
2557 151.517987 TCP 54 45886 > http [ACK] Seq=8269 Ack=44528 Win=65535 Len=0
2559 151.517999 TCP 54 45886 > http [ACK] Seq=8269 Ack=45216 Win=65535 Len=0
2561 151.524712 TCP 54 45886 > http [ACK] Seq=8269 Ack=46576 Win=65535 Len=0
2563 151.524725 TCP 54 45886 > http [ACK] Seq=8269 Ack=47264 Win=65535 Len=0
2565 151.527101 TCP 54 45886 > http [ACK] Seq=8269 Ack=48624 Win=65535 Len=0
2567 151.527112 TCP 54 45886 > http [ACK] Seq=8269 Ack=49312 Win=65535 Len=0
2569 151.532604 TCP 54 45886 > http [ACK] Seq=8269 Ack=50672 Win=65535 Len=0
2571 151.532612 TCP 54 45886 > http [ACK] Seq=8269 Ack=51360 Win=65535 Len=0
2573 151.535491 TCP 54 45886 > http [ACK] Seq=8269 Ack=52720 Win=65535 Len=0
2575 151.535503 TCP 54 45886 > http [ACK] Seq=8269 Ack=53408 Win=65535 Len=0
2577 151.537818 TCP 54 45886 > http [ACK] Seq=8269 Ack=54768 Win=65535 Len=0
2579 151.537828 TCP 54 45886 > http [ACK] Seq=8269 Ack=55456 Win=65535 Len=0
2583 151.543724 TCP 54 45886 > http [ACK] Seq=8269 Ack=57504 Win=65535 Len=0
2585 151.548877 TCP 54 45886 > http [ACK] Seq=8269 Ack=58501 Win=65535 Len=0
2645 155.535986 TCP 66 53517 > http [ACK] Seq=2 Ack=2 Win=1104 Len=0 TSval=76676164 TSecr=1806625501
2682 158.265727 TCP 66 53517 > http [FIN, ACK] Seq=2 Ack=2 Win=1104 Len=0 TSval=76676846 TSecr=1806625501
2684 158.265970 TCP 66 53518 > http [FIN, ACK] Seq=2 Ack=2 Win=255 Len=0 TSval=76676846 TSecr=1806619891
3306 196.607981 TCP 54 [TCP Keep-Alive] 45886 > http [ACK] Seq=8268 Ack=58501 Win=65535 Len=0
Internet Protocol Version 4, Src: , Dst:
Transmission Control Protocol, Src Port: 53518 (53518), Dst Port: http (80), Seq: 2, Ack: 2, Len: 0
Source port: 53518 (53518)
Destination port: http (80)
[Stream index: 0]

Hash tables

```
h = {}                  # empty table
h['foo'] = 'bar'        # insert 'bar'
Print h['foo']          # lookup
```

Non-crypto functions to produce ‘foo’:

```
for (; nKeyLength > 0; nKeyLength -=1) {
hash = ((hash << 5) + hash) + *arKey++;
}
```

Hash flooding attacks

Multicollisions forcing worst-case complexity of $\Theta(n^2)$, instead of $\Theta(n)$

[when table implemented as linked lists]

djbdns/cache.c, 1999

```
    nextpos = prevpos ^ get4(pos);
    prevpos = pos;
    pos = nextpos;
    if (++loop > 100) return 0; /* to protect against hash flooding */
  }

  return 0;
}
```

