Hash-flooding DoS reloaded: attacks and defenses

Jean-Philippe Aumasson, Kudelski Group
Daniel J. Bernstein, University of Illinois at Chicago
Martin Boßlet, freelancer

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Jean-Philippe

Cryptography expert at the Kudelski Group

Applied crypto researcher

https://131002.net   @aumasson

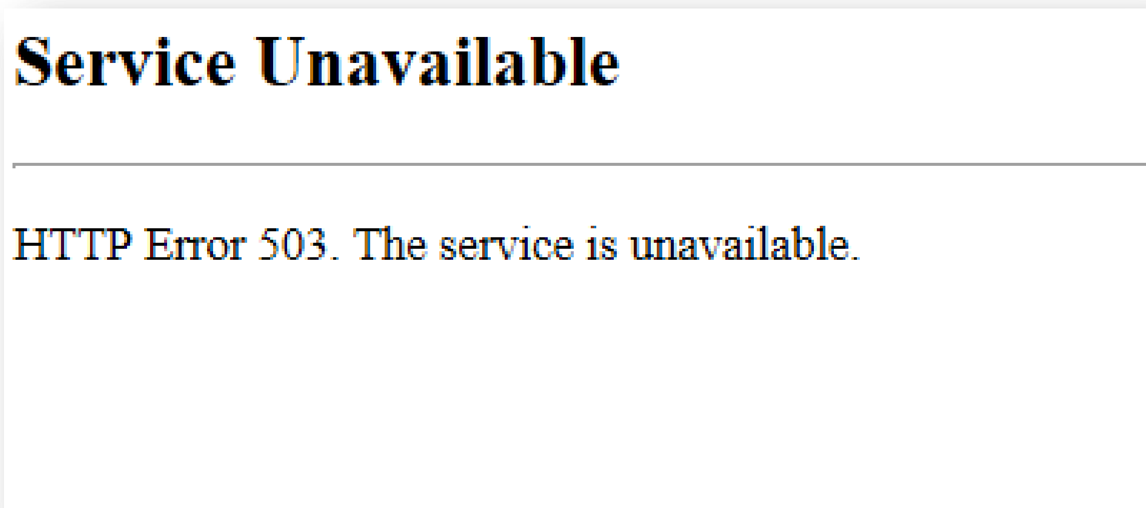
Martin

Independent SW engineer and security expert

Ruby core dev team member

http://www.martinbosslet.de @_emboss_

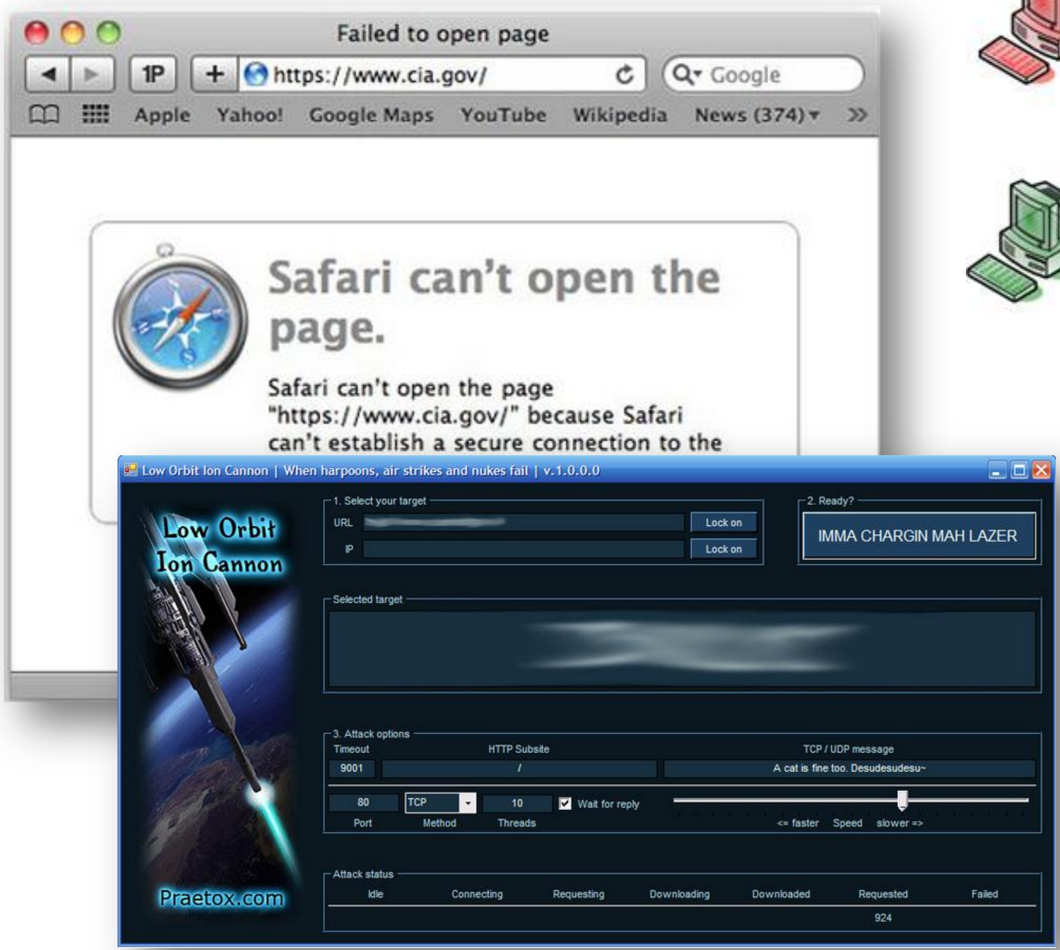
Hash-flooding DoS reloaded: attacks and defenses

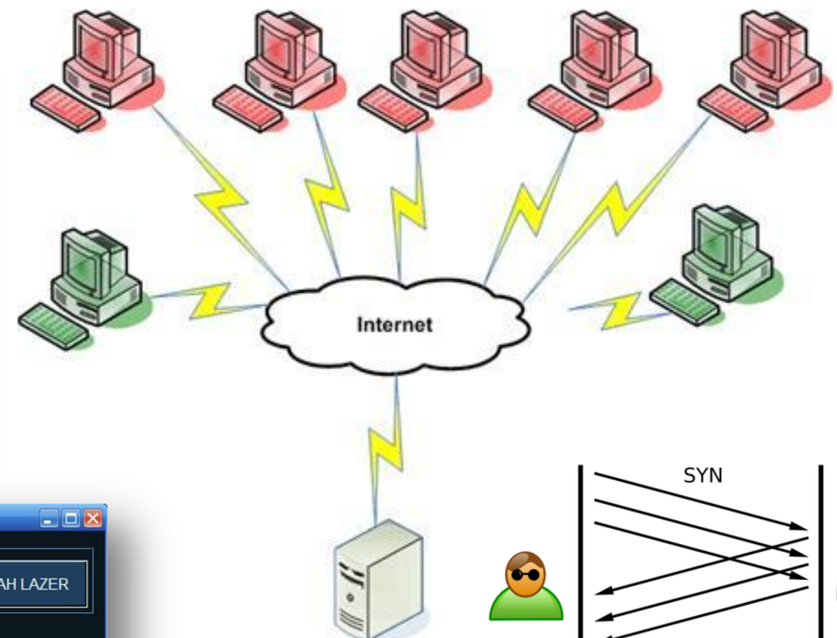


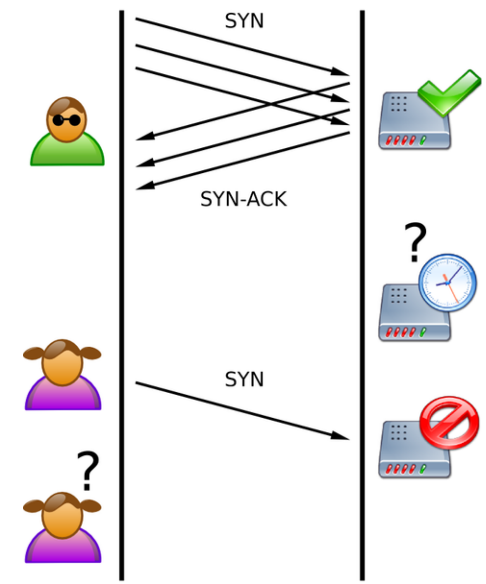
Denial-of-Service (DoS) attacks

"Attempt to make a machine or network resource unavailable to its intended users."
Wikipedia

