Hash-flooding DoS reloaded: attacks and defenses

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Ruby Core Team

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n→nine
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s→six→seven
t→two→three→ten
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e.g. strings `one`, `two`, . . . , `ten`;
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    /* to protect against
       hash flooding */
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December 1999, Bernstein, `dnscache` software (OpenDNS: >41000000000000 DNS requests from 50 million Internet users):

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But what about hash tables in general-purpose programming languages and libraries?
Can't throw entries away!

Bad solution:
Use SHA-3 for H.
SHA-3 is collision-resistant!

December 1999, Bernstein, `dnscache` software (OpenDNS: >4100000000000 DNS requests from 50 million Internet users):

```
if (++loop > 100) return 0;
  /* to protect against
     hash flooding */
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$H(s) \bmod \ell$
is *not* collision-resistant.

ℓ is small: e.g., $\ell = 2^{20}$.
No matter how strong H is, attacker can easily compute $H(s) \bmod 2^{20}$ for many s to find multicollisions.

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Attack examples:
Perl programming
Squid web cache,

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"We present a new class of
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the hash table will also
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Attack examples:
Perl programming language,
Squid web cache, etc.

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2011 (28
"Efficien
on web a

Java, JR
Python 2
Ruby, Ap
Tomcat,
Plone, R
Engine.

oCERT

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. . . but

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Attack examples:
Perl programming language,
Squid web cache, etc.

2011 (28C3), Klin

"Efficient denial o

on web applicatio

Java, JRuby, PHP

Python 2, Python

Ruby, Apache Ger

Tomcat, Oracle G

Plone, Rack, V8 J

Engine.

oCERT advisory 2

Application respo

use secret key to

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Attack examples:
Perl programming language,
Squid web cache, etc.

2011 (28C3), Klink–Wälde, "Efficient denial of service a on web application platform

Java, JRuby, PHP 4, PHP 5 Python 2, Python 3, Rubiniu Ruby, Apache Geronimo, Ap Tomcat, Oracle Glassfish, Je Plone, Rack, V8 Javascript Engine.

oCERT advisory 2011–003.

Application response:
use secret key to *randomize*
. . . but is this secure?

2003 USENIX Security Symposium, Crosby–Wallach, “Denial of service via algorithmic complexity attacks”:

“We present a new class of low-bandwidth denial of service attacks . . . if each element hashes to the same bucket, the hash table will also degenerate to a linked list.”

Attack examples:
Perl programming language,
Squid web cache, etc.

2011 (28C3), Klink–Wälde, “Efficient denial of service attacks on web application platforms”:

Java, JRuby, PHP 4, PHP 5, Python 2, Python 3, Rubinius, Ruby, Apache Geronimo, Apache Tomcat, Oracle Glassfish, Jetty, Plone, Rack, V8 Javascript Engine.

oCERT advisory 2011–003.

Application response:
use secret key to *randomize* H.
. . . but is this secure?

hash-flooding DoS reloaded: anatomy of an attack

MurmurHash2

"used in code by Google, Microsoft, Yahoo, and many others"

CRuby, JRuby, Redis

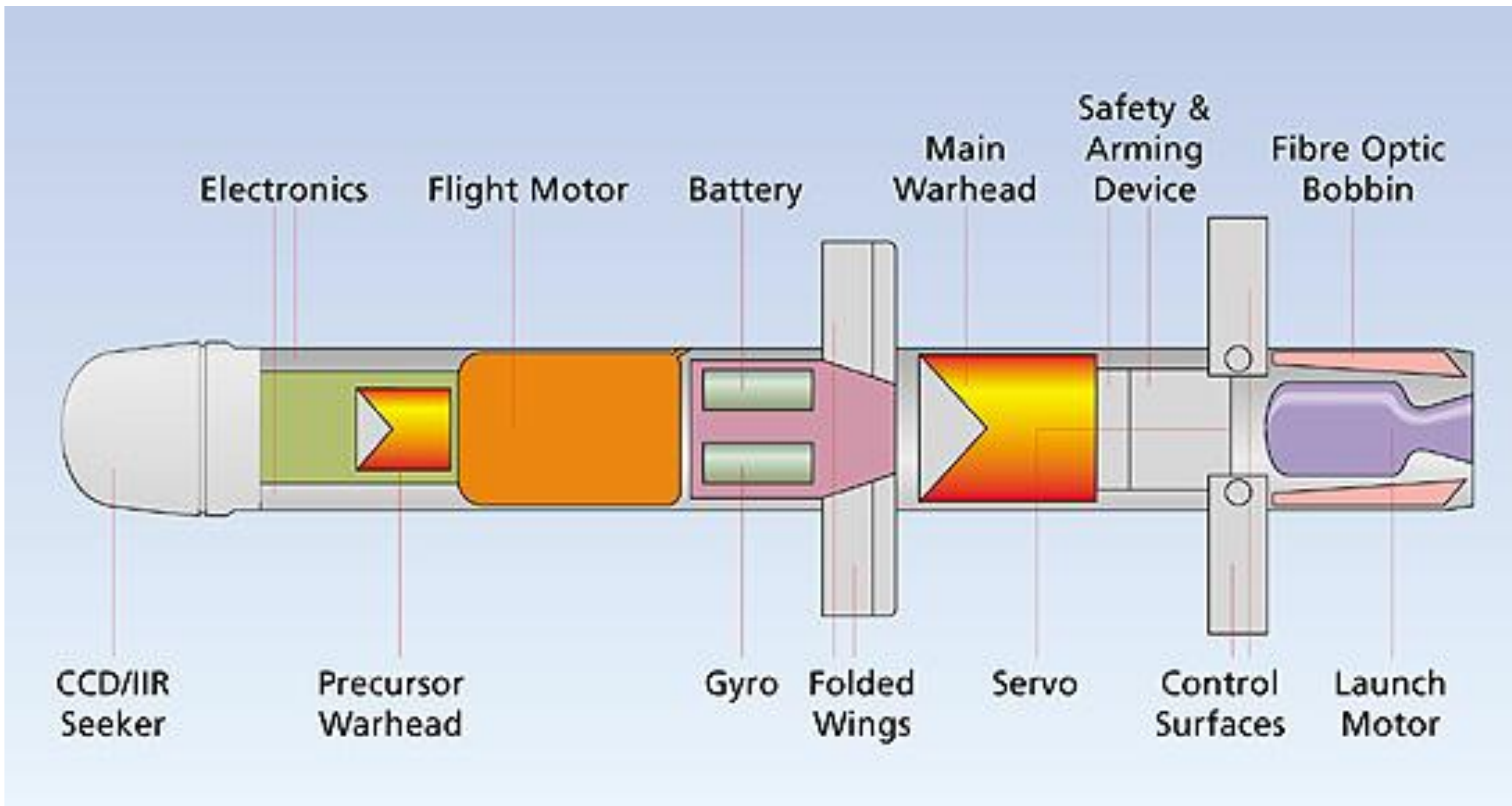
http://code.google.com/p/smhasher/wiki/MurmurHash

MurmurHash3

“successor to MurmurHash2”

Oracle & OpenJDK, Rubinius

1. Theory



Electronics
Flight Motor
Battery
Main Warhead
Safety & Arming Device
Fibre Optic Bobbin
CCD/IIR Seeker
Precursor Warhead
Gyro
Folded Wings
Servo
Control Surfaces
Launch Motor

MurmurHash2, 64 bit CRuby