USENIX 2003

Denial of Service via Algorithmic Complexity Attacks

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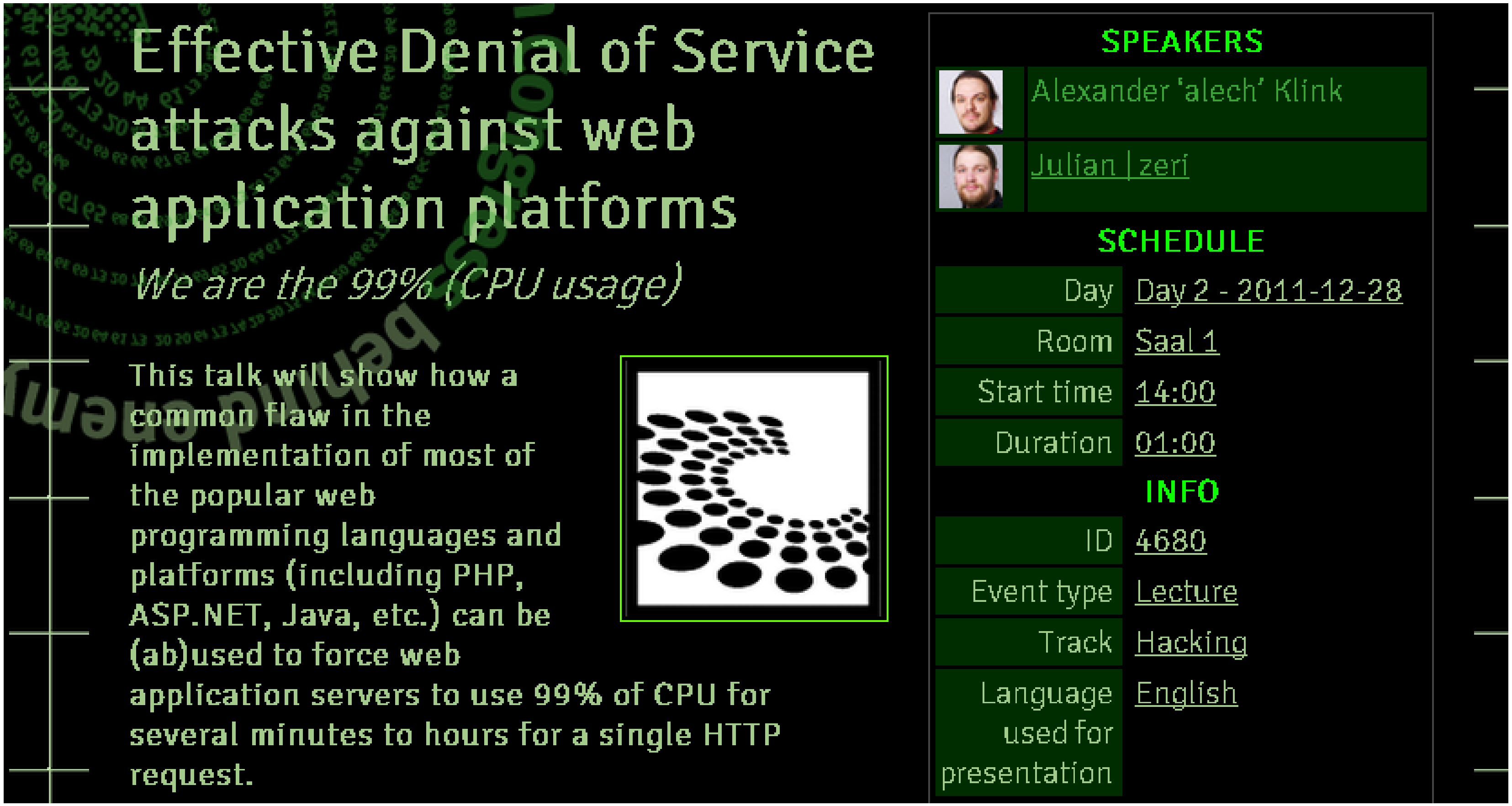
Abstract

We present a new class of low-bandwidth denial of service attacks that exploit algorithmic deficiencies

sume $O(n)$ time to insert n elements. However, if each element hashes to the same bucket, the hash table will also degenerate to a linked list, and it will take $O(n^2)$ time to insert n elements.

Vulnerabilities in Perl, web proxy, IDS

CCC 2011



Affected: PHP, ASP.net, Python, etc.

n.runs AG
http://www.nruns.com/ security(at)nruns.com
n.runs-SA-2011.004 28-Dec-2011

Vendors: PHP, http://www.php.net
Oracle, http://www.oracle.com
Microsoft, http://www.microsoft.com
Python, http://www.python.org
Ruby, http://www.ruby.org
Google, http://www.google.com Affected Products: PHP 4 and 5
Java
Apache Tomcat
Apache Geronimo
Jetty
Oracle Glassfish
ASP.NET
Python
Plone
CRuby 1.8, JRuby, Rubinius
v8

Vulnerability: Denial of Service through hash table
multi-collisions

How short?

