Hashes, certificates, OTR and Signal

CSE 548 Spring 2025

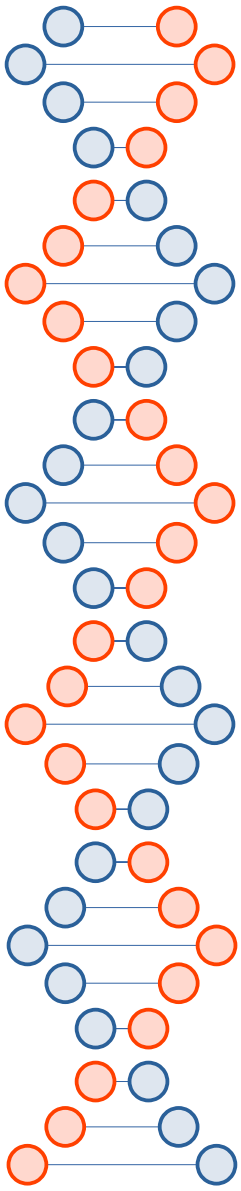
jedimaestro@asu.edu

How do you know who you’re talking to when you do encryption?

Authentication and non-repudiation

What if your private key gets stolen?

Forward secrecy and future secrecy



Check out...

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

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

Home -

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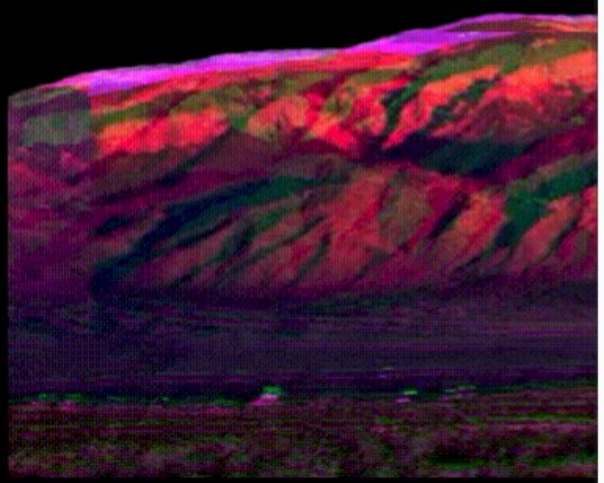


We are a non-profit founded in 20 ut

combined experience focusing on

goal is to provide technical expertise and capabilities to at-risk populations subjected t

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

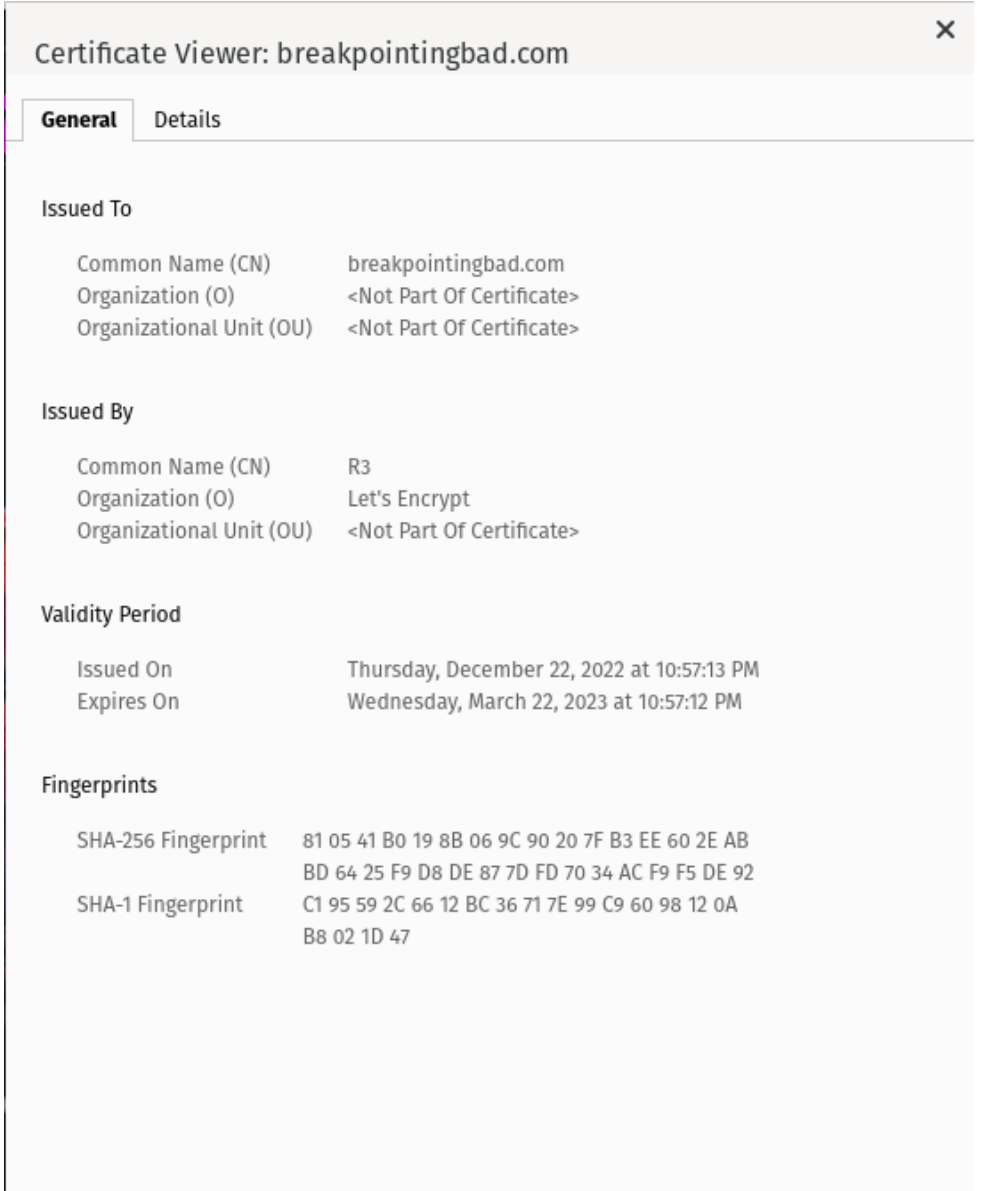
Common Name (CN)	R3
Organization (O)	Let's Encrypt
Organizational Unit (OU)	<Not Part Of Certificate>

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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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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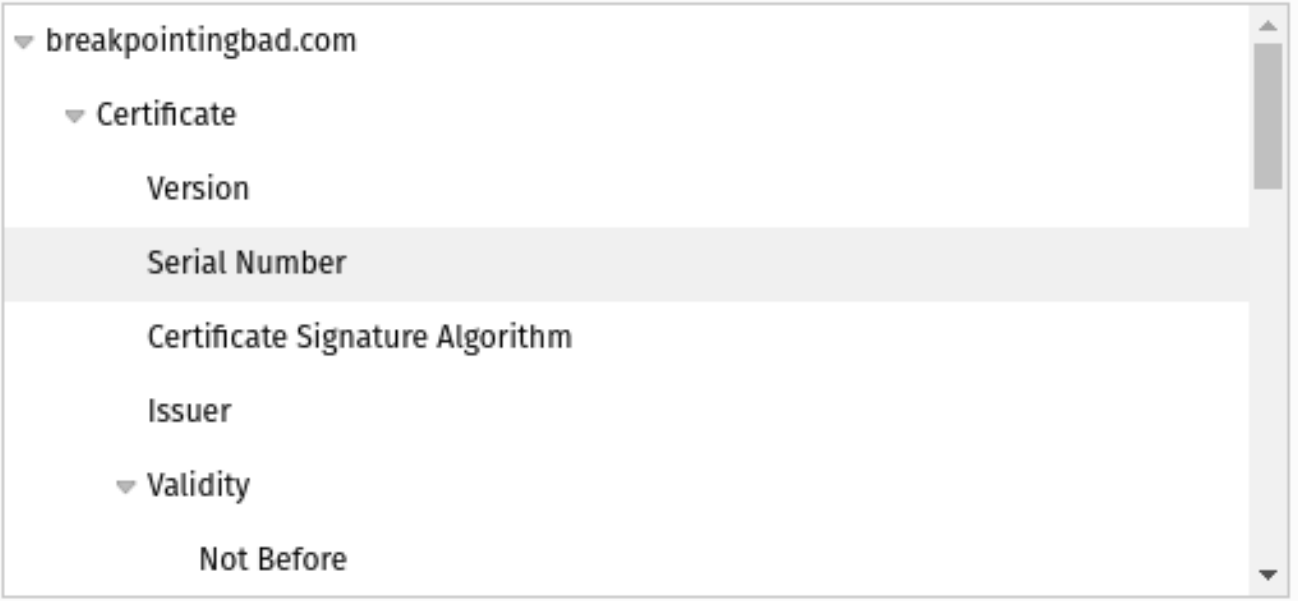
Certificate Fields



Field Value

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

Export...

breakpointingbad.com

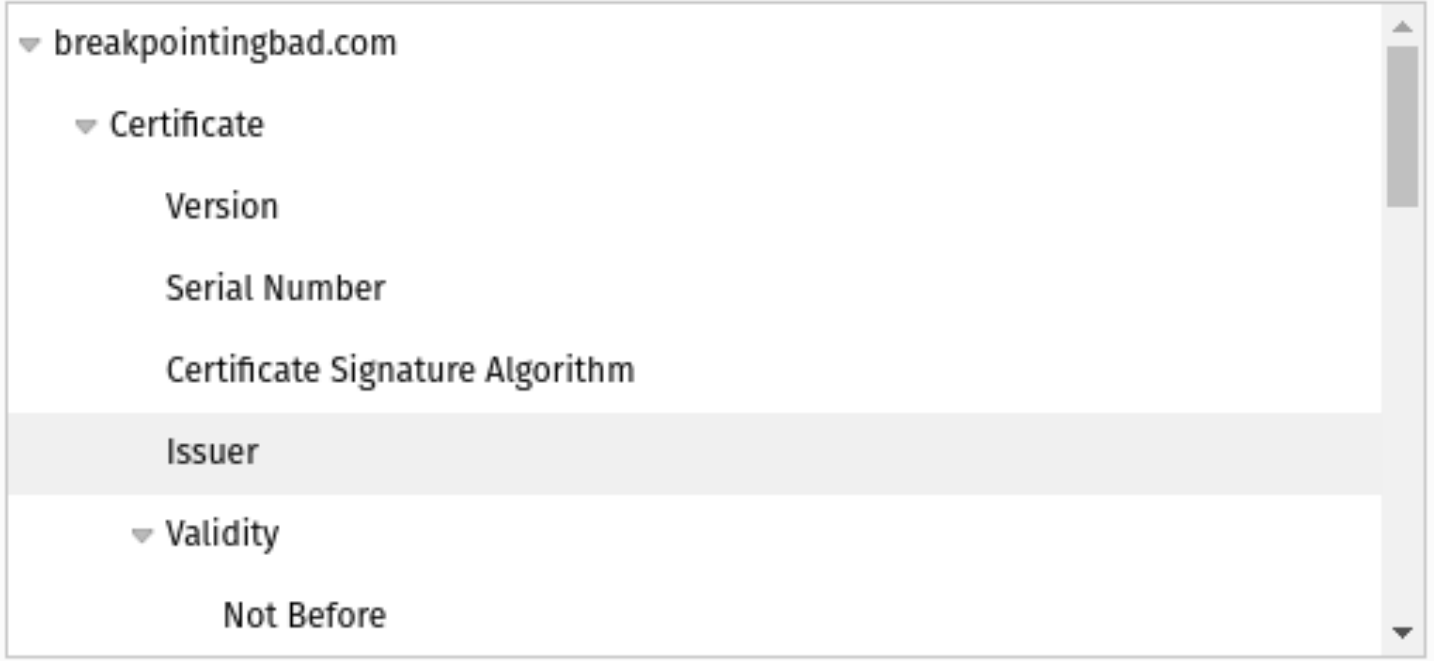
Certificate Fields

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

Field Value

PKCS #1 SHA-256 With RSA Encryption

Certificate Fields



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...