```
const uint64_t m = (0xc6a4a793 << 32) | 0x5bd1e995;
uint64_t h = seed ^ len;

while (len >= 8) {

  uint64_t k = *(uint64_t*)data;

  k *= m;
  k ^= k >> 24;
  k *= m;

  h *= m;
  h ^= k;

  data += 8;
  len -= 8;
}
```

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const uint64_t m = (0xc6a4a793 << 32) | 0x5bd1e995;
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   k *= m;
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   k *= m;

   h *= m;
   h ^= k;

   data += 8;
   len -= 8;
}
```

block processing independent of seed

```
…
/* finalization */

switch (len) {

    case 7: h ^= data[6] << 48;
    case 6: h ^= data[5] << 40;
    case 5: h ^= data[4] << 32;
    case 4: h ^= data[3] << 24;
    case 3: h ^= data[2] << 16;
    case 2: h ^= data[1] << 8;
    case 1: h ^= data[0];
    h *= m;

};

…
```

8-byte-aligned data => skip finalization differential cryptanalysis

introduce a difference
in the state h via input k

cancel it again with
a second well-chosen difference

```
const uint64_t m = (0xc6a4a793 << 32) | 0x5bd1e995;
uint64_t h = seed ^ len;

while (len >= 8) {  /* first block */

   uint64_t k = *(uint64_t*)data;

   k *= m;              /* inject difference D1 */
   k ^= k >> 24;
   k *= m;

   h *= m;
   h ^= k;

   data += 8;
   len -= 8;

}
```

```
const uint64_t m = (0xc6a4a793 << 32) | 0x5bd1e995;
uint64_t h = seed ^ len;

while (len >= 8) {  /* first block */

  uint64_t k = *(uint64_t*)data;

  k *= m;                /* inject difference D1 */
  k ^= k >> 24;
  k *= m;                /* diff in k: 0x8000000000000000 */

  h *= m;
  h ^= k;

  data += 8;
  len -= 8;
}
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const uint64_t m = (0xc6a4a793 << 32) | 0x5bd1e995;
uint64_t h = seed ^ len;

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   k *= m;               /* inject difference D1 */
   k ^= k >> 24;
   k *= m;               /* diff in k: 0x8000000000000000 */

   h *= m;
   h ^= k;               /* diff in h: 0x8000000000000000 */

   data += 8;
   len -= 8;
}
```

```
const uint64_t m = (0xc6a4a793 << 32) | 0x5bd1e995;
uint64_t h = seed ^ len;

while (len >= 8) {  /* second block */

   uint64_t k = *(uint64_t*)data;

   k *= m;                /* inject difference D2 */
   k ^= k >> 24;
   k *= m;                /* diff in k: 0x8000000000000000 */

   h *= m;
   h ^= k;

   data += 8;
   len -= 8;

}
```

```c
const uint64_t m = (0xc6a4a793 << 32) | 0x5bd1e995;
uint64_t h = seed ^ len;

while (len >= 8) {  /* second block */

   uint64_t k = *(uint64_t*)data;

   k *= m;              /* inject difference D2 */
   k ^= k >> 24;
   k *= m;              /* diff in k: 0x8000000000000000 */

   h *= m;              /* diff in h still: 0x8000000000000000 */
   h ^= k;

   data += 8;
   len -= 8;
}
```

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const uint64_t m = (0xc6a4a793 << 32) | 0x5bd1e995;
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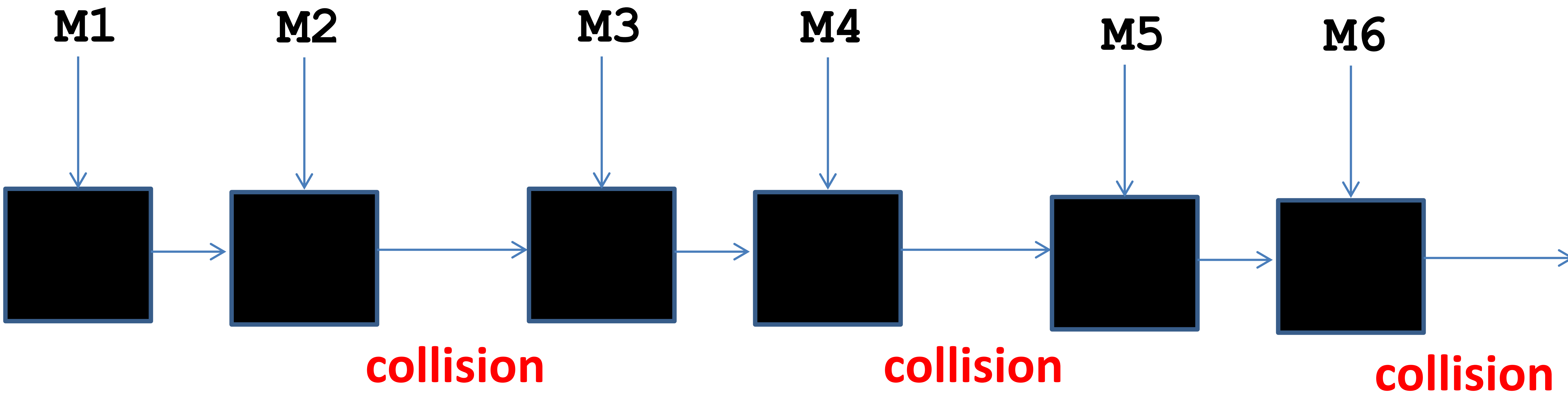
   k *= m;             /* inject difference D2 */
   k ^= k >> 24;
   k *= m;             /* diff in k: 0x8000000000000000 */

   h *= m;             /* diff in h still: 0x8000000000000000 */
   h ^= k;             /* COLLISION !!!
                          (0x80... ^ 0x80... = 0) */

   data += 8;
   len -= 8;