OpenDNS cache: **27 bytes** on average

Ruby on Rails web application: **<20 bytes**

Why SipHash?

Minimizes hash flooding

→ impact limited to sqrt(communication)

Well-defined security goal (PRF)

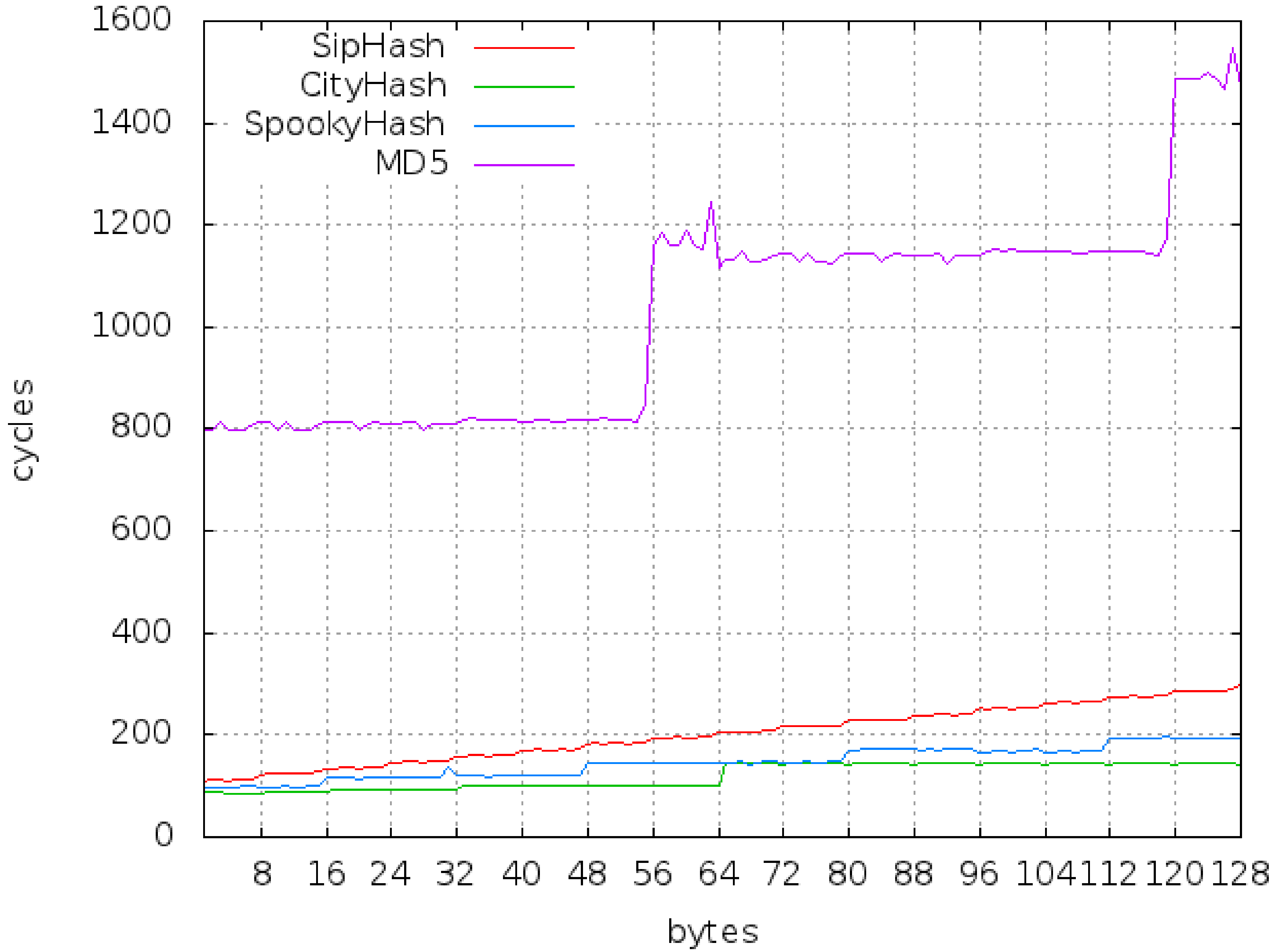
Competitive in speed with non-crypto hashes

How fast?

