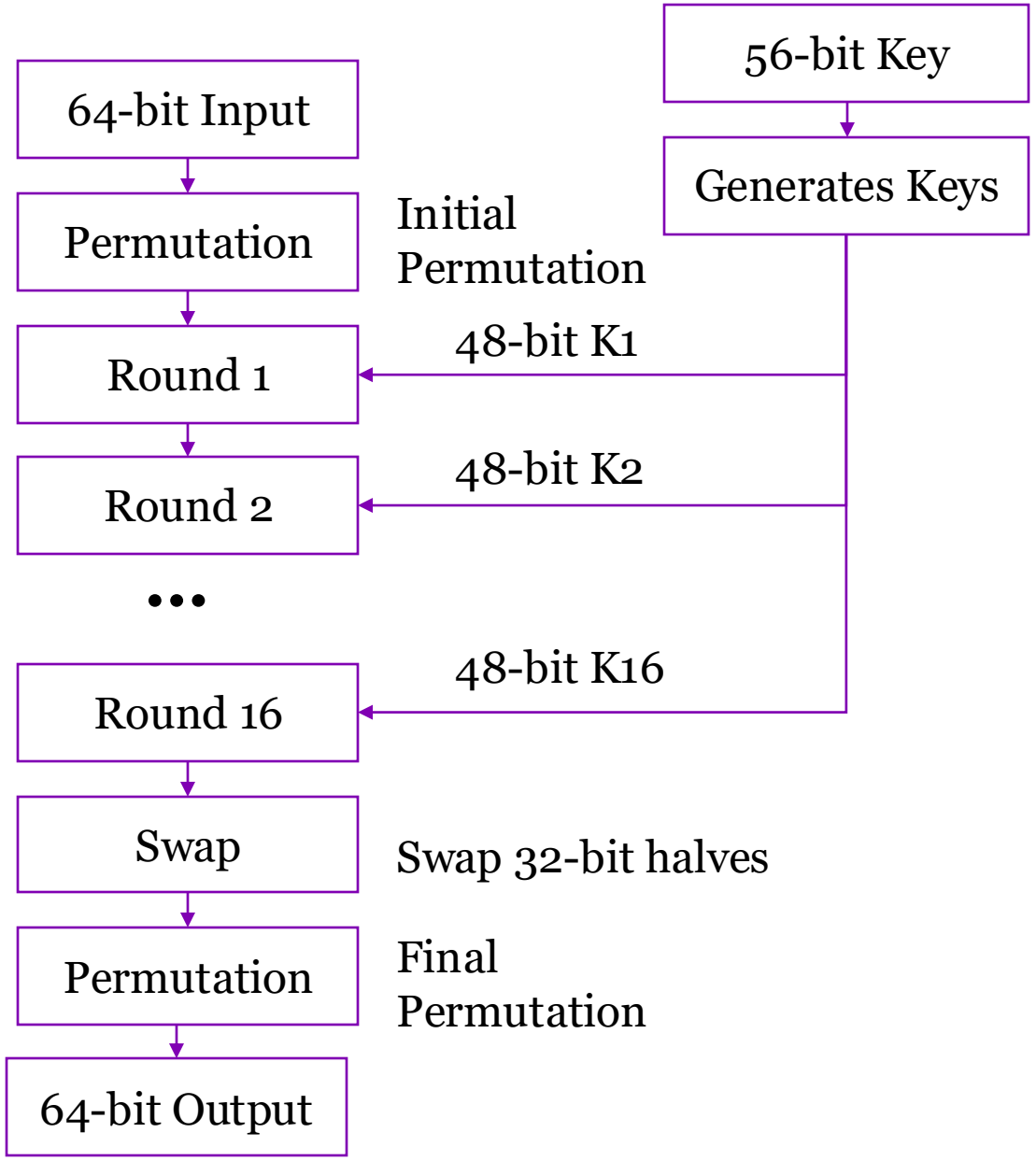
ECE458/ECE750T27: Computer Security

Cryptography

Dr. Kami Vaniea
Electrical and Computer Engineering
kami.vaniea@uwaterloo.ca

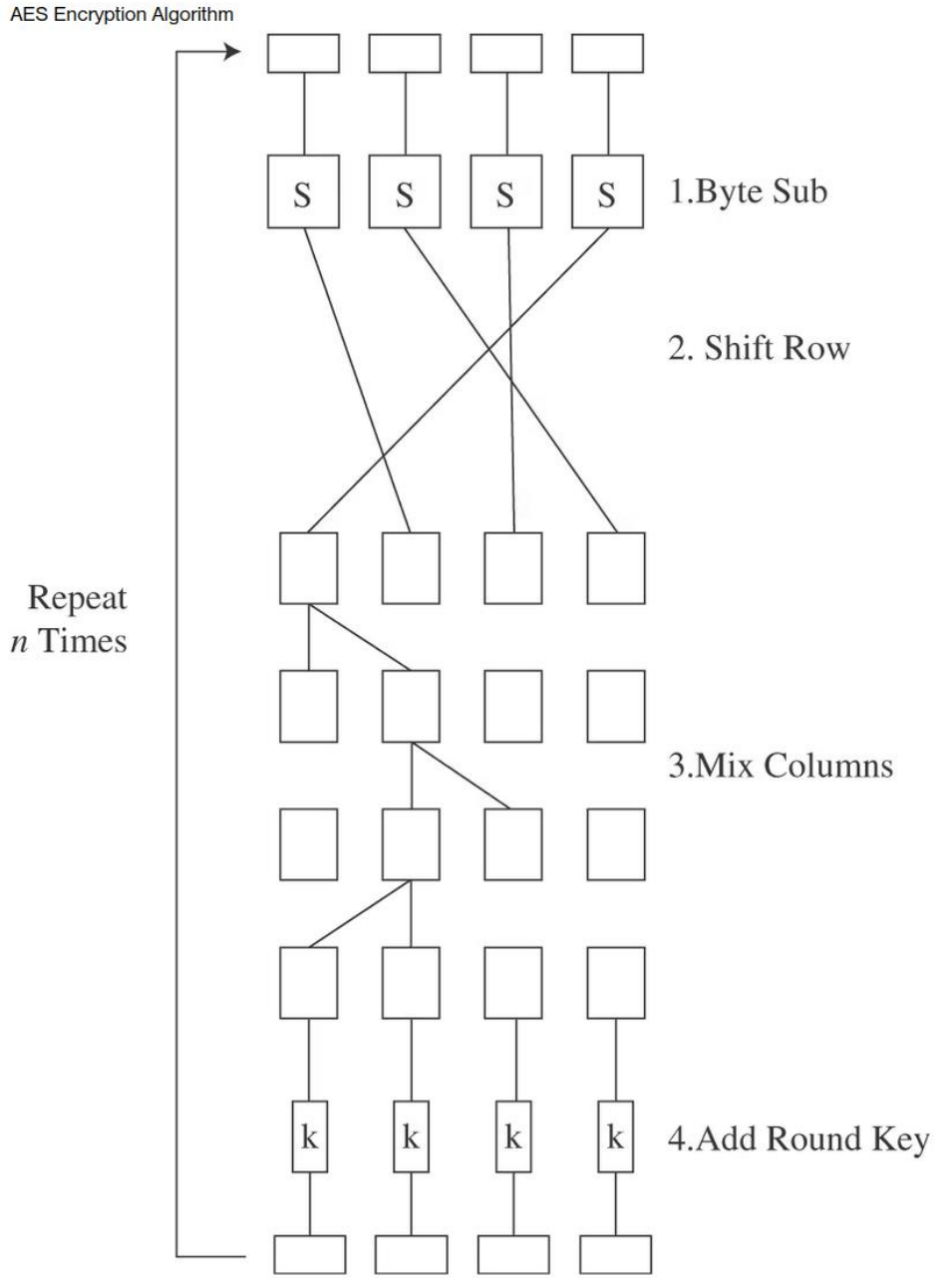
Data Encryption Standard (DES)

- Symmetric-key algorithm using 56 bit keys (64 bit initial but 8 bits are parity)
- Blocks of 64 bits
- Developed in 1970s at IBM
- Approved by NSA (after key length shortened) leading to quick adoption
- January 1999, distributed.net and the Electronic Frontier Foundation collaborated to publicly break a DES key in 22 hours and 15 minutes (Wikipedia)



Advanced Encryption System (AES)

- Became a standard in the US in 2001 after a public proposal call by NIST
- Symmetric key block cipher
- Primarily uses substitution, transposition, the shift, exclusive OR, and addition
- Can use 128, 192, 256 bit keys, and larger keys are possible
  - Key length impacts the number of rounds, longer key, more rounds



Advanced Encryption System (AES)

- Became a standard in the US in 2001 after a public proposal call by NIST
- Symmetric key block cipher
- Primarily uses substitution, transposition, the shift, exclusive OR, and addition
- Can use 128, 192, 256 bit keys, and larger keys are possible
  - Key length impacts the number of rounds, longer key, more rounds