Popular DoS techniques are distributed HTTP or TCP SYN flood... (DDoS)







More subtle techniques exploit properties of TCP-congestion-avoidance algorithms…

Low-Rate TCP-Targeted Denial of Service Attacks and Counter Strategies

Aleksandar Kuzmanovic and Edward W. Knightly

Hash-flooding DoS reloaded: attacks and defenses

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

  return 0;
}
```

Hash tables used in many applications to maintain an association between objects

Example: Python dictionaries

```
d={}                          # empty table
d[12345]=0xc                  # insertion
d['astring']='foo'            # insertion
d[('a','tuple')]=0            # insertion
print  d['a string']          # lookup
```

If the table is about as large as the number of elements to be stored (=n), insertion or lookup of n elements takes

O(n) operations on average

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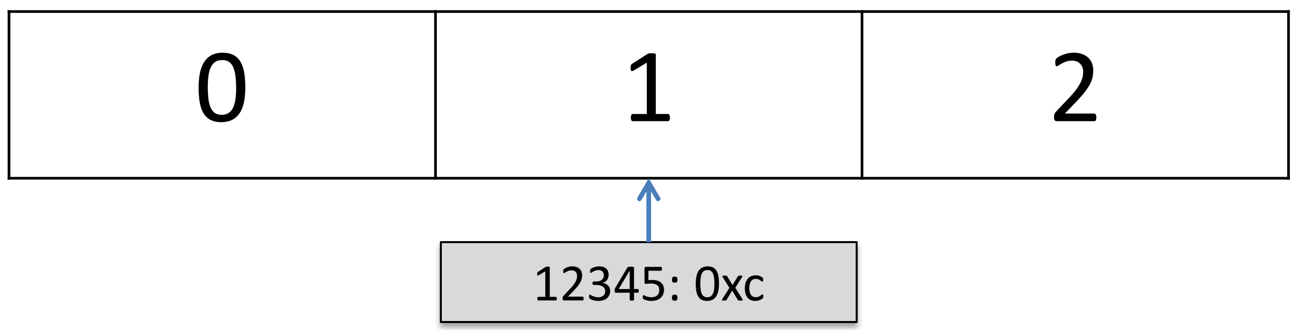
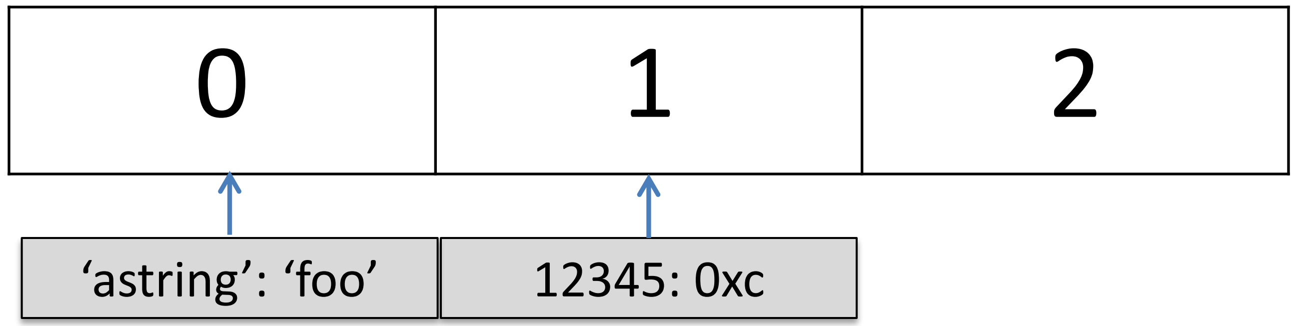


`d[12345]=0xc, hash(12345)=1`

If the table is about as large as the number of elements to be stored (=n), insertion or lookup of n elements takes

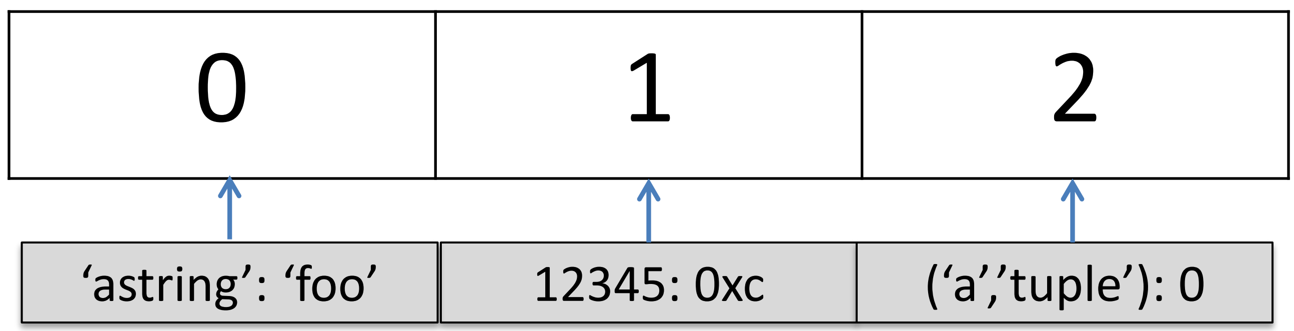
O(n) operations on average



`d[‘astring’]=‘foo’ , hash(‘astring’)=0`

If the table is about as large as the number of elements to be stored (=n), insertion or lookup of n elements takes

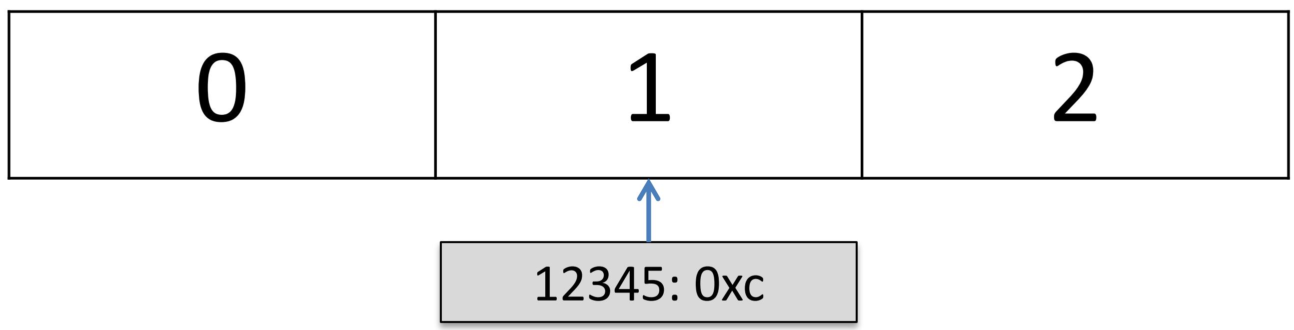
O(n) operations on average