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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

CN = breakpointingbad.com

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Certificate Fields

Not After

Subject

Subject Public Key Info

Subject Public Key Algorithm

Subject's Public Key

Extensions

Certificate Key Usage

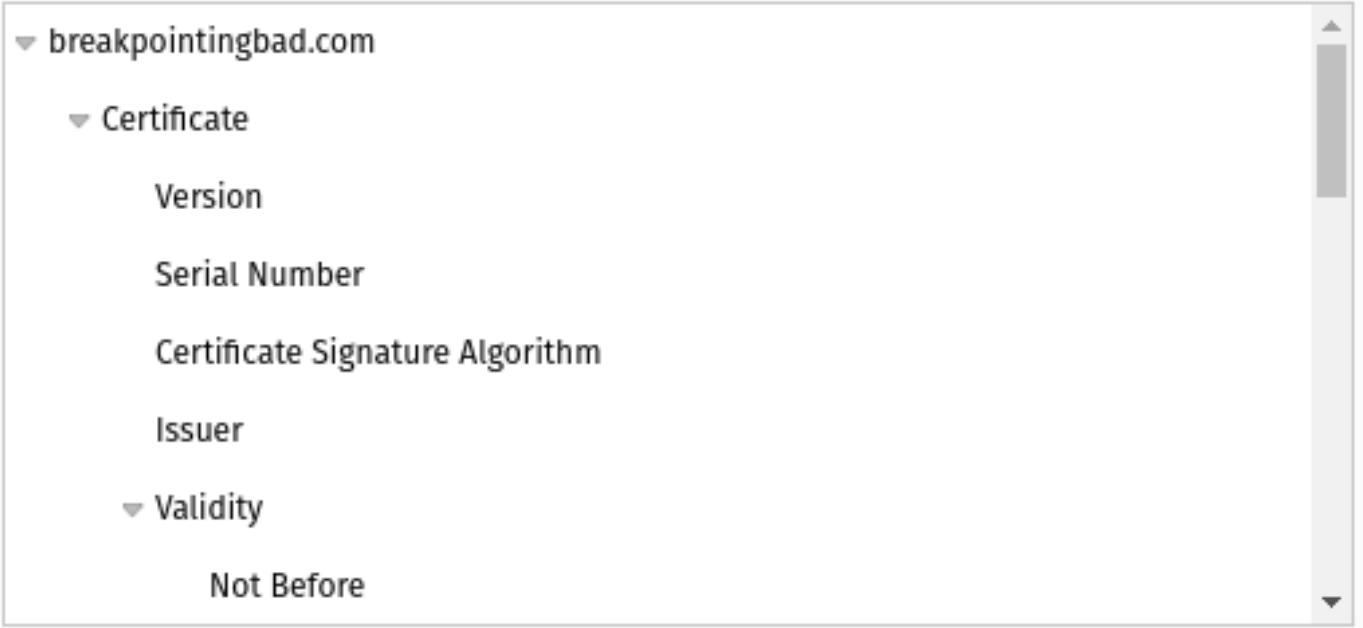
Extended Key Usage

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 FF F4 B5 AD 0A 94 75 AA F9 41

Export...

Certificate Fields



Field Value

Export...

Certificate Hierarchy

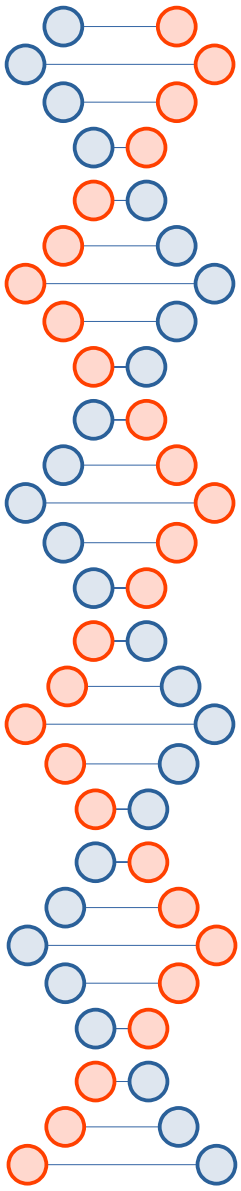
- Builtin Object Token:ISRG Root X1
  - R3
    - breakpointingbad.com

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

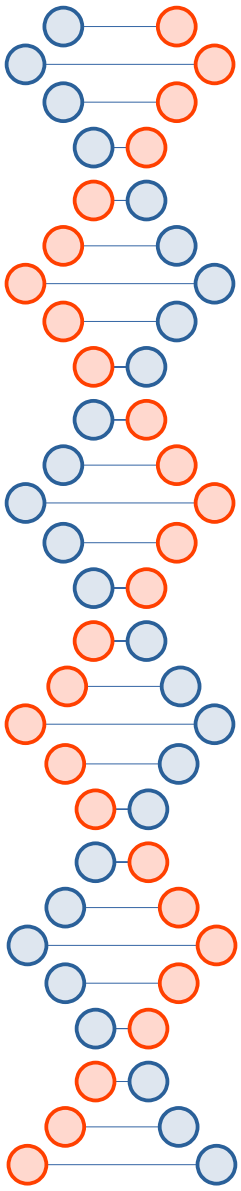
Field Value

Critical
Is not a Certification Authority



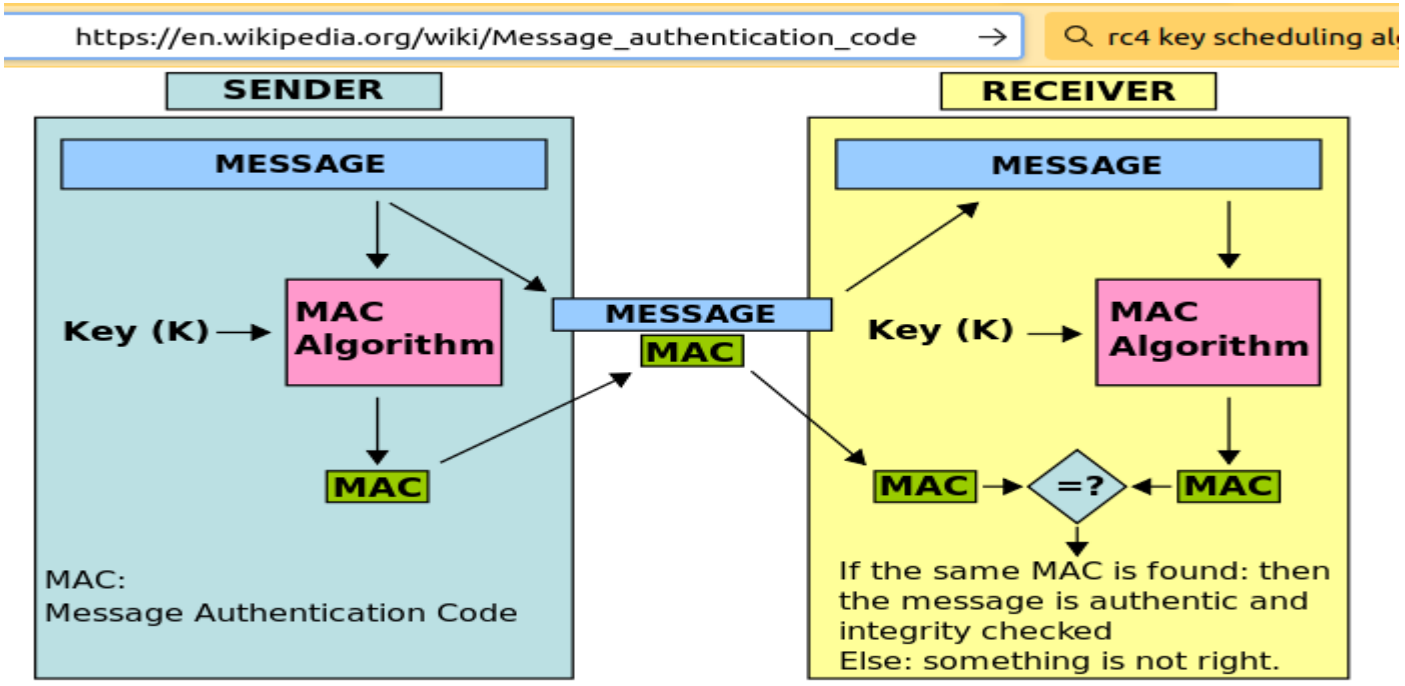
Why hash functions?

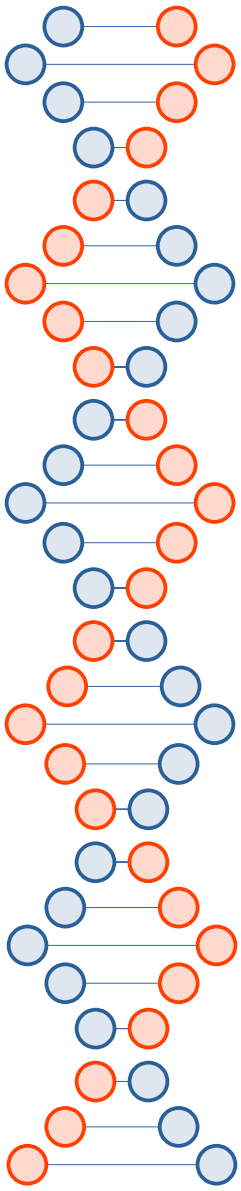
- Speed
  - Symmetric crypto is generally faster than asymmetric
  - Hashes are generally faster than either
- Error detection (*e.g.*, checksum)
- Security and privacy



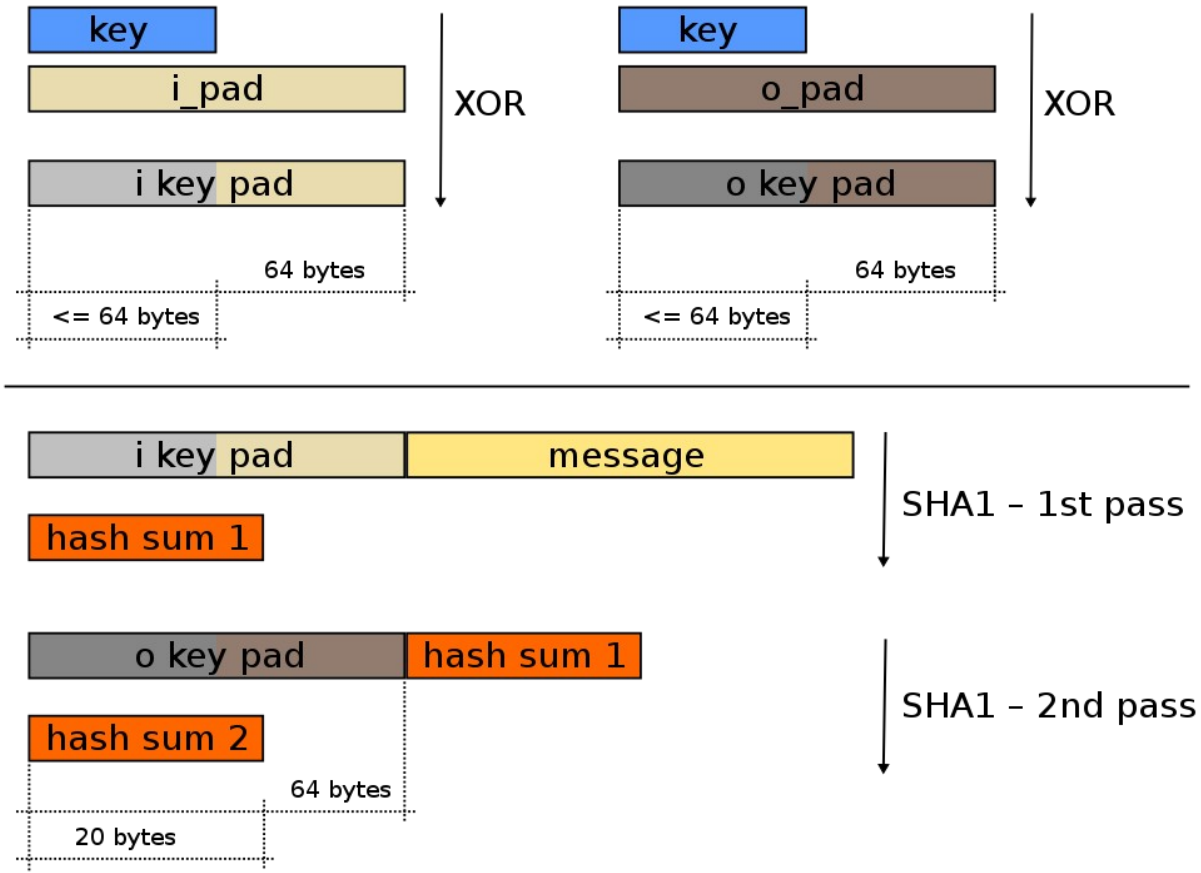
Why cryptographic hash functions?