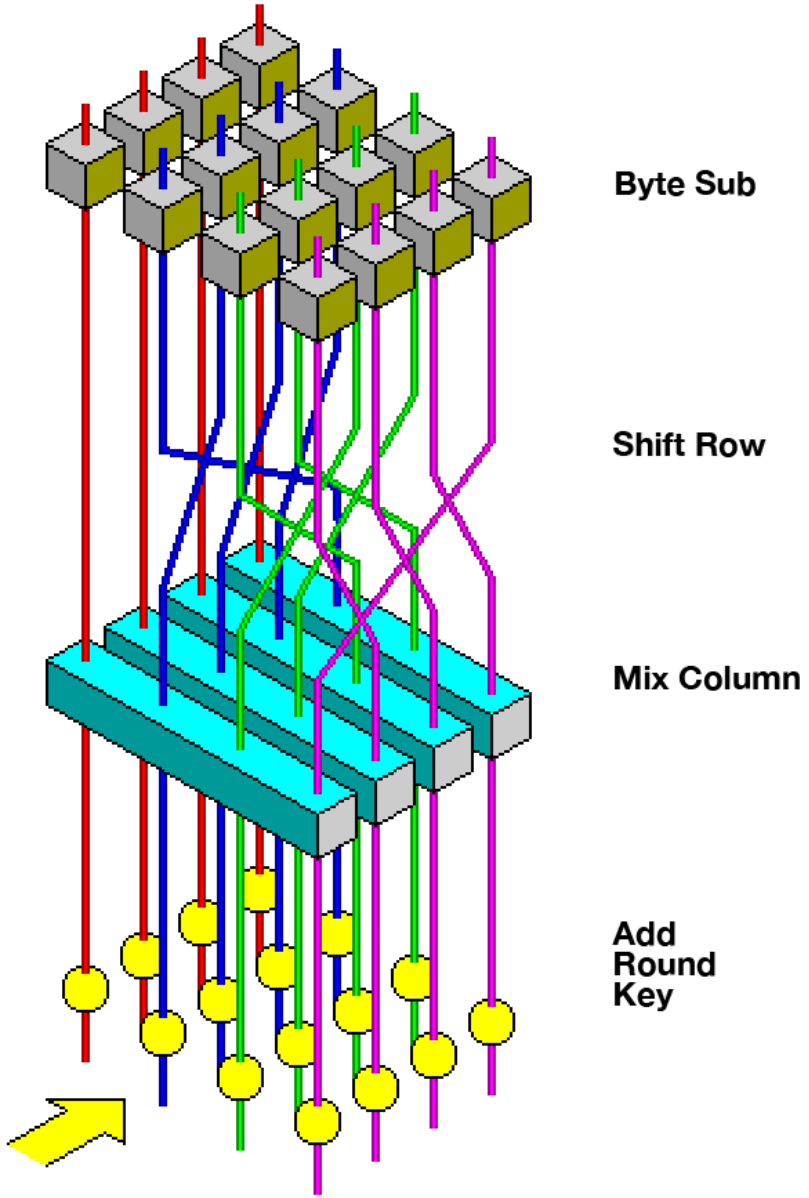


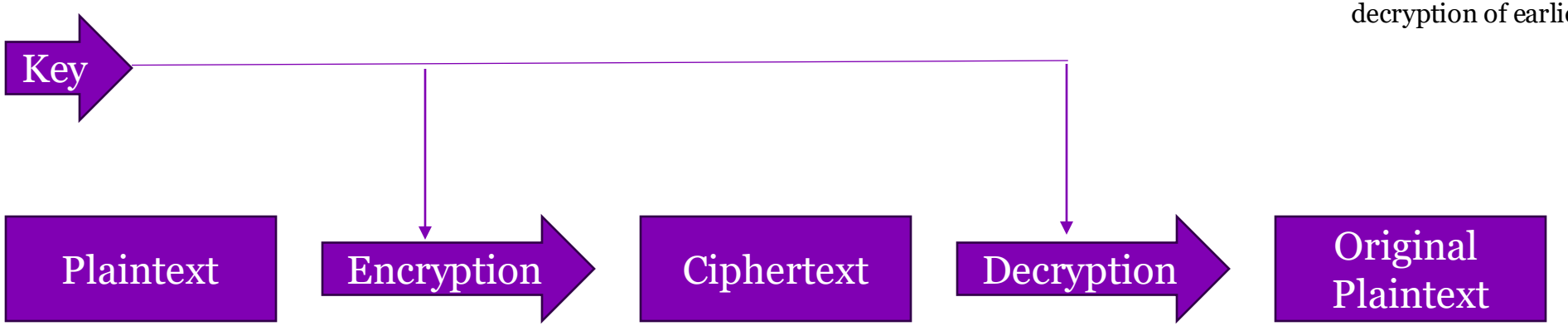
Diagram of the stages of the AES round function
John Savard -- Wikimedia

PUBLIC KEY CRYPTOGRAPHY

Symmetric ciphers

- The prior examples are all symmetric ciphers where the same key is used for encryption and decryption
- Sharing the key can be problematic

Leo Marks with letter One Time Pad written on silk. These were used during WWII by spies. Letters unraveled after use to prevent decryption of earlier messages if captured.

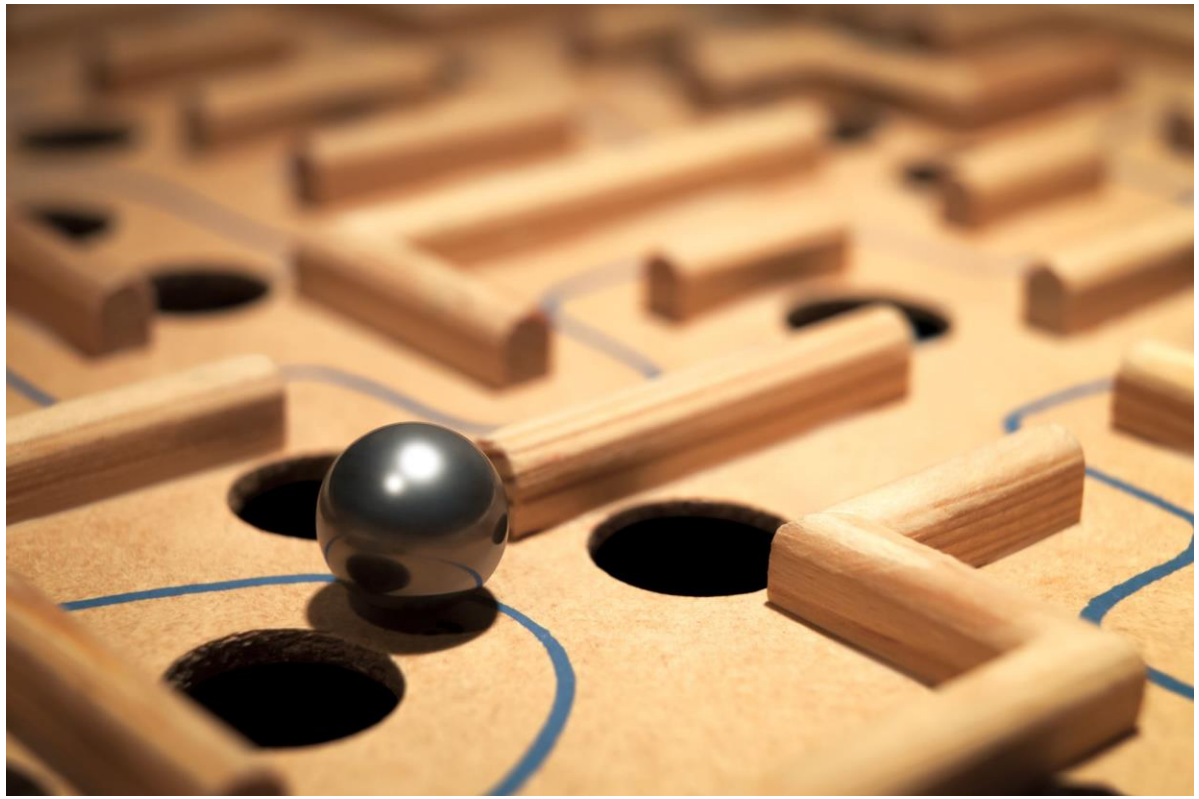


Asymmetric ciphers

- Different keys are used to encrypt and decrypt
- Asymmetric ciphers are less common as they rely on trapdoor functions

Trapdoor one-way function

- A function that is easy to compute but hard to impossible to reverse
- Classic example: Generate two prime numbers `p` and `q` and compute their product `N=q*p`



We can use trapdoor functions to securely create a shared key between two people communicating publicly.

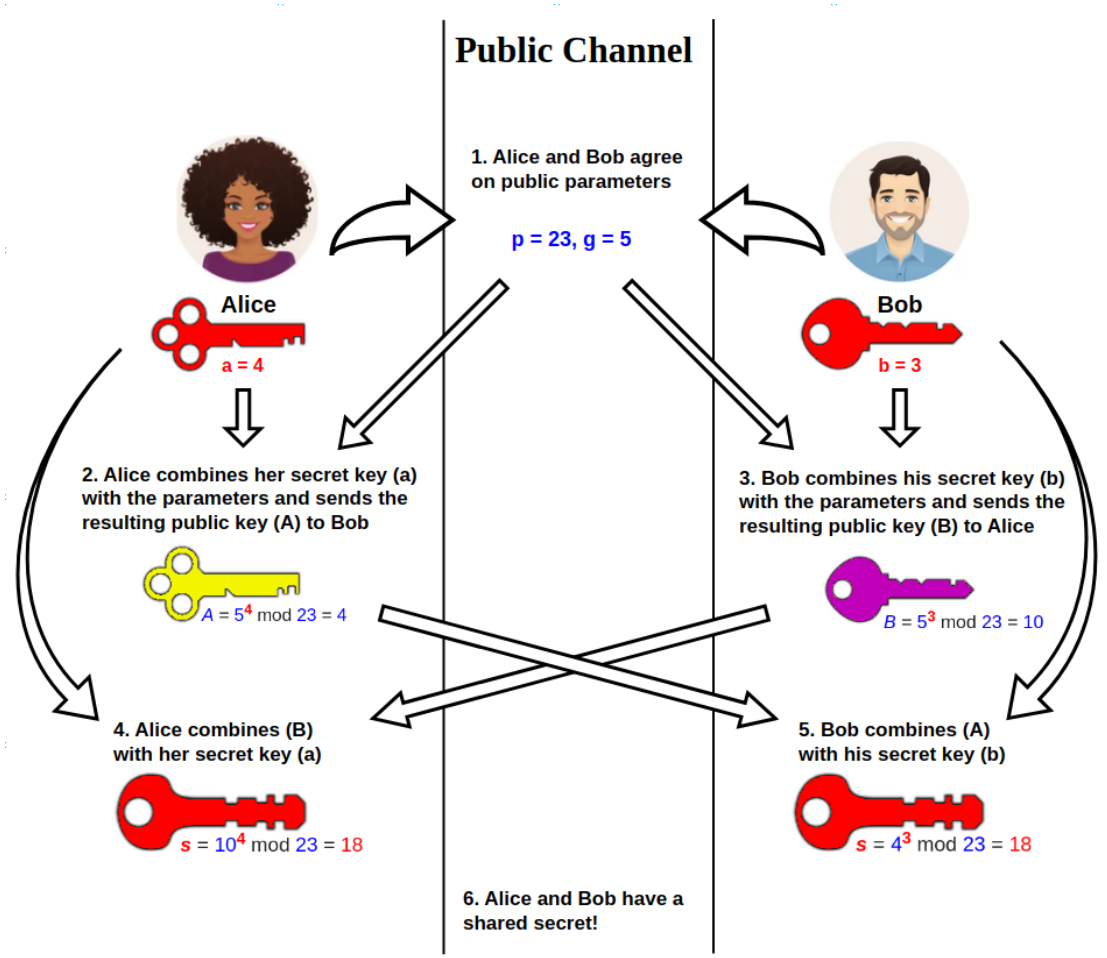
Diffie-Hellman key exchange (Invented 1976... or maybe 1969)

- Allows two entities to agree on a secret key while communicating publicly.
- Protocol uses the multiplicative group of integers modulo p where p is prime and g is a primitive root modulo p.

Primitive Root:

The number 3 is a primitive root modulo 7[5] because

$$
\begin{aligned}
3^1 &= 3^0 \times 3 \overset{\bmod 7}{\equiv} 1 \times 3 = 3 \overset{\bmod 7}{\equiv} 3 \pmod 7 \\
3^2 &= 3^1 \times 3 \equiv 3 \times 3 = 9 \equiv 2 \pmod 7 \\
3^3 &= 3^2 \times 3 \equiv 2 \times 3 = 6 \equiv 6 \pmod 7 \\
3^4 &= 3^3 \times 3 \equiv 6 \times 3 = 18 \equiv 4 \pmod 7 \\
3^5 &= 3^4 \times 3 \equiv 4 \times 3 = 12 \equiv 5 \pmod 7 \\
3^6 &= 3^5 \times 3 \equiv 5 \times 3 = 15 \equiv 1 \pmod 7
\end{aligned}
$$



Epachamo via Wikimedia Commons

Trapdoors can also be used to do cryptography using two keys (asymmetric).

