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Real World Cryptanalysis

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Real World Cryptanalysis

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Cryptographic Standards crucial for secure Internet

Gain confidence in security over time through extensive scrutiny
(Before & After Standardization)

Real World Cryptanalysis

Cryptographic Standards crucial for secure Internet

Occasionally leap in cryptanalysis exposes unknown weaknesses

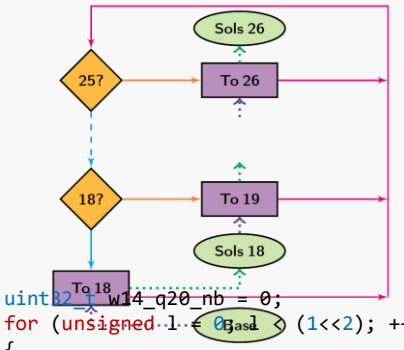
Deprecate Standard !

Real World Cryptanalysis

Theory
Analyze

t	Bits Q_t: $b_{31}\dots b_0$	#
−3	10001010 11111100 01010110 11011110	32
−2	11000100 10011010 01100010 −0−10110	32
−1	01111101 01010011 01101110 −0−11110	32
0	11101011 00011111 000010−+ +0−11010	32
1	..0..0.. ....11.. 0−0−..01 −1−.....	13
2	.1.!0+.. ....1+.. −0++..00 −−+.....	15
3	.1!.01.. .0..+−.. 1−0−.... −−+.....	14
4	!−..−1.. .0..+−!. +1++.... .+.....	13
5	!−00−.00 ^−001−.0 101+0000 1+000000	30
6	!+11−011 ++11−−01 1.+−1111 1.111111	30
7	!1..−... 00.^−−.! −.01.... .1^.^...	15
8	!1..+... 10!−.... −.0−.0.. ..+0+..0	15
9	..!.1... ...010.. −..+.0.. .!001^.0	14
10	00.!−010 00.1..10 .00+!+.0 .01+1−1−	25
11	110.−111 1100^011 01110+01 001−000+	31
12	.11^00+1 0010+1+^ 00^1111. 1−0−0+−0	30
13	^1+−−−0 1−0+0+0− +++++++1 +−−+−++0	32
14	−−1110−+ +++++0+1 00000010 +−−0−−−.	31
15	1+1+1−1− 011−1+10 0000000− 011−.10.	30
16	01...00+ 10111+1. ..+..1.. 100−^01.	21
17	.0.^.+.1 .1.^.+.. ..−..1.^ .0.0..0.	13
18	.......1 .+...+.. ..1..+.. .1.1..1.	8
19	0....^.+ ....0−.. ..−..... .−....−.	8
20	1...0... .^..1−.. 0....^.. .1.....0	9
21	+...1..^ ...0−0.. 1.^..... .0....^0	11
22	....+... ...1.^.. +....... .1.....+	6
23	^......0 ..0−^... 1....... .+.0....	8
24	....^..1 ..10.... 0.....0. ...1...^	8
25	.......− ..−+.... ....^.−....	5
26	..0..... ...−.... .....0+.	4
27	..1....^ ..^1.... .....1+. ...^....	7
28	..+..... ...0.... .....+−.	4
29	..0..... ....0.	2
30	..−..... ....^1.	3
31	..−.....	1
32	....	0
33	..!.....	1
34 − 60	....	0
61	....	
62	.... +.......	
63	.... +.......	
64	.... +.......	

Practice
Build




```
uint32_t w14_q20_nb = 0;
for (unsigned l = 0; l < (1<<2); ++l)
{
    NEXT_NB(w14_q20_nb, W14NBQ20M);
    m14 &= ~W14NBQ20M;
    m14 |= w14_q20_nb;
    q15 += w14_q20_nb;
    q16 += rotate_left(w14_q20_nb, 5);
    m17 ^= rotate_left(m14, 1);
    m20 ^= rotate_left(m17, 1);
    uint32_t w15_q20_nb = 0;
    for (unsigned k = 0; k < (1<<5); ++k)
    {
        NEXT_NB(w15_q20_nb, W15NBQ20M);
        m15 &= ~W15NBQ20M;
        m15 |= w15_q20_nb;
        m18 ^= rotate_left(m15, 1);
        q16 += w15_q20_nb;
```