- 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

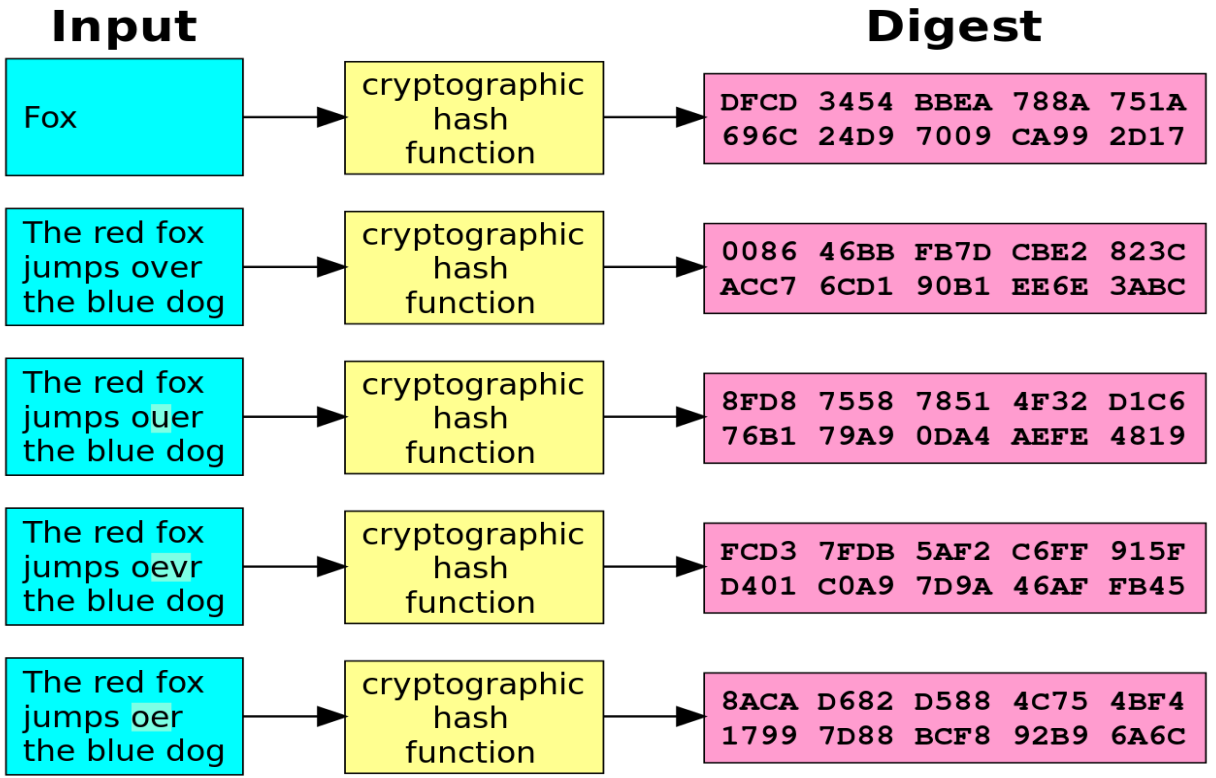

https://en.wikipedia.org/wiki/Message_authentication_code
rc4 key scheduling al
SENDER
RECEIVER
MESSAGE
MESSAGE
Key (K)
MAC Algorithm
MESSAGE
MAC
Key (K)
MAC Algorithm
MAC
MAC
=?
MAC
MAC:
Message Authentication Code
If the same MAC is found: then the message is authentic and integrity checked
Else: something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

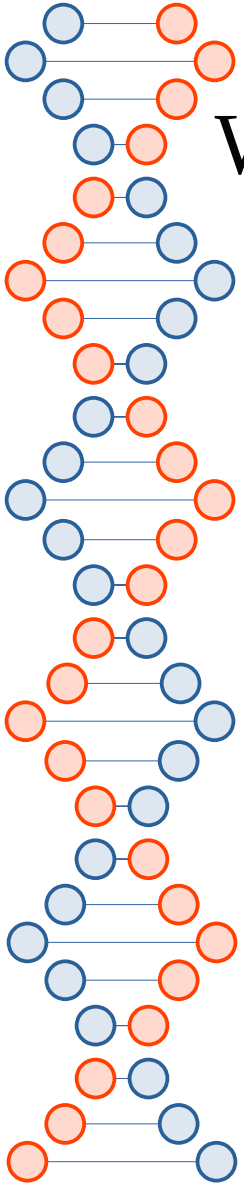


https://en.wikipedia.org/wiki/HMAC



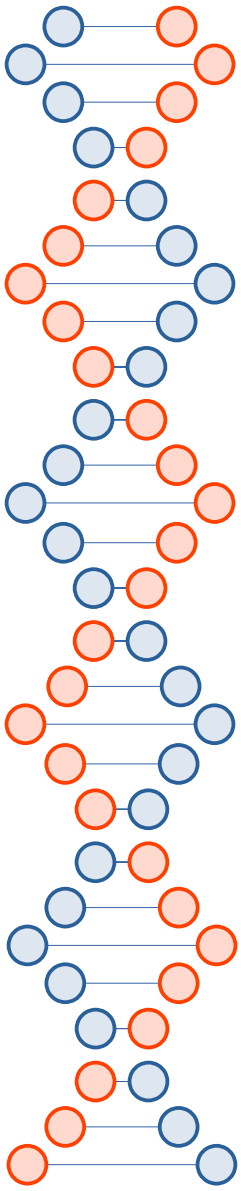
Hash function example





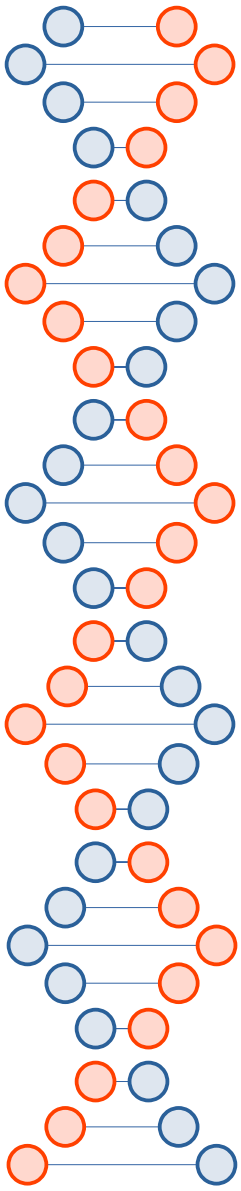
What makes a hash function cryptographic?

- 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-2: 224 to 512 bit digest
  - Merkle–Damgård construction
- SHA-3: 224 to 512 bit digest
  - Sponge construction
  - adopted in August of 2015
- CRC32: not cryptographic, very poor choice



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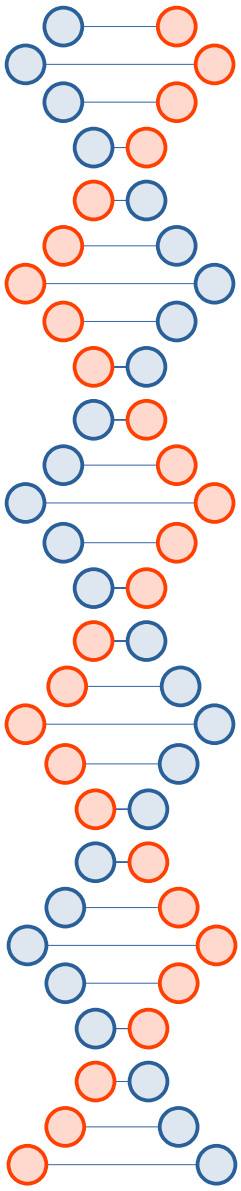
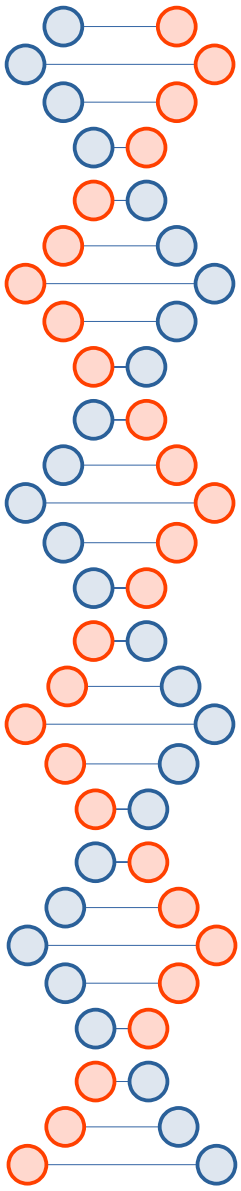


Property #1

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

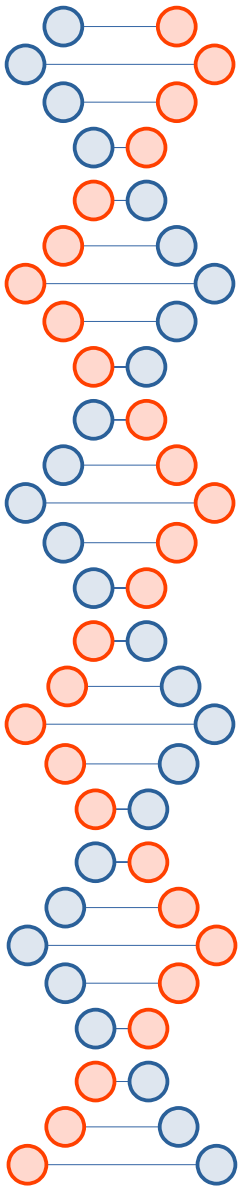
Neither MD5 nor SHA-3 are broken in this way, but MD5 digests are small.



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

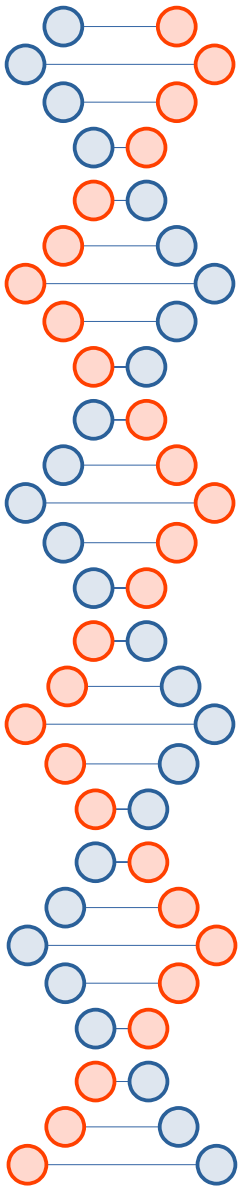
- Tsinghua University
- Contributed a lot of ideas to cracking MD5, SHA-0, and SHA-1

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-2 basically is, SHA-3 is not



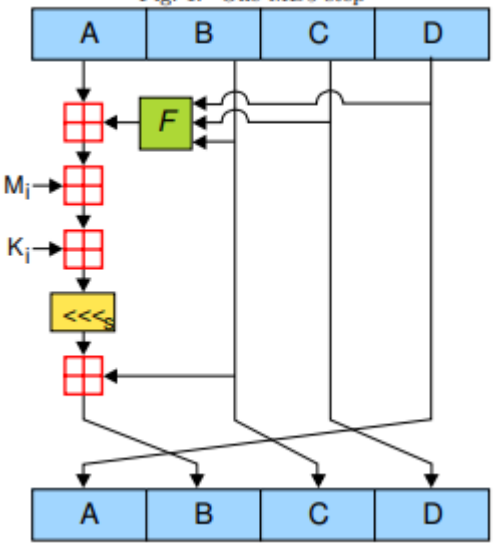
Length extension attack

- 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

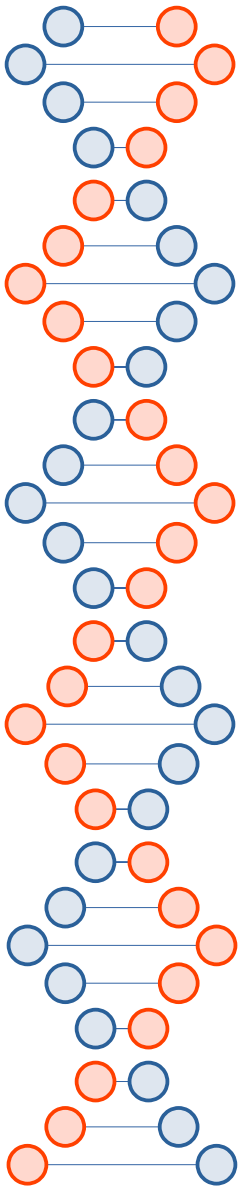
- Pad to multiple of 512 bits
- 4 rounds
- 4 32-bit words at a time
- Concatenate them at the end for a 128-bit digest
- F is non-linear, varies by round

Fig. 1. One MD5 step



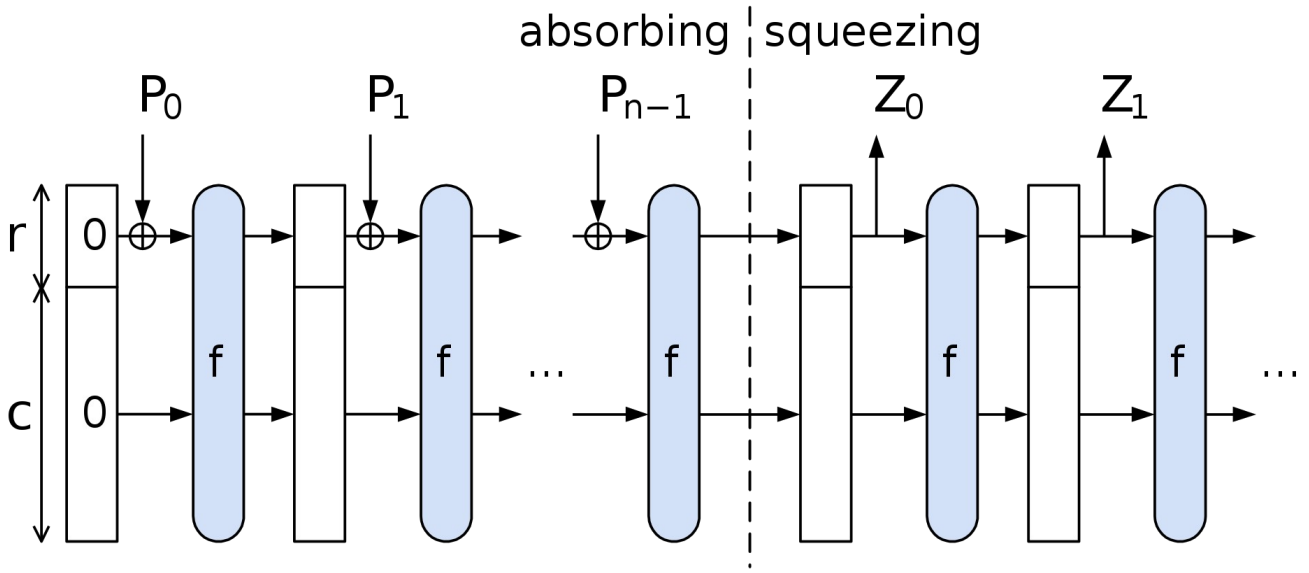
Round (i)	$F(X,Y,Z)$	g
0	$(X \wedge Y) \vee (\neg X \wedge Z)$	i
1	$(X \wedge Z) \vee (Y \wedge \neg Z)$	$(5 \times i + 1) \bmod 16$
2	$(X \oplus Y \oplus Z)$	$i(3 \times i + 5) \bmod 16$
3	$(Y \oplus (X \vee \neg Z))$	$(7 \times i) \bmod 16$

