Hash functions and certificates
CSE 468 Fall 2023

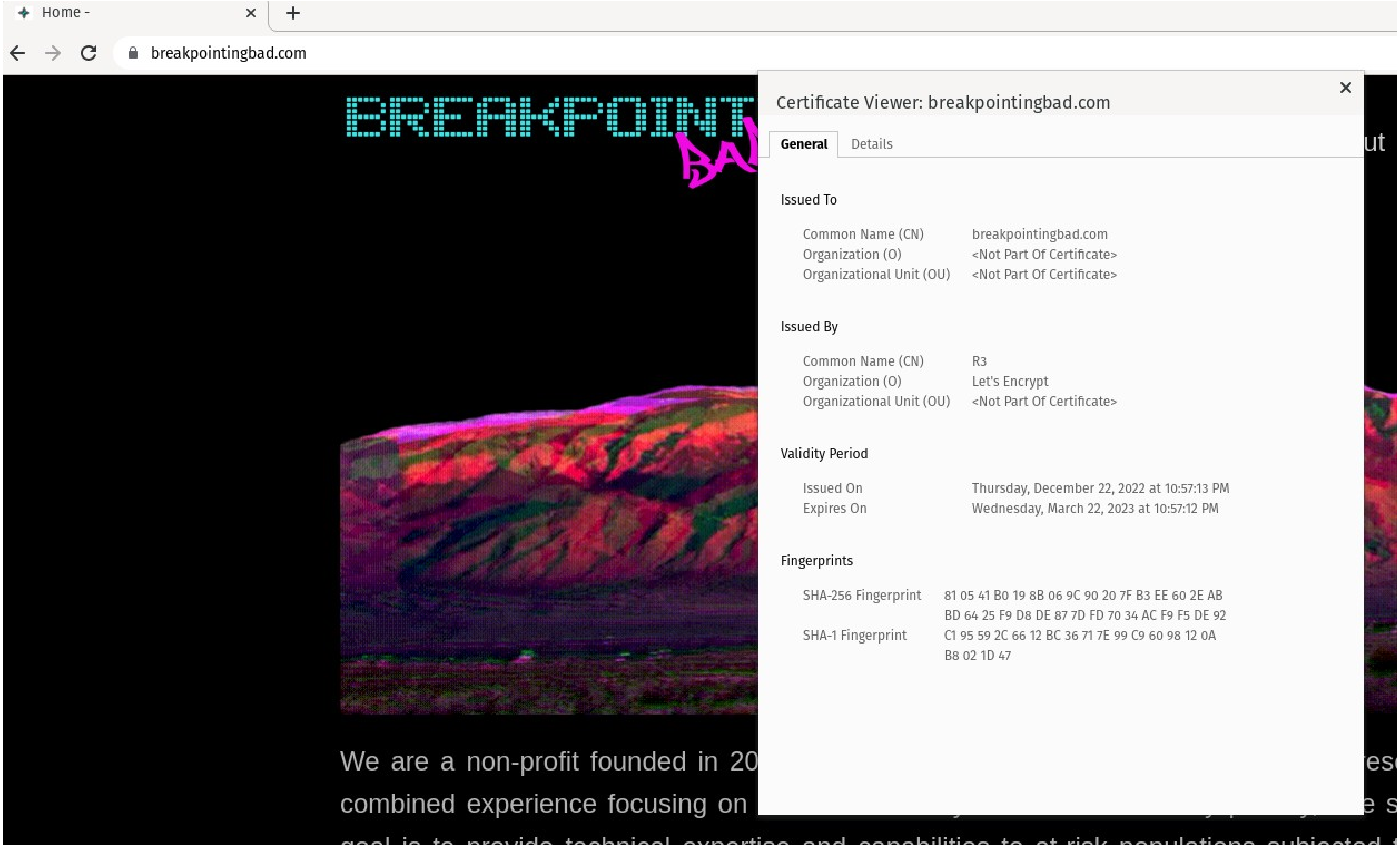
jedimaestro@asu.edu

To prepare for this lecture...

https://media.ccc.de/v/25c3-3023-en-making_the_theoretical_possible

Also check out:

https://www.win.tue.nl/hashclash/rogue-ca/


Home -
breakpointingbad.com
BREAKPOINT
BA
Certificate Viewer: breakpointingbad.com
General
Details
Issued To
Common Name (CN) breakpointingbad.com
Organization (O) <Not Part Of Certificate>
Organizational Unit (OU) <Not Part Of Certificate>
Issued By
Common Name (CN) R3
Organization (O) Let's Encrypt
Organizational Unit (OU) <Not Part Of Certificate>
Validity Period
Issued On Thursday, December 22, 2022 at 10:57:13 PM
Expires On Wednesday, March 22, 2023 at 10:57:12 PM
Fingerprints
SHA-256 Fingerprint 81 05 41 B0 19 8B 06 9C 90 20 7F B3 EE 60 2E AB BD 64 25 F9 D8 DE 87 7D FD 70 34 AC F9 F5 DE 92
SHA-1 Fingerprint C1 95 59 2C 66 12 BC 36 71 7E 99 C9 60 98 12 0A B8 02 1D 47
ut
We are a non-profit founded in 20
combined experience focusing on

Certificate Viewer: breakpointingbad.com

General Details

Issued To

Common Name (CN)	breakpointingbad.com
Organization (O)	<Not Part Of Certificate>
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SHA-1 Fingerprint	C1 95 59 2C 66 12 BC 36 71 7E 99 C9 60 98 12 0A B8 02 1D 47

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Certificate Fields

- breakpointingbad.com
  - Certificate
    - Version
    - Serial Number
    - Certificate Signature Algorithm
    - Issuer
    - Validity
      - Not Before

Field Value

04:B5:2A:1D:FD:B3:AC:F1:34:37:27:94:9F:F5:A8:5A:12:E6

Export...

breakpointingbad.com

Certificate Fields

breakpointingbad.com

Certificate

Version

Serial Number

Certificate Signature Algorithm

Issuer

Validity

Not Before

Field Value

PKCS #1 SHA-256 With RSA Encryption

Certificate Fields

breakpointingbad.com

Certificate

Version

Serial Number

Certificate Signature Algorithm

Issuer

Validity

Not Before

Field Value

CN = R3
O = Let's Encrypt
C = US

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Certificate Fields

Certificate Signature Algorithm

Issuer

Validity

Not Before

Not After

Subject

Subject Public Key Info

Subject Public Key Algorithm

Field Value

3/22/23, 10:57:12 PM MST

Export...

breakpointingbad.com

Certificate Fields

Certificate Signature Algorithm

Issuer

Validity

Not Before

Not After

Subject

Subject Public Key Info

Subject Public Key Algorithm

Field Value

CN = breakpointingbad.com

breakpointingbad.com

Certificate Fields

Not After

Subject

Subject Public Key Info

Subject Public Key Algorithm

Subject's Public Key

Extensions

Certificate Key Usage

Extended Key Usage

Field Value

Modulus (2048 bits):
DC DA F0 96 47 5C 62 91 27 27 AD B2 95 EE 3D 51
CF 26 EB EC 27 EE ED 2E 9F DA 1D BF 83 2F 12 F0
EA CC 96 5B 8C C1 3E A1 C6 46 90 4D E5 93 20 E1
5C 9B 62 BB 82 3A 7F 77 7C 85 CB 8C F3 0F B9 0D
38 24 9C 0D 39 8C EE F4 B5 AD 0A 94 75 AA F9 41

Certificate Fields

- breakpointingbad.com
  - Certificate
    - Version
    - Serial Number
    - Certificate Signature Algorithm
    - Issuer
    - Validity
      - Not Before

Field Value

```
98 2F 52 F3 68 5E 6D BC 18 2C 93 42 8B C5 41 D1
40 B4 0F 53 D9 BD BA 22 F9 52 90 76 37 F0 C4 56
31 F8 8D C7 B8 21 3E FB 0F 83 B8 A7 CF F3 B4 A1

  Public Exponent (17 bits):
  01 00 01
```

Export...