I am going to start by explaining at a high level, then we will discuss how it is done.

Encryption properties we want:

1. The communication between you and the other party is **confidential** and has **not been changed (integrity)**
   - No one can read what you sent
   - No one can change what you sent
2. **Knowing who** you are communicating with (authenticity)
   - You are talking to who you think you are talking to and not someone else

Public/private key cryptography

- Generate two “keys” that are paired
- **What one key encrypts only the other key can decrypt**

- Public keys are given out to everybody

- Private keys are kept private

- k_{PRIV} can encrypt and k_{PUB} can decrypt

  $P = D(k_{PUB}, E(k_{PRIV}, P))$

- k_{PUB} can encrypt and k_{PRIV} can decrypt

  $P = D(k_{PRIV}, E(k_{PUB}, P))$

My public key

-----BEGIN PGP PUBLIC KEY BLOCK-----
Version: GnuPG v2

mQENBFHMcgABCAC9WrYDO6K2L3VHyi4eHN6suHLqMpJ+SO+IUTuLEVnUzIoXAUXH
KozHejfV/9XoG8j933ZtszXKCog3aMESe0E0z6fNGfolvaCe5B4jwqoJt8NHwb5L
B2dnq0CplgXcN2GJxfEHHUaf27COSobCJxPMeshUh4ZHke+g6DatmiEtBpVp41Ot
1zgxdMQkgb2H2xw28RYfYkdDoueteIkOrFLrCy9ZF9KdMhA1eBH94KnwIQshdiZR
QYEX25+M8cKCb++Rc9H6an7EG9WHOFRW40UsY52OfveOyfQPzkkRto7u2339hvHo
B/h+7xLM6FQbOUZQ9BD5w7IQHgYtXJVsUjodABEBAAG0IkthbWkgVmFuaWVhIDxr
dmFuaWVhQGluZi5lZC5hYy51az6JAT8EEwEIACkFAlYKYvECGyMFCQlmAYAHCwkI
BwMCAQYVCAIJCgsEFgIDAQIeAQIXgAAKCRCTdsxl9/HZffG+CACShuKxje3QAqew
GWh8K4gCdiYoxDqJwq3PHxmyhZmQeN/1a1KcOrIjI2b+Q75/5t+EgXOHpR0PIxfG
lZ6zOEpf6A18iFXx3JgQZdwPD0jtBiWNpOyMeBGTgIvEYG3so2VueQoeXcq3dbYp
5vstVxtD+TKHQ5CioIT75P2bzYq/XLT5aIbNQhQDPcTo0DgbRH+FvqsRXr7yeaef
JaPnxX0+1L33t2QY9zctiGyebwrvHMrIPBJ2VYCDzQkJ7uQ5eFh4ZhsMgOmzLQD4
YiGr5weIMFwAvxZOaRxEa9Vf48jiWvrxuJ8YfHWS0hEScNOcYC2P8q20lJwwE26T
lpdtrwCqtB1LYW1pIFZhbmllYSA8a2FtaUB2YW5pZWEuY29tPokBQgQTAQIALAIb
IwUJCWYBgAcLCQgHAwIBBhUIAgkKCwQWAgMBAh4BAheABQJWCmMeAhkBAAoJEJN2
zGX38dl9JJAIAIW0rxrlYsrmKS6CbW8MgTxxTDOXaCt1b7F0W0QZHskIUQhEcE+a
XBYib1A5uHaatLfyjeXaD3qMEoZnQHoYMGE0GKu00wWsbhfoQzHPgwzRLkD1i75M
BIbaww0KW0VB9e4AkMakXJCnF5BXeo6AHRL2v15V205DikVnlCRXocKtu8b7LnkM
cLn70Lobr1de1uyKoNzbSnO/vpKDJp0/EY5yUeV90IypZy/6wFQBehg1sXye6zn0
9wb9uUsu9+/P8pz4JILMDSevjfT7zSRSl/YP3fOfZ6N4bc+KOdwPM7u5Iyoeu9zh
pzibv3ge7VhH2xIWz8vYZ/2xT1345tWRRMOJAhwEEwECAAYFAlTnSpEACgkQjyxM
p99tBt2B8A/+OpIzOsQbQJB8yxti4I7PpD1weJDf3a81Vhm7JyXE/Xy66ypfdt3w
XmFRUuIrwezY1NebWNCRQHzQvRv/VJwjbTUx+Q3HsjIkKlHbE7iCiQXXtTRkoEny
2nudcjGI2v03C3B2JCucEw6esF1x79PI/lPv2+6tgUBKmDfOpsB2vbtqrHnmAYKL
4lQBFH1YSJgnzwo2Jkh0hcHdF90Zem1eMeiDEeVkH63893N8Swk5fBKdTj+SKZ/L
rQElBBlpMR9BmeY6bPvWRuycVKonIMR80G9iFABxjTpWBL8aGk6EeVK5EqYDGvkd
ZIarK84r+KU1KD5IfgOCN7nhwgy7VImE68caZHSRiPWZP1fVVMhydiRJv8WsoUs6
INfVU3nxH+ZYthPbY0T86leGSchBT5K/fBQvbjhrRTbTFwvjzSifb9efWylDi994
nzP6cNorir3GIpsT8gPgBB2/NjxaWiM6y3X1az1vRnsunQHuyKkFWPZwnEvDJYaC
NN/3jWcbhLFwKBDsaHps2+1meFP0oJFvNetzp2bjT9a9pXaQ6KhOmo5DnhLcaV97
bFBpsUuBGaYZTSS05x1RdXHqpEbgap8dtuHhVvJw9QYDQBJr0K4aKyG9qqMD8cta
Pl/FAdyAqwH8Nw9efqAK+RQxSVUaue9BYEnbIRpsDK6MkP3YMFmu5ki5AQ0EUcxy
AAEIALyXYy8G2ZaTDJpdGcRhmIqOOSUlzPV7/5E5BbYKBNu4KU3nX+JLVcF5jxPQ
42c7i/WRVxE1BJTiarKGsEvCi94TTXSIUKAt3T1oGBtXmGvqbGBq8ljSGl1UTwdF
5yu50JyRSf2fqRND6P/2eHNXejDUtdvhUXIUt8h9MuUO/ipD0DnwIvMnAATJHA+R
Zqw6oNpyjRGzvr3iuWUwe4PtyJDI3ELAFkbp/NAc5TIuVHRHNOWNplcIJhM5zHuB
QQb3G/EsCn2PQZ5w5SDzavF2SpvQfDqxYpDaTLAXtF+wsJL5iaUjxwRgJPOdbCZf
2Tozd7h9MXtGJDlPKJ8eLG8ogcMAEQEAAYkBJQQYAQIADwUCUcxyAAIbDAUJCWYB
gAAKCRCTdsxl9/HZfS+hB/9BJqSmIgcoHFXnb1PVIKxekzL8+WVm5Pk/EgMQSLZ2
HX4p3ial5PEPcYgUw9YnaG4i00dwJGw5/daTWRrTzcnKd8Yq0P+DU0t96HZDSu3m
mCzE9NVAQYboFbVmGOx0eo627UBSvFqaXvAxBDYkoR8B0TnKhrQFwXkZVb30hKwD
TgAFjOGlZiE6uAdST231tFaq0bizYfe5AVXRqro20xBqNbaJNqs3SW0D831Syvdv
llOBx83/R0gg7hUkI6F2vzXicWmUwFSXRrggCSbLosHsP6isBWwvlHeRmna/aQab
YKG3gbV9iyczAS31gbogVLAZqNSWhp8vVIEE28Fyf/Ed
=x5FK
-----END PGP PUBLIC KEY BLOCK-----

I want to send Bob a message that no one else can read

- I encrypt (lock) the message with Bob's public key.
- Only Bob has his private key, so only Bob can decrypt (unlock) the message.