Demonstrate
Apply

```
%PDF-1.3.%.....
.1 0 obj.<</Widt
h 2 0 R/Height 3
 0 R/Type 4 0 R/
Subtype 5 0 R/Fi
lter 6 0 R/Color
Space 7 0 R/Leng
th 8 0 R/BitsPer
Component 8>>.st
eam.....$SHA-1
is dead!!!!!./.
#9u.9...<L.....
F....~.;.....V.
.g....K.Ly..+=.
.m.i...kE.S....
8.rr/..r..I..F.
0W..........+.5
```

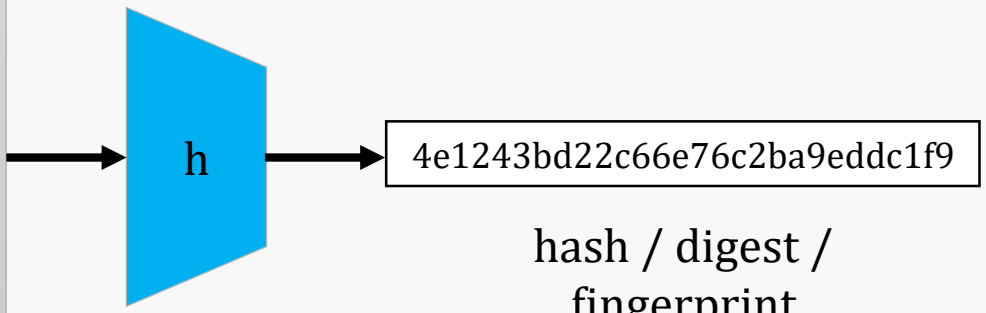
Cryptographic hash functions

Cryptographic hash functions

A hash function is a deterministic mapping

from arbitrary length inputs to a fixed length output

This is an input to a cryptographic hash function. The input is a very long string, that is reduced by the hash function to a string of fixed length. There are additional security conditions: it should be very hard to find an input hashing to a given value (a preimage) or to find two colliding inputs (a collision).



hash / digest / fingerprint

MDC-2
MD2, MD4, MD5
SHA-1
old & weak

RIPEMD-160
SHA-2-{256,512}
secure

SHA-3-{256,512}
New Std in 2015
NIST: use SHA-2

Collision resistance

Collision resistance

Find $m \neq k$ such that $H(m) = H(k)$

Only max. (n/2)-bit security!

128-bit hash ⇒ 64-bit security
160-bit hash ⇒ 80-bit security
256-bit hash ⇒ 128-bit security
512-bit hash ⇒ 256-bit security

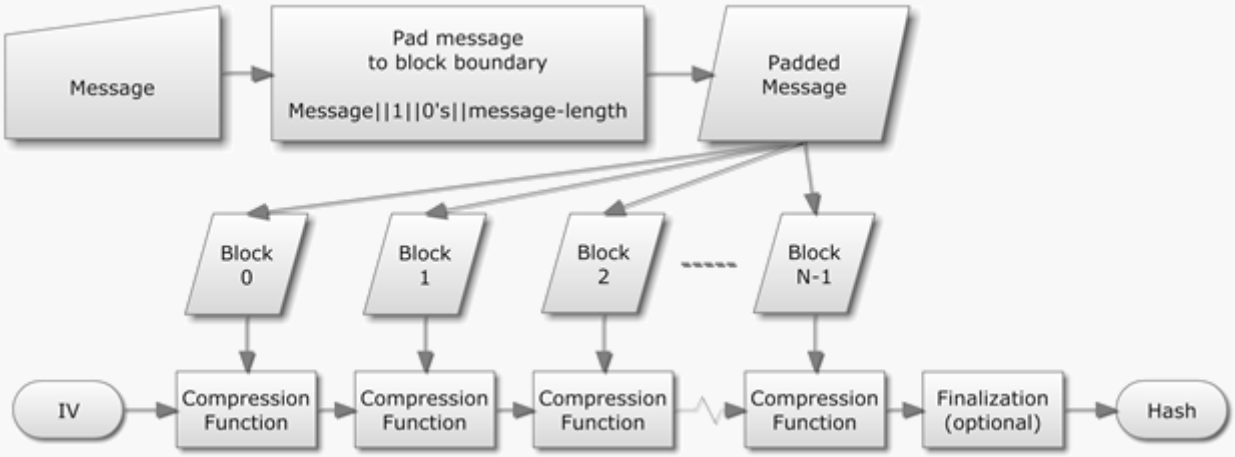
Note:
Bitcoin network computes

- 2^{64} SHA-2 / sec
- $2^{80.5}$ SHA-2 / day
- 2^{84} SHA-2 / 12days
- 2^{89} SHA-2 / year

⇒
breaks 80-bit security
brute-force in 1 day!