}
```



chain collisions ⇒ multicollisions

16n bytes ⇒ 2^n colliding inputs

multicollision works for any seed

⇒ "universal" multicollisions

same principle

slightly more complicated for

MurmurHash3

consequence

systems using MurmurHash2/3
remain
vulnerable to hash-flooding

2. Practice

Breaking Murmur:

we‘ve got the recipe –

now all we need is the (hash) cake

where are hashes used?

parser symbol tables
method lookup tables
attributes / instance variables
ip addresses
transaction ids
database indexing
session ids
http headers
json representation
url-encoded post form data
deduplication (HashSet)
A* search algorithm
dictionaries

...

=› where aren’t they used?

just recently

hash-DoS in btrfs file system (!)

http://crypto.junod.info/2012/12/13/hash-dos-and-btrfs/

can’t we use something different?

we could

but amortized constant time
is just too sexy

possible real-life attacks

need a high-profile target

web application

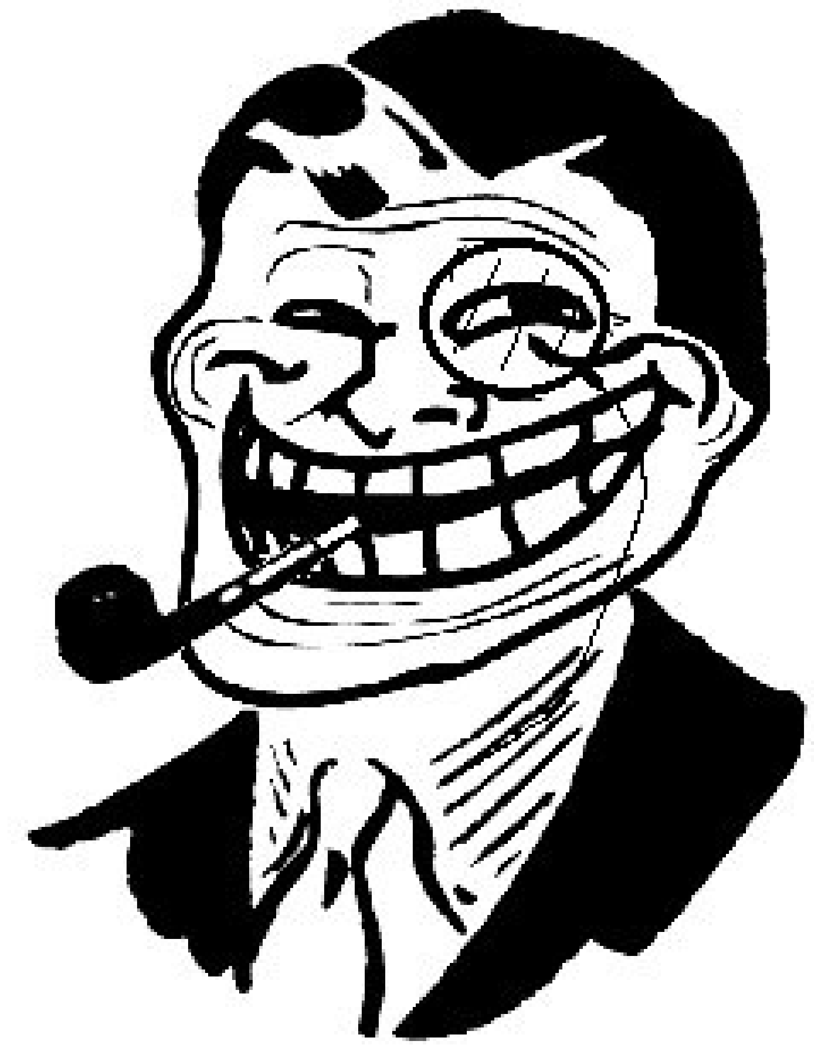
example #1

rails

first

attacking MurmurHash in ruby

apply the **recipe**



le demo

should work with rails

out of the box, no?

unfortunately, no

```ruby
def parse_nested_query(qs, d = nil)

  params = KeySpaceConstrainedParams.new

  (qs || '').split(d ? /[#{d}] */n : DEFAULT_SEP).each do |p|

    k, v = p.split('=', 2).map { |s| unescape(s) }
    normalize_params(params, k, v)

  end

  return params.to_params_hash

end
```

```ruby
def unescape(s, encoding = Encoding::UTF_8)
  URI.decode_www_form_component(s, encoding)
end
```

```ruby
def self.decode_www_form_component(str, enc=Encoding::UTF_8)
  raise ArgumentError, "invalid %-encoding (#{str})"
      unless /\A[^%]*(?:%\h\h[^%]*)*\z/ =~ str
  str.gsub(/\+|%\h\h/, TBLDECWWWCOMP_).force_encoding(enc)
end
```

```
/\A[^%]*(?:%\h\h[^%]*)*\z/
```

???

catches **invalid % encodings**

(e.g. %ZV, %%1 instead of %2F)

```ruby
def parse_nested_query(qs, d = nil)

  params = KeySpaceConstrainedParams.new

  (qs || '').split(d ? /[#{d}] */n : DEFAULT_SEP).each do |p|

    k, v = p.split('=', 2).map { |s| unescape(s) }
    normalize_params(params, k, v)

  end

  return params.to_params_hash

end
```

```ruby
def normalize_params(params, name, v = nil)
  name =~ %r(\A[\[\]]*([^\[\]]+)\]*)
  k = $1 || ''
  …
end
```