Bob's public key

Bob's private key

My public key

-----BEGIN PGP PUBLIC KEY BLOCK-----
Version: GnuPG v2

mQENBFHMcgABCAC9WrYDO6K2L3VHyi4eHN6suHLqMpJ+SO+IUTuLEVnUzIoXAUXH
KozHejfV/9XoG8j933ZtszXKCog3aMESe0E0z6fNGfolvaCe5B4jwq0Jt8NHwb5L
B2dnq0CplgXcN2GJxfEHHUaf27COSobCJxPMeshUh4ZHke+g6DatmiEtBpVp41Ot
1zgxdMQkgb2H2xw28RYfYkdDoueteIkOrFLrCy9ZF9KdMhA1eBH94KnwIQshdiZR
QYEX25+M8cKCb++Rc9H6an7EG9WHOFRW40UsY52OfveOyfQPzkkRto7u2339hvHo
B/h+7xLM6FQbOUZQ9BD5w7IQHgYtXJVsUjodABEBAAG0IkthbWkgVmFuaWVhIDxr
dmFuaWVhQGluZi5lZC5hYy51az6JAT8EEwEIACkFAlYKYvECGyMFCQlmAYAHCwkI
BwMCAQYVCAIJCgsEFgIDAQIeAQIXgAAKCRCTdsxl9/HZffG+CACShuKxje3QAqew
GWh8K4gCdiYoxDqJwq3PHxmyhZmQeN/1a1KcOrIjI2b+Q75/5t+EgXOHpR0PIxfG
lZ6zOEpf6A18iFXx3JgQZdwPD0jtBiWNpOyMeBGTgIvEYG3so2VueQoeXcq3dbYp
5vstVxtD+TKHQ5CioIT75P2bzYq/XLT5aIbNQhQDPcTo0DgbRH+FvqsRXr7yeaef
JaPnxX0+1L33t2QY9zctiGyebwrvHMrIPBJ2VYCDzQkJ7uQ5eFh4ZhsMgOmzLQD4
YiGr5weIMFwAvxZOaRxEa9Vf48jiWvrxuJ8YfHWS0hEScNOcYC2P8q20lJwwE26T
lpdtrwCqtB1LYW1pIFZhbmllYSA8a2FtaUB2YW5pZWEuY29tPokBQgQTAQIALAIb
IwUJCWYBgAcLCQgHAwIBBhUIAgkKCwQWAgMBAh4BAheABQJWCmMeAhkBAAoJEJN2
zGX38dl9JJAIAIW0rxrlYsrmKS6CbW8MgTxxTDOXaCt1b7F0W0QZHskIUQhEcE+a
XBYib1A5uHaatLfyjeXaD3qMEoZnQHoYMGE0GKu00wWsbhfoQzHPgwzRLkD1i75M
BIbaww0KWoVB9e4AkMakXJCnF5BXeo6AHRL2v15V205DikVnlCRXocKtu8b7LnkM
cLn70L0br1de1uyKoNzbSnO/vpKDJp0/EY5yUeV90IypZy/6wFQBehg1sXye6zn0
9wb9uUsu9+/P8pz4JILMDSevjfT7zSRSl/YP3fOfZ6N4bc+KOdwPM7u5Iyoeu9zh
pzibv3ge7VhH2xIWz8vYZ/2xT1345tWRRMOJAhwEEwECAAYFAlTnSpEACgkQjyxM
p99tBt2B8A/+OpIzOsQbQJB8yxti4I7PpD1weJDf3a81Vhm7JyXE/Xy66ypfdt3w
XmFRUuIrwezY1NebWNCRQHzQvRv/VJwjbTUx+Q3HsjIkKlHbE7iCiQXXtTRkoEny
2nudcjGI2v03C3B2JCucEw6esF1x79PI/lPv2+6tgUBKmDfOpsB2vbtqrHnmAYKL
4lQBFH1YSJgnzwo2Jkh0hcHdF90Zem1eMeiDEeVkH63893N8Swk5fBKdTj+SKZ/L
rQElBBlpMR9BmeY6bPvWRuycVKonIMR80G9iFABxjTpWBL8aGk6EeVK5EqYDGvkd
ZIarK84r+KU1KD5IfgOCN7nhwgy7VImE68caZHSRiPWZP1fVVMhydiRJv8WsoUs6
INfVU3nxH+ZYthPbY0T86leGSchBT5K/fBQvbjhrRTbTFwvjzSifb9efWylDi994
nzP6cNorir3GIpsT8gPgBB2/NjxaWiM6y3X1az1vRnsunQHuyKkFWPZwnEvDJYaC
NN/3jWcbhLFwKBDsaHps2+1meFP0oJFvNetzp2bjT9a9pXaQ6KhOmo5DnhLcaV97
bFBpsUuBGaYZTSS05x1RdXHqpEbgap8dtuHhVvJw9QYDQBJr0K4aKyG9qqMD8cta
Pl/FAdyAqwH8Nw9efqAK+RQxSVUaue9BYEnbIRpsDK6MkP3YMFmu5ki5AQ0EUcxy
AAEIALyXYy8G2ZaTDJpdGcRhmIqOOSUlzPV7/5E5BbYKBNu4KU3nX+JLVcF5jxPQ
42c7i/WRVxE1BJTiarKGsEvCi94TTXSIUKAt3T1oGBtXmGvqbGBq8ljSGl1UTwdF
5yu50JyRSf2fqRND6P/2eHNXejDUtdvhUXIUt8h9MuUO/ipD0DnwIvMnAATJHA+R
Zqw6oNpyjRGzvr3iuWUwe4PtyJDI3ELAFkbp/NAc5TIuVHRHNOWNplcIJhM5zHuB
QQb3G/EsCn2PQZ5w5SDzavF2SpvQfDqxYpDaTLAXtF+wsJL5iaUjxwRgJPOdbCZf
2Tozd7h9MXtGJDlPKJ8eLG8ogcMAEQEAAYkBJQQYAQIADwUCUcxyAAIbDAUJCWYB
gAAKCRCTdsxl9/HZfS+hB/9BJqSmIgcoHFXnb1PVIKxekzL8+WVm5Pk/EgMQSLZ2
HX4p3ial5PEPcYgUw9YnaG4i00dwJGw5/daTWRrTzcnKd8Yq0P+DU0t96HZDSu3m
mCzE9NVAQYboFbVmGOx0eo627UBSvFqaXvAxBDYkoR8BoTnKhrQFwXkZVb30hKwD
TgAFjOGlZiE6uAdST231tFaq0bizYfe5AVXRqro20xBqNbaJNqs3SW0D831Syvdv
llOBx83/R0gg7hUkI6F2vzXicWmUwFSXRrggCSbLosHsP6isBWwvlHeRmna/aQab
YKG3gbV9iyczAS31gbogVLAZqNSWhp8vVIEE28Fyf/Ed
=x5FK
-----END PGP PUBLIC KEY BLOCK-----

I want to send Bob a message that no one else can read

- I encrypt (lock) the message with Bob's public key.
- Only Bob has his private key, so only Bob can decrypt (unlock) the message.
- Using the same key twice just creates an error (meaningless output)

My public key

-----BEGIN PGP PUBLIC KEY BLOCK-----
Version: GnuPG v2

mQENBFHMcgABCAC9WrYDO6K2L3VHyi4eHN6suHLqMpJ+SO+IUTuLEVnUzIoXAUXH
KozHejfV/9XoG8j933ZtszXKCog3aMESe0E0z6fNGfolvaCe5B4jwqoJt8NHwb5L
B2dnq0CplgXcN2GJxfEHHUaf27COSobCJxPMeshUh4ZHke+g6DatmiEtBpVp41Ot
1zgxdMQkgb2H2xw28RYfYkdDoueteIkOrFLrCy9ZF9KdMhA1eBH94KnwIQshdiZR
QYEX25+M8cKCb++Rc9H6an7EG9WHOFRW40UsY52OfveOyfQPzkkRto7u2339hvHo
B/h+7xLM6FQbOUZQ9BD5w7IQHgYtXJVsUjodABEBAAG0IkthbWkgVmFuaWVhIDxr
dmFuaWVhQGluZi5lZC5hYy51az6JAT8EEwEIACkFAlYKYvECGyMFCQlmAYAHCwkI
BwMCAQYVCAIJCgsEFgIDAQIeAQIXgAAKCRCTdsxl9/HZffG+CACShuKxje3QAqew
GWh8K4gCdiYoxDqJwq3PHxmyhZmQeN/1a1KcOrIjI2b+Q75/5t+EgXOHpR0PIxfG
lZ6zOEpf6A18iFXx3JgQZdwPD0jtBiWNpOyMeBGTgIvEYG3so2VueQoeXcq3dbYp
5vstVxtD+TKHQ5CioIT75P2bzYq/XLT5aIbNQhQDPcTo0DgbRH+FvqsRXr7yeaef
JaPnxX0+1L33t2QY9zctiGyebwrvHMrIPBJ2VYCDzQkJ7uQ5eFh4ZhsMgOmzLQD4
YiGr5weIMFwAvxZOaRxEa9Vf48jiWvrxuJ8YfHWS0hEScNOcYC2P8q20lJwwE26T
lpdtrwCqtB1LYW1pIFZhbmllYSA8a2FtaUB2YW5pZWEuY29tPokBQgQTAQIALAIb
IwUJCWYBgAcLCQgHAwIBBhUIAgkKCwQWAgMBAh4BAheABQJWCmMeAhkBAAoJEJN2
zGX38dl9JJAIAIW0rxrlYsrmKS6CbW8MgTxxTDOXaCt1b7F0W0QZHskIUQhEcE+a
XBYib1A5uHaatLfyjeXaD3qMEoZnQHoYMGE0GKu00wWsbhfoQzHPgwzRLkD1i75M
BIbaww0KWoVB9e4AkMakXJCnF5BXeo6AHRL2v15V205DikVnlCRXocKtu8b7LnkM
cLn70L0br1de1uyKoNzbSnO/vpKDJp0/EY5yUeV90IypZy/6wFQBehg1sXye6znO
9wb9uUsu9+/P8pz4JILMDSevjfT7zSRSl/YP3fOfZ6N4bc+KOdwPM7u5Iyoeu9zh
pzibv3ge7VhH2xIWz8vYZ/2xT1345tWRRMOJAhwEEwECAAYFAlTnSpEACgkQjyxM
p99tBt2B8A/+OpIzOsQbQJB8yxti4I7PpD1weJDf3a81Vhm7JyXE/Xy66ypfdt3w
XmFRUuIrwezY1NebWNCRQHzQvRv/VJwjbTUx+Q3HsjIkKlHbE7iCiQXXtTRkoEny
2nudcjGI2v03C3B2JCucEw6esF1x79PI/lPv2+6tgUBKmDfOpsB2vbtqrHnmAYKL
4lQBFH1YSJgnzwo2Jkh0hcHdF90Zem1eMeiDEeVkH63893N8Swk5fBKdTj+SKZ/L
rQElBBlpMR9BmeY6bPvWRuycVKonIMR80G9iFABxjTpWBL8aGk6EeVK5EqYDGvkd
ZIarK84r+KU1KD5IfgOCN7nhwgy7VImE68caZHSRiPWZP1fVVMhydiRJv8WsoUs6
INfVU3nxH+ZYthPbY0T86leGSchBT5K/fBQvbjhrRTbTFwvjzSifb9efWylDi994
nzP6cNorir3GIpsT8gPgBB2/NjxaWiM6y3X1az1vRnsunQHuyKkFWPZwnEvDJYaC
NN/3jWcbhLFwKBDsaHps2+1meFP0oJFvNetzp2bjT9a9pXaQ6KhOmo5DnhLcaV97
bFBpsUuBGaYZTSS05x1RdXHqpEbgap8dtuHhVvJw9QYDQBJro K4aKyG9qqMD8cta
Pl/FAdyAqwH8Nw9efqAK+RQxSVUaue9BYEnbIRpsDK6MkP3YMFmu5ki5AQ0EUcxy
AAEIALyXYy8G2ZaTDJpdGcRhmIqOOSUlzPV7/5E5BbYKBNu4KU3nX+JLVcF5jxPQ
42c7i/WRVxE1BJTiarKGsEvCi94TTXSIUKAt3T10GBtXmGvqbGBq8ljSGl1UTwdF
5yu50JyRSf2fqRND6P/2eHNXejDUtdvhUXIUt8h9MuUO/ipD0DnwIvMnAATJHA+R
Zqw6oNpyjRGzvr3iuWUwe4PtyJDI3ELAFkbp/NAc5TIuVHRHNOWNplcIJhM5zHuB
QQb3G/EsCn2PQZ5w5SDzavF2SpvQfDqxYpDaTLAXtF+wsJL5iaUjxwRgJPOdbCZf
2Tozd7h9MXtGJDlPKJ8eLG8ogcMAEQEAAYkBJQQYAQIADwUCUcxyAAIbDAUJCWYB
gAAKCRCTdsxl9/HZfS+hB/9BJqSmIgcoHFXnb1PVIKxekzL8+WVm5Pk/EgMQSLZ2
HX4p3ial5PEPcYgUw9YnaG4i00dwJGw5/daTWRrTzcnKd8Yq0P+DU0t96HZDSu3m
mCzE9NVAQYboFbVmGOx0eo627UBSvFqaXvAxBDYkoR8BoTnKhrQFwXkZVb30hKwD
TgAFjOGlZiE6uAdST231tFaq0bizYfe5AVXRqro20xBqNbaJNqs3SW0D831Syvdv
llOBx83/R0gg7hUkI6F2vzXicWmUwFSXRrggCSbLosHsP6isBWwvlHeRmna/aQab
YKG3gbV9iyczAS31gbogVLAZqNSWhp8vVIEE28Fyf/Ed
=x5FK
-----END PGP PUBLIC KEY BLOCK-----

I want to send Bob a message that no one else can read

- I encrypt (lock) the message with Bob's public key.
- Only Bob has his private key, so only Bob can decrypt (unlock) the message.