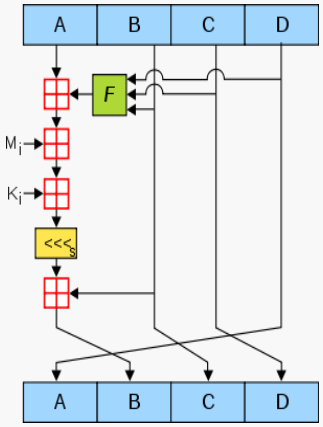
Design of hash functions

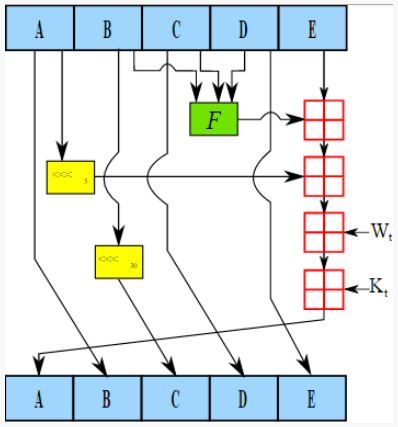
- **Merkle-Damgård Construction**
  - Splits message into 512-bit blocks
  - Processes blocks iteratively using compression function

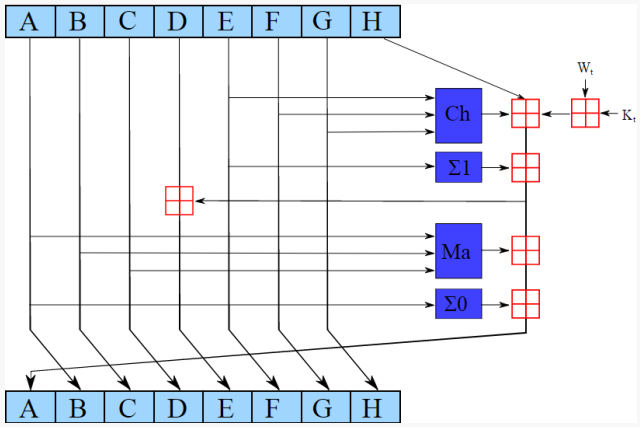


- Security reduction
  - collision hash function $\Rightarrow$ collision compression function

MD5 / SHA-1 / SHA-256 compression function







MD5

very weak

permutation

SHA-1

theoretically weak

linear recurrence

SHA-2

secure

non-linear

message expansion

16 x 32-bit → {64,80} x 32-bit

Differential cryptanalysis

Differential cryptanalysis

- Consider two different instances

  Compress(CV,M)

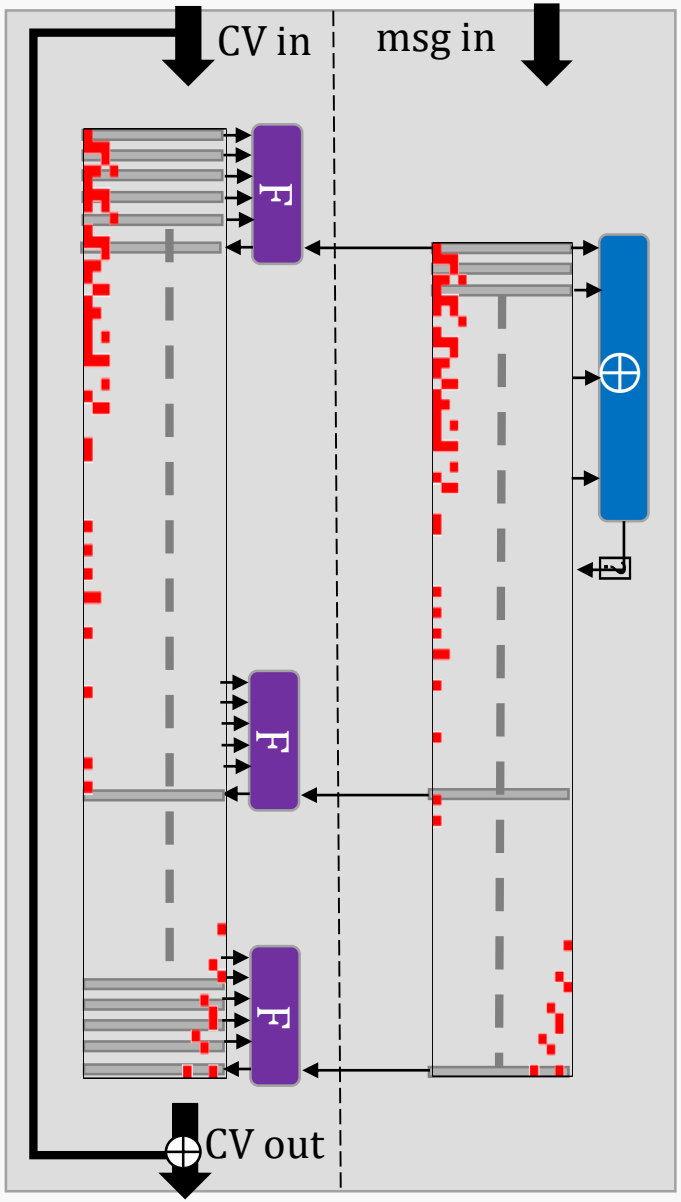
  Compress(CV',M')