```
%r(\A[\[\]]*([^\[\]]+)\]*)
```

???

helps transform [[]] to []

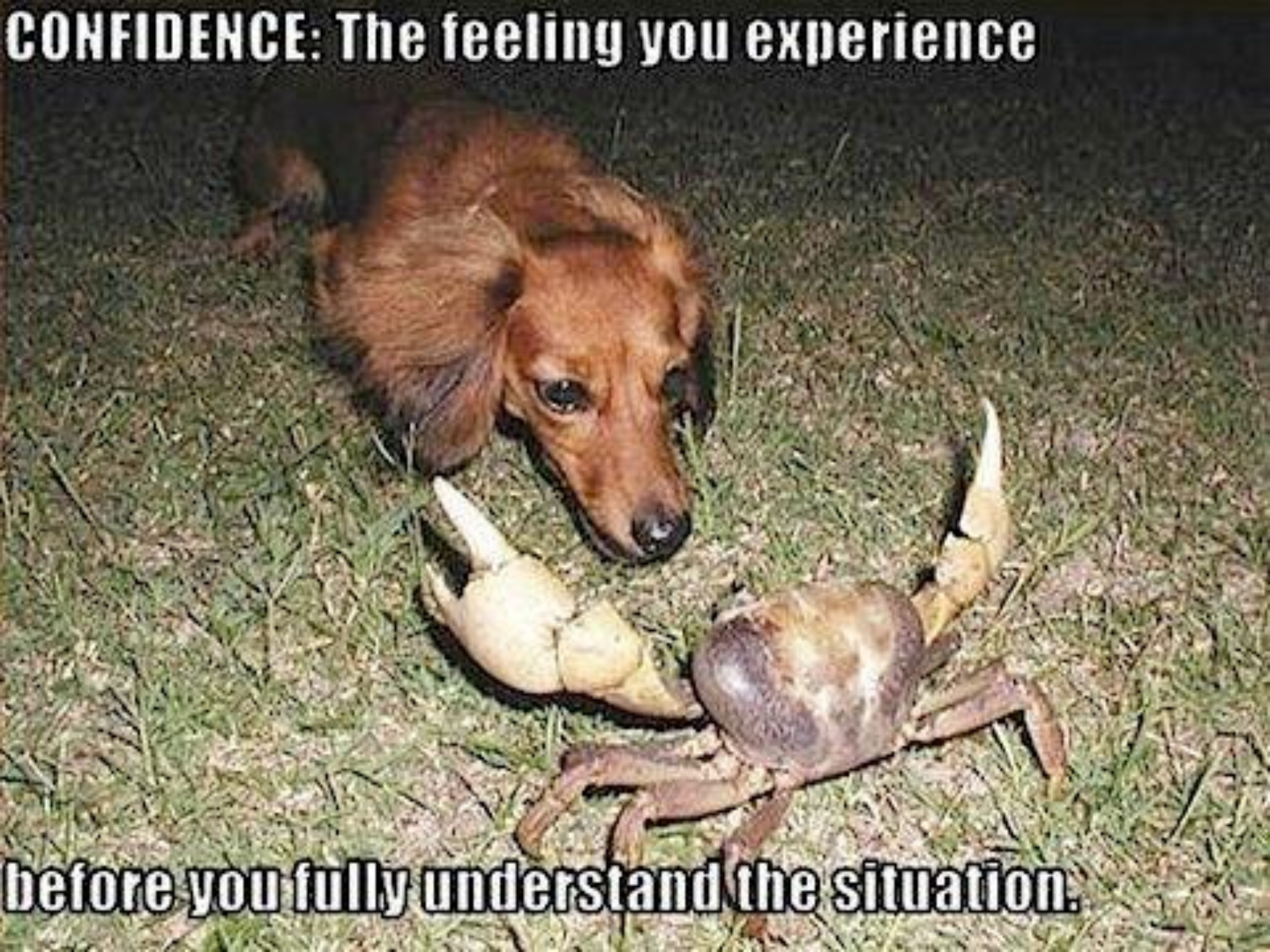
idea

pre-generate matching values

create random values

passing the regular expressions

that should do it, right?


CONFIDENCE: The feeling you experience
before you fully understand the situation.

```ruby
def parse_nested_query(qs, d = nil)
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  (qs || '').split(d ? /[#{d}] */n : DEFAULT_SEP).each do |p|
    k, v = p.split('=', 2).map { |s| unescape(s) }
    normalize_params(params, k, v)
  end
  return params.to_params_hash
end
```
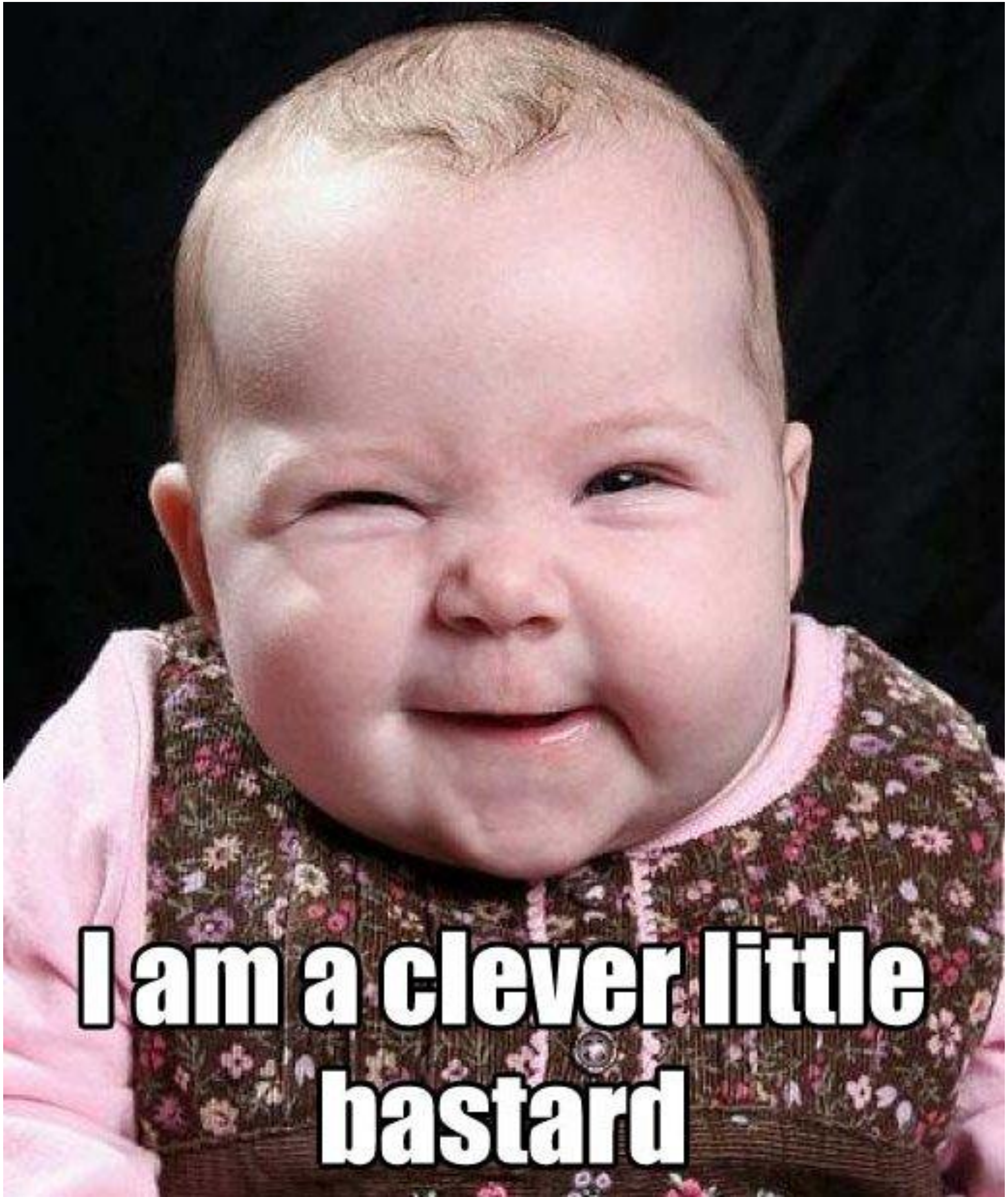