Certificate Hierarchy

Builtin Object Token:ISRG Root X1

R3

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Certificate Fields

Subject's Public Key

Extensions

Certificate Key Usage

Extended Key Usage

Certificate Basic Constraints

Certificate Subject Key ID

Certification Authority Key ID

Authority Information Access

Field Value

Critical
Is not a Certification Authority

R3

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Certificate Fields

Certificate Subject Alternative Name

Certificate Policies

OID.1.3.6.1.4.1.11129.2.4.2

Certificate Signature Algorithm

Certificate Signature Value

Fingerprints

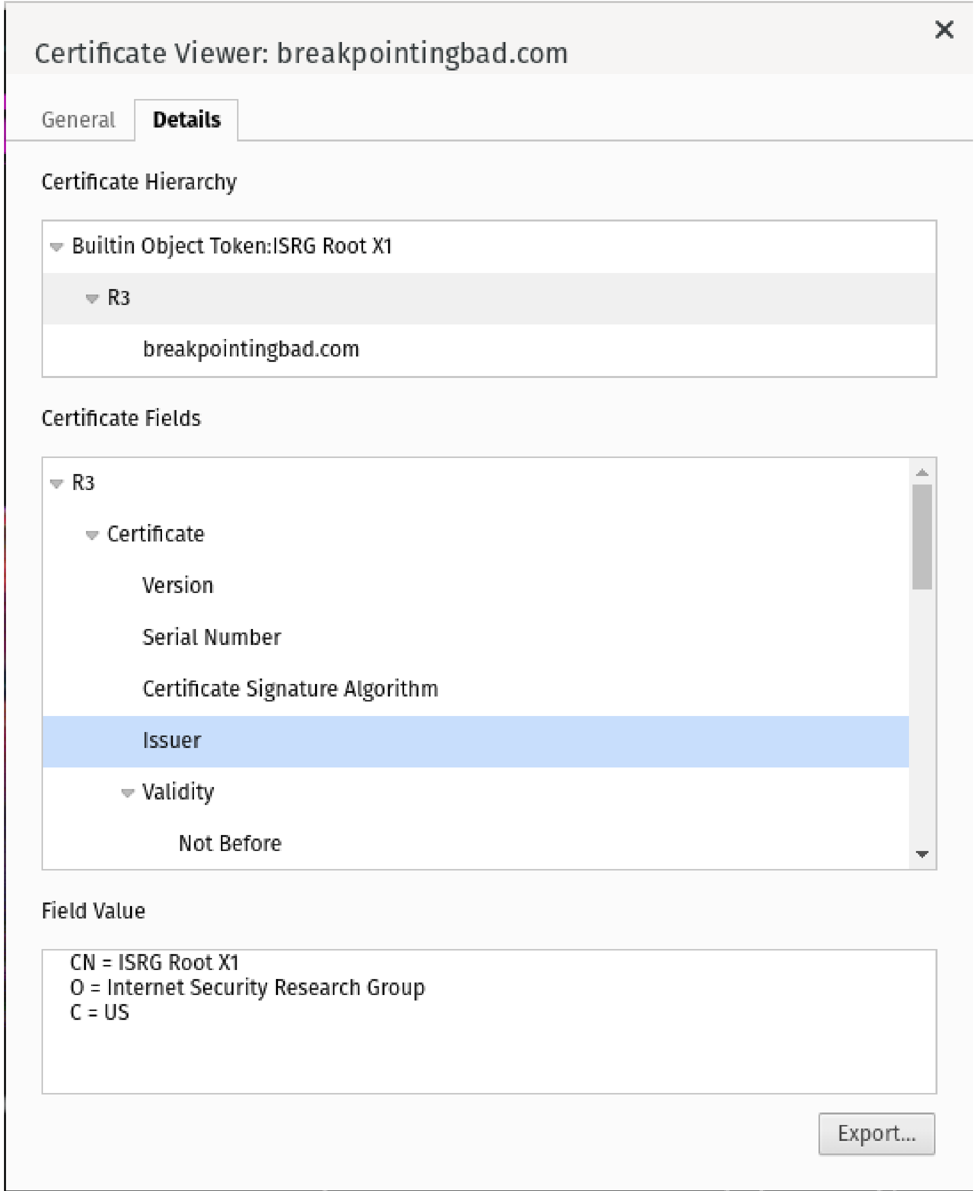
SHA-256 Fingerprint

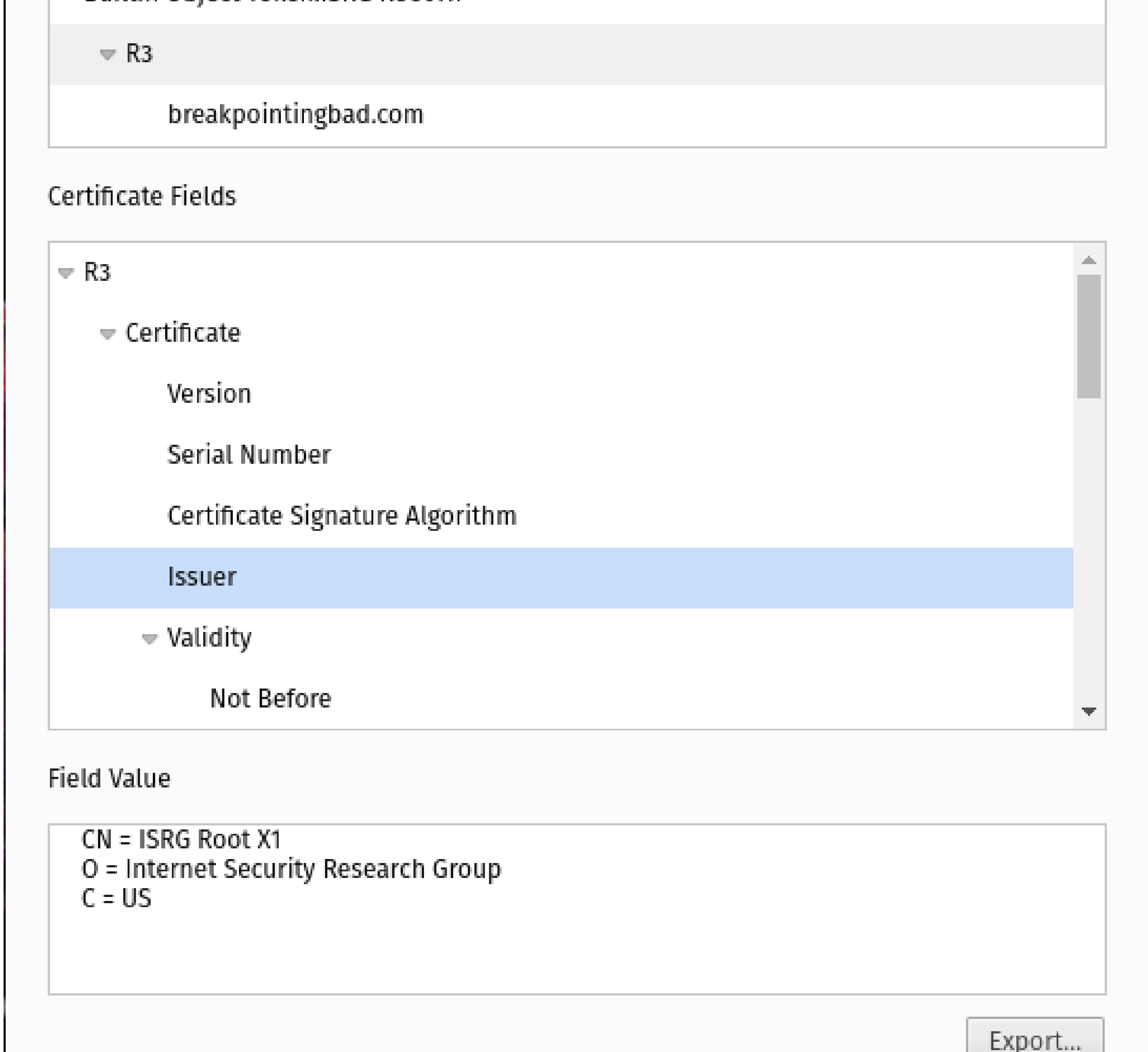
SHA-1 Fingerprint

Field Value

81 05 41 B0 19 8B 06 9C 90 20 7F B3 EE 60 2E AB
BD 64 25 F9 D8 DE 87 7D FD 70 34 AC F9 F5 DE 92

Export


Certificate Viewer: breakpointingbad.com
General
Details
Certificate Hierarchy
Builtin Object Token:ISRG Root X1
R3
breakpointingbad.com
Certificate Fields
R3
Certificate
Version
Serial Number
Certificate Signature Algorithm
Issuer
Validity
Not Before
Field Value
CN = ISRG Root X1
O = Internet Security Research Group
C = US
Export...


R3
breakpointingbad.com
Certificate Fields
R3
Certificate
Version
Serial Number