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

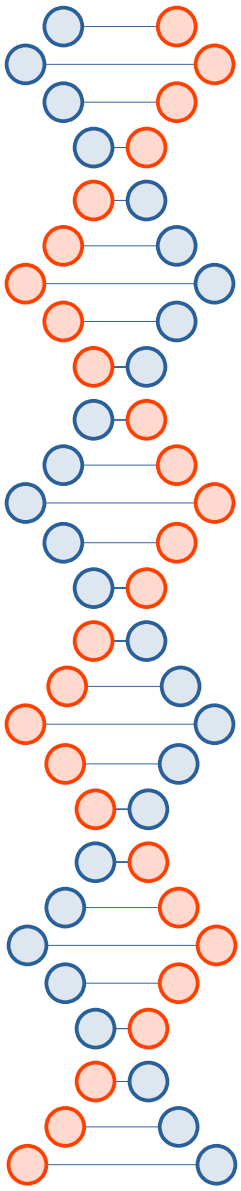


SHA-3

- Sponge construction, 1600 bits of internal state



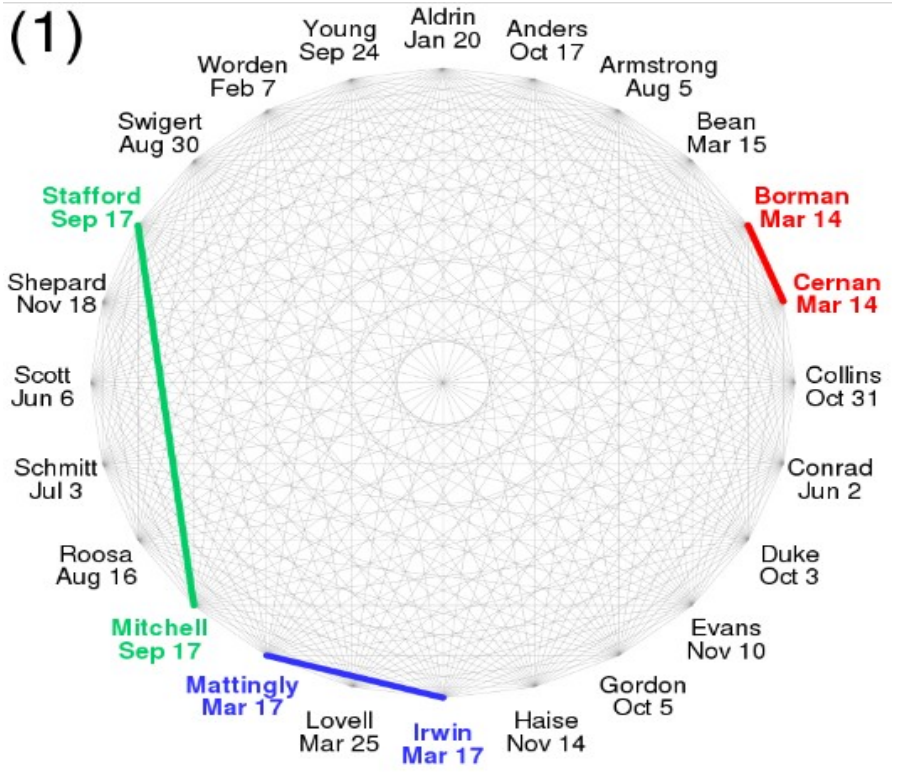
https://en.wikipedia.org/wiki/SHA-3



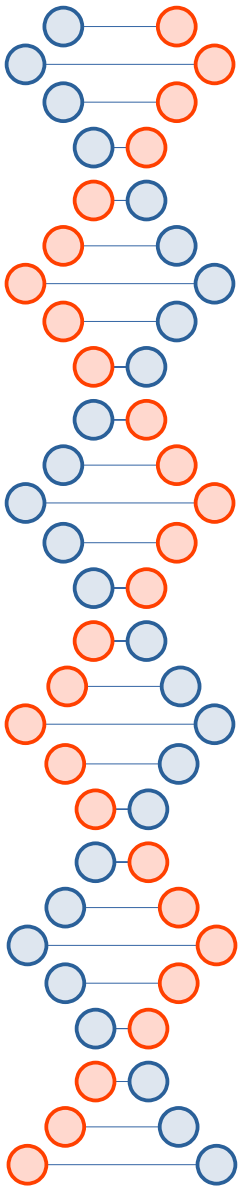
Birthday attack

- 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?

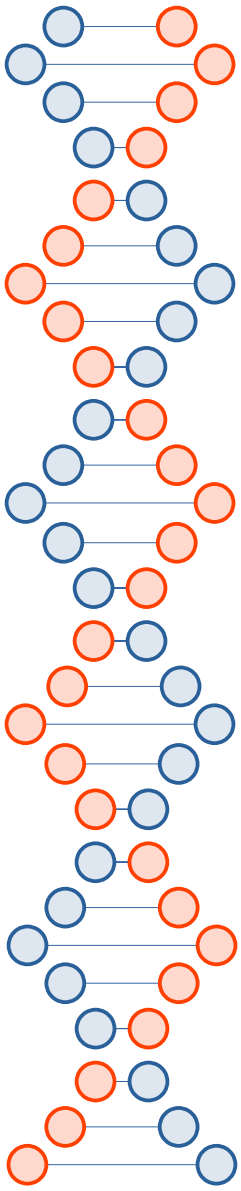


https://commons.wikimedia.org/wiki/File:Birthday_attack_vs_paradox.svg



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.



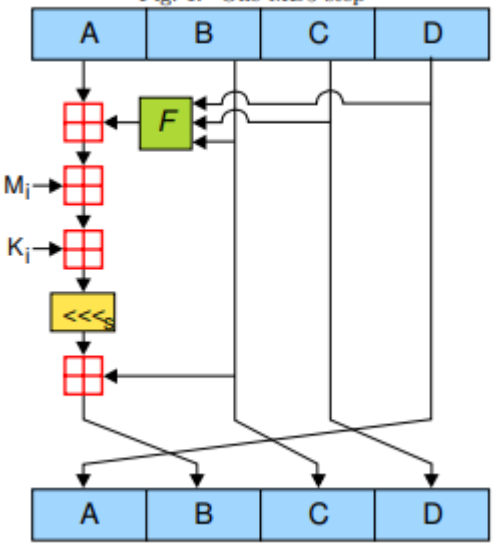
Ingredients for a practical chosen prefix attack on MD5

- 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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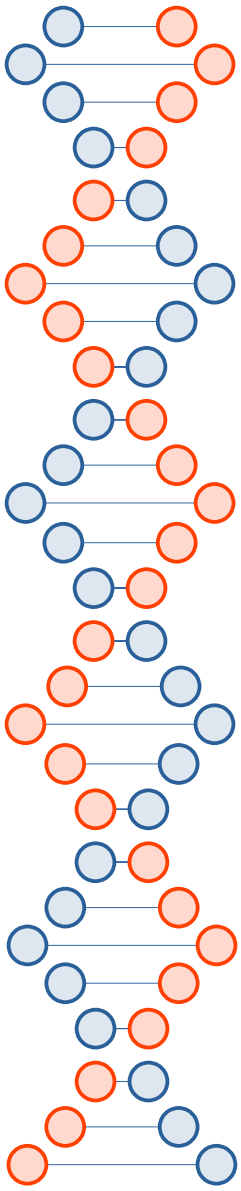


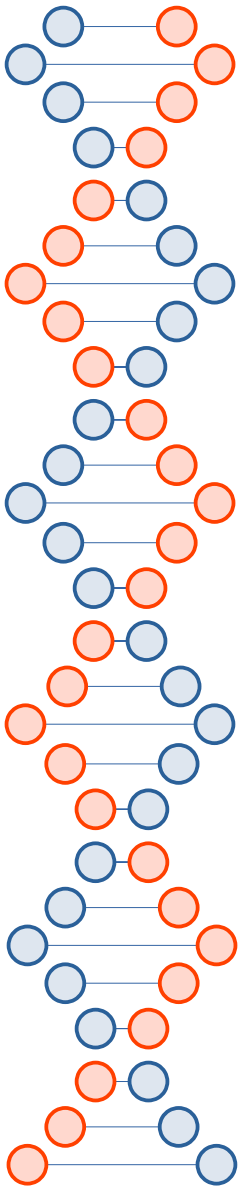
An example

Both have digest 79054025255fb1a26e4bc422aef54eb4

```
d131dd02c5e6eec4693d9a0698aff95c2fcab58712467eab4004583eb8fb7f89
55ad340609f4b30283e4888325 71415a085125e8f7cdc99fd91dbdf280373c5b
d8823e3156348f5bae6dacd436c919c6dd53e2b487da03fd02396306d248cda0
e99f33420f577ee8ce54b67080a80d1ec69821bcb6a8839396f9652b6ff72a70
```

```
d131dd02c5e6eec4693d9a0698aff95c2fcab50712467eab4004583eb8fb7f89
55ad340609f4b30283e4888325f1415a085125e8f7cdc99fd91dbd7280373c5b
d8823e3156348f5bae6dacd436c919c6dd53e23487da03fd02396306d248cda0
e99f33420f577ee8ce54b6708028 0d1ec69821bcb6a8839396f965ab6ff72a70
```

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]