```
d[(‘a’,’tuple’)=0; hash((‘a’,’tuple’))=2
```

If the table is about as large as the number of elements to be stored (=n), insertion or lookup of n elements takes

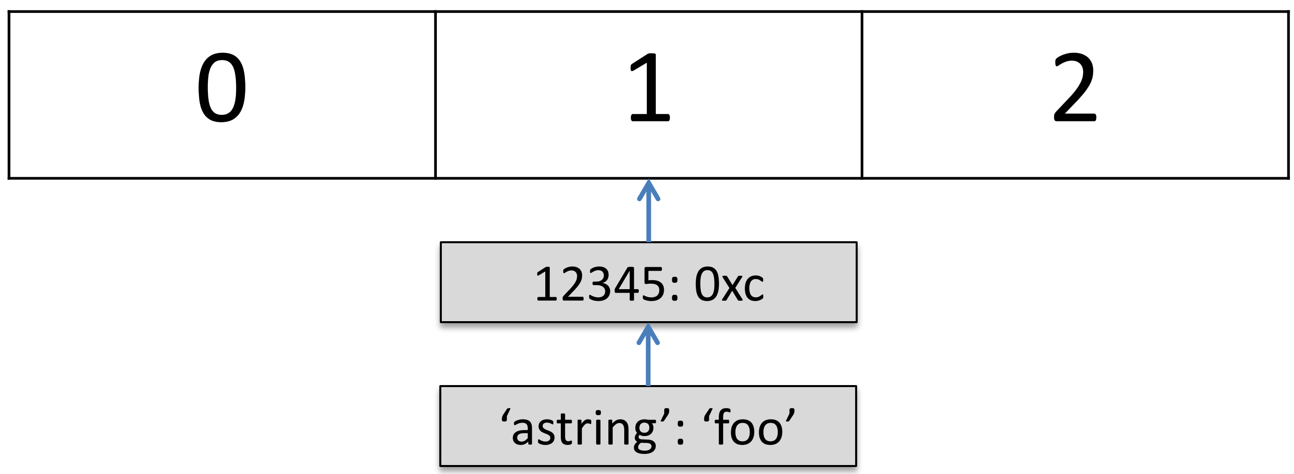
O(n^2) operations in the worst case



`d[12345]=0xc, hash(12345)=1`

If the table is about as large as the number of elements to be stored (=n), insertion or lookup of n elements takes

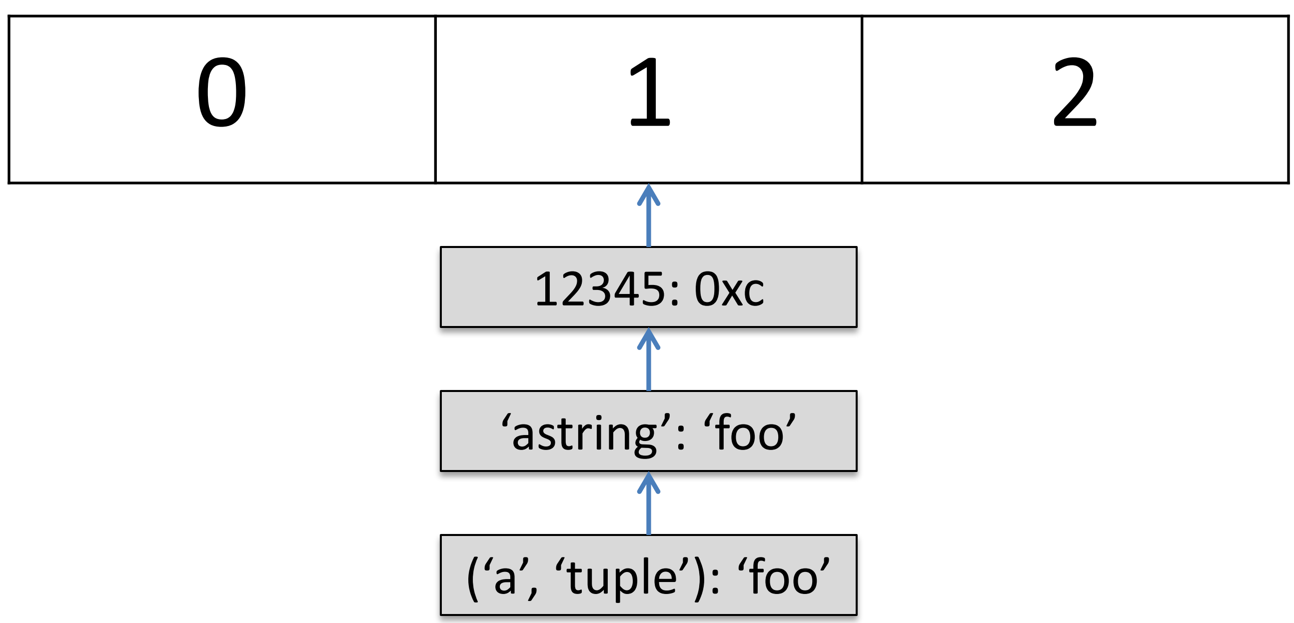
O(n^2) operations in the worst case




```
d[‘astring’]=‘foo’ , hash(‘astring’)=0
```

If the table is about as large as the number of elements to be stored (=n), insertion or lookup of n elements takes

$O(n^2)$ operations in the worst case




```
d[(‘a’,’tuple’)=0; hash((‘a’,’tuple’))=2
```

Hash flooding:

Send to a server many inputs with a same hash (a *multicollision*) so as to enforce worst-case insert time send 2MB of POST data consisting of 200.000 colliding 10B strings

≈ 40.000.000.000 string comparisons (at least 10s on a 2GHz machine…)

Previous work

Crosby, Wallach. *Denial of Service via Algorithmic Complexity Attacks*, USENIX Security 2003

-> attack formalized and applied to Perl, Squid, etc.

Klink, Wälde. *Efficient Denial of Service Attacks on Web Application Platforms*. CCC 28c3

-> application to PHP, Java, Python, Ruby, etc.

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-> application to PHP, Java, Python, Ruby, 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

Tracking IDs: oCERT-2011-003
CERT VU#903934

Patches released consisting of a stronger hash with randomization (to make colliding values impossible to find)

MurmurHash2

“used in code by Google, Microsoft, Yahoo, and many others”

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

CRuby, JRuby

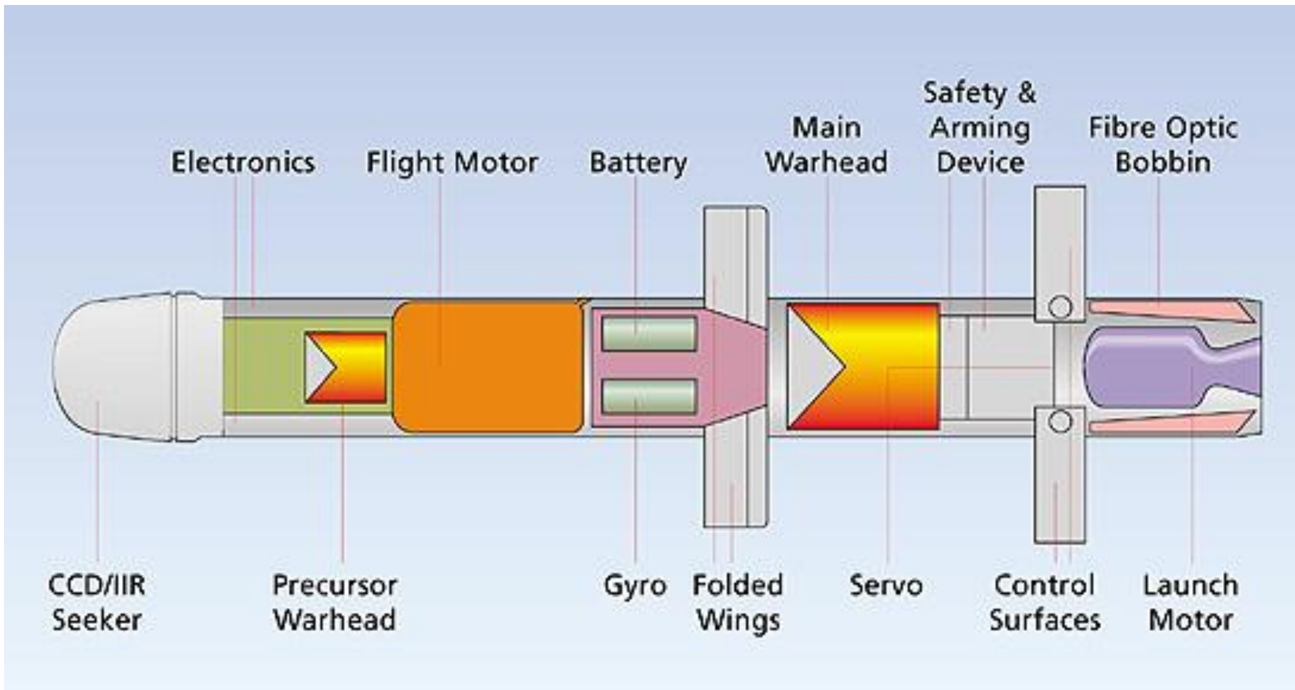
MurmurHash3

“successor to MurmurHash2”

Oracle’s **Java SE, Rubinius**

Hash-flooding DoS reloaded: attacks and defenses

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

MurmurHash3 core

Processes the input per blocks of 4 bytes