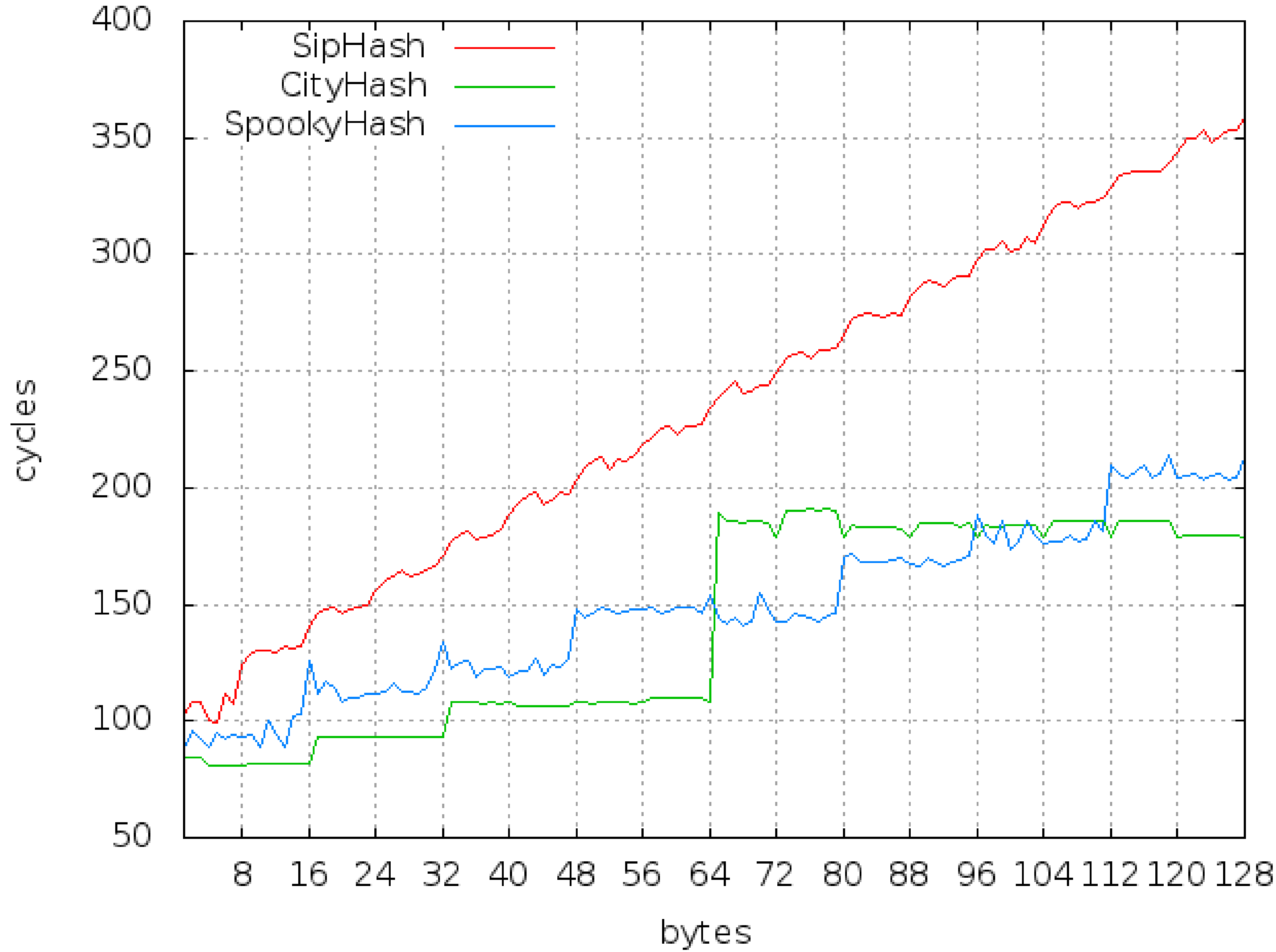
SipHash-2-4 on an AMD Athlon II Neo

Byte length	8	16	32	64
Cycles (per byte)	123 (15.38)	134 (8.38)	158 (4.25)	204 (3.19)