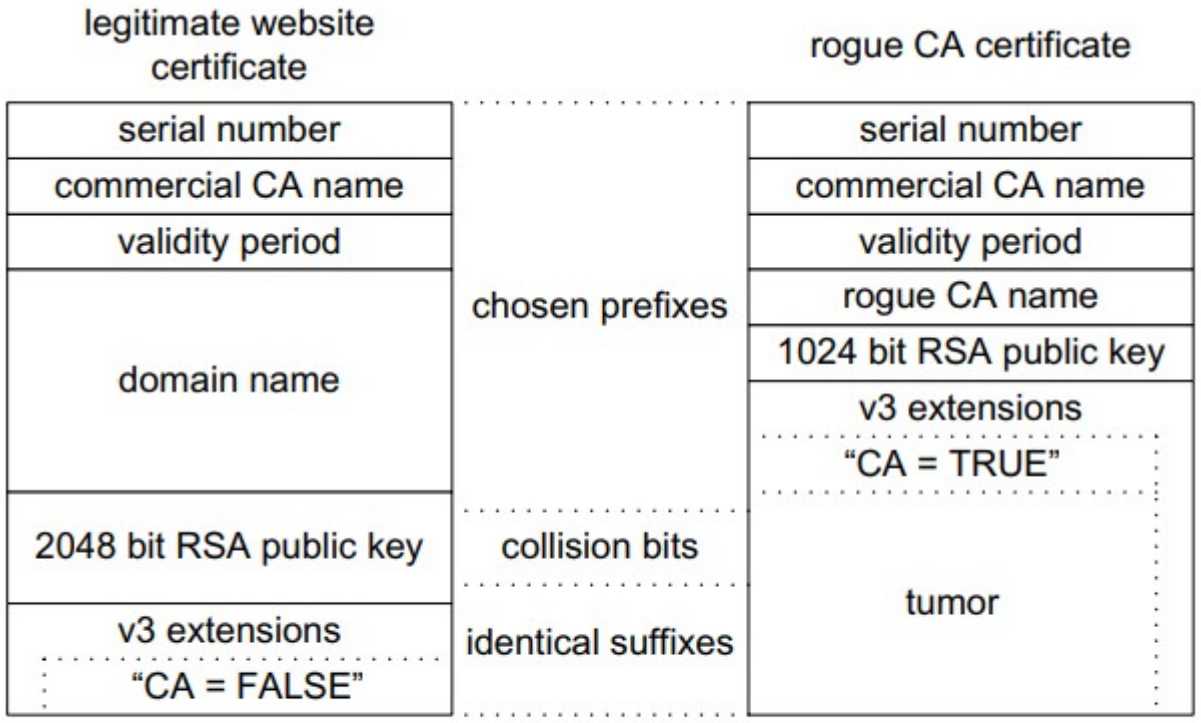
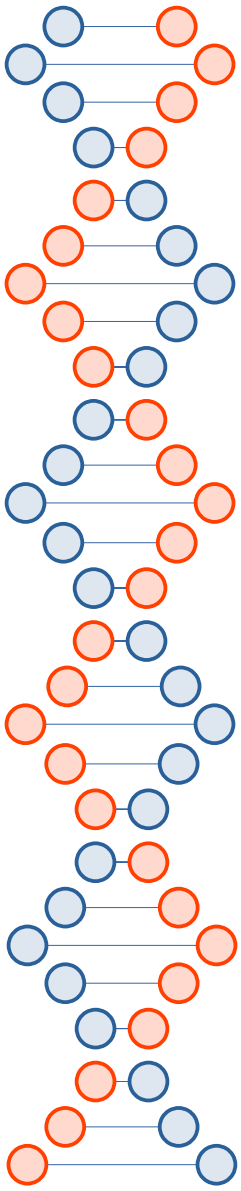
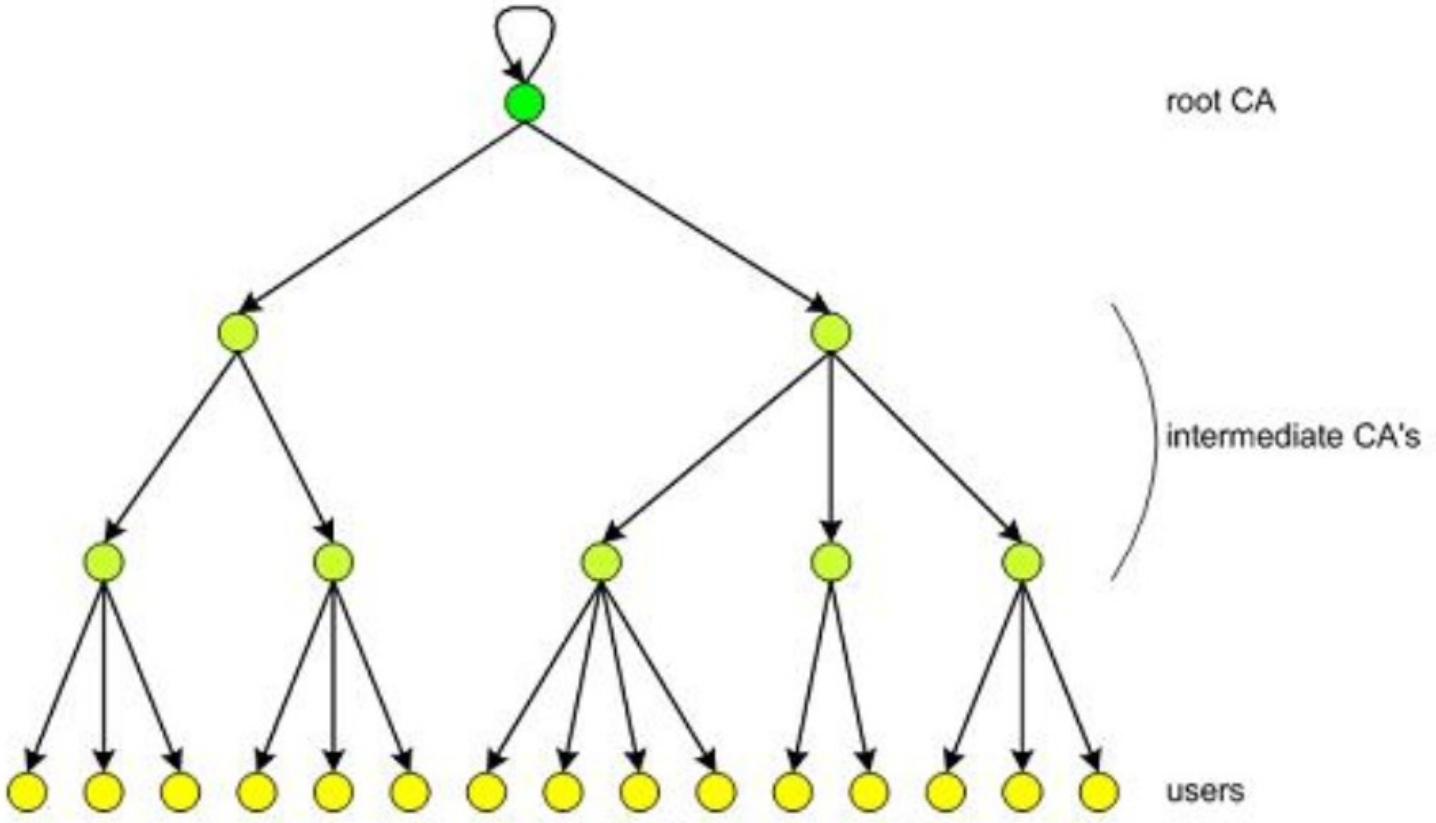
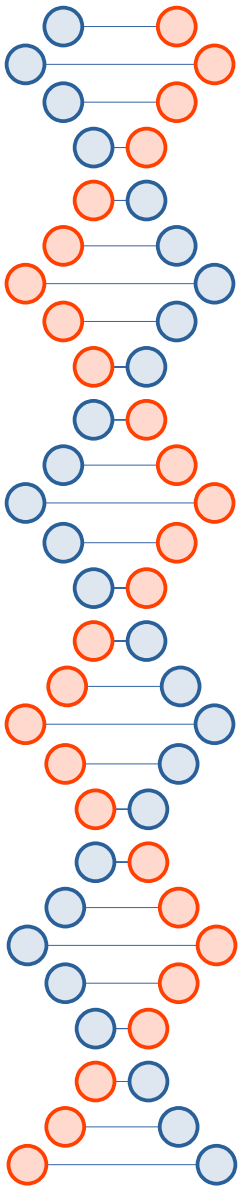


Fig. 1. The to-be-signed parts of the colliding certificates





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



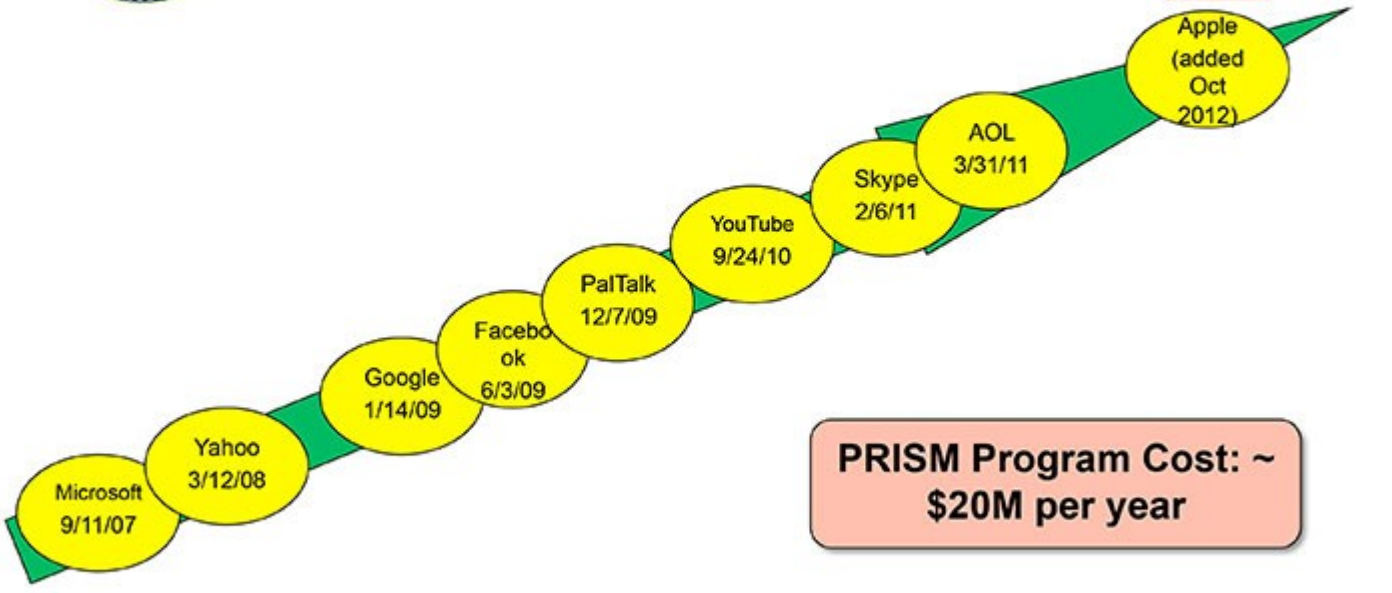
OTR and Signal...

https://en.wikipedia.org/wiki/Source_(journalism)

- **"On the record"**: all that is said can be quoted and attributed.
- **"Unattributable"**: what is said can be reported but not attributed.
- **"Off the record"**: the information is provided to inform a decision or provide a confidential explanation, not for publication.

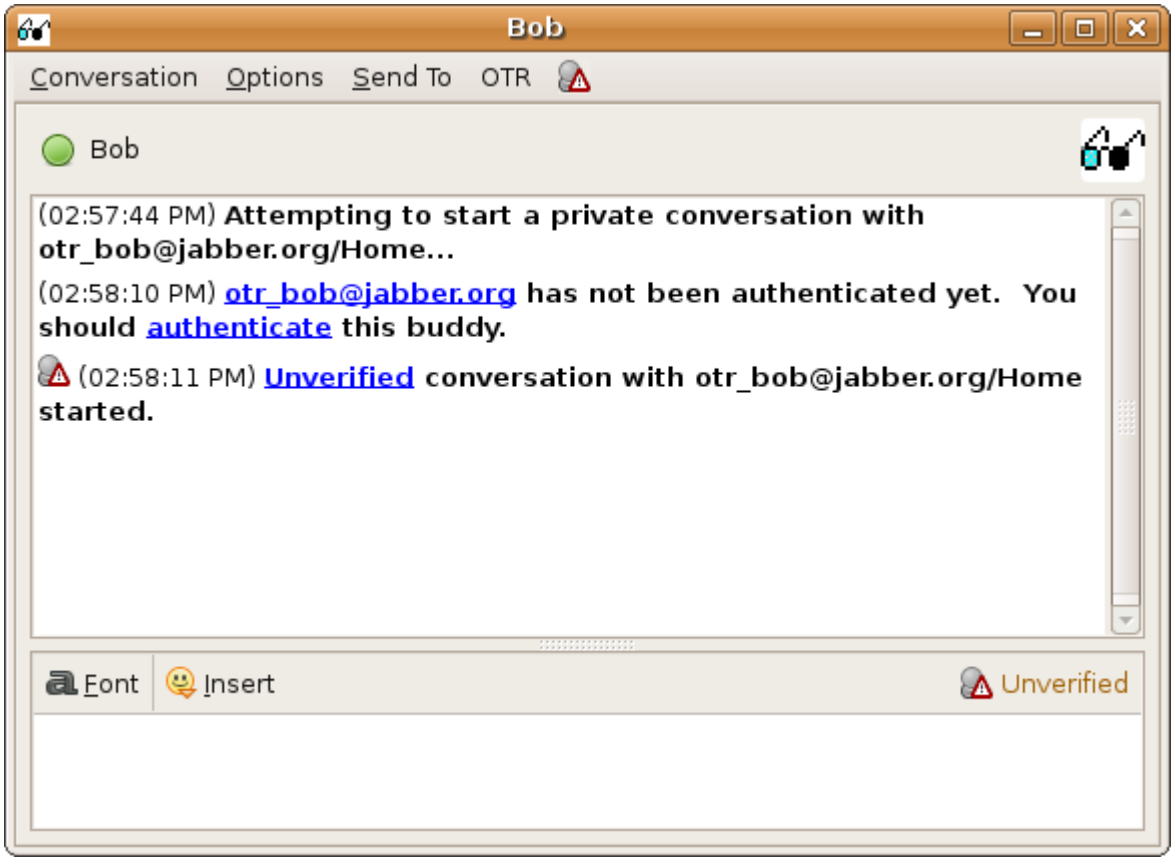
https://www.theguardian.com/film/2014/oct/11/citizenfour-review-snowden-vindicated-poitras-nsa-journalism

(TS//SI//NF) Dates When PRISM Collection Began For Each Provider



OTR

- Off-The-Record messaging
- 2004, Nikita Borisov, Ian Goldberg, Eric Brewer. "Off-the-Record Communication, or, Why Not To Use PGP"
- (PGP is from 1991, basically RSA for email)



https://otr.cypherpunks.ca/help/3.2.0/authenticate.php?lang=en

Requirements, OTR *vs.* TLS...