- Analyze differences

Differential path

- Precise description of all differences propagating through compression function

- Translate differential path into **system of equations** to solve to find M, M'



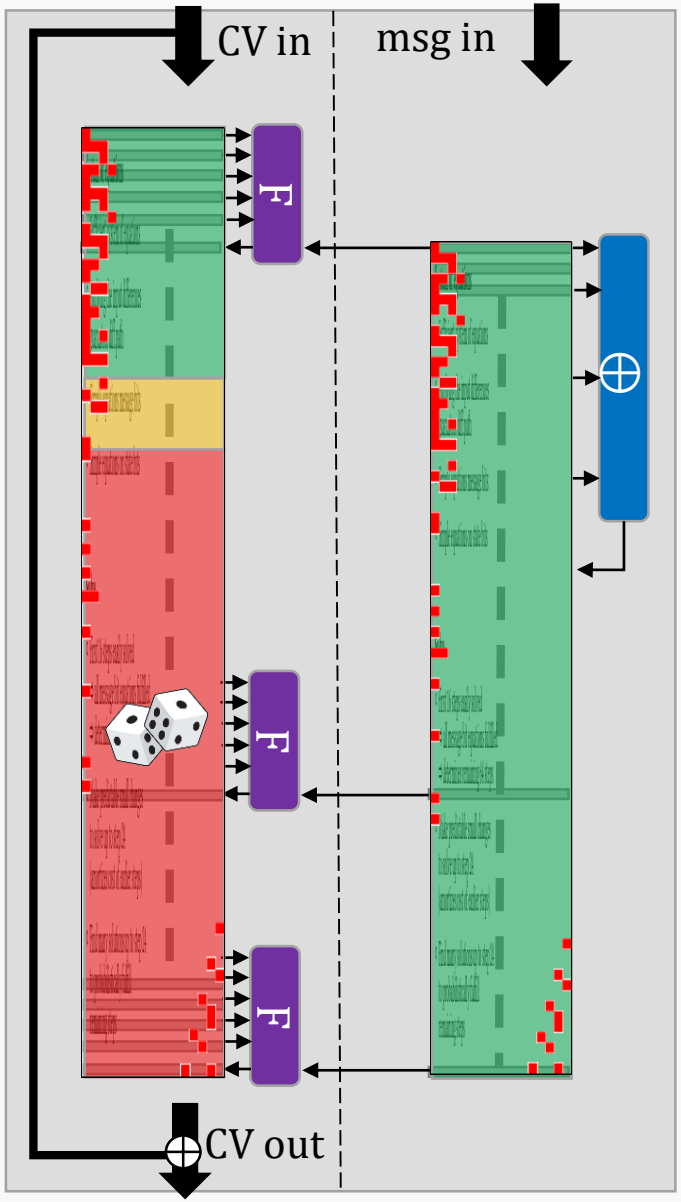
Differential cryptanalysis

System of equations

- Sufficient system of equations:
  Applying the input differences
  guarantees diff.path
- Simple equations
  on message and state bits

Solve

- First 16 steps easily solved
  ⇒ all message bit equations fulfilled
- Make predictable small changes
  to solve up to step 24
  (amortizes cost of earlier steps)
- Probabilistically fulfill
  remaining steps
  (with many solutions up to step 24)



Deprecating MD5 in 2008

(known to be practically broken since 2004)