```ruby
class KeySpaceConstrainedParams

  def []=(key, value)

    @size += key.size if key && !@params.key?(key)

    raise RangeError, 'exceeded available parameter key space‘
        if @size > @limit

    @params[key] = value

  end

end
```


I am a clever little
bastard

what now? rails is safe?

remember:

hashes are used everywhere

so if

application/x-www-form-urlencoded

doesn’t work, how about

application/json

?

again, with the encoding...

fast-forward...

le demo

conclusion

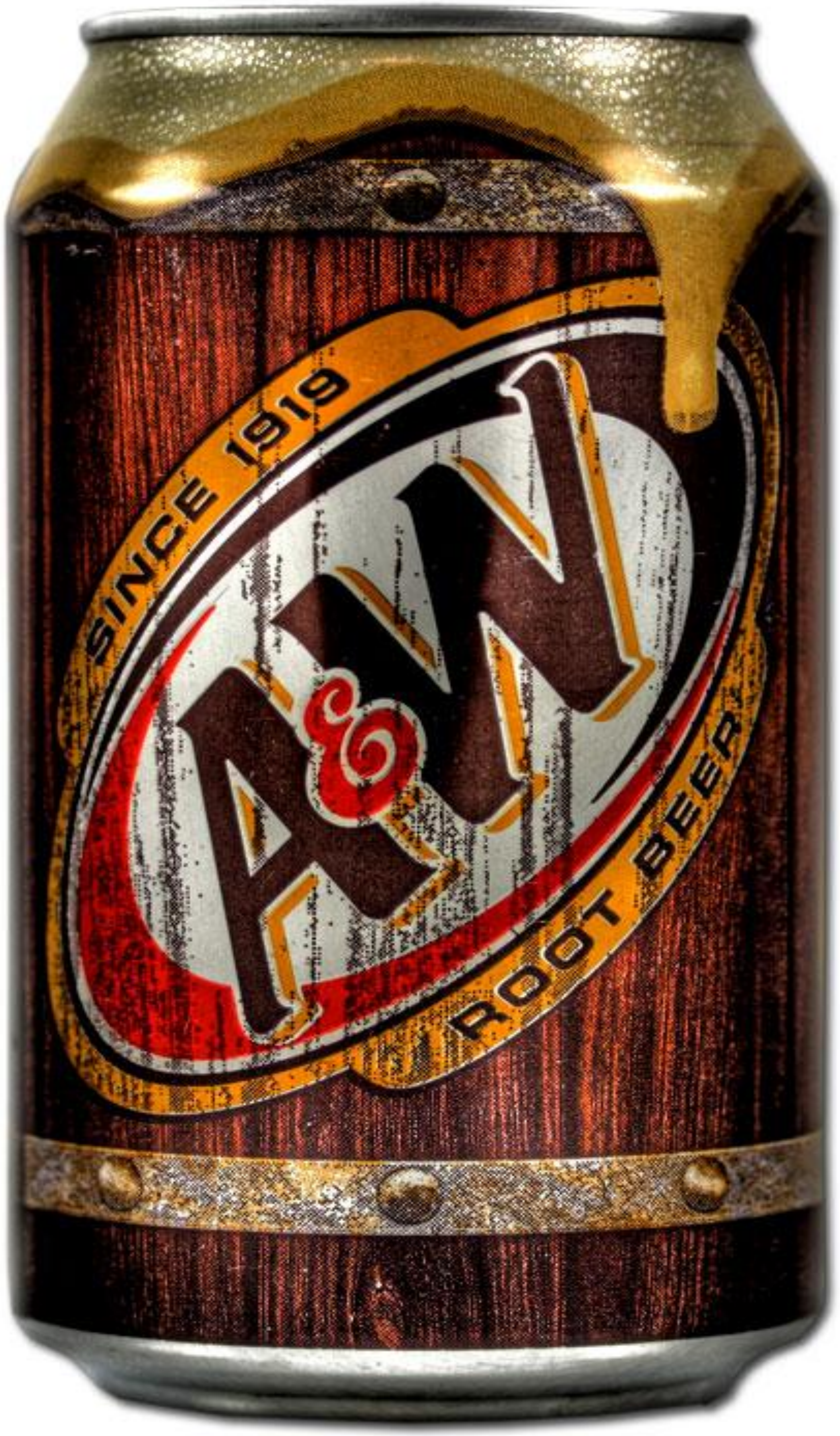
patchwork is not helping

too many places

code bloat

yet another loophole will be found

Fix it



at the

root

example #2

java, enterprise™ edition

just apply the recipe (?)

String(byte[] bytes)

```
public String(byte bytes[], int offset, int length,
                 Charset charset) {
  …

  char[] v = StringCoding.decode(charset, bytes, offset, length);