Bob's public key

Bob's private key

My public key

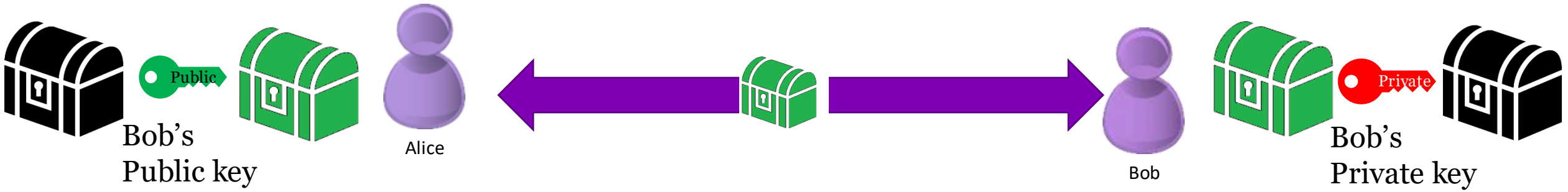
-----BEGIN PGP PUBLIC KEY BLOCK-----
Version: GnuPG v2

mQENBFHMcgABCAC9WrYDO6K2L3VHyi4eHN6suHLqMpJ+SO+IUTuLEVnUzIoXAUXH
KozHejfV/9XoG8j933ZtszXKCog3aMESe0E0z6fNGfolvaCe5B4jwq0Jt8NHwb5L
B2dnq0CplgXcN2GJxfEHHUaf27COSobCJxPMeshUh4ZHke+g6DatmiEtBpVp41Ot
1zgxdMQkgb2H2xw28RYfYkdDoueteIkOrFLrCy9ZF9KdMhA1eBH94KnwIQshdiZR
QYEX25+M8cKCb++Rc9H6an7EG9WHOFRW40UsY52OfveOyfQPzkkRto7u2339hvHo
B/h+7xLM6FQbOUZQ9BD5w7IQHgYtXJVsUjodABEBAAG0IkthbWkgVmFuaWVhIDxr
dmFuaWVhQGluZi5lZC5hYy51az6JAT8EEwEIACkFAlYKYvECGyMFCQlmAYAHCwkI
BwMCAQYVCAIJCgsEFgIDAQIeAQIXgAAKCRCTdsxl9/HZffG+CACShuKxje3QAqew
GWh8K4gCdiYoxDqJwq3PHxmyhZmQeN/1a1KcOrIjI2b+Q75/5t+EgXOHpR0PIxfG
lZ6zOEpf6A18iFXx3JgQZdwPD0jtBiWNpOyMeBGTgIvEYG3so2VueQoeXcq3dbYp
5vstVxtD+TKHQ5CioIT75P2bzYq/XLT5aIbNQhQDPcTo0DgbRH+FvqsRXr7yeaef
JaPnxX0+1L33t2QY9zctiGyebwrvHMrIPBJ2VYCDzQkJ7uQ5eFh4ZhsMgOmzLQD4
YiGr5weIMFwAvxZOaRxEa9Vf48jiWvrxuJ8YfHWS0hEScNOcYC2P8q20lJwwE26T
lpdtrwCqtB1LYW1pIFZhbmllYSA8a2FtaUB2YW5pZWEuY29tPokBQgQTAQIALAIb
IwUJCWYBgAcLCQgHAwIBBhUIAgkKCwQWAgMBAh4BAheABQJWCmMeAhkBAAoJEJN2
zGX38dl9JJAIAIW0rxrlYsrmKS6CbW8MgTxxTDOXaCt1b7F0W0QZHskIUQhEcE+a
XBYib1A5uHaatLfyjeXaD3qMEoZnQHoYMGE0GKu00wWsbhfoQzHPgwzRLkD1i75M
BIbaww0KWoVB9e4AkMakXJCnF5BXeo6AHRL2v15V205DikVnlCRXocKtu8b7LnkM
cLn70Lobr1de1uyKoNzbSnO/vpKDJp0/EY5yUeV90IypZy/6wFQBehg1sXye6zn0
9wb9uUsu9+/P8pz4JILMDSevjfT7zSRSl/YP3fOfZ6N4bc+KOdwPM7u5Iyoeu9zh
pzibv3ge7VhH2xIWz8vYZ/2xT1345tWRRMOJAhwEEwECAAYFAlTnSpEACgkQjyxM
p99tBt2B8A/+OpIzOsQbQJB8yxti4I7PpD1weJDf3a81Vhm7JyXE/Xy66ypfdt3w
XmFRUuIrwezY1NebWNCRQHzQvRv/VJwjbTUx+Q3HsjIkKlHbE7iCiQXXtTRkoEny
2nudcjGI2v03C3B2JCucEw6esF1x79PI/lPv2+6tgUBKmDfOpsB2vbtqrHnmAYKL
4lQBFH1YSJgnzwo2Jkh0hcHdF90Zem1eMeiDEeVkH63893N8Swk5fBKdTj+SKZ/L
rQElBBlpMR9BmeY6bPvWRuycVKonIMR80G9iFABxjTpWBL8aGk6EeVK5EqYDGvkd
ZIarK84r+KU1KD5IfgOCN7nhwgy7VImE68caZHSRiPWZP1fVVMhydiRJv8WsoUs6
INfVU3nxH+ZYthPbY0T86leGSchBT5K/fBQvbjhrRTbTFwvjzSifb9efWylDi994
nzP6cNorir3GIpsT8gPgBB2/NjxaWiM6y3X1az1vRnsunQHuyKkFWPZwnEvDJYaC
NN/3jWcbhLFwKBDsaHps2+1meFP0oJFvNetzp2bjT9a9pXaQ6KhOmo5DnhLcaV97
bFBpsUuBGaYZTSS05x1RdXHqpEbgap8dtuHhVvJw9QYDQBJr0K4aKyG9qqMD8cta
Pl/FAdyAqwH8Nw9efqAK+RQxSVUaue9BYEnbIRpsDK6MkP3YMFmu5ki5AQ0EUcxy
AAEIALyXYy8G2ZaTDJpdGcRhmIqOOSUlzPV7/5E5BbYKBNu4KU3nX+JLVcF5jxPQ
42c7i/WRVxE1BJTiarKGsEvCi94TTXSIUKAt3T1oGBtXmGvqbGBq8ljSGl1UTwdF
5yu50JyRSf2fqRND6P/2eHNXejDUtdvhUXIUt8h9MuUO/ipD0DnwIvMnAATJHA+R
Zqw6oNpyjRGzvr3iuWUwe4PtyJDI3ELAFkbp/NAc5TIuVHRHNOWNplcIJhM5zHuB
QQb3G/EsCn2PQZ5w5SDzavF2SpvQfDqxYpDaTLAXtF+wsJL5iaUjxwRgJPOdbCZf
2Tozd7h9MXtGJDlPKJ8eLG8ogcMAEQEAAYkBJQQYAQIADwUCUcxyAAIbDAUJCWYB
gAAKCRCTdsxl9/HZfS+hB/9BJqSmIgcoHFXnb1PVIKxekzL8+WVm5Pk/EgMQSLZ2
HX4p3ial5PEPcYgUw9YnaG4i00dwJGw5/daTWRrTzcnKd8Yq0P+DU0t96HZDSu3m
mCzE9NVAQYboFbVmGOx0eo627UBSvFqaXvAxBDYkoR8BoTnKhrQFwXkZVb30hKwD
TgAFjOGlZiE6uAdST231tFaq0bizYfe5AVXRqro20xBqNbaJNqs3SW0D831Syvdv
llOBx83/R0gg7hUkI6F2vzXicWmUwFSXRrggCSbLosHsP6isBWwvlHeRmna/aQab
YKG3gbV9iyczAS31gbogVLAZqNSWhp8vVIEE28Fyf/Ed
=x5FK
-----END PGP PUBLIC KEY BLOCK-----

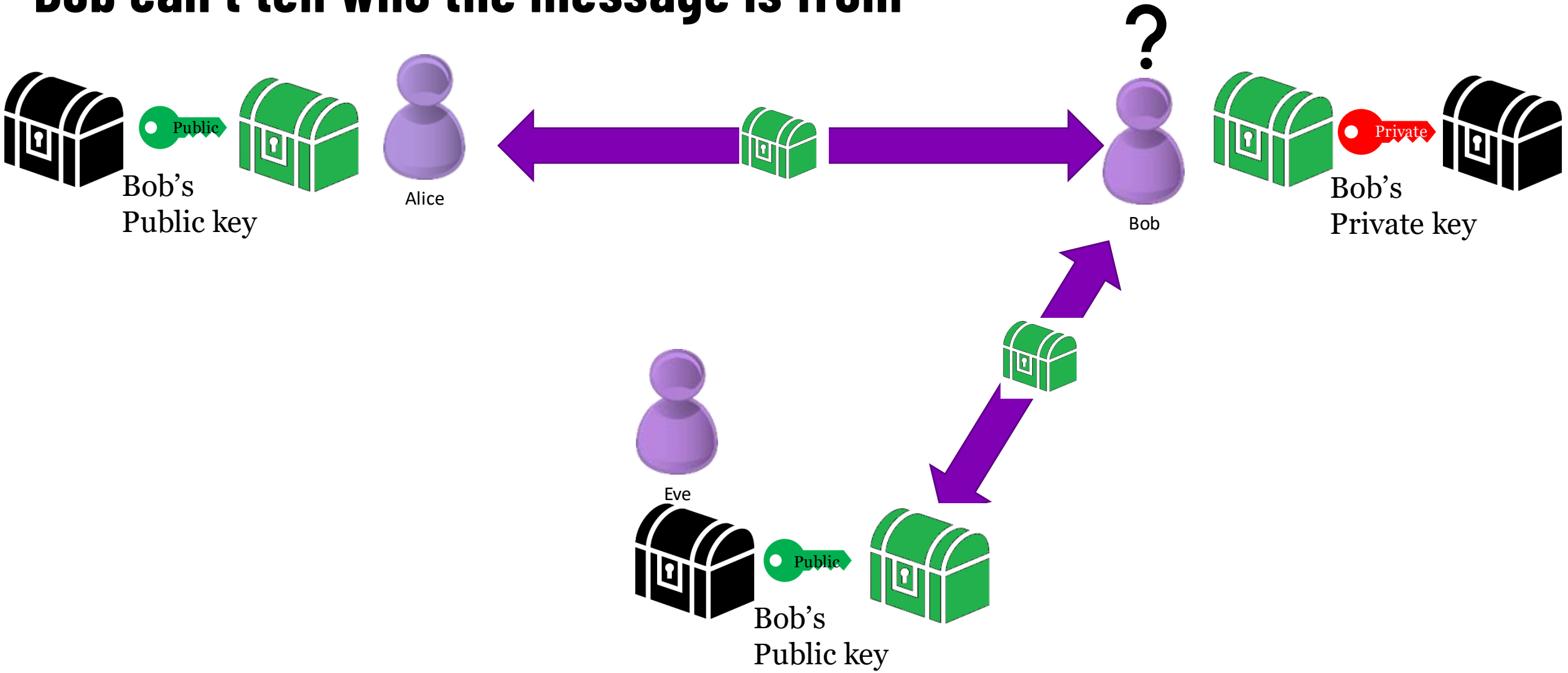
Encryption properties we want:

1. The communication between you and the other party is **confidential** and has **not been changed (integrity)**
   - No one can read what you sent
   - No one can change what you sent
2. **Knowing who** you are communicating with
   - You are talking to who you think you are talking to and not someone else

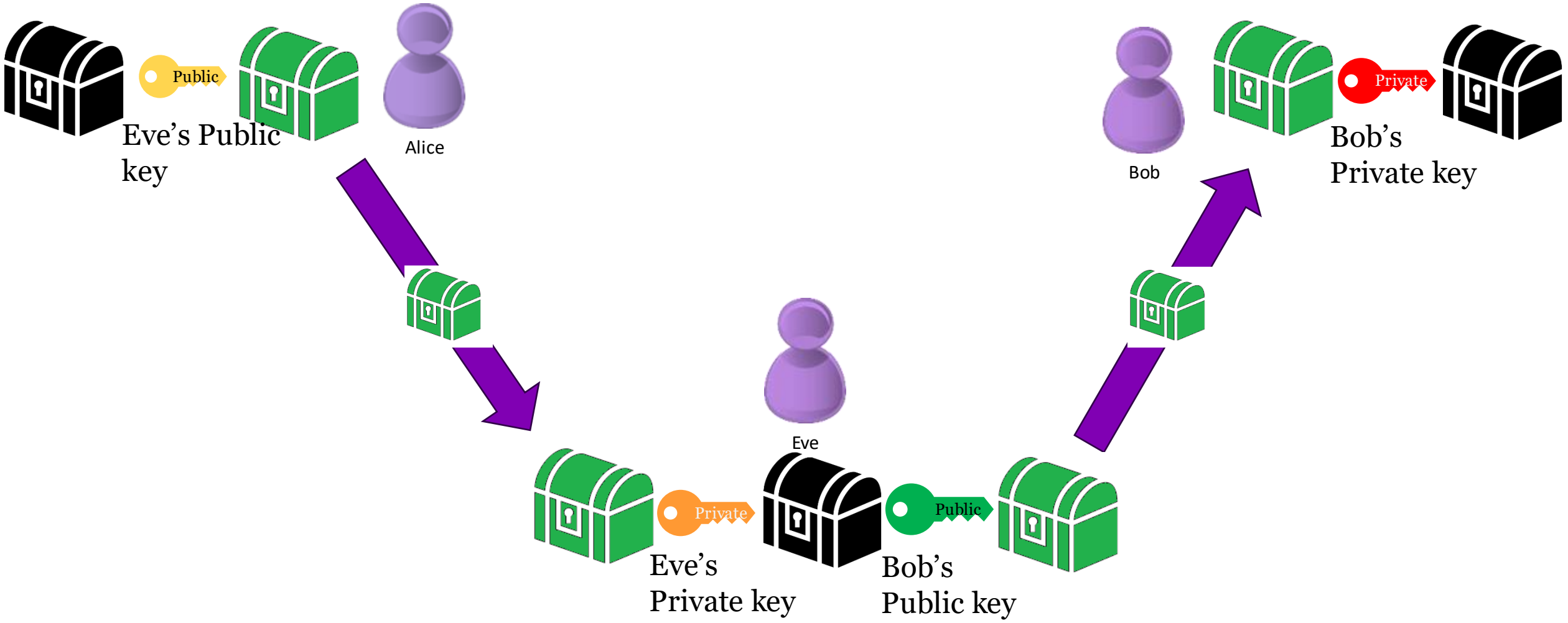
Bob can’t tell who the message is from



Bob can’t tell who the message is from



Full Man in the Middle (MITM)



Vital to keep private keys private

- The FBI convinced the system administrator to switch out the private key for one the FBI knew
- FBI was able to listen in on all the chats and got lots of evidence

The Register®
Biting the hand that feeds IT

Security

Who cracked El Chapo's encrypted chats and brought down the Mexican drug kingpin? Er, his IT manager

Feds flipped techie and recorded hundreds of calls

By Kieren McCarthy in San Francisco 9 Jan 2019 at 21:33 71 SHARE ▼

In an extraordinary twist, it was revealed on Tuesday that the man most likely responsible for bringing drug kingpin "El Chapo" Joaquin Guzman to justice was none other than his sysadmin.

Vital to keep private keys private

- The FBI convinced the system administrator to switch out the private key for one the FBI knew
- FBI was able to listen in on all the chats and got lots of evidence
- How? A high ranking drug trafficker forgot his password and called the admin unencrypted. After FBI heard the conversation they thought the admin might like some protection.

But the drug trafficker isn't happy, complaining about having to get the computer himself, and about the long password needed to get into a different machine: A situation that every sysadmin on the globe will recognize. Except with one big difference - your boss is unlikely to track you down and kill you if you upset him.

"You didn't send me the engineer to install my machine. So, then, it's all your fault," Jorge Cifuentes complained. "No!" responded to Rodriguez.

"It's all your fault."
"No, Don Jorge, don't stress me out more, man, because..."
"Don't complain that I... what can I do? I haven't been able to do it."
"Hadn't we agreed that you were going to buy a mini computer and you were going to call us to configure it?"
"I'm so busy. I didn't even have time to breathe... I have a computer but, you know that I haven't been able to open it? A Vaio... Do you remember the small Vaio?"
"Yes, sir."
"Good, but that has a very long password."
"Yes, sir."
"The long one, that password that you place...is this the password?
"Yes, sir."
"What a drag! It has symbols and things."

Encryption: I want to send Bob a message that no one else can read

- I encrypt (lock) the message with Bob's public key.
- Only Bob has his private key, so only Bob can decrypt (unlock) the message.

Bob's public key

Bob's private key

My public key

-----BEGIN PGP PUBLIC KEY BLOCK-----
Version: GnuPG v2

mQENBFHMcgABCAC9WrYDO6K2L3VHyi4eHN6suHLqMpJ+SO+IUTuLEVnUzIoXAUXH
KozHejfV/9XoG8j933ZtszXKCog3aMESe0E0z6fNGfolvaCe5B4jwq0Jt8NHwb5L
B2dnq0CplgXcN2GJxfEHHUaf27COSobCJxPMeshUh4ZHke+g6DatmiEtBpVp41Ot
1zgxdMQkgb2H2xw28RYfYkdDoueteIkOrFLrCy9ZF9KdMhA1eBH94KnwIQshdiZR
QYEX25+M8cKCb++Rc9H6an7EG9WHOFRW40UsY52OfveOyfQPzkkRto7u2339hvHo
B/h+7xLM6FQbOUZQ9BD5w7IQHgYtXJVsUjodABEBAAG0IkthbWkgVmFuaWVhIDxr
dmFuaWVhQGluZi5lZC5hYy51az6JAT8EEwEIACkFAlYKYvECGyMFCQlmAYAHCwkI
BwMCAQYVCAIJCgsEFgIDAQIeAQIXgAAKCRCTdsxl9/HZffG+CACShuKxje3QAqew
GWh8K4gCdiYoxDqJwq3PHxmyhZmQeN/1a1KcOrIjI2b+Q75/5t+EgXOHpR0PIxfG
lZ6zOEpf6A18iFXx3JgQZdwPD0jtBiWNpOyMeBGTgIvEYG3so2VueQoeXcq3dbYp
5vstVxtD+TKHQ5CioIT75P2bzYq/XLT5aIbNQhQDPcTo0DgbRH+FvqsRXr7yeaef
JaPnxX0+1L33t2QY9zctiGyebwrvHMrIPBJ2VYCDzQkJ7uQ5eFh4ZhsMgOmzLQD4
YiGr5weIMFwAvxZOaRxEa9Vf48jiWvrxuJ8YfHWS0hEScNOcYC2P8q20lJwwE26T
lpdtrwCqtB1LYW1pIFZhbmllYSA8a2FtaUB2YW5pZWEuY29tPokBQgQTAQIALAIb
IwUJCWYBgAcLCQgHAwIBBhUIAgkKCwQWAgMBAh4BAheABQJWCmMeAhkBAAoJEJN2
zGX38dl9JJAIAIW0rxrlYsrmKS6CbW8MgTxxTDOXaCt1b7F0W0QZHskIUQhEcE+a
XBYib1A5uHaatLfyjeXaD3qMEoZnQHoYMGE0GKu00wWsbhfoQzHPgwzRLkD1i75M
BIbaww0KWoVB9e4AkMakXJCnF5BXeo6AHRL2v15V205DikVnlCRXocKtu8b7LnkM
cLn70L0br1de1uyKoNzbSnO/vpKDJp0/EY5yUeV90IypZy/6wFQBehg1sXye6zn0
9wb9uUsu9+/P8pz4JILMDSevjfT7zSRSl/YP3fOfZ6N4bc+KOdwPM7u5Iyoeu9zh
pzibv3ge7VhH2xIWz8vYZ/2xT1345tWRRMOJAhwEEwECAAYFAlTnSpEACgkQjyxM
p99tBt2B8A/+OpIzOsQbQJB8yxti4I7PpD1weJDf3a81Vhm7JyXE/Xy66ypfdt3w
XmFRUuIrwezY1NebWNCRQHzQvRv/VJwjbTUx+Q3HsjIkKlHbE7iCiQXXtTRkoEny
2nudcjGI2v03C3B2JCucEw6esF1x79PI/lPv2+6tgUBKmDfOpsB2vbtqrHnmAYKL
4lQBFH1YSJgnzwo2Jkh0hcHdF90Zem1eMeiDEeVkH63893N8Swk5fBKdTj+SKZ/L
rQElBBlpMR9BmeY6bPvWRuycVKonIMR80G9iFABxjTpWBL8aGk6EeVK5EqYDGvkd
ZIarK84r+KU1KD5IfgOCN7nhwgy7VImE68caZHSRiPWZP1fVVMhydiRJv8WsoUs6
INfVU3nxH+ZYthPbY0T86leGSchBT5K/fBQvbjhrRTbTFwvjzSifb9efWylDi994
nzP6cNorir3GIpsT8gPgBB2/NjxaWiM6y3X1az1vRnsunQHuyKkFWPZwnEvDJYaC
NN/3jWcbhLFwKBDsaHps2+1meFP0oJFvNetzp2bjT9a9pXaQ6KhOmo5DnhLcaV97
bFBpsUuBGaYZTSS05x1RdXHqpEbgap8dtuHhVvJw9QYDQBJr0K4aKyG9qqMD8cta
Pl/FAdyAqwH8Nw9efqAK+RQxSVUaue9BYEnbIRpsDK6MkP3YMFmu5ki5AQ0EUcxy
AAEIALyXYy8G2ZaTDJpdGcRhmIqOOSUlzPV7/5E5BbYKBNu4KU3nX+JLVcF5jxPQ
42c7i/WRVxE1BJTiarKGsEvCi94TTXSIUKAt3T1oGBtXmGvqbGBq8ljSGl1UTwdF
5yu50JyRSf2fqRND6P/2eHNXejDUtdvhUXIUt8h9MuUO/ipD0DnwIvMnAATJHA+R
Zqw6oNpyjRGzvr3iuWUwe4PtyJDI3ELAFkbp/NAc5TIuVHRHNOWNplcIJhM5zHuB
QQb3G/EsCn2PQZ5w5SDzavF2SpvQfDqxYpDaTLAXtF+wsJL5iaUjxwRgJPOdbCZf
2Tozd7h9MXtGJDlPKJ8eLG8ogcMAEQEAAYkBJQQYAQIADwUCUcxyAAIbDAUJCWYB
gAAKCRCTdsxl9/HZfS+hB/9BJqSmIgcoHFXnb1PVIKxekzL8+WVm5Pk/EgMQSLZ2
HX4p3ial5PEPcYgUw9YnaG4i00dwJGw5/daTWRrTzcnKd8Yq0P+DU0t96HZDSu3m
mCzE9NVAQYboFbVmGOx0eo627UBSvFqaXvAxBDYkoR8BoTnKhrQFwXkZVb30hKwD
TgAFjOGlZiE6uAdST231tFaq0bizYfe5AVXRqro20xBqNbaJNqs3SW0D831Syvdv
llOBx83/R0gg7hUkI6F2vzXicWmUwFSXRrggCSbLosHsP6isBWwvlHeRmna/aQab
YKG3gbV9iyczAS31gbogVLAZqNSWhp8vVIEE28Fyf/Ed
=x5FK
-----END PGP PUBLIC KEY BLOCK-----