```
for (i=0;i<nblocks;i++) {
    uint32_t k1 = getblock(blocks, i);
    k1 *= 0xcc9e2d51 ;
    k1 = ROTL32(k1 ,15);
    k1 *= 0x1b873593;

    h1 ^= k1;
    h1 = ROTL32 ( h1 ,13);
    h1 = h1 *5+0 xe6546b64;}
```

Differential cryptanalysis strategy

1/ introduce a difference in the state `h1` via the input `k1`

2/ cancel this difference with a second well chosen difference

```
for (i=0;i<nblocks;i++) {
    uint32_t k1 = getblock(blocks, i);
    k1 *= 0xcc9e2d51 ;
    k1 = ROTL32(k1 ,15);
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    h1 ^= k1;
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```

Differential cryptanalysis strategy

1/ introduce a difference in the state `h1` via the input `k1`

2/ cancel this difference with a second well chosen difference

```
for (i=0;i<nblocks;i++) {    i=0
    uint32_t k1 = getblock(blocks, i);
    k1 *= 0xcc9e2d51 ;    inject difference D1
    k1 = ROTL32(k1 ,15);
    k1 *= 0x1b873593;    diff in k1 : 0x00040000

    h1 ^= k1;
    h1 = ROTL32 ( h1 ,13);
    h1 = h1 *5+0 xe6546b64;}
```

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    k1 = ROTL32(k1 ,15);
    k1 *= 0x1b873593;            diff in k1 : 0x00040000

    h1 ^= k1;                    diff in h1  0x00040000
    h1 = ROTL32 ( h1 ,13);
    h1 = h1 *5+0 xe6546b64;}
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Differential cryptanalysis strategy

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    k1 *= 0x1b873593;

    h1 ^= k1;
    h1 = ROTL32 ( h1 ,13);
    h1 = h1 *5+0 xe6546b64;}
```

i=0

inject difference **D1**

diff in **k1** : **0x00040000**

diff in **h1** **0x00040000**

0x80000000

0x80000000

Differential cryptanalysis strategy

1/ introduce a difference in the state `h1` via the input `k1`

2/ cancel this difference with a second well chosen difference

```
for (i=0;i<nblocks;i++) {    i=1
    uint32_t k1 = getblock(blocks, i);
    k1 *= 0xcc9e2d51 ;    inject difference D2
    k1 = ROTL32(k1 ,15);
    k1 *= 0x1b873593;

    h1 ^= k1;
    h1 = ROTL32 ( h1 ,13);
    h1 = h1 *5+0 xe6546b64;}
```

Differential cryptanalysis strategy

1/ introduce a difference in the state `h1` via the input `k1`

2/ cancel this difference with a second well chosen difference

```
for (i=0;i<nblocks;i++) {    i=1
    uint32_t k1 = getblock(blocks, i);
    k1 *= 0xcc9e2d51 ;        inject difference D2
    k1 = ROTL32(k1 ,15);
    k1 *= 0x1b873593;         diff in k1 : 0x80000000

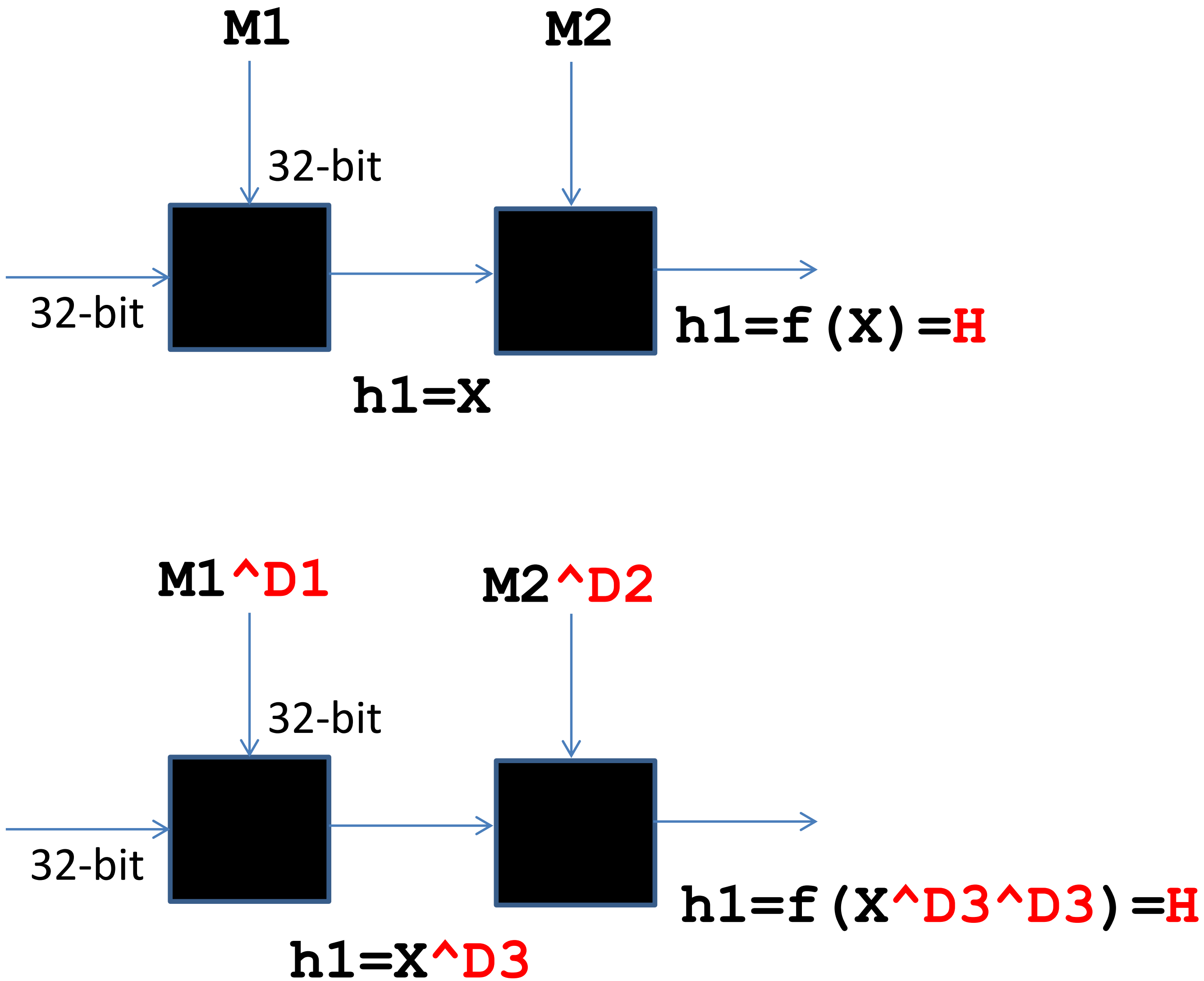
    h1 ^= k1;
    h1 = ROTL32 ( h1 ,13);
    h1 = h1 *5+0 xe6546b64;}
```

Differential cryptanalysis strategy

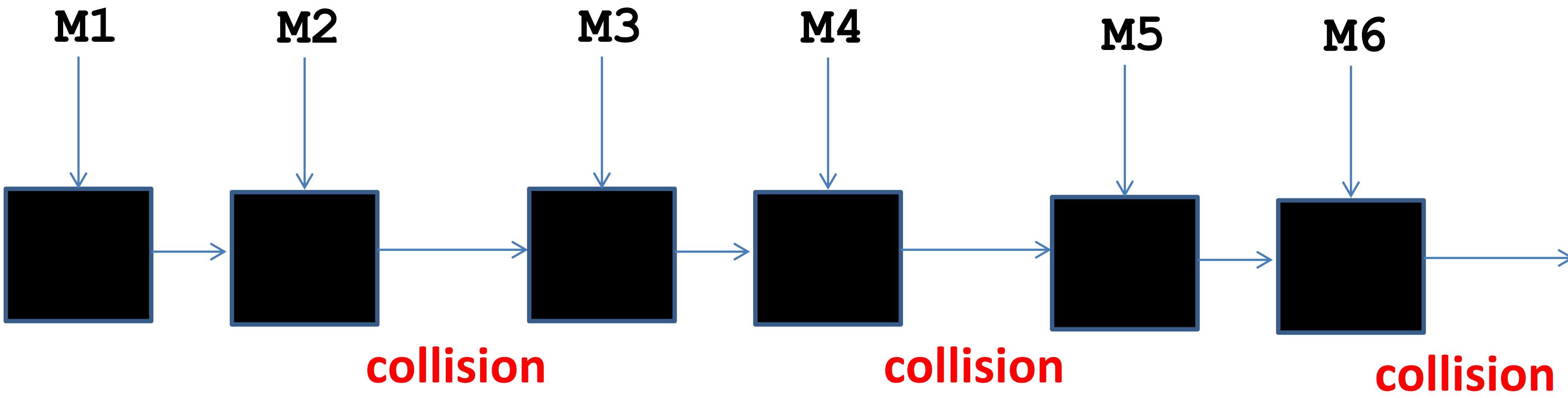
1/ introduce a difference in the state `h1` via the input `k1`

2/ cancel this difference with a second well chosen difference