  …
}
```

problem, byte[] ?

tough nut to crack

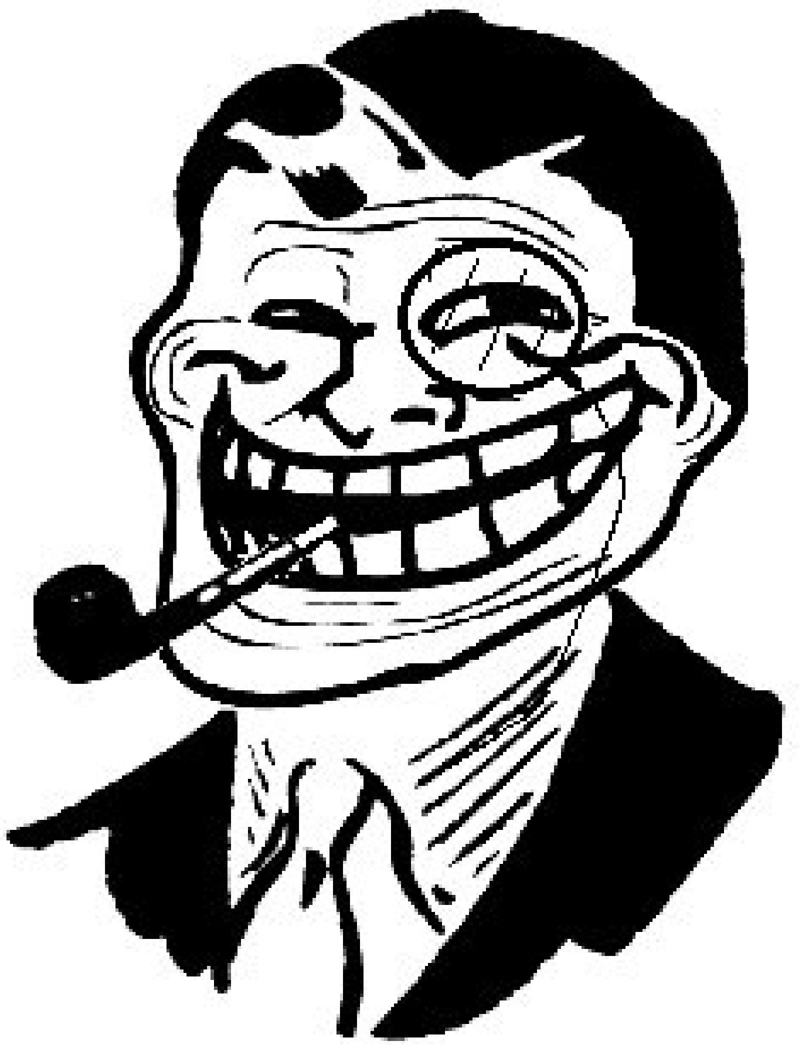
what now? java is safe?

String(char[] value)

```java
public String(char value[]) {

    int size = value.length;
    this.offset = 0;
    this.count = size;
    this.value = Arrays.copyOf(value, size);

}
```

no decoding!

substitute byte[] operations
with equivalent operations
on char[]



le demo

disclosure

oracle (java): sep 11

cruby, jruby, rubinius: aug 30

oCERT advisory

CVEs were assigned

http://www.ocert.org/advisories/ocert-2012-001.html more:

http://emboss.github.com/blog

code:

https://github.com/emboss/schadcode

reactions

java

...

ruby

cruby && jruby && rubinius == fixed

=> true

http://www.ruby-lang.org/en/news/2012/11/09/ruby19-hashdos-cve-2012-5371/

http://jruby.org/2012/12/03/jruby-1-7-1.html

https://github.com/rubinius/rubinius/commit/a9a40fc6a1256bcf6382631b710430105c5dd868 they did a fantastic job

(like last year)

so what was the fix?

how can we fix this?

WAIT

I'll fix it

Don’t use MurmurHash

CityHash?

“Inside Google, where CityHash was developed starting in 2010, we use variants of CityHash64() mainly in hash tables such as `hash_map<string, int>`.”

https://code.google.com/p/cityhash/

CityHash is weaker than MurmurHash

```
CityHash64( 0Y|L&:$;+[&HASH!, 16 )      = b553de6f34e878f
CityHash64( JkMR_ 0\7](HASH!, 16 )      = b553de6f34e878f
CityHash64( <jiI7g;s,`(HASH!, 16 )      = b553de6f34e878f
CityHash64( e: yn"sg^a(HASH!, 16 )      = b553de6f34e878f
CityHash64( dt6PG8}?oz(HASH!, 16 )      = b553de6f34e878f
CityHash64( 8c-lkD%_Eo)HASH!, 16 )      = b553de6f34e878f
CityHash64( TdIx>DnK-1*HASH!, 16 )      = b553de6f34e878f
CityHash64( iM:9l=S"|e*HASH!, 16 )      = b553de6f34e878f
CityHash64( Z,r_|5xM0l*HASH!, 16 )      = b553de6f34e878f
CityHash64( .QH~S!9P(p*HASH!, 16 )      = b553de6f34e878f
CityHash64( {pF*"wkd[F+HASH!, 16 )      = b553de6f34e878f
CityHash64( i< @)`oy+?,HASH!, 16 )      = b553de6f34e878f
CityHash64( BU9[85WWp/ HASH!, 16 )      = b553de6f34e878f
CityHash64( 8{YDLn;d.2 HASH!, 16 )      = b553de6f34e878f
CityHash64( d+nkK&t?yr HASH!, 16 )      = b553de6f34e878f
CityHash64( {A.#v5i]V{ HASH!, 16 )      = b553de6f34e878f
```

Python's hash()?