Signature: I want to prove a message is from me

- I encrypt (lock) the message with my private key
- Anyone with the public key can use it to decrypt (unlock) the file. If it decrypts (unlocks), then it must have been encrypted (locked) by my private key and no other.

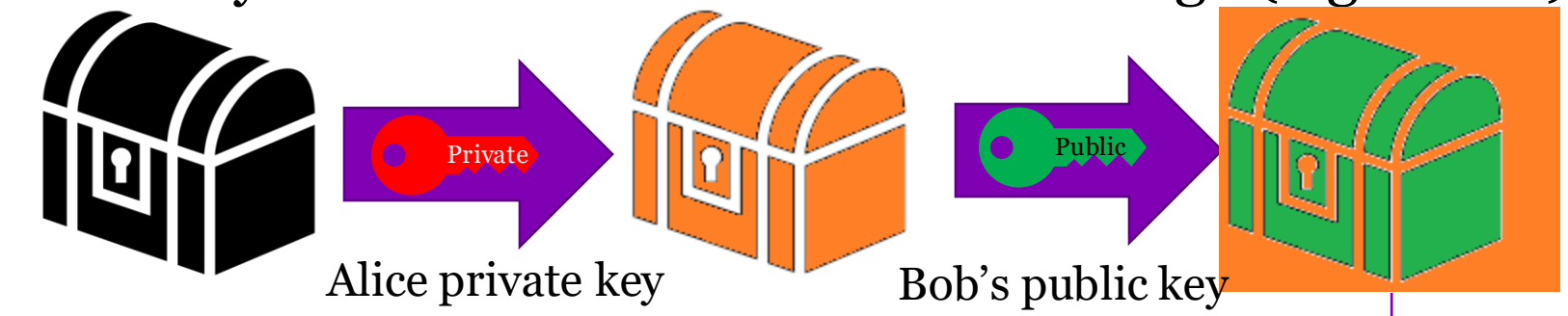
My public key

-----BEGIN PGP PUBLIC KEY BLOCK-----
Version: GnuPG v2

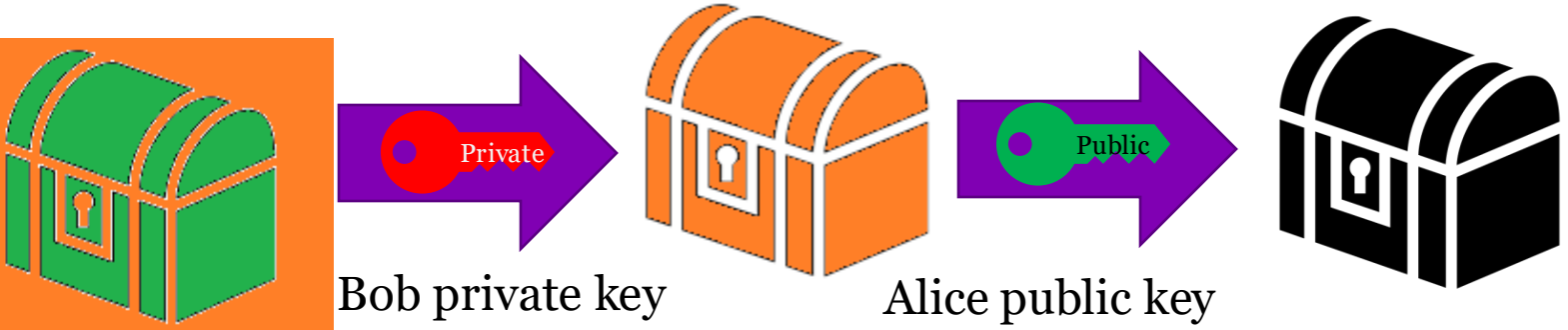
mQENBFHMcgABCAC9WrYDO6K2L3VHyi4eHN6suHLqMpJ+SO+IUTuLEVnUzIoXAUXH
KozHejfV/9XoG8j933ZtszXKCog3aMESe0E0z6fNGfolvaCe5B4jwq0Jt8NHwb5L
B2dnq0CplgXcN2GJxfEHHUaf27COSobCJxPMeshUh4ZHke+g6DatmiEtBpVp41Ot
1zgxdMQkgb2H2xw28RYfYkdDoueteIkOrFLrCy9ZF9KdMhA1eBH94KnwIQshdiZR
QYEX25+M8cKCb++Rc9H6an7EG9WHOFRW40UsY52OfveOyfQPzkkRto7u2339hvHo
B/h+7xLM6FQbOUZQ9BD5w7IQHgYtXJVsUjodABEBAAG0IkthbWkgVmFuaWVhIDxr
dmFuaWVhQGluZi5lZC5hYy51az6JAT8EEwEIACkFAlYKYvECGyMFCQlmAYAHCwkI
BwMCAQYVCAIJCgsEFgIDAQIeAQIXgAAKCRCTdsxl9/HZffG+CACShuKxje3QAqew
GWh8K4gCdiYoxDqJwq3PHxmyhZmQeN/1a1KcOrIjI2b+Q75/5t+EgXOHpR0PIxfG
lZ6zOEpf6A18iFXx3JgQZdwPD0jtBiWNpOyMeBGTgIvEYG3so2VueQoeXcq3dbYp
5vstVxtD+TKHQ5CioIT75P2bzYq/XLT5aIbNQhQDPcTo0DgbRH+FvqsRXr7yeaef
JaPnxX0+1L33t2QY9zctiGyebwrvHMrIPBJ2VYCDzQkJ7uQ5eFh4ZhsMgOmzLQD4
YiGr5weIMFwAvxZOaRxEa9Vf48jiWvrxuJ8YfHWS0hEScNOcYC2P8q20lJwwE26T
lpdtrwCqtB1LYW1pIFZhbmllYSA8a2FtaUB2YW5pZWEuY29tPokBQgQTAQIALAIb
IwUJCWYBgAcLCQgHAwIBBhUIAgkKCwQWAgMBAh4BAheABQJWCmMeAhkBAAoJEJN2
zGX38dl9JJAIAIW0rxrlYsrmKS6CbW8MgTxxTDOXaCt1b7F0W0QZHskIUQhEcE+a
XBYib1A5uHaatLfyjeXaD3qMEoZnQHoYMGE0GKu00wWsbhfoQzHPgwzRLkD1i75M
BIbaww0KW0VB9e4AkMakXJCnF5BXeo6AHRL2v15V205DikVnlCRXocKtu8b7LnkM
cLn70L0br1de1uyKoNzbSnO/vpKDJp0/EY5yUeV90IypZy/6wFQBehg1sXye6znO
9wb9uUsu9+/P8pz4JILMDSevjfT7zSRSl/YP3fOfZ6N4bc+KOdwPM7u5Iyoeu9zh
pzibv3ge7VhH2xIWz8vYZ/2xT1345tWRRMOJAhwEEwECAAYFAlTnSpEACgkQjyxM
p99tBt2B8A/+OpIzOsQbQJB8yxti4I7PpD1weJDf3a81Vhm7JyXE/Xy66ypfdt3w
XmFRUuIrwezY1NebWNCRQHzQvRv/VJwjbTUx+Q3HsjIkKlHbE7iCiQXXtTRkoEny
2nudcjGI2v03C3B2JCucEw6esF1x79PI/lPv2+6tgUBKmDfOpsB2vbtqrHnmAYKL
4lQBFH1YSJgnzwo2Jkh0hcHdF90Zem1eMeiDEeVkH63893N8Swk5fBKdTj+SKZ/L
rQElBBlpMR9BmeY6bPvWRuycVKonIMR80G9iFABxjTpWBL8aGk6EeVK5EqYDGvkd
ZIarK84r+KU1KD5IfgOCN7nhwgy7VImE68caZHSRiPWZP1fVVMhydiRJv8WsoUs6
INfVU3nxH+ZYthPbY0T86leGSchBT5K/fBQvbjhrRTbTFwvjzSifb9efWylDi994
nzP6cNorir3GIpsT8gPgBB2/NjxaWiM6y3X1az1vRnsunQHuyKkFWPZwnEvDJYaC
NN/3jWcbhLFwKBDsaHps2+1meFP0oJFvNetzp2bjT9a9pXaQ6KhOmo5DnhLcaV97
bFBpsUuBGaYZTSS05x1RdXHqpEbgap8dtuHhVvJw9QYDQBJro K4aKyG9qqMD8cta
Pl/FAdyAqwH8Nw9efqAK+RQxSVUaue9BYEnbIRpsDK6MkP3YMFmu5ki5AQ0EUcxy
AAEIALyXYy8G2ZaTDJpdGcRhmIqOOSUlzPV7/5E5BbYKBNu4KU3nX+JLVcF5jxPQ
42c7i/WRVxE1BJTiarKGsEvCi94TTXSIUKAt3T1oGBtXmGvqbGBq8ljSGl1UTwdF
5yu50JyRSf2fqRND6P/2eHNXejDUtdvhUXIUt8h9MuUO/ipD0DnwIvMnAATJHA+R
Zqw6oNpyjRGzvr3iuWUwe4PtyJDI3ELAFkbp/NAc5TIuVHRHNOWNplcIJhM5zHuB
QQb3G/EsCn2PQZ5w5SDzavF2SpvQfDqxYpDaTLAXtF+wsJL5iaUjxwRgJPOdbCZf
2Tozd7h9MXtGJDlPKJ8eLG8ogcMAEQEAAYkBJQQYAQIADwUCUcxyAAIbDAUJCWYB
gAAKCRCTdsxl9/HZfS+hB/9BJqSmIgcoHFXnb1PVIKxekzL8+WVm5Pk/EgMQSLZ2
HX4p3ial5PEPcYgUw9YnaG4i00dwJGw5/daTWRrTzcnKd8Yq0P+DU0t96HZDSu3m
mCzE9NVAQYboFbVmGOx0eo627UBSvFqaXvAxBDYkoR8BoTnKhrQFwXkZVb30hKwD
TgAFjOGlZiE6uAdST231tFaq0bizYfe5AVXRqro20xBqNbaJNqs3SW0D831Syvdv
llOBx83/R0gg7hUkI6F2vzXicWmUwFSXRrggCSbLosHsP6isBWwvlHeRmna/aQab
YKG3gbV9iyczAS31gbogVLAZqNSWhp8vVIEE28Fyf/Ed
=x5FK
-----END PGP PUBLIC KEY BLOCK-----