Certificate Signature Algorithm
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Export...

Builtin Object Token:ISRG Root X1

R3

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Certificate Fields

Subject's Public Key

Extensions

Certificate Key Usage

Extended Key Usage

Certificate Basic Constraints

Certificate Subject Key ID

Certification Authority Key ID

Authority Information Access

Field Value

Critical
Is a Certification Authority
Maximum number of intermediate CAs: 0

Certificate Hierarchy

- Builtin Object Token:ISRG Root X1
  - R3
    - breakpointingbad.com

Certificate Fields

- Builtin Object Token:ISRG Root X1
  - Certificate
    - Version
    - Serial Number
    - Certificate Signature Algorithm
    - Issuer
    - Validity
      - Not Before

Field Value

CN = ISRG Root X1
O = Internet Security Research Group
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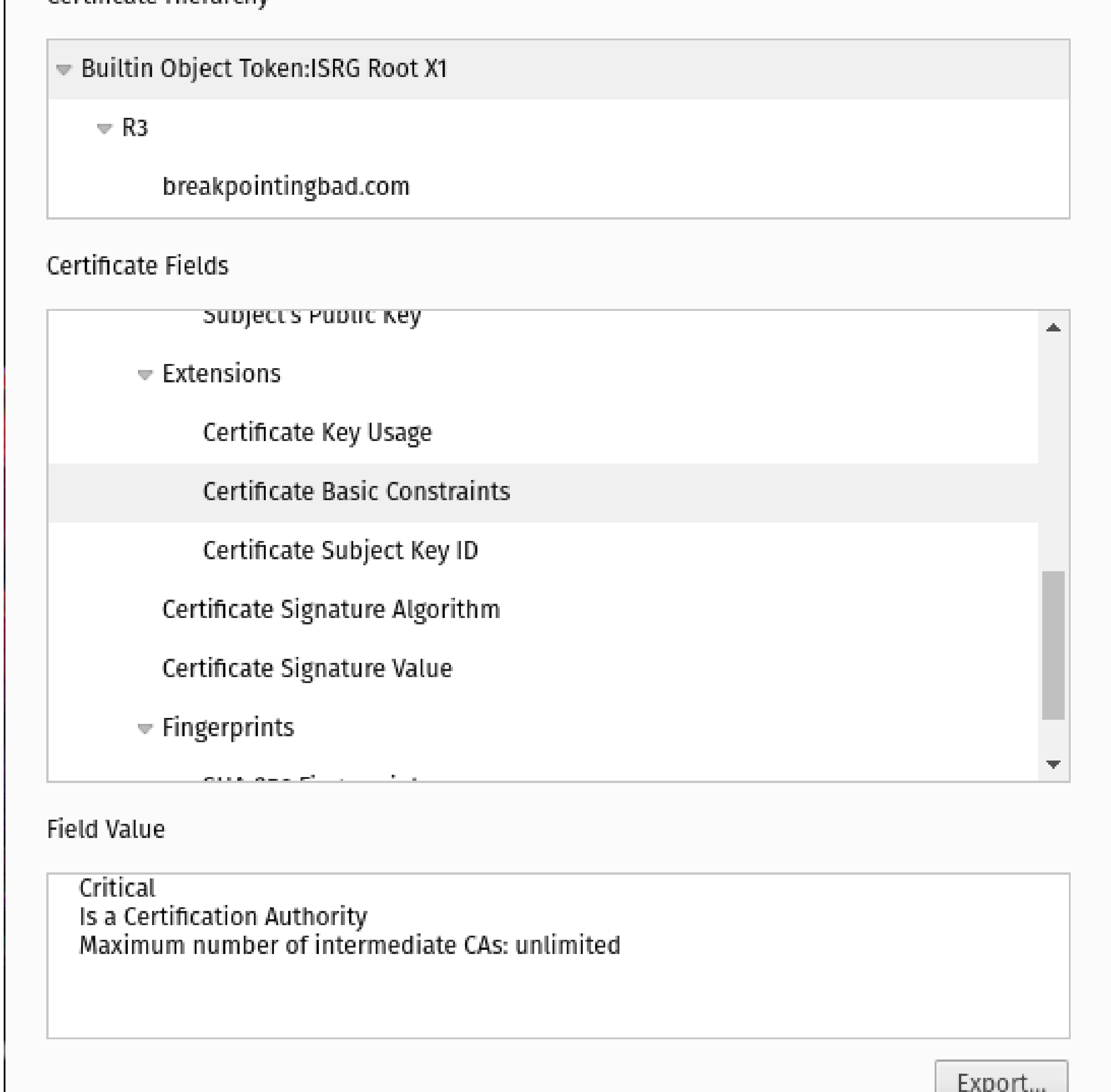

Builtin Object Token:ISRG Root X1
R3
breakpointingbad.com
Certificate Fields
Subject's Public Key
Extensions
Certificate Key Usage
Certificate Basic Constraints
Certificate Subject Key ID
Certificate Signature Algorithm
Certificate Signature Value
Fingerprints
Field Value
Critical
Is a Certification Authority
Maximum number of intermediate CAs: unlimited
Export...