```
$ python -V
Python 2.7.3
$ time -p python -R poc.py
64 candidate solutions
Verified solutions for
_Py_HashSecret:
145cc9aade7d2453 275daf6070a41b99
945cc9aade7d2453 a75daf6070a41b99
real 0.32
user 0.17
sys 0.02
```

Python 2.x and 3.x

- Randomization of hash() optional (-R)
- Instantaneous key recovery
- Multicollisions with TMTO

.NET's Marvin32?

Something designed to be secure?

SipHash: a fast short-input PRF

New keyed hash to fix hash-flooding:

- Rigorous security requirements and analysis
- Speed competitive with that of weak hashes
- Can serve as MAC or PRF

Peer-reviewed research paper (A., Bernstein).
published at DIAC 2012, INDOCRYPT 2012

SipHash initialization

256-bit state v0 v1 v2 v3

128-bit key k0 k1

$v0 = k0 \oplus 0x736f6d6570736575$

$v1 = k1 \oplus 0x646f72616e646f6d$

$v2 = k0 \oplus 0x6c7967656e657261$

$v3 = k1 \oplus 0x7465646279746573$

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 ⊕= **m1**

c iterations of SipRound

v0 ⊕= **m1**

SipHash compression

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

v3 $\oplus$= **m2**

c iterations of SipRound

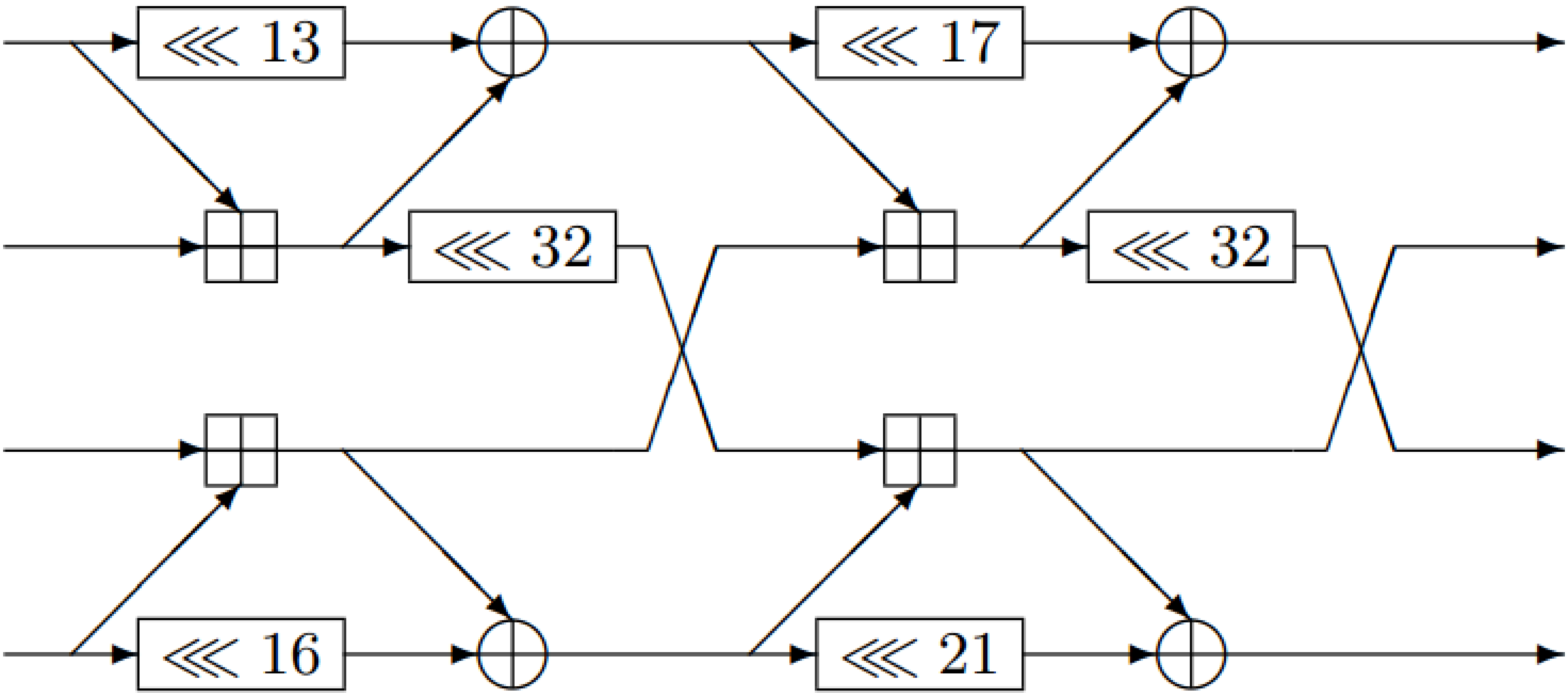
v0 $\oplus$= **m2**

SipHash compression

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

Etc.

SipRound



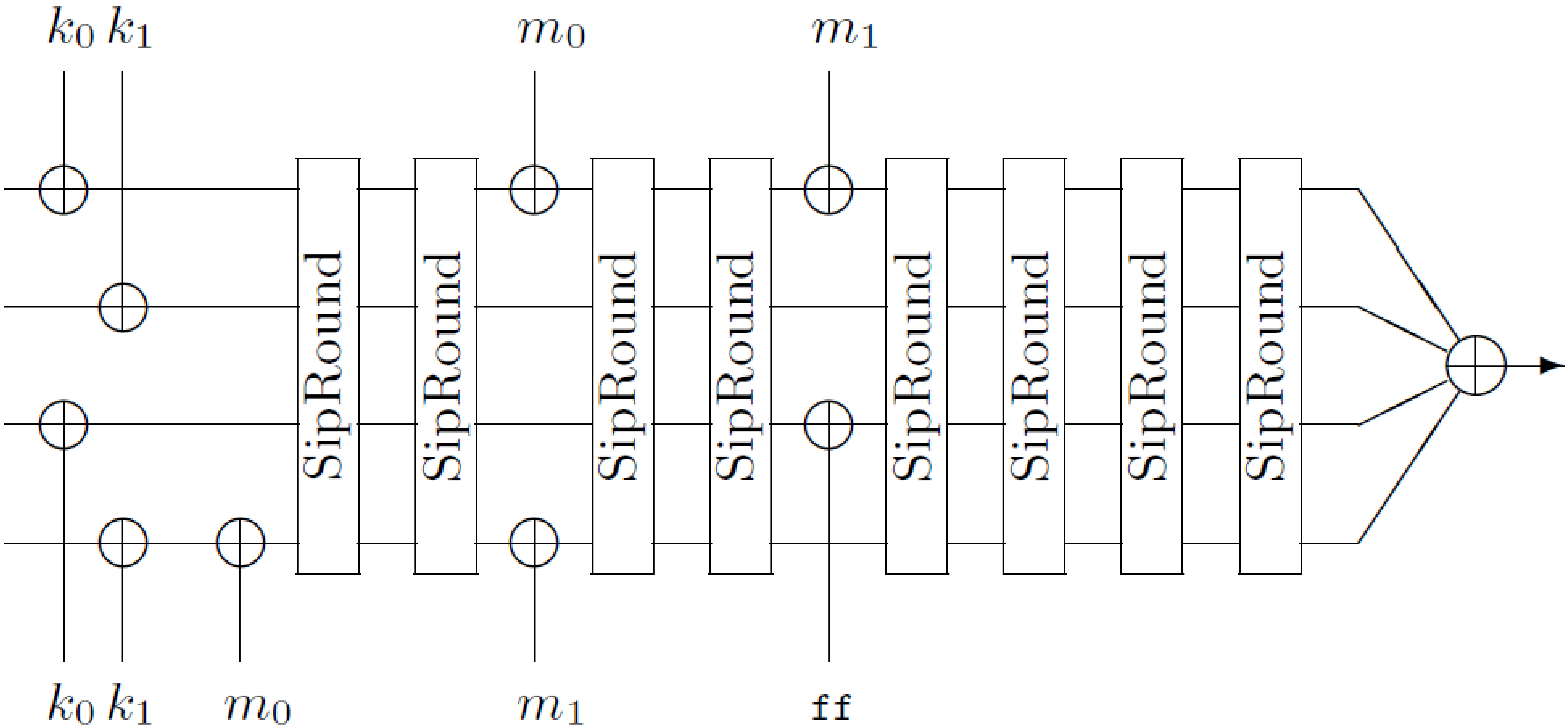
SipHash finalization