```
for (i=0;i<nblocks;i++) {     i=1
    uint32_t k1 = getblock(blocks, i);
    k1 *= 0xcc9e2d51 ;     inject difference D2
    k1 = ROTL32(k1 ,15);
    k1 *= 0x1b873593;     diff in k1 : 0x80000000
    diff in h1 :  0x80000000 ^ 0x80000000 = 0
    h1 ^= k1;
    h1 = ROTL32 ( h1 ,13);     COLLISION!
    h1 = h1 *5+0 xe6546b64;}
```



2 colliding 8-byte inputs



Chain collisions => multicollisions

8n bytes => 2^n colliding inputs

A multicollision works for any seed

=> "Universal" multicollisions

```
h1=seed;
for (i=0;i<nblocks;i++) {
      uint32_t k1 = getblock(blocks, i);
      k1 *= 0xcc9e2d51 ;
      k1 = ROTL32(k1 ,15);
      k1 *= 0x1b873593;
      // transform of k1 independent of the seed!
      h1 ^= k1;
      h1 = ROTL32 ( h1 ,13);
      h1 = h1 *5+0 xe6546b64;}
```

Even simpler for MurmurHash2

Consequence:

Systems using MurmurHash2/3 remain vulnerable to hash-flooding

Other hash attacked

CityHash provides hash functions for strings. The latest stable version is cityhash-1.1.0.tar.gz. Differences between versions are explained in the NEWS file.

The functions mix the input bits thoroughly but are not suitable for cryptography. We provide reference implementations in C++, with a friendly MIT license. The code's portable; let us know if you encounter problems. To download the code use the .tar.gz file or use svn with these instructions.

The README contains a good explanation of the various CityHash functions. However, here is a short summary:

CityHash64() and similar return a 64-bit hash. Inside Google, where CityHash was developed starting in 2010, we use variants of CityHash64() mainly in hash tables such as hash_map<string, int>.

CityHash32() returns a 32-bit hash. It's mostly useful in 32-bit code (e.g., x86).

CityHash128() and similar return a 128-bit hash and are tuned for strings of at least a few hundred bytes. Depending on your compiler and hardware, it may be faster than CityHash64() on sufficiently long strings. It is known to be slower than necessary on shorter strings, but we expect that case to be relatively unimportant. Inside Google we use variants of CityHash128() mainly for code that wants to minimize collisions.

Even weaker than MurmurHash2…

Also vulnerable to hash flooding

```
CityHash64( BU9[85WWp/ HASH!, 16 ) = b82e7612e6933d2f
CityHash64( 8{YDLn;d.2 HASH!, 16 ) = b82e7612e6933d2f
CityHash64( d+nkK&t?yr HASH!, 16 ) = b82e7612e6933d2f
CityHash64( {A.#v5i]V{ HASH!, 16 ) = b82e7612e6933d2f
CityHash64( FBC=/\hJeA!HASH!, 16 ) = b82e7612e6933d2f
CityHash64( $03$=K1.-H!HASH!, 16 ) = b82e7612e6933d2f
CityHash64( 3o'L'Piw\\!HASH!, 16 ) = b82e7612e6933d2f
CityHash64( duDu%qaUS@"HASH!, 16 ) = b82e7612e6933d2f
CityHash64( IZVo|0S=BX"HASH!, 16 ) = b82e7612e6933d2f
CityHash64( X2V|P=<u,=#HASH!, 16 ) = b82e7612e6933d2f
CityHash64( 9<%45yG]qG#HASH!, 16 ) = b82e7612e6933d2f
CityHash64( 6?4O:'<Vho#HASH!, 16 ) = b82e7612e6933d2f
CityHash64( 2u 2}7g^>3$HASH!, 16 ) = b82e7612e6933d2f
CityHash64( kqwnZH=cKG$HASH!, 16 ) = b82e7612e6933d2f
CityHash64( Nl+:rtvw}K$HASH!, 16 ) = b82e7612e6933d2f
CityHash64( s/pI!<5u*]$HASH!, 16 ) = b82e7612e6933d2f
CityHash64( f|P~n*<xPc$HASH!, 16 ) = b82e7612e6933d2f
CityHash64( Cj7TCG|G}}$HASH!, 16 ) = b82e7612e6933d2f
CityHash64( a4$>Jf3PF'%HASH!, 16 ) = b82e7612e6933d2f
```

2. Practice

Breaking Murmur:

We‘ve got the recipe –

Now all we need is the (hash) cake

Where are hashes used?

Internally vs. Externally

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?

Can’t we use something different?

We could,

but amortized constant time is just too sexy

Possible real-life attacks

Attack internal use?

Elegant, but low impact

Need a high-profile target

Web Application

Example #1

Rails

First:

Attacking MurmurHash in Ruby

Straight-forward with a few quirks

Apply the recipe

Demo

Should work with Rails

out of the box, no?

Unfortunately, no

Demo

```
def POST
  …
  @env["rack.request.form_hash"] = parse_query(form_vars)
  …
end
```