- Privacy and security
- Appearance
- Search engine
- Default browser
- On startup

- Languages
- Downloads
- Accessibility
- System
- Reset settings

- Extensions
- About Chromium

org-GlobalSign nv-sa

org-GoDaddy.com, Inc.

org-Google Trust Services LLC

org-Government Root Certification Authority

org-GUANG DONG CERTIFICATE AUTHORITY CO.,LTD.

org-Hellenic Academic and Research Institutions Cert. Authority

org-Hongkong Post

org-IdenTrust

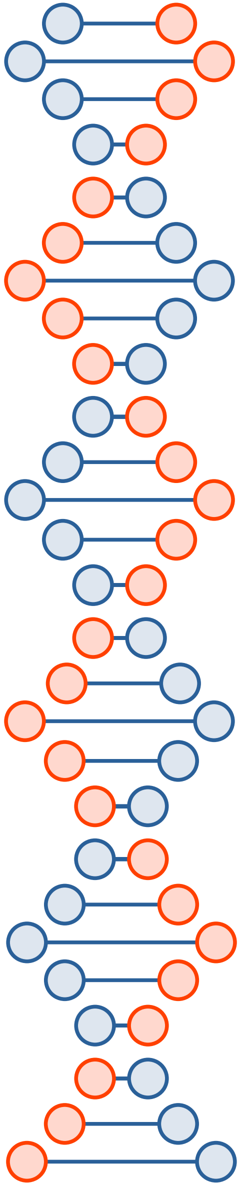
org-Internet Security Research Group

org-IZENPE S.A.

org-Japan Certification Services, Inc.

org-Krajowa Izba Rozliczeniowa S.A.

org-LuxTrust S.A.

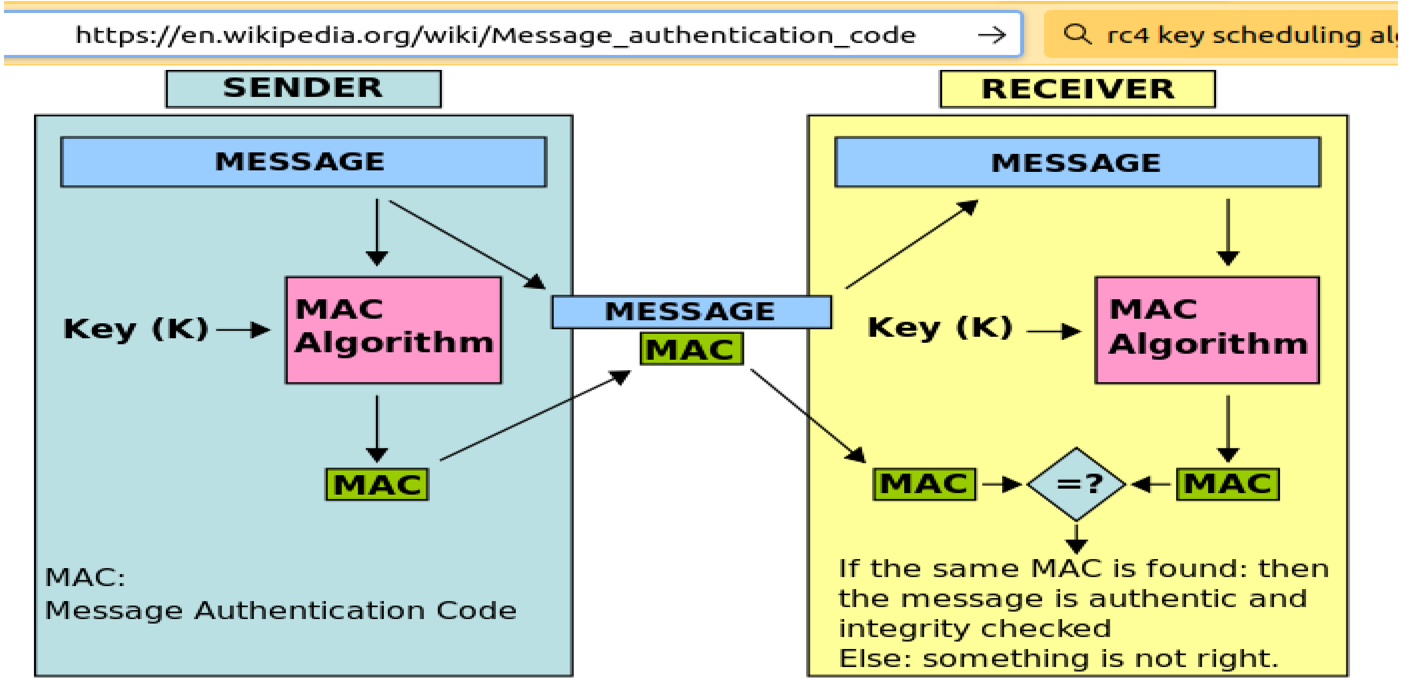


Why hash functions?

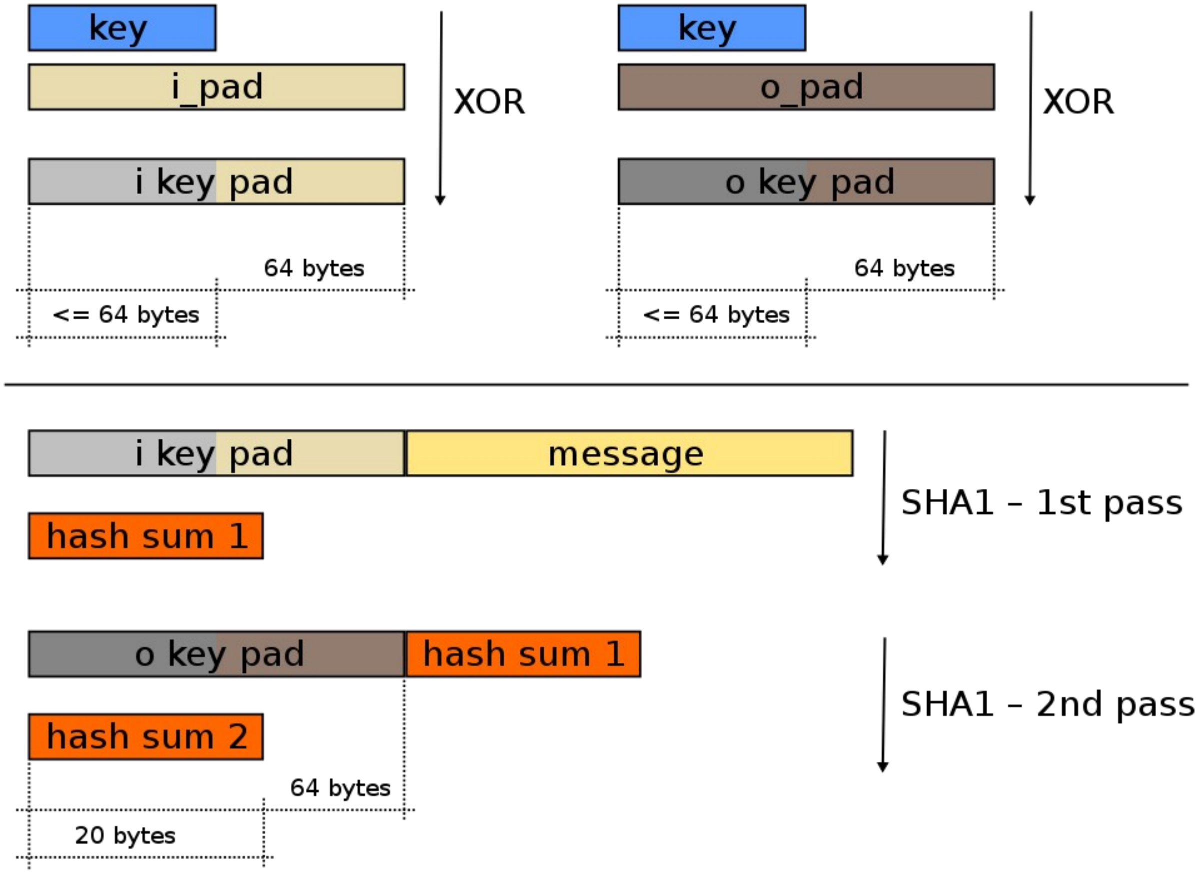
- Speed
- Error detection (*e.g.*, checksum)
- Security and privacy