$v2 \oplus= 255$

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.

Security claims

$\approx 2^{128}$ key recovery

$\approx 2^{192}$ state recovery

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

$\approx 2^{s}$ forgery with probab. 2^{s-64}

Fast diffusion of differences, thanks to optimized rotation counts

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

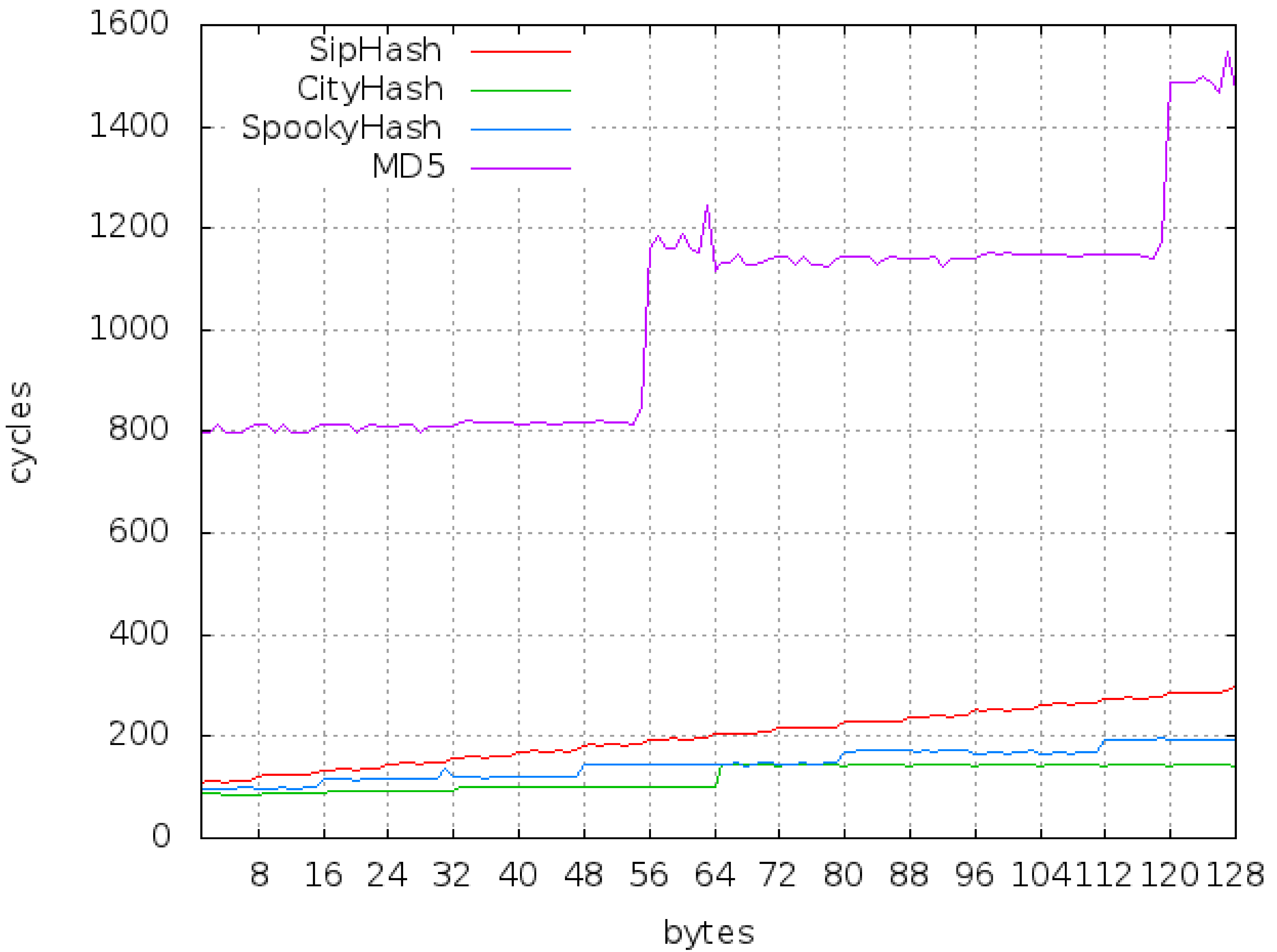
Combination of ADD and XOR ensures a high nonlinearity (e.g. against cube attacks)

How fast is SipHash-2-4?

On an old AMD Athlon II Neo (@1.6GHz)

Bytes	8	16	32	64
Cycles (per byte)	123 (15.38)	134 (8.38)	158 (4.25)	204 (3.19)
MiBps	99	182	359	478

Long messages: **1.44** cycles/byte (**1 GiBps**)


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

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); **Perl6** (Julin)

Who is using SipHash?

OpenDNS

Perl 5

Rust

CRuby

redis

JRuby

Rubinius

Soon:

Take home message

Hash-flooding DoS works by enforcing worst case in data structure operations through large multicollisions in the hash function

Java and Rubies found vulnerable, due to their use of MurmurHash v2 or v3

CityHash and Python’s hash are weak too…

SipHash offers both security and performance

SipHash paper, code, etc. available on

https://131002.net/siphash

Attacks paper coming soon...