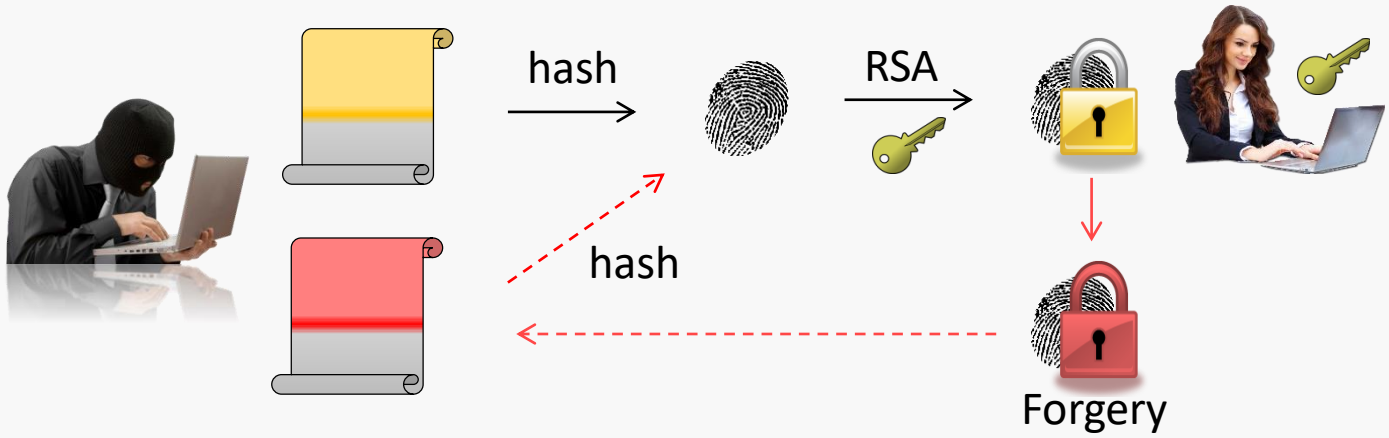
Joint work with:

Alexander Sotirov, Jacob Applebaum, Arjen Lenstra, David Molnar, Dag Arne Osvik, Benne de Weger

Rogue C.A.

2008 [SSALMOdW]: Breakthrough on MD5

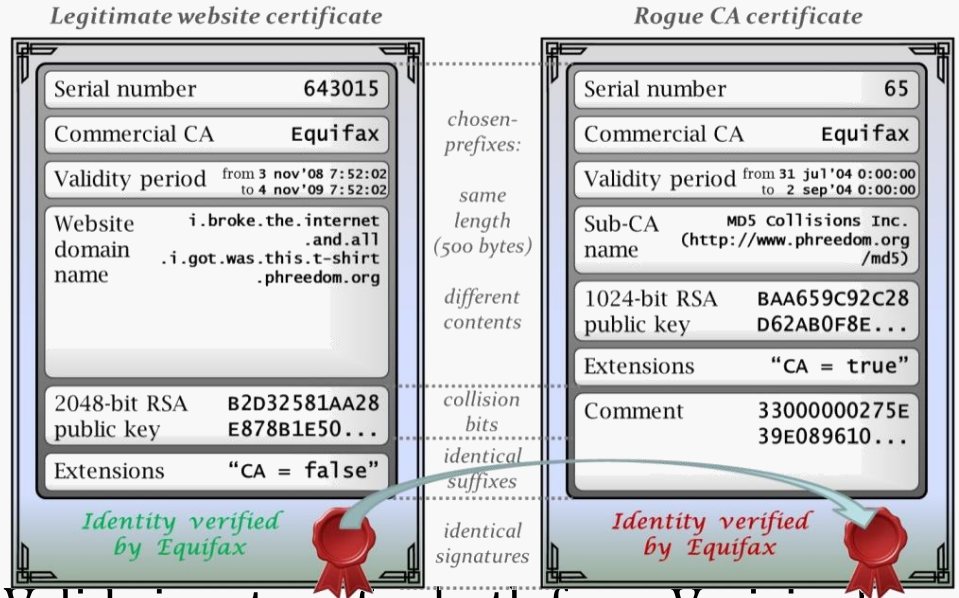
- Practical *chosen-prefix collision* attack on MD5
- Arbitrary different prefixes made to collide



Rogue C.A.

Example chosen-prefix collision between

- Our website: https://i.broke.the.internet.and.all.i.got.was.this.t-shirt.phreedom.org
- A hand-crafted sub-C.A. certificate 😈



- Valid signature for both from Verisign!