```ruby
def parse_query(qs)
  Utils.parse_nested_query(qs)
end
```

```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)

```
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:

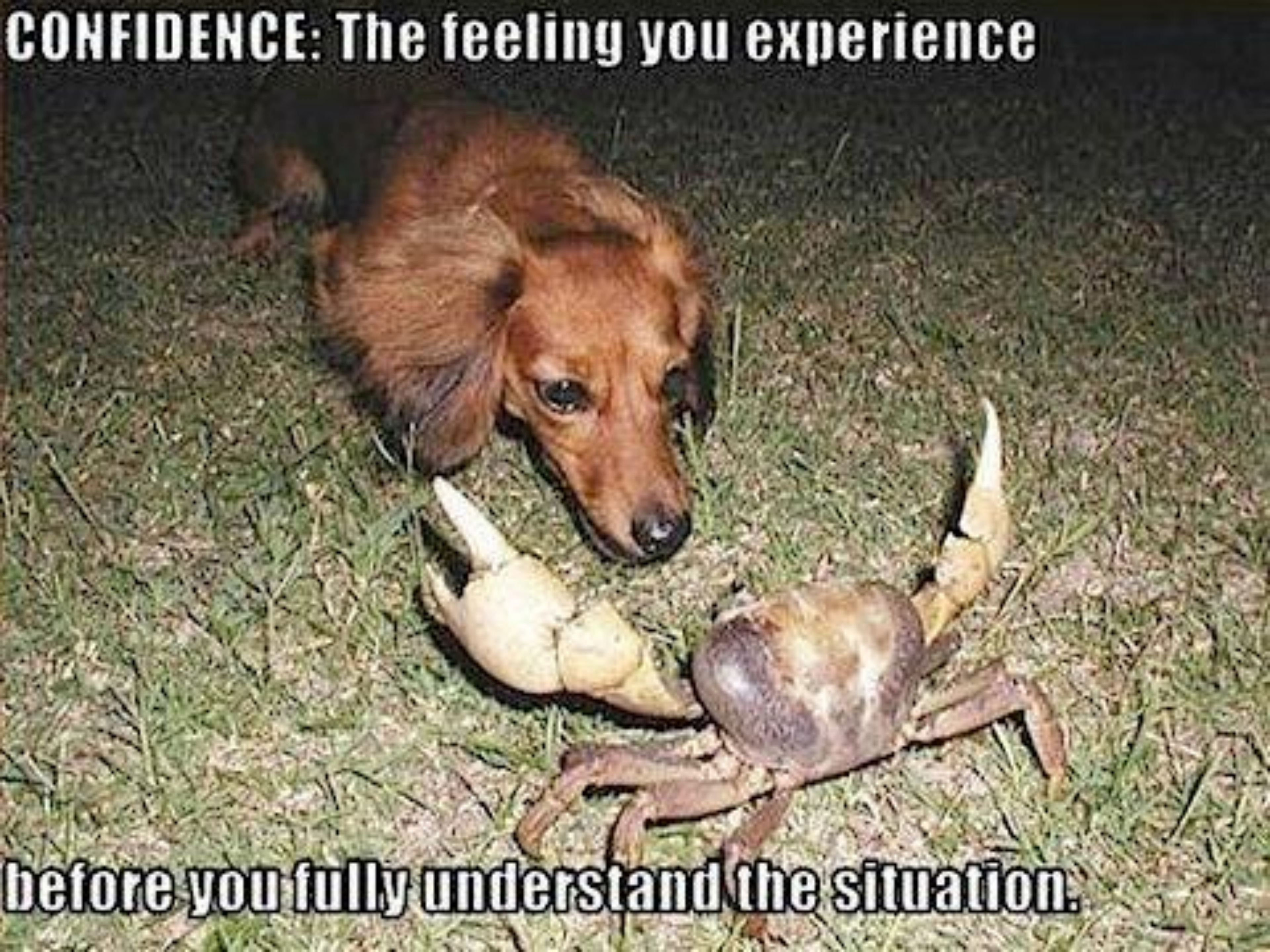
pre-generate matching values

create random values

passing the regular expressions

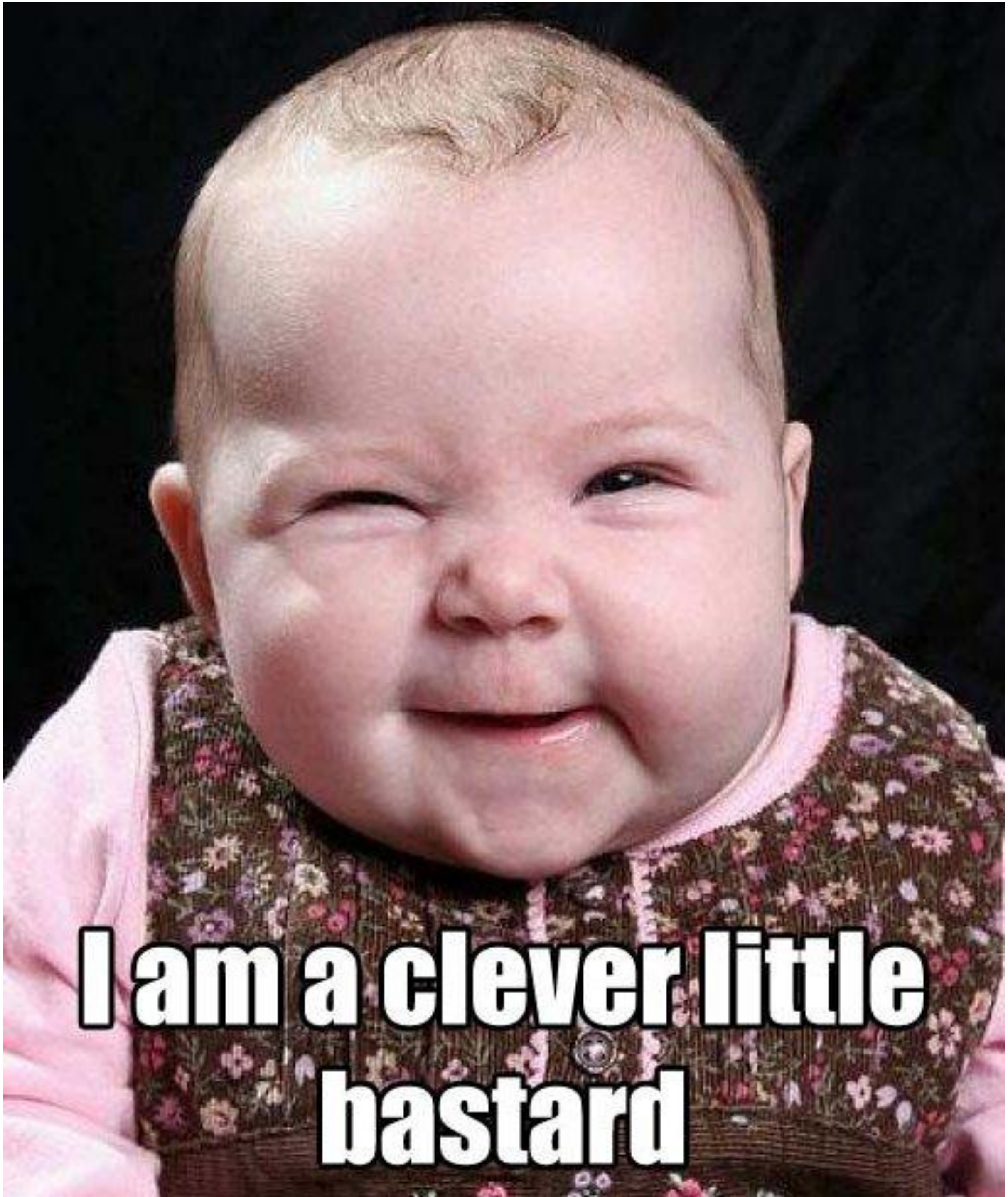
that should do it, right?

Demo


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

```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
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...