Why cryptographic hash functions?

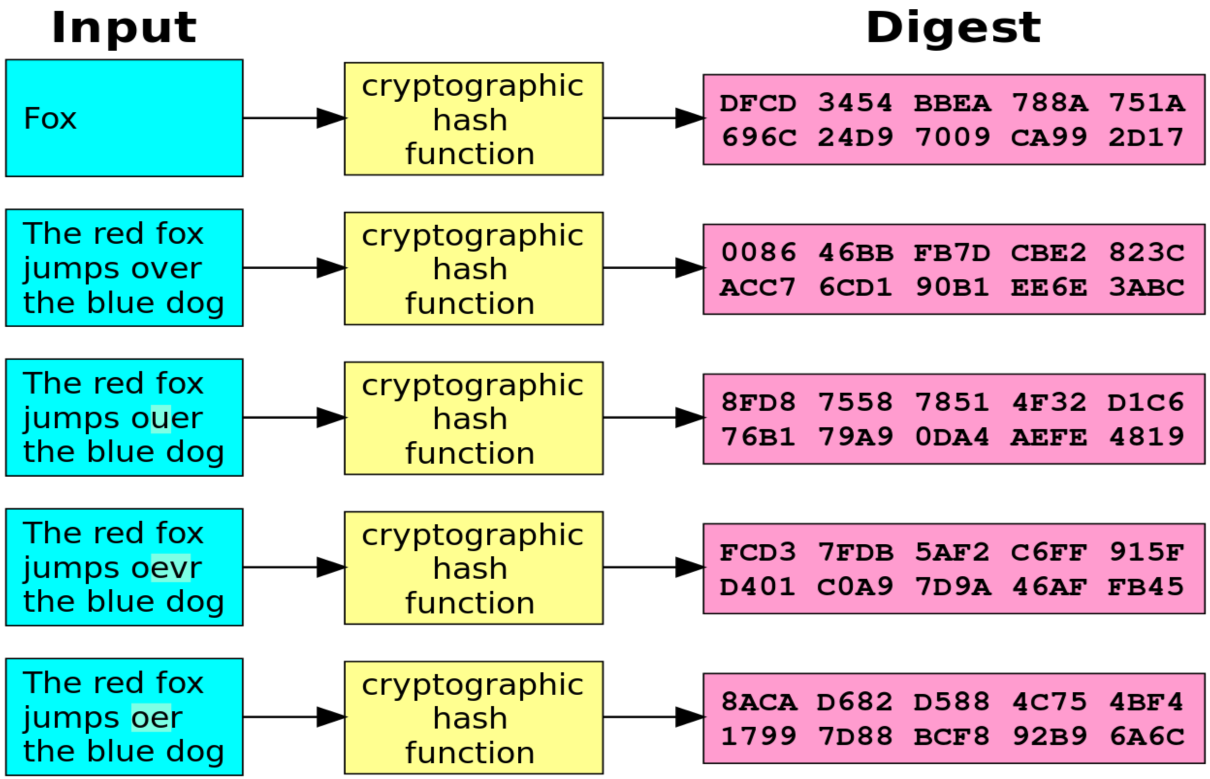
- Unique identifier for an object
- Integrity of an object
  - *E.g.*, message authentication codes
- Digital signatures
  - Sign the digest
    - E.g., 1024-bit RSA, 100MB message, 256-bit digest
- Passwords
- Proof of work


https://en.wikipedia.org/wiki/Message_authentication_code
rc4 key scheduling al
SENDER
MESSAGE
Key (K)
MAC Algorithm
MAC
MAC:
Message Authentication Code
MESSAGE
MAC
RECEIVER
MESSAGE
Key (K)
MAC Algorithm
MAC
=?
MAC
If the same MAC is found: then the message is authentic and integrity checked
Else: something is not right.

https://en.wikipedia.org/wiki/HMAC



Hash function example



By User:Jorge Stolfi based on Image:Hash_function.svg by Helix84 - Original work for Wikipedia, Public Domain, https://commons.wikimedia.org/w/index.php?curid=5290240

What makes a hash function cryptographic?

- One-way function
- Deterministic (same input, same output)
- Infeasible to find message that digests to specific hash value
- Infeasible to find two messages that digest to the same hash
- Avalanche effect (small change in message leads to big changes in digest---digests seemingly uncorrelated)
- *Still want it to be quick*

Example algorithms

- MD5: 128-bit digest, seriously broken
- SHA-1: 160-bit digest, not secure against well-funded adversaries
- SHA-3: 224 to 512 bit digest, adopted in August of 2015
- CRC32: not cryptographic, very poor choice

Example algorithms

- MD5: 128-bit digest, seriously broken
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- SHA-3: 224 to 512 bit digest, adopted in August of 2015
- CRC32: not cryptographic, very poor choice

Property #1

- Pre-image resistance
- Given *h*, it should be infeasible to find *m* such that *h* = *hash(m)*

Neither MD5 nor SHA-3 are broken in this way, but MD5 digests are small.

Property #2

- Second pre-image resistance
- Given a message m_1, it should be infeasible to find another message m_2 such that...
  $hash(m_1) = hash(m_2)$

Neither MD5 nor SHA-3 are broken in this way, but MD5 digests are small.

Property #3

- Collision resistance
- It should be infeasible to find two messages, m_1 *and* m_2 such that...
  $hash(m_1) = hash(m_2)$

SHA-3 is not broken in this way, MD5 broken in seconds on your laptop, SHA-1 with $100K or so.