- Forward secrecy
  - Both OTR and TLS care, for different reasons
- Deniable authentication *a.k.a.* off-the-record
  - TLS doesn’t care about this, OTR does
- Future secrecy
  - TLS doesn’t care about this, OTR does it by accident
- Out-of-order messages, parties offline for long periods of time, groups…
  - TLS doesn’t need to worry about any of these, nor does OTR (Signal does)

Off-The-Record (OTR) Messaging

- Based on Diffie-Hellman and AES, and originally SHA-1
  - There are new versions
- Deniable Authentication
  - “Off the record” in journalism
- Forward secrecy
  - Ephemeral key exchange
- Future secrecy (not a design goal, but has it)

Deniable Authentication

- Concept of “malleability”
- Basic idea has two parts:
  - Hash the decryption key for a message, use the hash digest as an authentication key
  - Reveal the authentication key in the next message

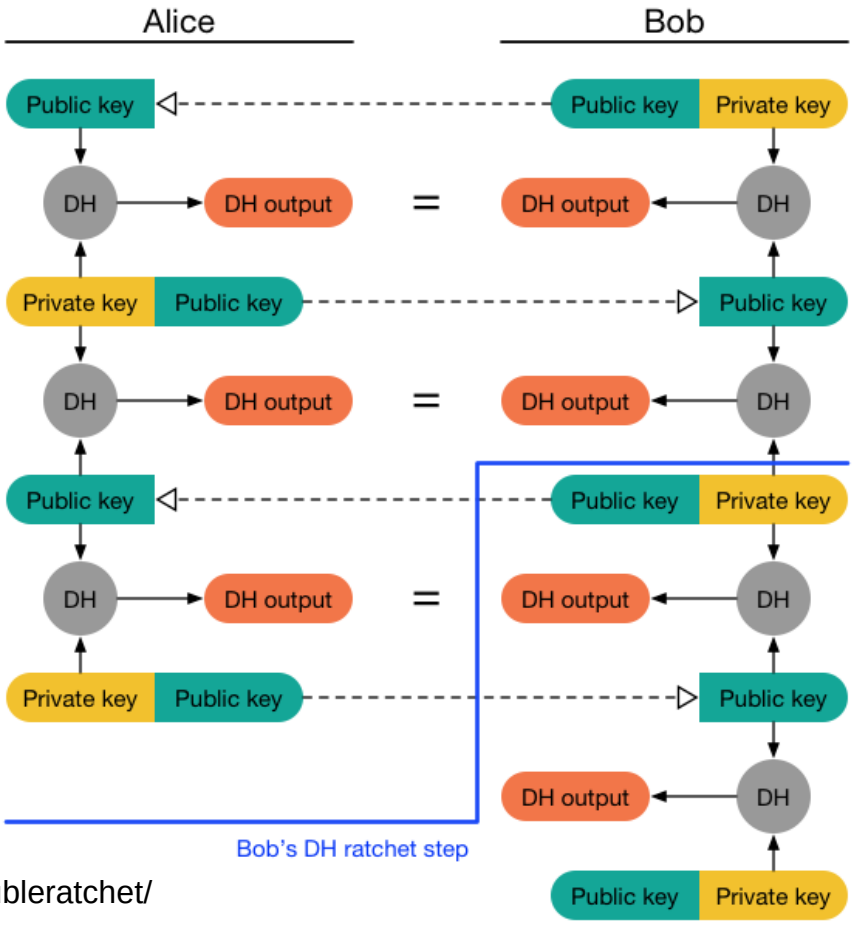
Forward secrecy

- If Alice or Bob’s key is compromised, past messages cannot be decrypted by the adversary

Ratchet in sailing...

https://www.westmarine.com/harken-snubbair-ratcheting-drum-19471861.html

Forward Secrecy (ratchet)



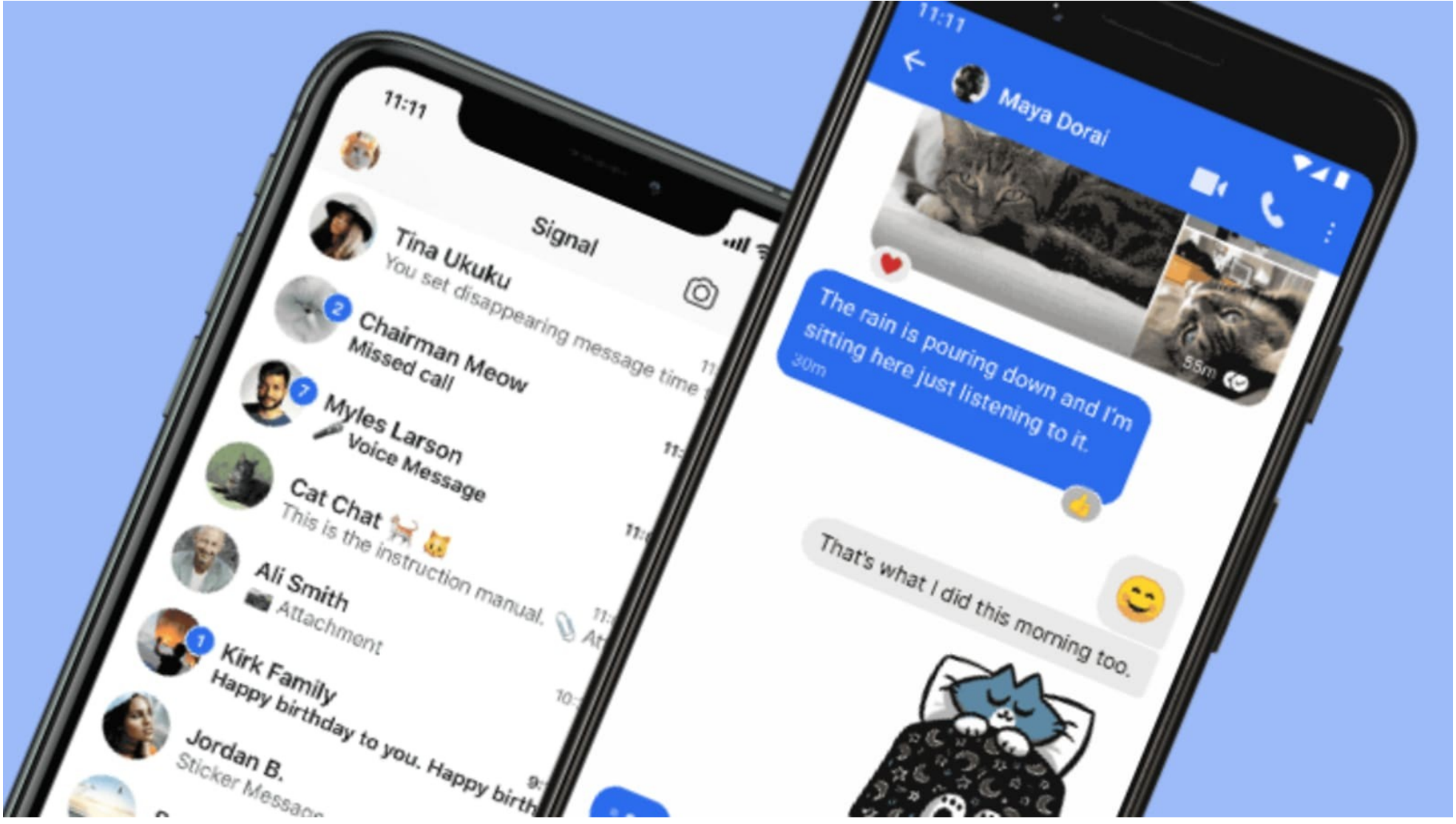
https://signal.org/docs/specifications/doubleratchet/

Future Secrecy

- *Future* secrecy is not the same as *forward* secrecy, and is in fact sometimes called *backward* secrecy
- If a private key is compromised, the attacker needs to intercept every message thereafter or else the crypto will “self heal”
- We get this for free because of the Diffie-Hellman key exchange every time we ratchet in OTR

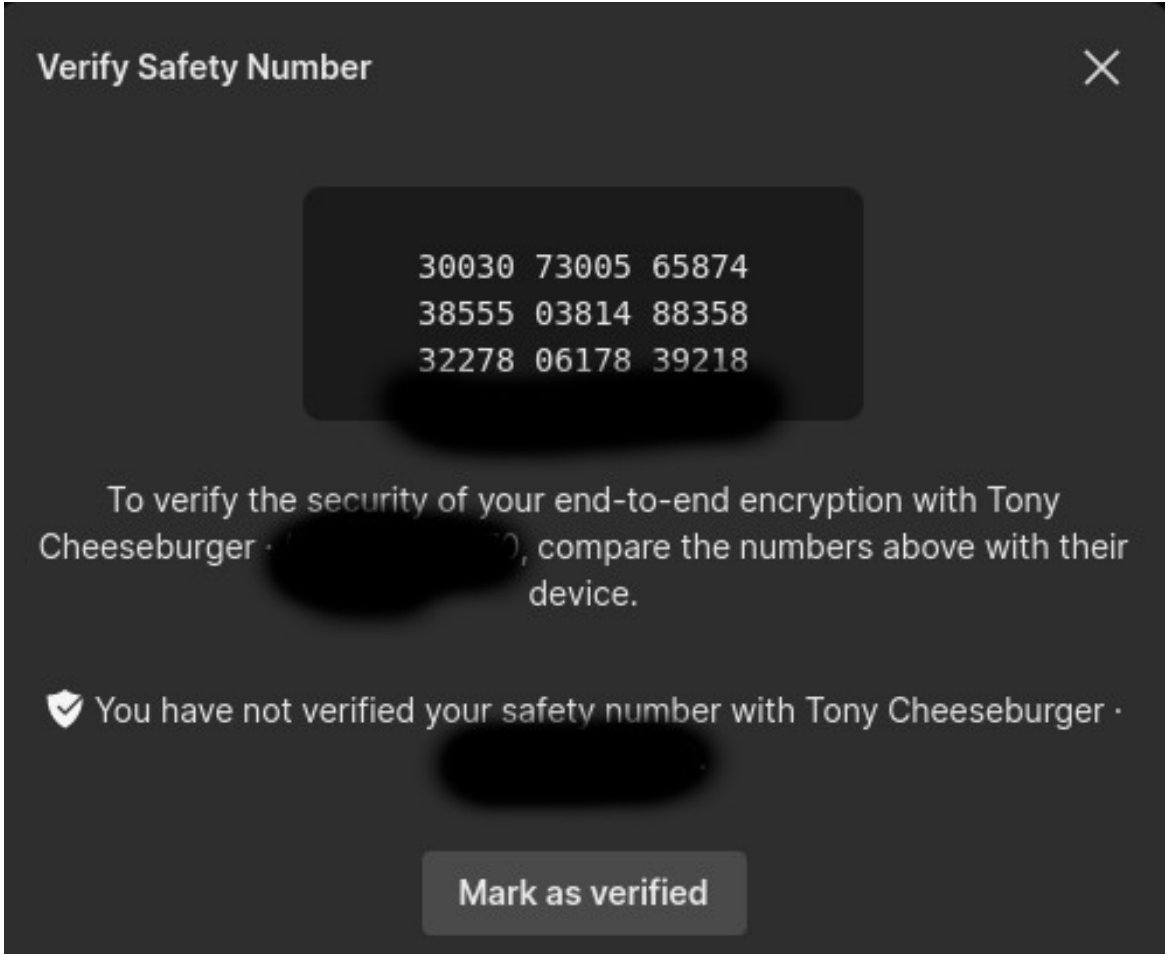
Signal

- Multiple devices, some or all can be offline for long periods of time
- Group messages

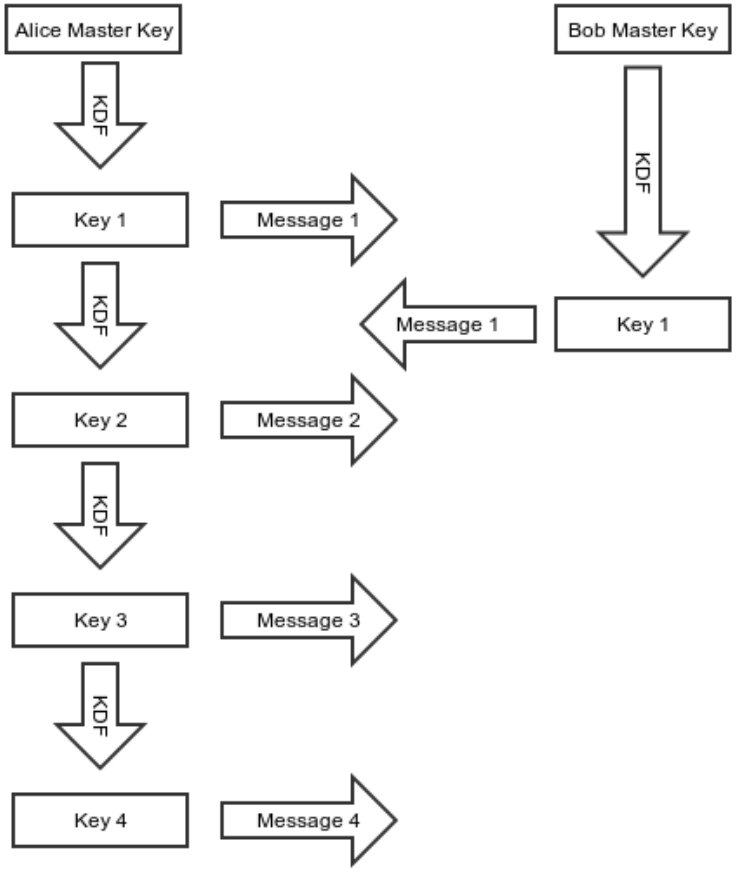


https://www.cnbc.com/2021/01/12/how-to-use-signal-instead-of-whatsapp.html

Typical authentication



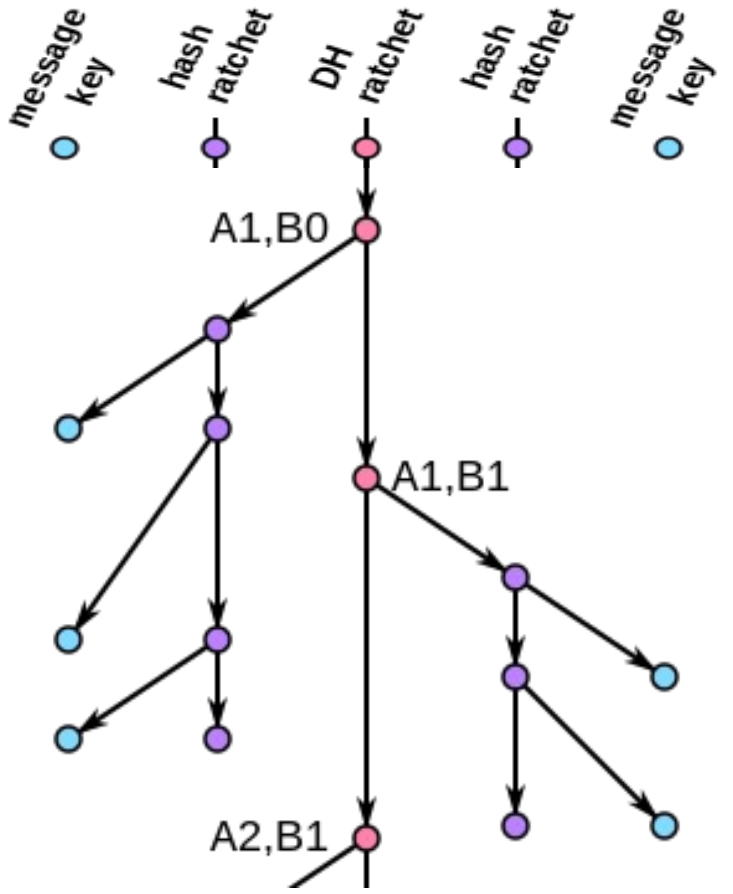
Silent Circle SCIMP ratchet



Tradeoffs

- Both have forward secrecy, but SCIMP's is better
  - In synchronous case, can ratchet and delete old key right away if Bob acknowledges it and ratchets, too
- OTR ratchet not great for multiple devices, devices that go offline
- SCIMP ratchet leaves key material around for a long time if messages are lost or out of order
- OTR ratchet "self heals", *i.e.*, future/backward sececy