Using 200 PlayStation 3s

Rogue C.A.

- Realistic Man-in-the-Middle attack against any secure website

- Responsible disclosure
  - Pre-informed Browsers and C.A.s
  - Rogue C.A. purposely crippled: only valid in August 2004
- MD5 deprecated within hours
- Software released for research
  - Anyone can create chosen-prefix collisions
  - ≈1 day on quadcore machine
  - https://github.com/cr-marcstevens/hashclash

What happened since?

- 2009: CABforum: MD5 deprecated for signatures
- 2012: supermalware Flame uses forged MD5 signature
  to push fake Windows Updates
  Discovery of yet-unknown variant MD5 collision attack
- 2016: SLOTH: Transcript collision attacks against TLS, IKE, SSH
- 2017: Oracle JRE rejects MD5 signatures
  Originally planned for Januari, was postponed till April
- 2018: US SWGDE (Scientific Working Group on Digital Evidence)
  Publication "*explains that the use of the MD5 and SHA1 hash algorithms remains acceptable*"

Deprecating SHA-1 in 2017

(known to be weak since 2005)

Joint work with

Ange Albertini, Elie Bursztein, Pierre Karpman, Yarik Markov

Weaknesses

SHA-1 is not collision resistant

Collision attack with complexity 2^{69} (4M core-years) [WangYY 2005]

Later improved to 2^{61} (15,300 core-years) [Stevens 2012]

Projected costs of SHA-1 collisions [Schneier 2012]

$2.77M in 2012
$700K by 2015
$173K by 2018 ⇒ "we can postpone 5 years.."
$43K by 2021

(based on [Stevens 2012], Amazon EC2 rates & Moore's Law)

Practical SHA-1 collision remained open problem

GPU ≫ CPU

- [S13]: SHA-1 collision attack with complexity $\approx 2^{61}$
- ⇒ CPU attack: 15.3K coreyears

- [SPK16]: attack complexity $\approx 2^{62.2}$ on GTX-970
- ⇒ GPU attack: 112 GPUyears
- ≈ $100k renting fee (on Amazon EC2)
- ×**7** lower cost in 2015 than predicted earlier by Schneier
- Initiated collaboration with Google

First SHA-1 Collision

- **Collaboration with Google [SBKAM17]**
  - Google Infrastructure:
    Large heterogenous cluster of CPUs & GPUs
  - But: no direct access, proprietary Compile & Job system
  - 'Blind' adaptation source-code by Google

  - **First near-collision attack**
    - Took 3583 core years ≈ $\mathbf{2^{60}}$ SHA-1 compressions
    - Run on 100k+ PCs in several weeks

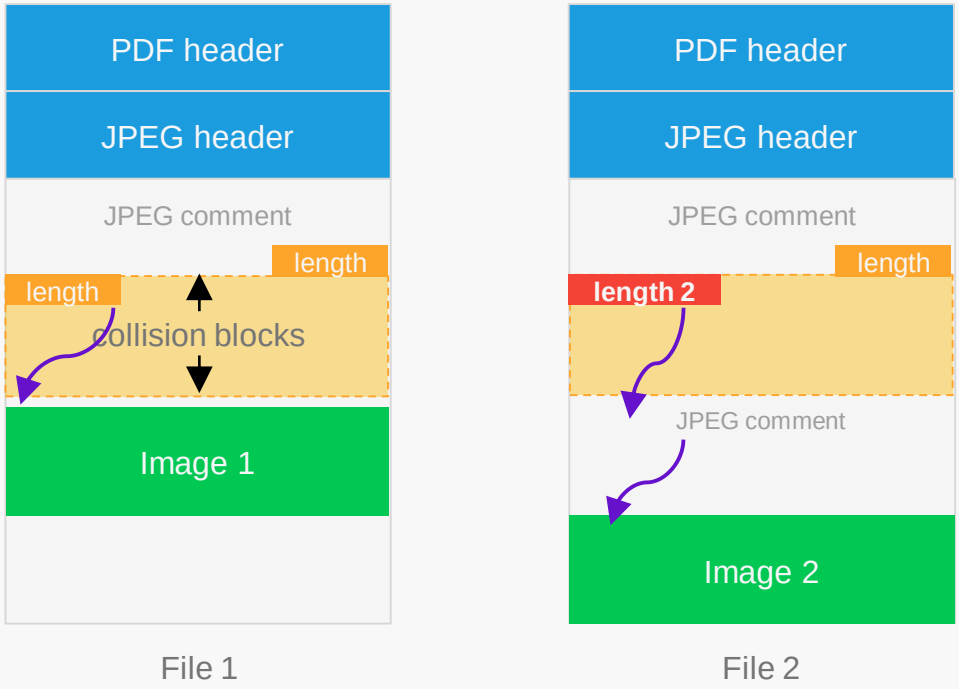
  - **Second near-collision attack**
    - Tailored to 1st NC output
    - Using NVIDIA Tesla K20, K40, K80
    - Took ≈ 114 K20years ≈ 71 K80years ≈ $\mathbf{2^{62.8}}$ SHA-1
    - Run on >3000 GPUs in just 8 calendar days