Long data: **1.44** cycles/byte

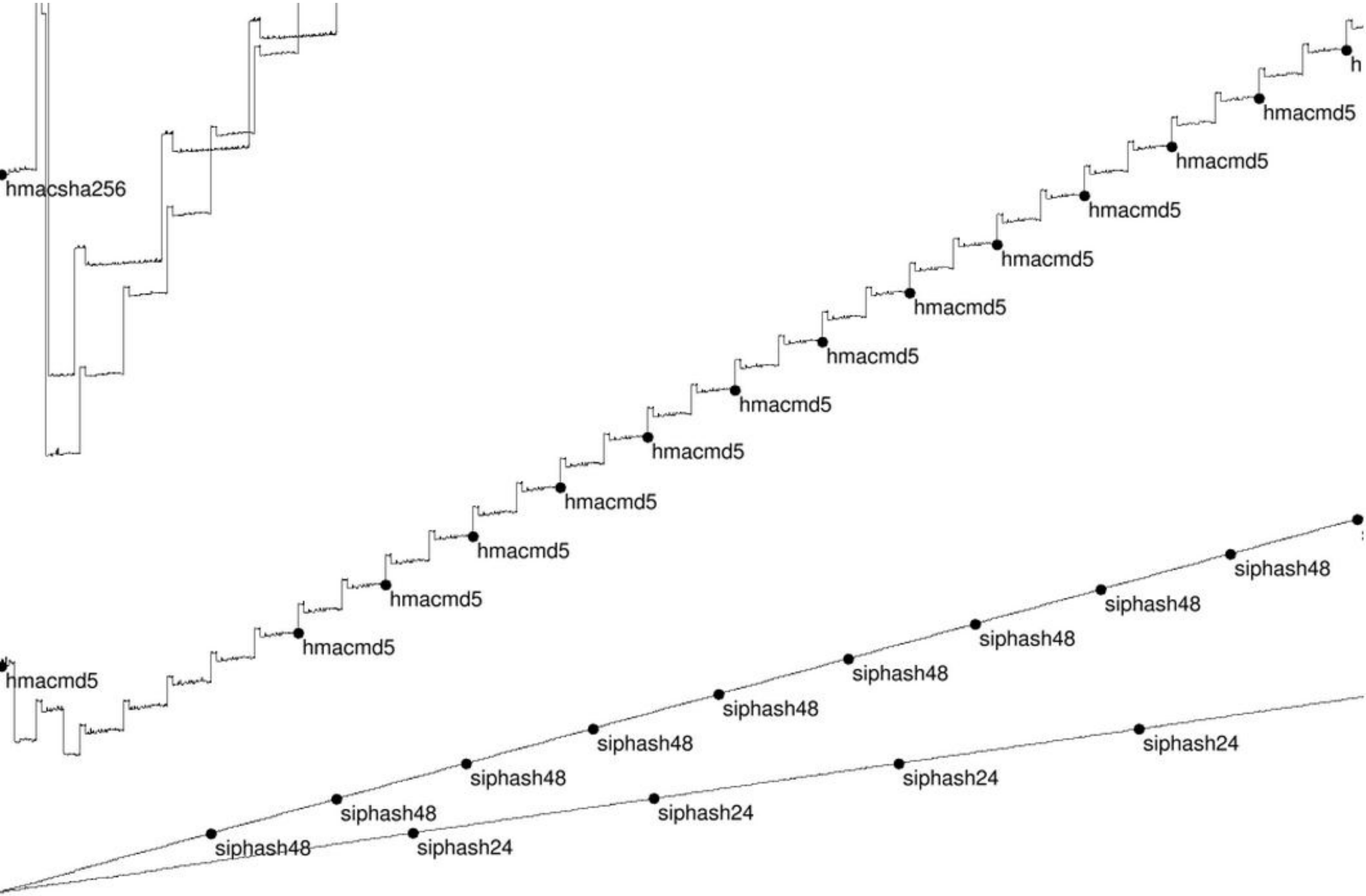


SipHash
CityHash
SpookyHash
MD5
cycles
bytes
0
200
400
600
800
1000
1200
1400
1600
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128