Demo

Conclusion

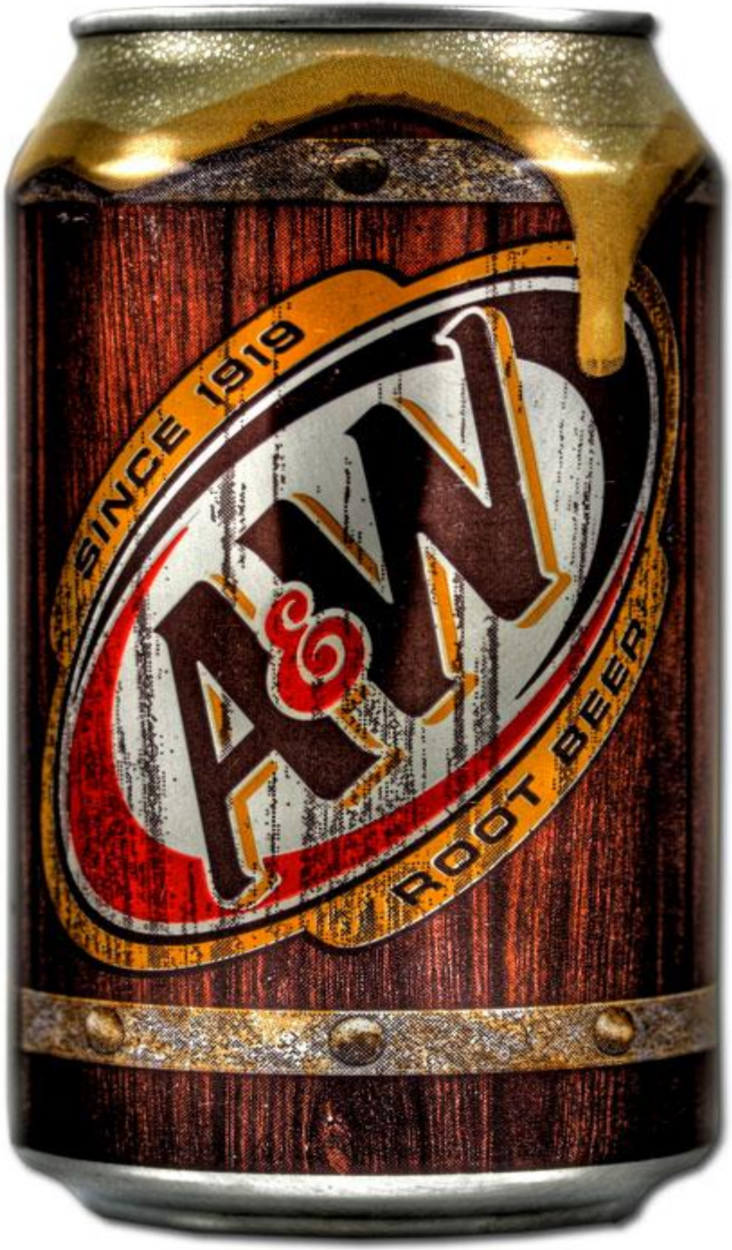
Patchwork is not helping

too many places

code bloat

yet another loophole will be found

Fix it



at the

root

Example #2

Java

String(byte[] bytes)