  - Collision on https://shattered.io/

Colliding PDFs

Reusable meaningful SHA-1 collision:

- 1 collision: infinite colliding PDF-pairs with distinct embedded JPGs
- Use JPG for page-content ⇒ arbitrary distinct page contents
- Use PDF image cropping ⇒ arbitrary distinct multi-page contents



- DIY: https://github.com/nneonneo/sha1collider

Impact

- Project Webpage, Google Drive & Gmail check for SHA-1 collisions

- Unexpectedly collision can break Subversion repositories
  - Webkit developer submitted test to prove WebKit resistant to SHA-1 collisions
  - Broke Webkit repository
  - Internal deduplication uses SHA-1 and keeps only 1 colliding file
  - MD5 is used to check integrity ⇒ will always fail on checkout
- Git started moving away from SHA-1
- Git & GitHub now using strengthened SHA-1 implementation by default

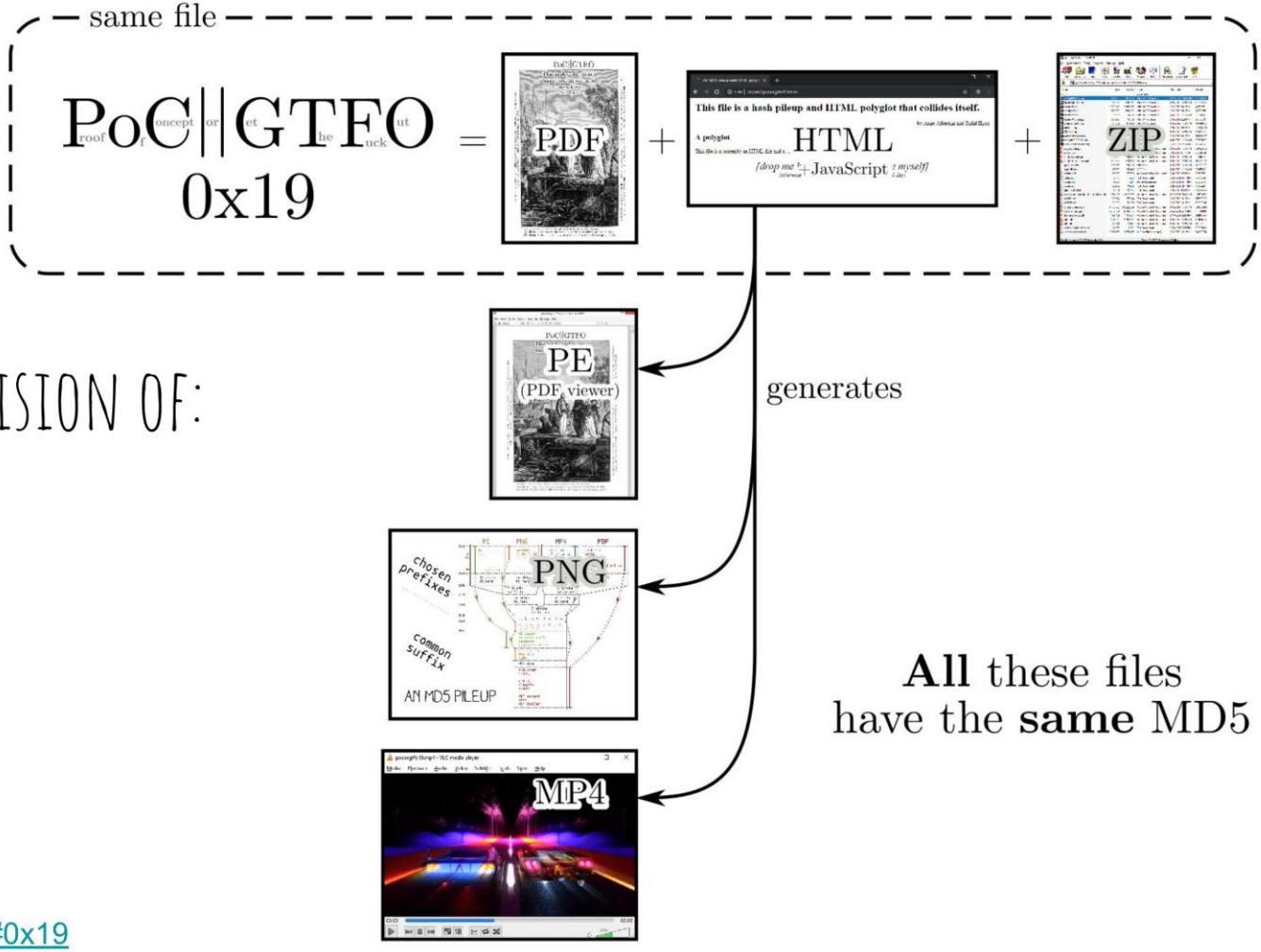
- CA/Browser Forum: Ballot 152
  - Extend issuance SHA-1 certificates up to 1 Jan. 2017 (before: 1 Jan. 2016)
  - (unaltered: deprecate SHA-1 certificates after 1 Jan. 2017)
  - Our recommendations on 8 Oct. ensured Ballot did not pass on 16 Oct.
- TLS 1.3 draft 9
  - Deprecated all uses of SHA-1 digital signatures