Wang Xiaoyun

- Tsinghua University
- Contributed a lot of ideas to cracking MD5, SHA-0, and SHA-1

Length extension attack

```
jedi@mariposa:~$ echo "password='lDEnr45#d3'&donut=choc&quantity=1" | md5sum
91a9fc74a98997dba291a26a91c9648e  -
jedi@mariposa:~$ echo "password='lDEnr45#d3'&donut=choc&quantity=100" | md5sum
8fdd2d4515bcba887b1b80a653f21e0c  -
```

```
jedi@mariposa:~$ echo "password=[redacted]'&donut=choc&quantity=1" | md5sum
91a9fc74a98997dba291a26a91c9648e  -
jedi@mariposa:~$ echo "password=[redacted]'&donut=choc&quantity=100" | md5sum
8fdd2d4515bcba887b1b80a653f21e0c  -
```

MD5 and SHA-1 vulnerable, SHA-3 is not

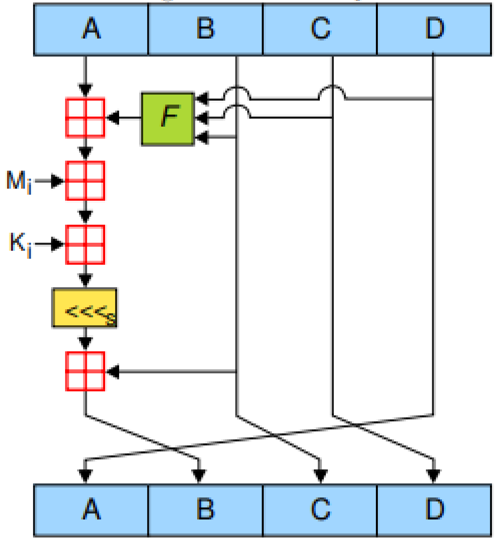
Length extension attack

- One issue is if the attacker doesn’t know the password
- Another issue is if the password is different but the attacker finds a collision later on
- MD5 and SHA-1 are vulnerable, SHA-3 is not

MD5

- Pad to multiple of 512 bits
- 4 rounds
- 4 32-bit words at a time
- Concatenate them at the end for a 128-bit digest
- F is non-linear, varies by round

Fig. 1. One MD5 step

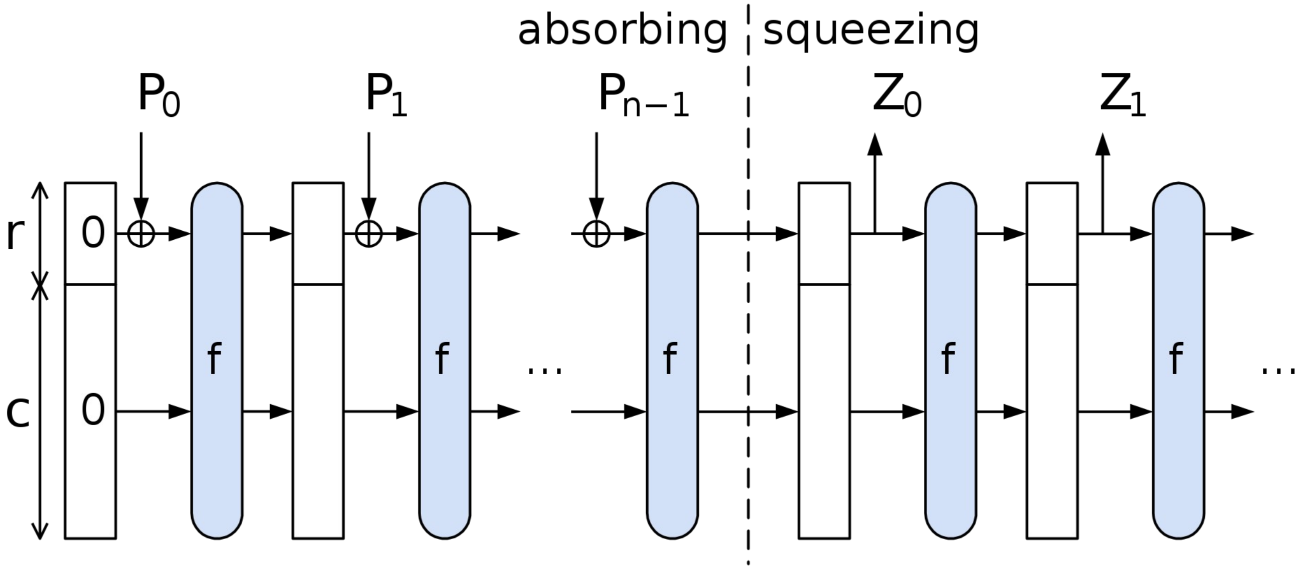


Round (i)	$F(X,Y,Z)$	g
0	$(X \wedge Y) \vee (\neg X \wedge Z)$	i
1	$(X \wedge Z) \vee (Y \wedge \neg Z)$	$(5 \times i + 1) \bmod 16$
2	$(X \oplus Y \oplus Z)$	$i(3 \times i + 5) \bmod 16$
3	$(Y \oplus (X \vee \neg Z))$	$(7 \times i) \bmod 16$

http://koclab.cs.ucsb.edu/teaching/cren/project/2008/savage.pdf

SHA-3

- Sponge construction, 1600 bits of internal state

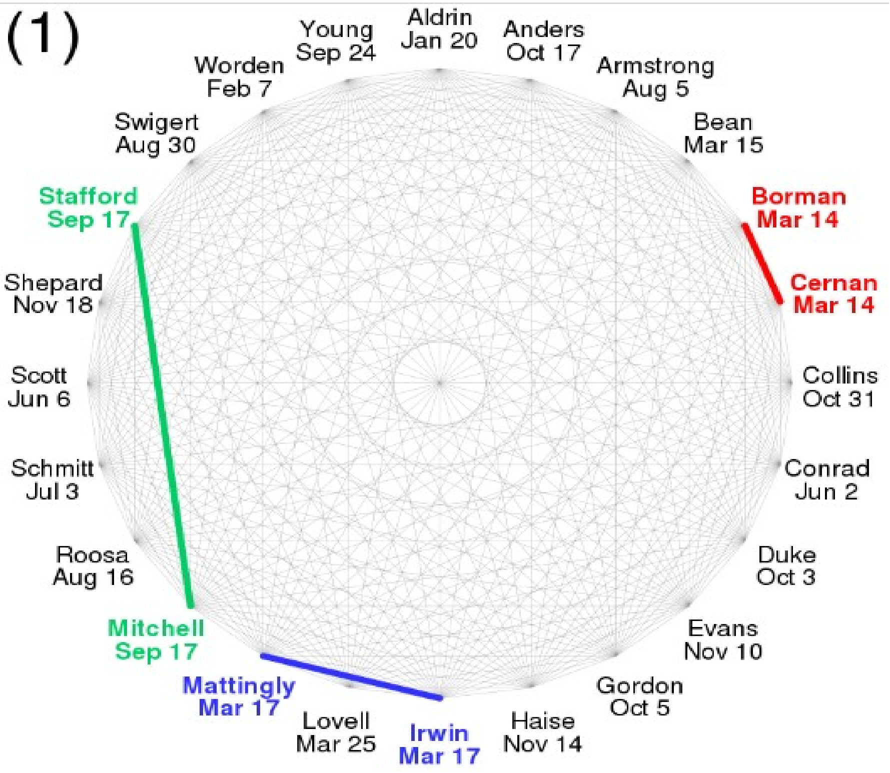


https://en.wikipedia.org/wiki/SHA-3

Birthday attack

- Probability of collision is *1* in 2^n, but the expected number of hashes until two of them collide is $sqrt(2^n)=2^{n/2}$
  - Why? Third try has two opportunities to collide, fourth has three opportunities, fifth has six, and so on...