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

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

…

}
```

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[]

Demo

Disclosure

Oracle (Java): Sep 11

CRuby, JRuby, Rubinius: Aug 30

Hash-flooding DoS reloaded: attacks and defenses

SipHash: a fast short-input PRF

New crypto algorithm to fix hash-flooding:

- Rigorous security requirements and analysis
- Speed competitive with that of weak hashes

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 ⊕ 736f6d6570736575

v1 = k1 ⊕ 646f72616e646f6d

v2 = k0 ⊕ 6c7967656e657261

v3 = k1 ⊕ 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 ⊕= **m2**

c iterations of SipRound

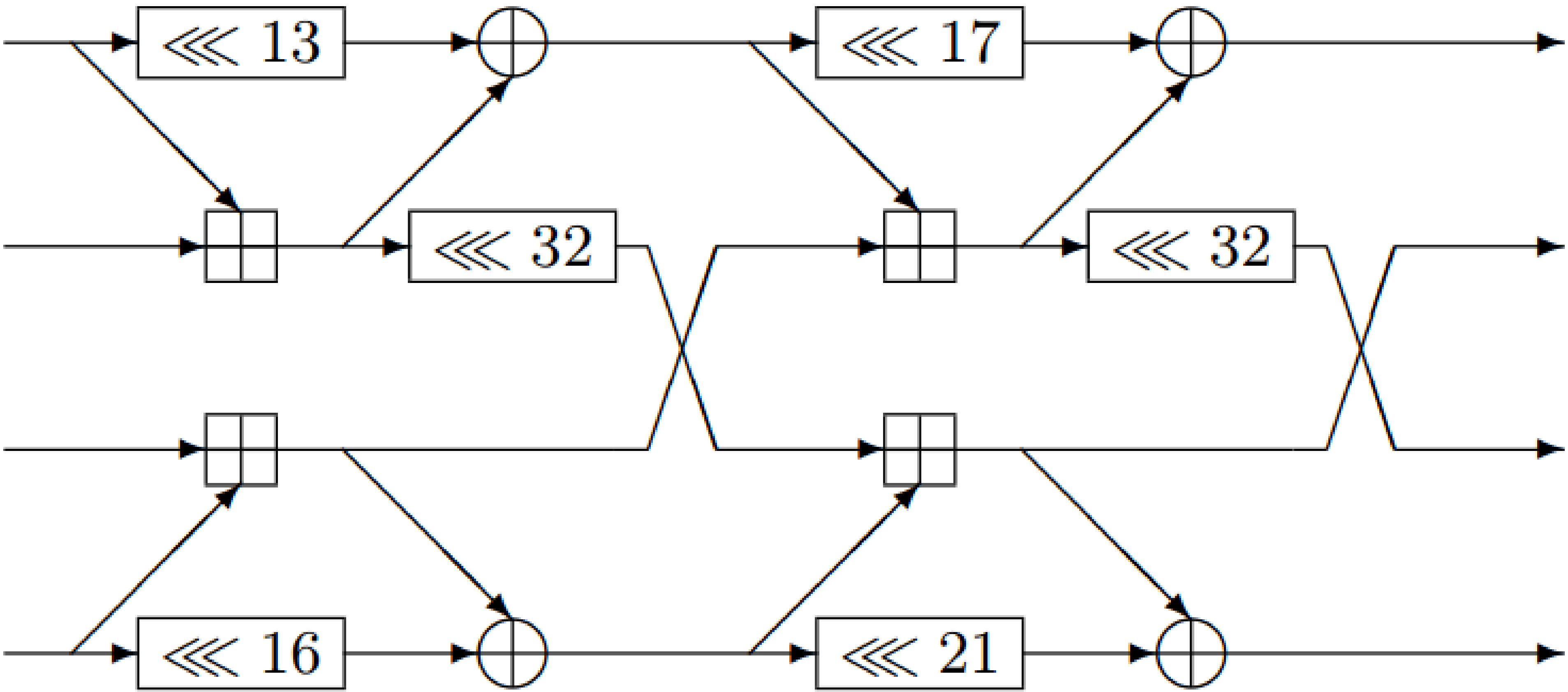
v0 ⊕= **m2**

SipHash compression

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

Etc.

SipRound



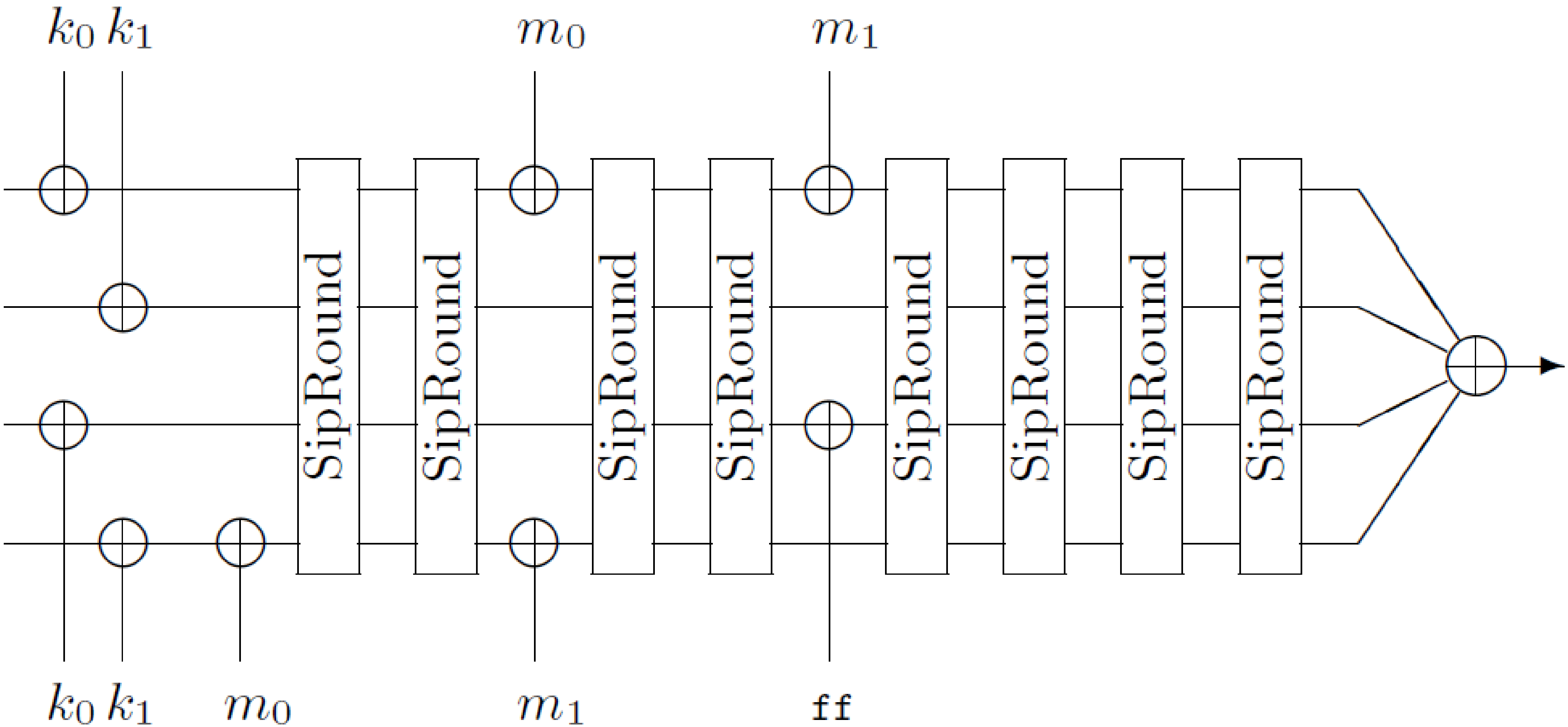
SipHash finalization

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**

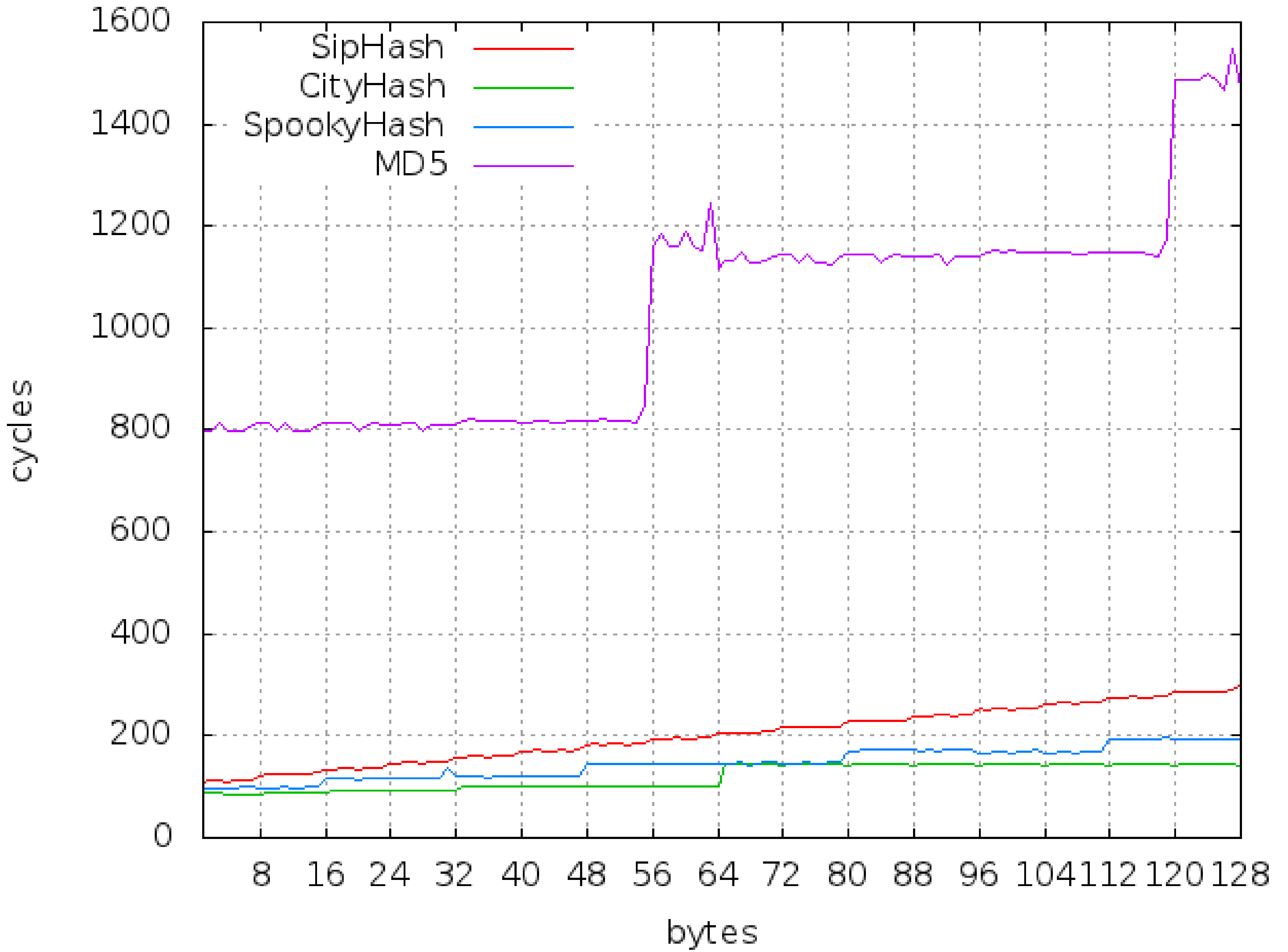
Conservative proposal: SipHash-**4**-**8**

Weaker versions for cryptanalysis:

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

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

Etc.



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

http://www.opendns.com/

http://www.rust-lang.org/

Soon?

Take home message

- DoS is doable with only small data/bandwidth
- Java- and Ruby-based web applications vulnerable to DoS (and maybe others…)
- SipHash offers both security and performance

Contact us if you need to check your application

Hash-flooding DoS reloaded: attacks and defenses

THANK YOU!