From attacks to toys

Instant Collisions

- Instant collision scripts for many file formats
  - Instant, re-usable and generic collisions
  - Take any pair of files, run script, get colliding files
- SHA-1: PDF, HTML
- MD5
  - PDF
  - PNG, JPG, JP2
  - MP4, GIF
  - PE (windows executable)

Toys



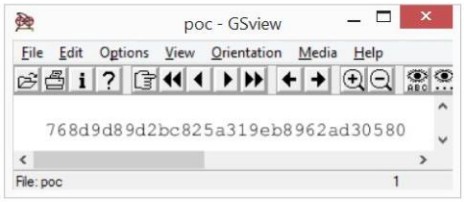
An instant collision of:

- a document
- an executable
- an image
- a video.

https://github.com/angea/pocorgtfo#0x19

Toys

Hashquines: documents that show their own MD5 hash

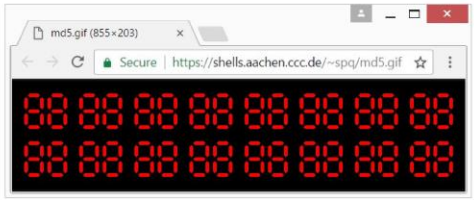


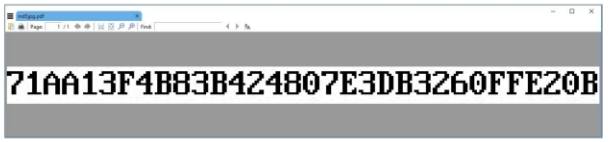
THE FIRST EVER!

PostScript by Greg

ANIMATED

GIFs by spq

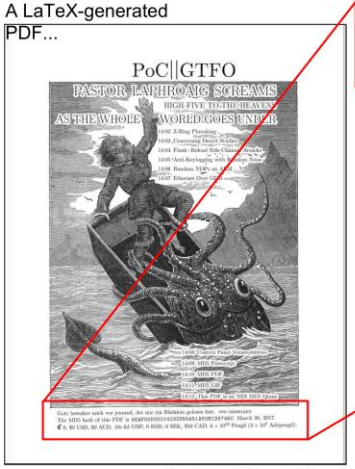




As images

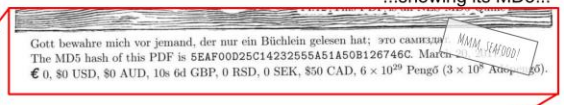
PDFs by Mako

A LaTeX-generated PDF...



(15x32=480 collisions)

...showing its MD5...



...also a NES rom...

...showing the same MD5!
(4x32=128 collisions)

608?

As text

```
$ pdftotext -q md5text.pdf -
66DA5E07C0FD4C921679A65931FF8393
$ md5sum md5text.pdf
66da5e07c0fd4c921679a65931ff8393 md5text.pdf
```

Thank you!