Double Ratchet



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

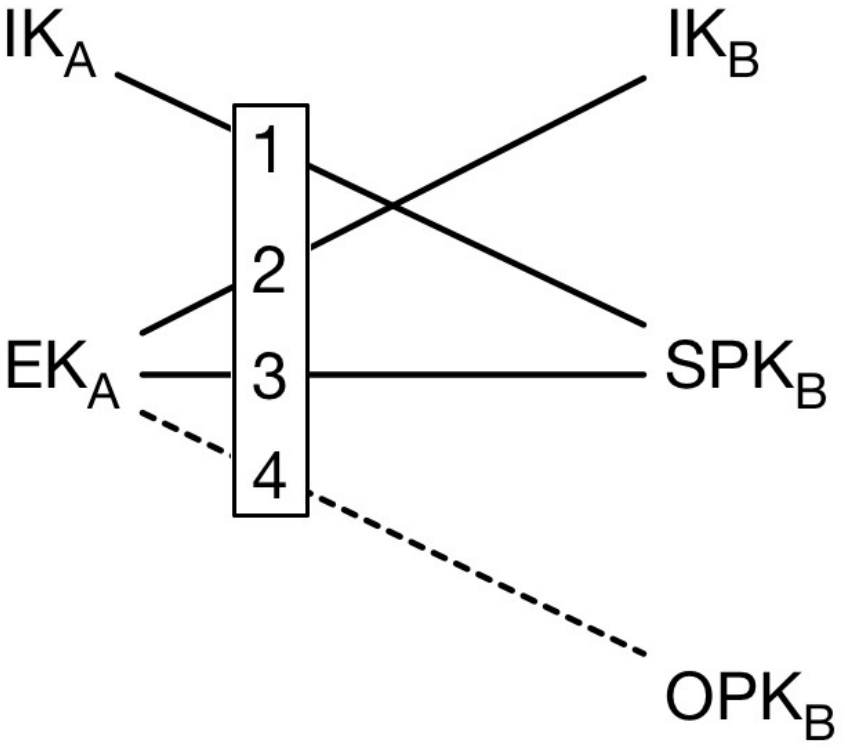
X3DH

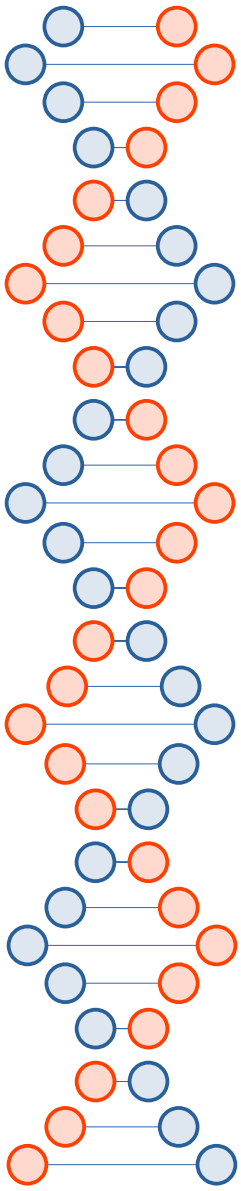
IK = Identity Key
EK = Ephemeral Key
SPK = Signed Pre-Key
OPK = One-Time Pre-Key

SK = KDF(DH1 || DH2 || DH3 || DH4)

Alice's first message encrypts the two on the left, authentication for Bob's SPK comes from the signature.

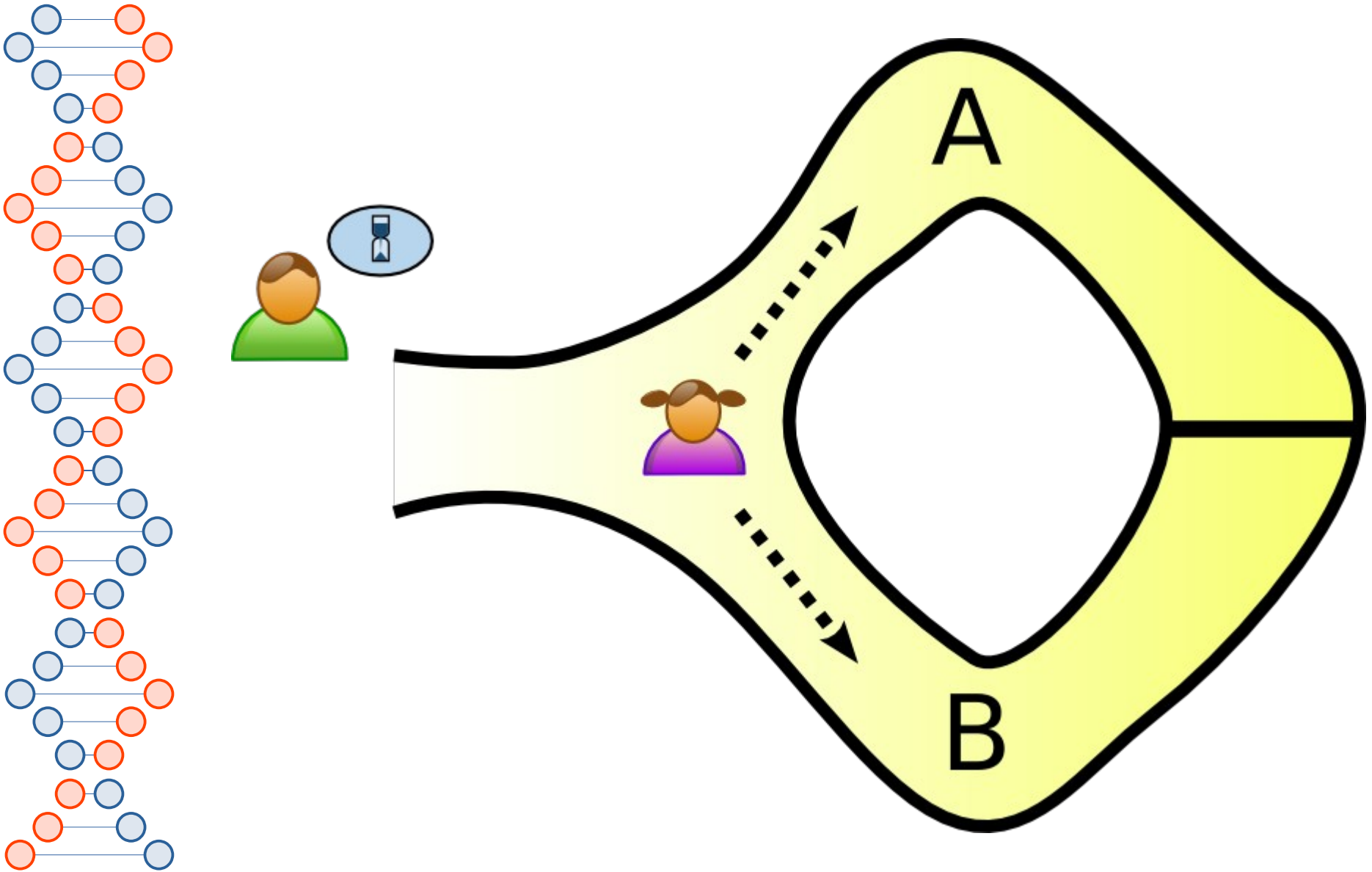
Deniability?

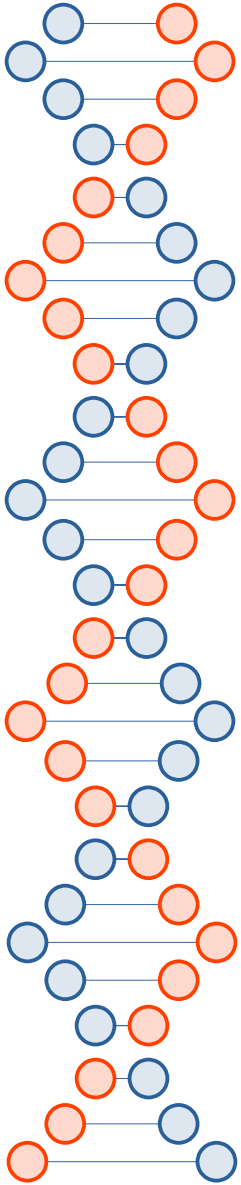


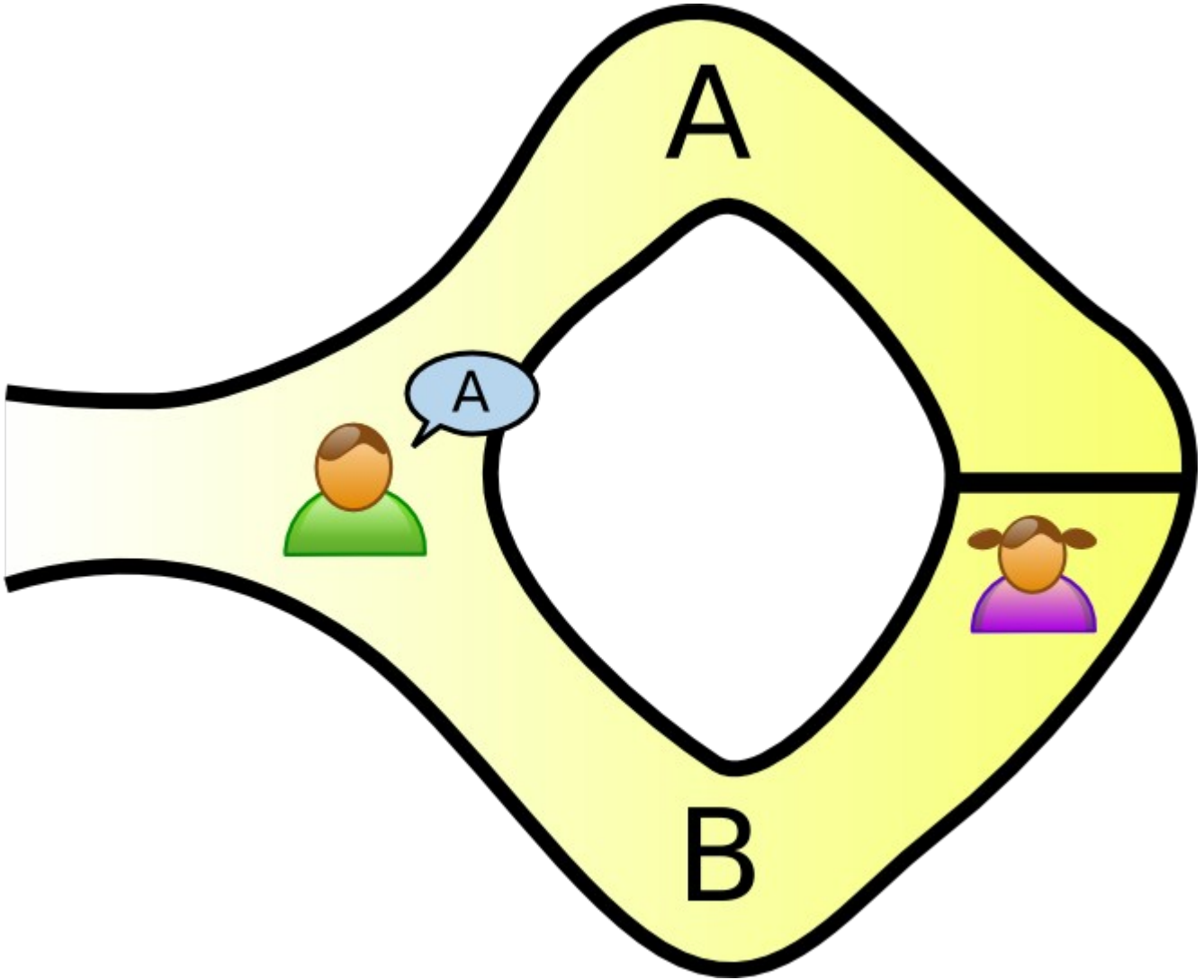


Zero Knowledge Proofs

- Used for forming groups in Signal
- “a method by which one party (the prover) can prove to another party (the verifier) that a given statement is true while the prover avoids conveying any additional information apart from the fact that the statement is indeed true”
  - https://en.wikipedia.org/wiki/Zero-knowledge_proof (also the source of the following images and examples)