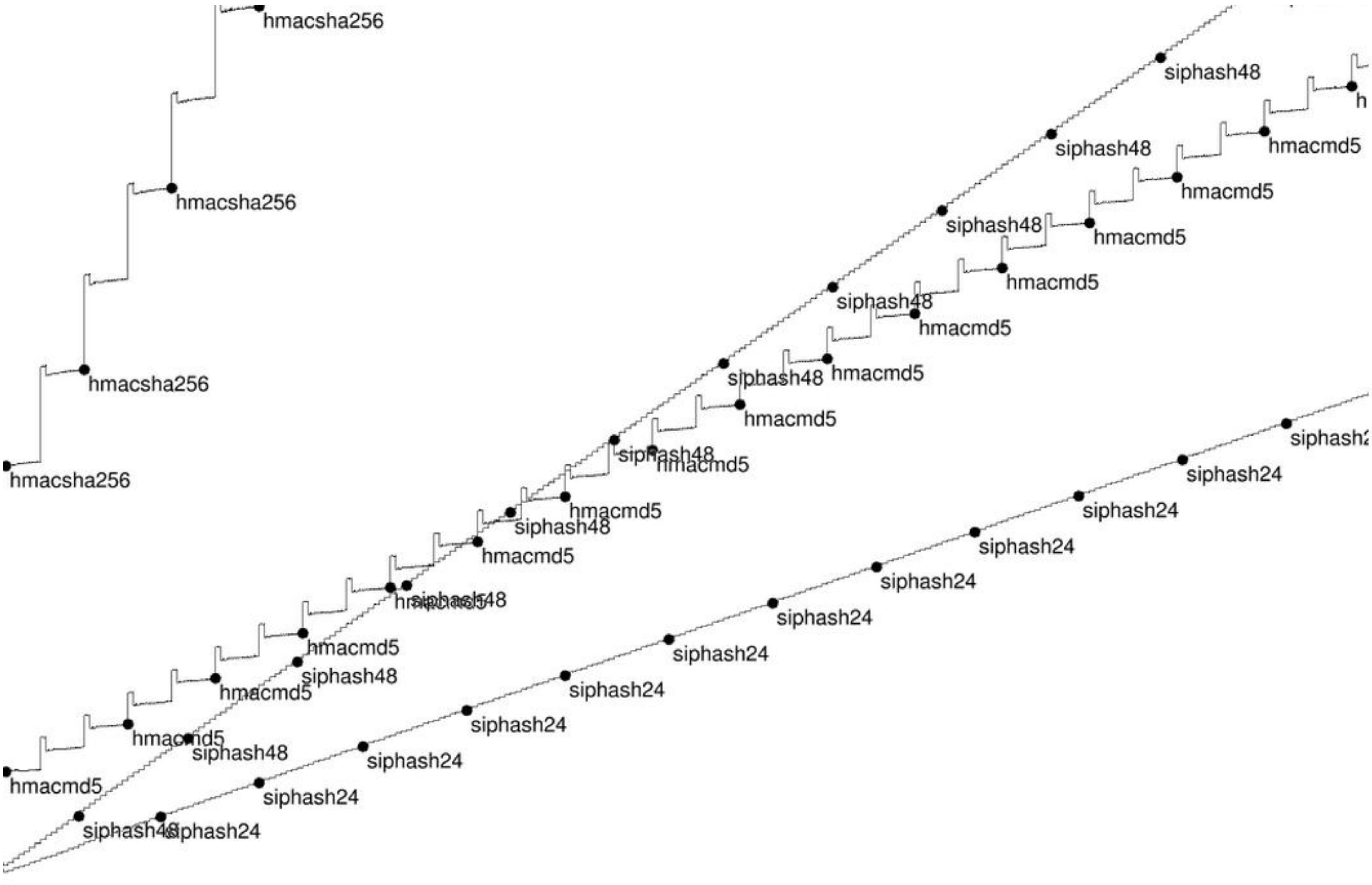


SipHash
CityHash
SpookyHash
cycles
bytes
400
350
300
250
200
150
100
50
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128