24 people, same birthday?



https://commons.wikimedia.org/wiki/File:Birthday_attack_vs_paradox.svg

Chosen-prefix collision attack

- Given two prefixes p_1 and p_2, find m_1 and m_2 such that $hash(p_1||m_1)=hash(p_2||m_2)$
- p1 and p2 could be domain names in a certificate, images, PDFs, *etc.* … any digital image.

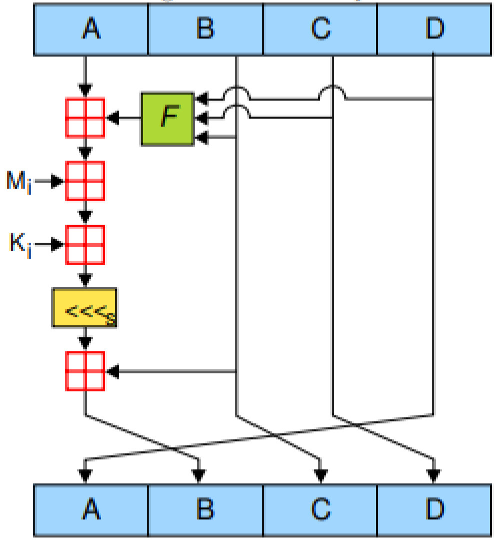
Ingredients for a practical chosen prefix attack on MD5

- Collision attack on MD5
  - That works for any initialization vector (so you can put bits in front)
- Length extension attack
  - So you can put identical bits on the end
- Birthday attack
  - So you can bridge the prefix to a block that meets the requirements of the collision attack

MD5 collision attack by Wang and Yu

$$C_0 = (0, 0, 0, 0, 2^{31}, 0, 0, 0, 0, 0, 0, 2^{15}, 0, 0, 2^{31}, 0)$$
and
$$C_1 = (0, 0, 0, 0, 2^{31}, 0, 0, 0, 0, 0, 0, -2^{15}, 0, 0, 2^{31}, 0)$$

Fig. 1. One MD5 step



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1	$(X \wedge Z) \vee (Y \wedge \neg Z)$	$(5 \times i + 1)$ mod 16
2	$(X \oplus Y \oplus Z)$	$i(3 \times i + 5)$ mod 16
3	$(Y \oplus (X \vee \neg Z))$	$(7 \times i)$ mod 16

http://koclab.cs.ucsb.edu/teaching/cren/project/2008/savage.pdf

An example

Both have digest 79054025255fb1a26e4bc422aef54eb4

```
d131dd02c5e6eec4693d9a0698aff95c2fcab58712467eab4004583eb8fb7f89
55ad340609f4b30283e488832571415a085125e8f7cdc99fd91dbdf280373c5b
d8823e3156348f5bae6dacd436c919c6dd53e2b487da03fd02396306d248cda0
e99f33420f577ee8ce54b67080a80d1ec69821bcb6a8839396f9652b6ff72a70
```

```
d131dd02c5e6eec4693d9a0698aff95c2fcab50712467eab4004583eb8fb7f89
55ad340609f4b30283e4888325f1415a085125e8f7cdc99fd91dbd7280373c5b
d8823e3156348f5bae6dacd436c919c6dd53e23487da03fd02396306d248cda0
e99f33420f577ee8ce54b67080280d1ec69821bcb6a8839396f965ab6ff72a70
```

https://www.mscs.dal.ca/~selinger/md5collision/

Short Chosen-Prefix Collisions for MD5 and the Creation of a Rogue CA Certificate

Marc Stevens[1], Alexander Sotirov[2],
Jacob Appelbaum[3], Arjen Lenstra[4,5], David Molnar[6],
Dag Arne Osvik[4], and Benne de Weger[7]