A
B




A
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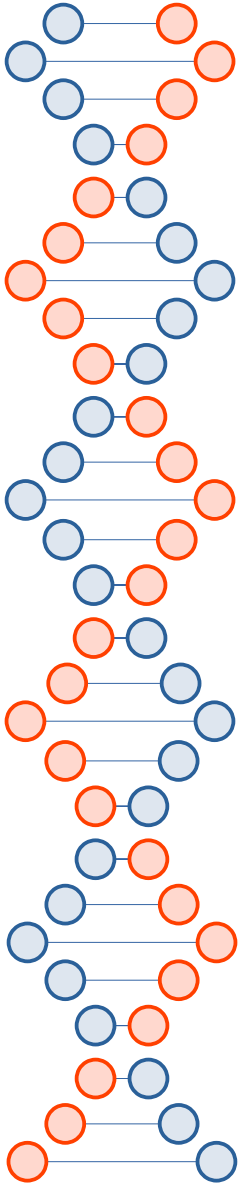
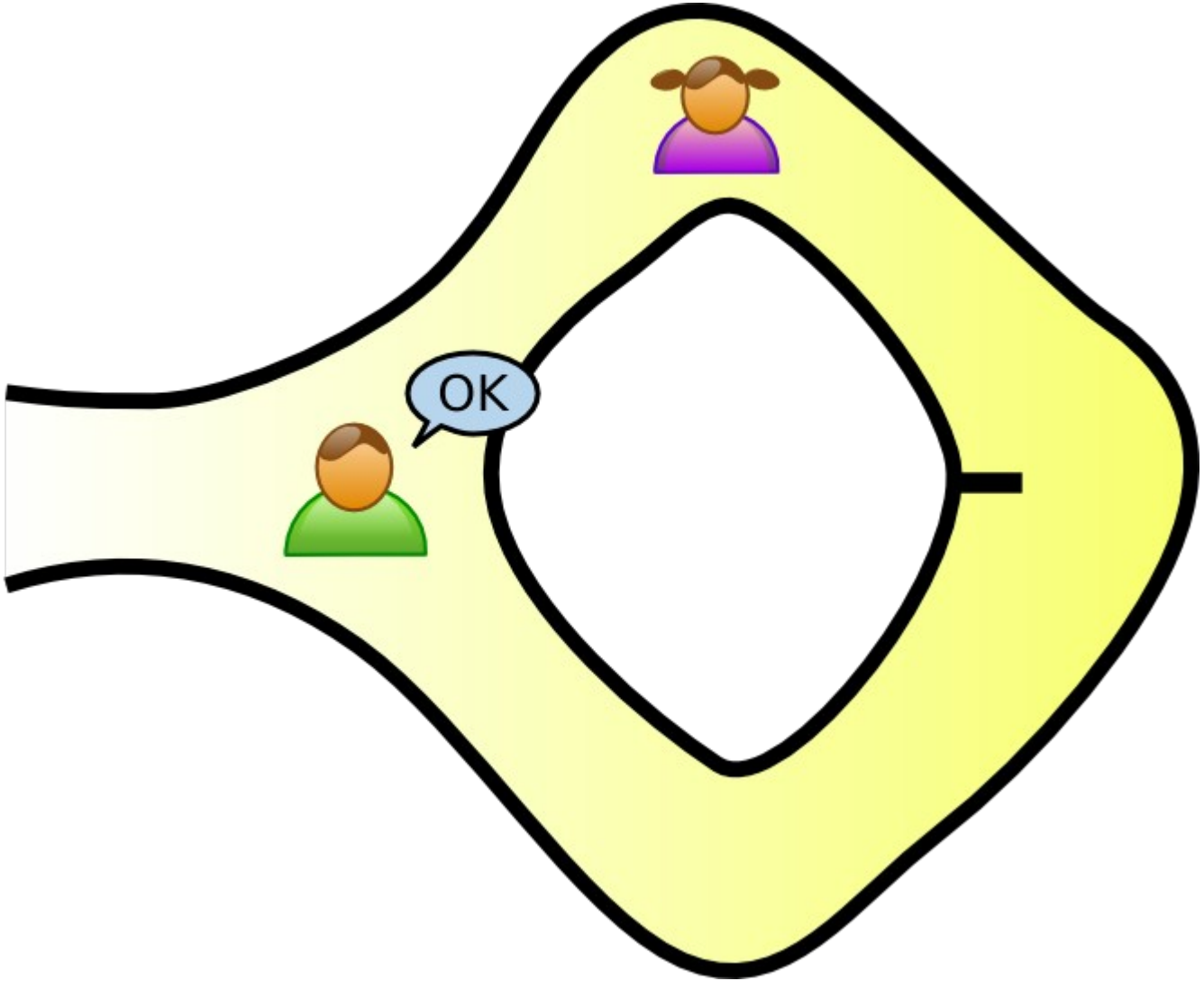
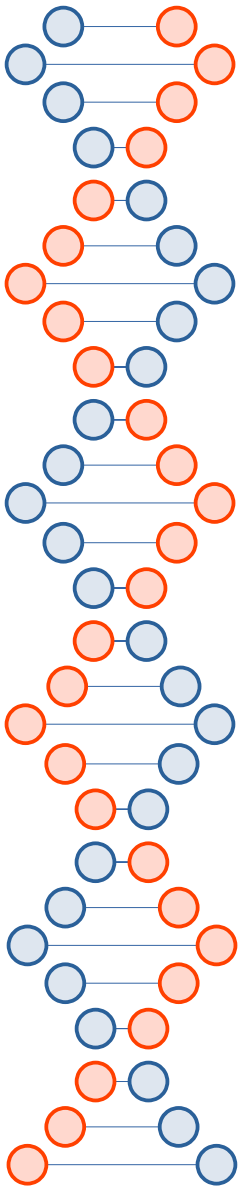
B




OK



Example with discrete log

- $g^x \bmod p = y$
  - Peggy wants to prove she knows x
- Each round, Peggy computes $C = g^r \bmod p$
  - She generates r randomly
- In each round, Victor can ask for…
  - **r** --or--
  - **$(x + r) \bmod (p - 1)$**

$g^{(x + r) \bmod (p - 1)} \bmod p = g^x g^r \bmod p = Cy \bmod p$

Signal Messenger Introduces PQXDH Quantum-Resistant Encryption

Sep 20, 2023 THN Encryption / Privacy

Two key differences with Signal:

- -Federated
- -No deniability

Messaging Layer Security (MLS)

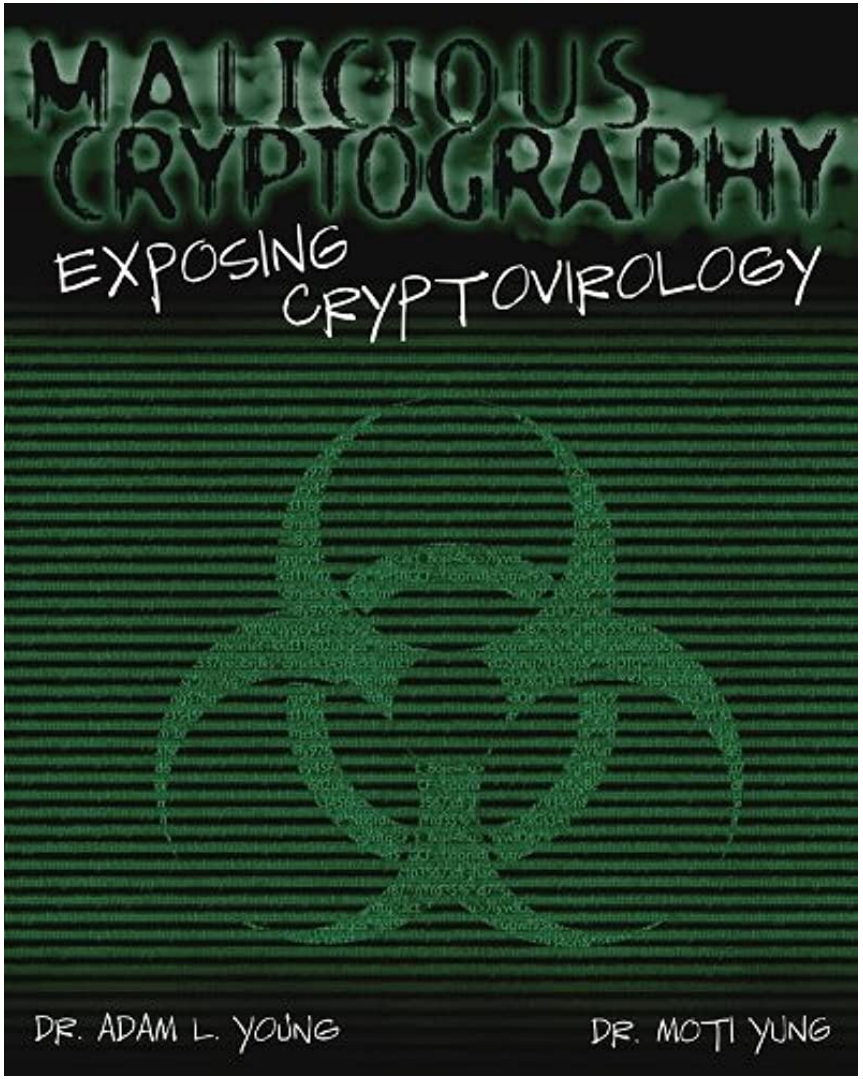
MLS

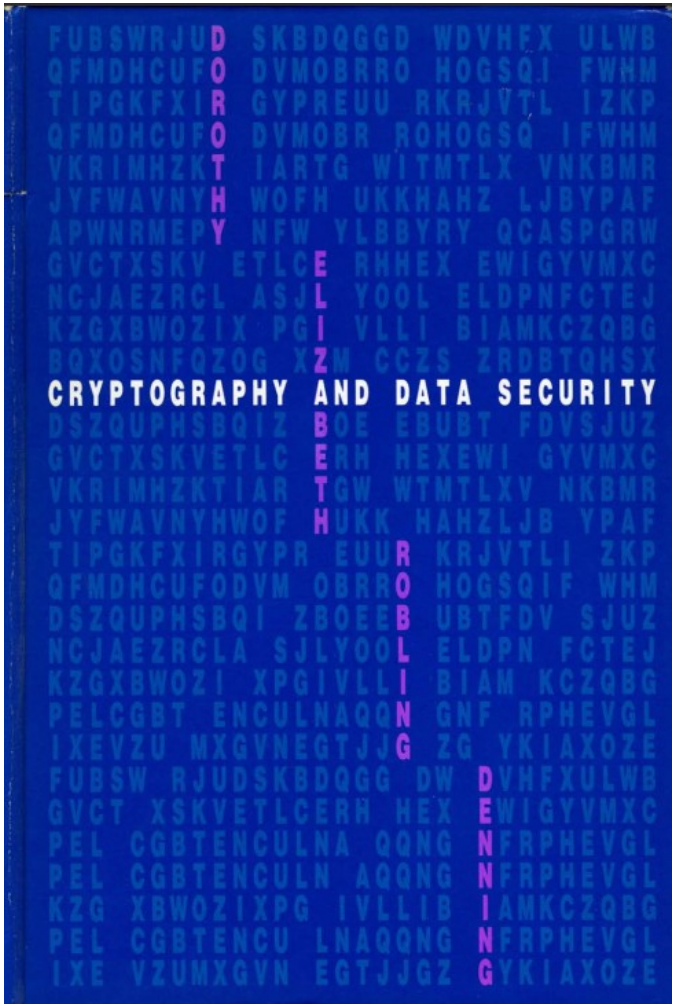
Messaging Layer Security (MLS) is an IETF working group building a modern, efficient, secure group messaging protocol.

View My GitHub Profile

Resources

- https://signal.org/blog/advanced-ratcheting/
- https://en.wikipedia.org/wiki/Off-the-Record_Messaging
- https://en.wikipedia.org/wiki/Double_Ratchet_Algorithm
- https://signal.org/docs/specifications/doubleratchet/
- https://signal.org/docs/specifications/x3dh/
- https://www.youtube.com/watch?v=7WnwSovjYMs
- https://en.wikipedia.org/wiki/Global_surveillance_disclosures_(2013%E2%80%93present)
- https://en.wikipedia.org/wiki/Global_surveillance_disclosures_(2013%E2%80%93present)
- https://thehackernews.com/2023/09/signal-messenger-introduces-pqxdh.html


MALICIOUS CRYPTOGRAPHY
EXPOSING CRYPTOVIROLOGY
DR. ADAM L. YOUNG
DR. MOTI YUNG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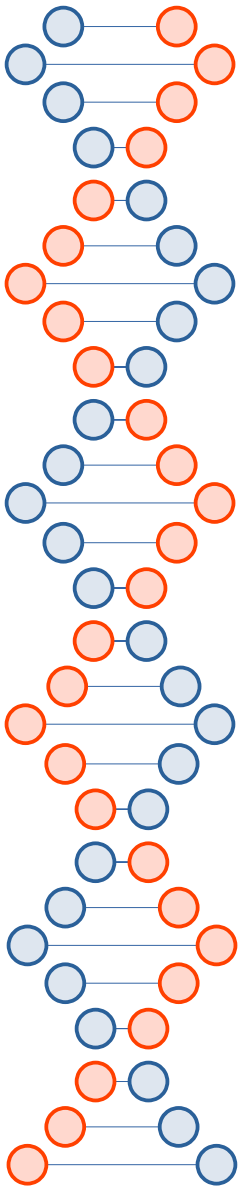

Cryptography Engineering by Ferguson *et al.*