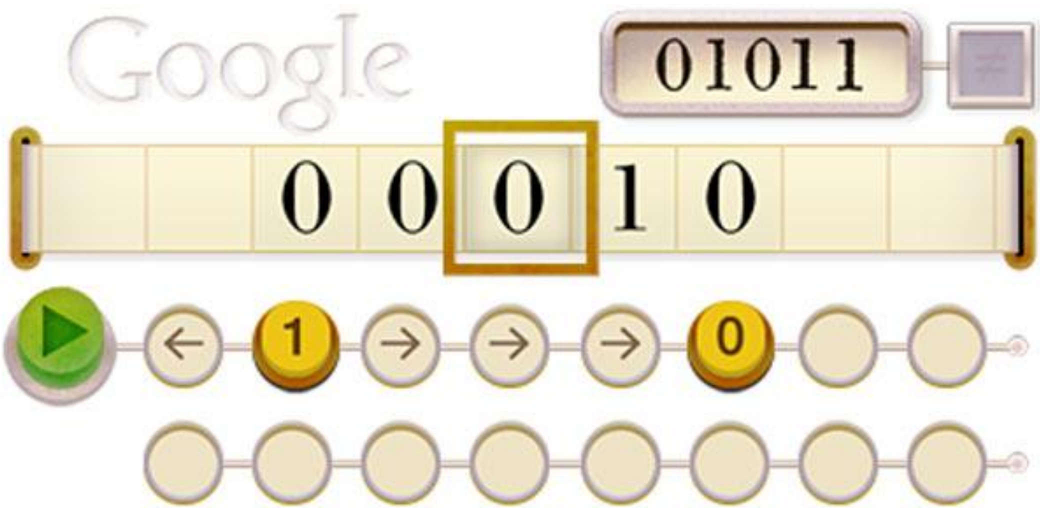
amd64; K10 45nm; 2010 AMD Phenom II X6 1090T



x86; K10 45nm; 2010 AMD Phenom II X6 1090T



Cryptanalysis



Generic attacks

$\approx 2^{128}$ key recovery

$\approx 2^{192}$ state recovery

$\approx 2^{128}$ internal-collision forgeries

$\approx 2^{s}$ forgery attack with success probability 2^{s-64}

Round	Differences	Prob.
1	`................ ................ ................ 8...............` `................ ................ 8............... 8...........8...`	1 (1)
2	`8...........8... 8............... ........8....... 8.....1...1.8...` `....8........... ............9... 8.....1.8.1.8... 8.1.......1.....`	13 (14)
3	`..1.8.....1..... 8.....11a.1.1... 8.1.1...8.....1. 8.1.82.......2..` `a...1...8.1.8.11 8.12b413a2...... ....92..8....21. 82..92..82..82..`	42 (56)
4	`22..82...21..211 e835621322.1.235 22...21.8.122613 621.c21.42..42.3` `2.11..24ca35e.13 66778453..57bd22 4.1.c...c212641. 82..82..8.11.6..`	103 (159)
5	`a21182244a24e613 2ec144fcb8.115dd c245d93226674453 e2.18..48a34a6.3` `f225f3ce8cd.c6d8 a44f51d8d.9e5616 2.445936ac53e25. a.4.d3.2.a5...51`	152 (311)
6	`52652.cc868.c689 27baa9d2d.e.fcd8 7ccdb44684.b.8ee 32246acc8cb4ce93` `566.3a5175df891e 2.e5d3.249fb3ea6 4ee9de8a.8bfc67d 2425523ec62cf459`	187 (498)

Characteristic verified with ARXtools

http://www.di.ens.fr/~leurent/arxtools.html

Proof of insecurity

SipRound(0) = 0

That is, SipRound is not ideal

Therefore SipHash is insecure

Proof of simplicity

June 20: paper published online

June 28: **18** third-party implementations

C (Floodyberry, Boßlet, Neves); **C#** (Haynes)
Cryptol (Lazar); **Erlang**, **Javascript**, **PHP** (Denis)
Go (Chestnykh); **Haskell** (Hanquez);
Java, **Ruby** (Boßlet); **Lisp** (Brown);

More on SipHash:

http://131002.net/siphash

Thanks to all implementers!