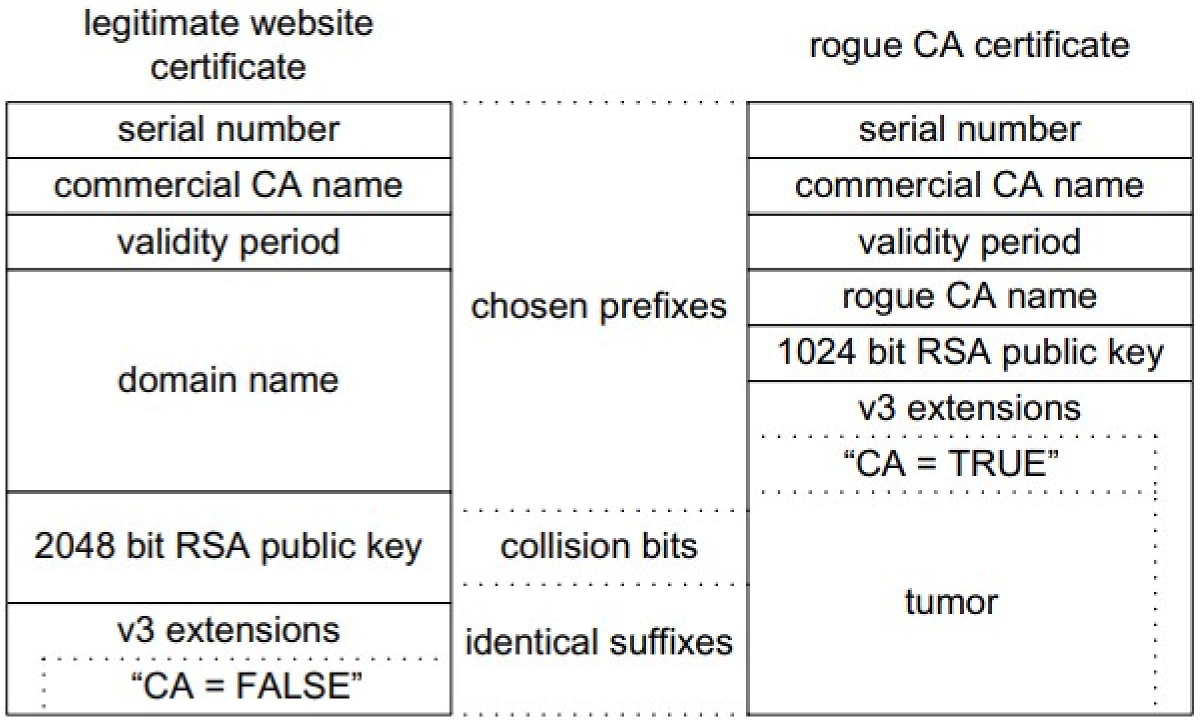
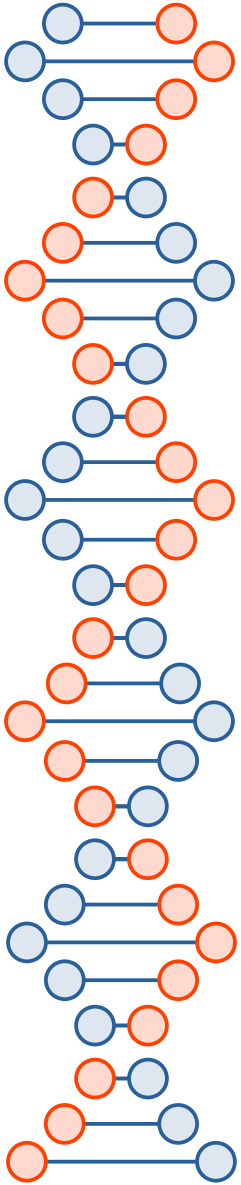
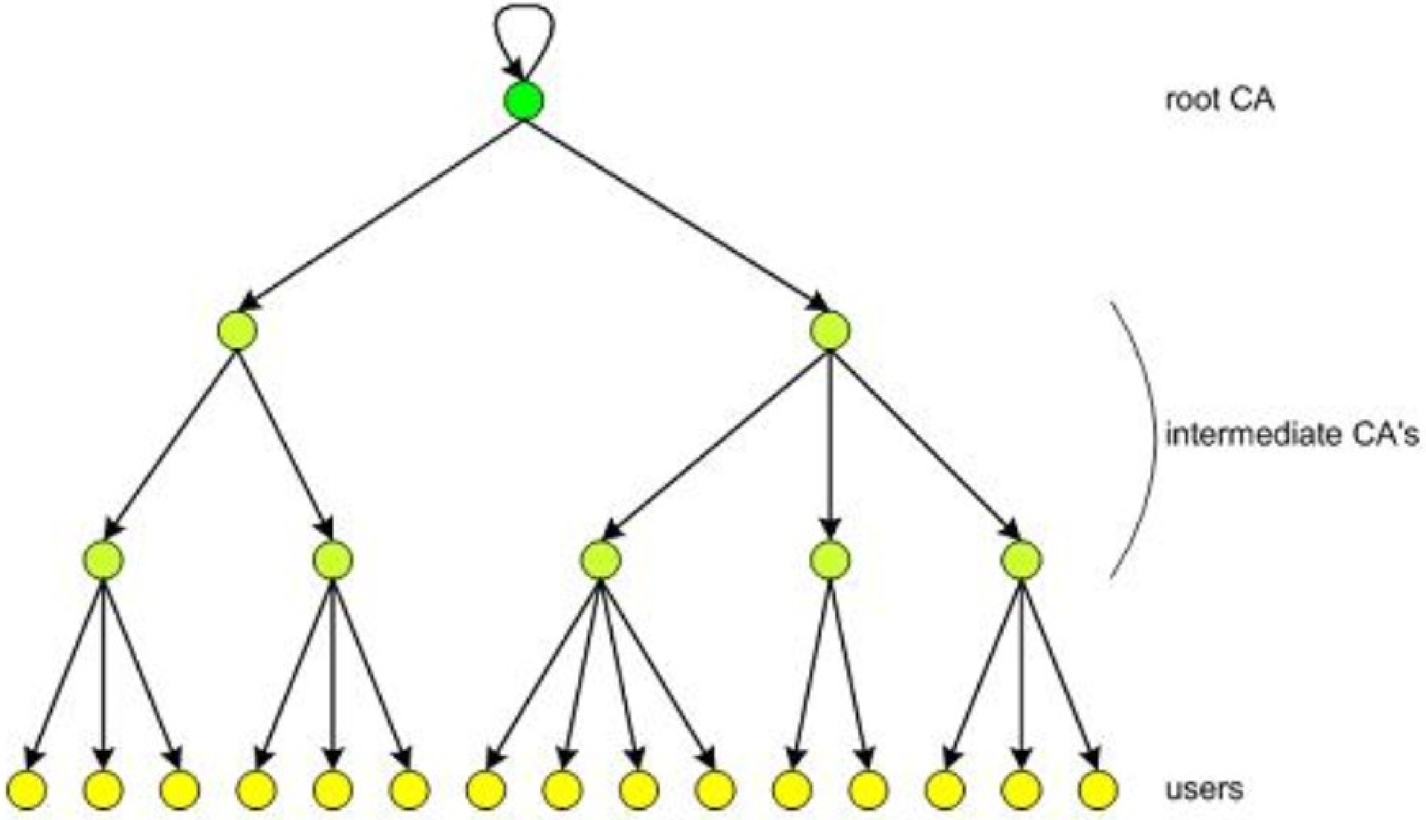


Fig. 1. The to-be-signed parts of the colliding certificates

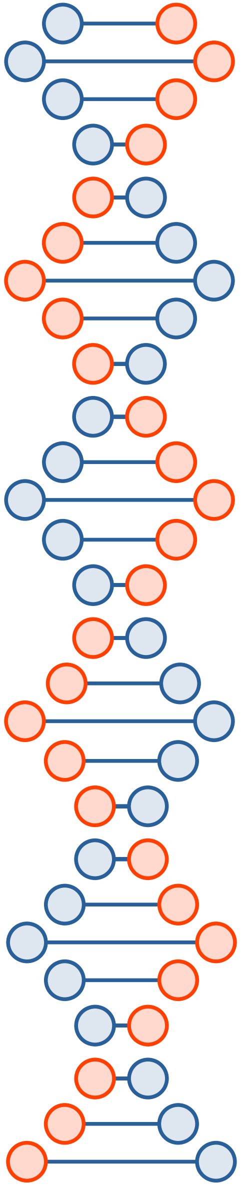




Slide from MD5 Considered Harmful Today, Creating a rogue CA certificate by Sotirov *et al.*

CN=Starfield Services Root Certificate Authority - G2,O=Starfield Technologies, Inc.,L=Scottsdale,ST=Arizona,C=US

CN=COMODO RSA Certification Authority,O=COMODO CA Limited,L=Salford,ST=Greater Manchester,C=GB



CN=Amazon Root CA 3,O=Amazon,C=US

CN=Microsoft RSA Root Certificate Authority 2017,O=Microsoft Corporation,C=US

CN=Autoridad de Certificacion Firmaprofesional CIF A62634068,C=ES

OU=certSIGN ROOT CA G2,O=CERTSIGN SA,C=RO

CN=TUBITAK Kamu SM SSL Kok Sertifikasi - Surum 1,OU=Kamu Sertifikasyon Merkezi - Kamu SM,O=Turkiye Bilimsel ve Teknolojik Arastirma Kurumu - TUBITAK,L=Gebze - Kocaeli,C=TR

CN=CFCA EV ROOT,O=China Financial Certification Authority,C=CN

CN=GlobalSign,OU=GlobalSign ECC Root CA - R5,O=GlobalSign

Preparation for next lecture...

https://www.youtube.com/watch?v=fZ1R9RliM1w

References

- [Cryptography Engineering] *Cryptography Engineering: Design Principles and Applications,* by Niels Ferguson, Bruce Schneier, and Tadayoshi Kohno. Wiley Publishing, 2010.
- Lots of images and info plagiarized from Wikipedia