If Alice does both of those at the same time she can prove that:

1. only Alice could have sent the message (signature)



2. only Bob can read it (encryption)



- Signature:
  k_{PRIV} can encrypt and k_{PUB} can decrypt

  $P = D(k_{PUB}, E(k_{PRIV}, P))$

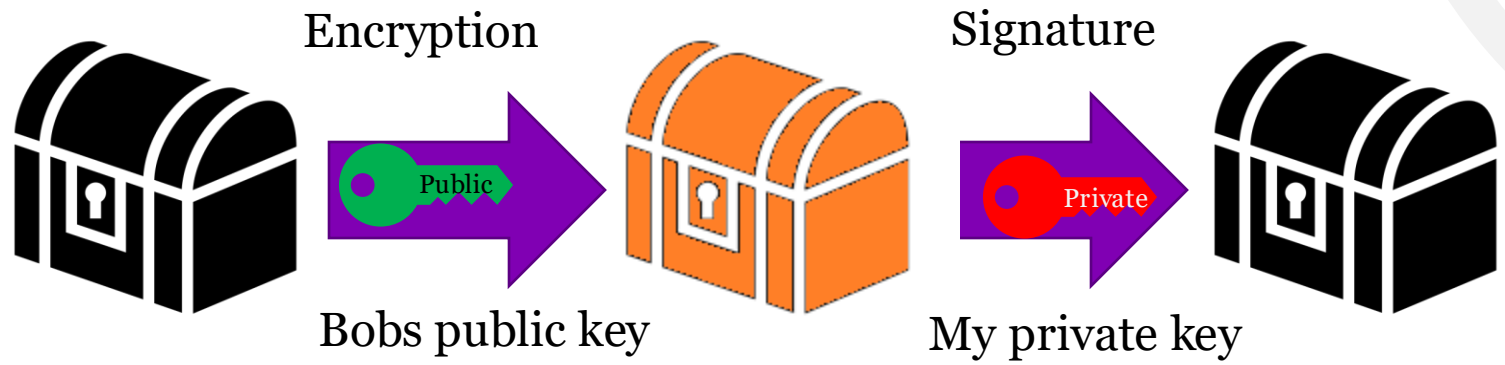
- Encryption:
  k_{PUB} can encrypt and k_{PRIV} can decrypt

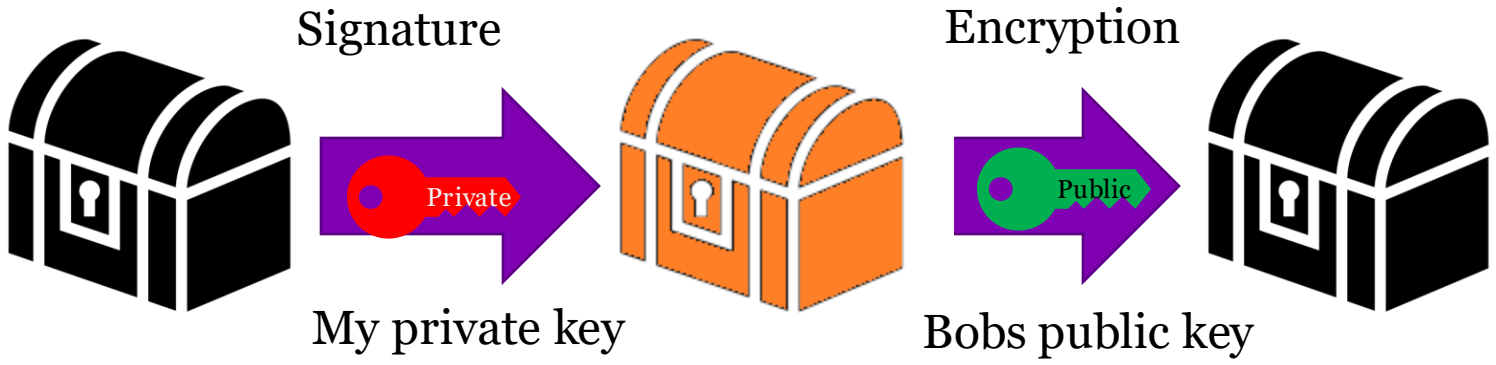
  $P = D(k_{PRIV}, E(k_{PUB}, P))$

- Signing and encrypting:
  $P = D(A_{PUB}, D(B_{PRIV}, E(B_{PUB}, E(A_{PRIV}, P))))$

Think-pair-share

- When both encrypting and signing a message. The order of encryption and signature matters. What attack is possible if the order is reversed?





Encryption properties we want:

1. The communication between you and the other party is **confidential** and has **not been changed**
   - No one can read what you sent
   - No one can change what you sent
2. **Knowing who** you are communicating with
   - You are talking to who you think you are talking to and not someone else

ASYMMETRIC KEY GENERATION

Knapsack problem

Given a set of items, each with a weight and a value, determine which items to include in the collection so that the total weight is less than or equal to a given limit and the total value is as large as possible.

Knapsack cryptosystem

- Not secure by modern systems, but much easier to understand than RSA
- Based on the NP hard Knapsack problem: given a set of weights of items find the set of items that equal an exact weight
- Easy to solve for superincreasing knapsacks where each weight is > the sum of all prior weights
- Example: {3,6,11,25,46,95,200,411}

Given a set of n weights
$W=(W_0,W_1,\ldots,W_{n-1})$

and a desired sum S,

find $(a_0,a_1,\ldots a_{n-1})$ where $a_i \in \{0,1\}$

Such that
$S=a_0W_0+a_1W_1+\ldots+ a_{n-1}W_{n-1}$

Knapsack cryptosystem

1. Select a superincreasing knapsack {2,3,7,14,30,57,120,251} – private key
2. Convert to general-looking knapsack using a selected multiplier (41) and modulus (491)
   - Resulting generic knapsack is NP hard to solve
   - {82,123,287,83,248,373,10,471} – public key
3. Compute the multiplicative inverse of the conversion factor, i.e. $m^{-1} \bmod n$
   - 12 = (2,3,7,14,30,57,120,251) and 41^{-1} (mod 491)

Conversion to generic knapsack

Computation	Generic Knapsack
2*41 mod 491	82
3*41 mod 491	123
7*41 mod 491	287
14*41 mod 491	83
30*41 mod 491	248
57*41 mod 491	373
120*41 mod 491	10
251*41 mod 491	471

Knapsack: Alice wants to encrypt for Bob

- M = 10010110
- Bob's public key: {82,123,287,83,248,373,10,471}
- Use Bob's public key to select values

K_{pub}	82	123	287	83	248	373	10	471
M	1	0	0	1	0	1	1	0
C	82			83		373	10	

- Add values: 548 = 82+83+373+10
- Alice sends 548

- Bob computes: $m^{-1} \cdot C \pmod n = 12 \cdot 548 \pmod{491} = 193$
- Bob uses his private key to compute 193

K_{priv}	2	3	7	14	30	57	120	251
M								

Try and work out what should be in the plaintext (message) row

Knapsack: Alice wants to encrypt for Bob

- M = 10010110
- Bob's public key: {82,123,287,83,248,373,10,471}
- Use Bob's public key to select values

K_{pub}	82	123	287	83	248	373	10	471
M	1	0	0	1	0	1	1	0
C	82			83		373	10	

- Add values: 548 = 82+83+373+10
- Alice sends 548

- Bob computes: $m^{-1} \cdot C \pmod n = 12 \cdot 548 \pmod{491} = 193$
- Bob uses his private key to compute 193

K_{priv}	2	3	7	14	30	57	120	251
M	1	0	0	1	0	1	1	0

Knapsack cryptosystem

- Not secure by modern systems, but much easier to understand than RSA
- Knapsack is NP hard, which makes it a sorta ok cryptosystem even today. But it can be broken.

Elfenland Board Game – Basically the traveling salesman problem. Even NP hard problems can be easy/fun at small scale.

RSA – Rivest, Shamir, and Adleman (the inventors)

- Modern standard used by many products
- Unlike Knapsack it is based on prime factorization, which is not proven to be NP complete
- RSA security rests on prime factorization being a hard problem

Adi Shamir, co-inventor of RSA

Photo credit: Ira Abramov from Even Yehuda, Israel - https://www.flickr.com/photos/38872520@N00/3814143223/

RSA – Rivest, Shamir, and Adleman (the inventors)

- To generate, chose two large prime numbers p and q and form their product
  - $N = pq$
- Choose e relatively prime to the product
  - $d=(p-1)(q-1)$
- Public key: (N,e)
  Private key: d
- Compute the cypher C of message M
  - $C = M^e \bmod N$
- Decrypt C
  - $M = C^d \bmod N$
- This works if we assume:
  - $M = C^d \bmod N = M^{ed} \bmod N$

LINKING KEYS AND IDENTITIES

But we still have a problem:

All that assumes that we know which key goes with which person.

One of the founding problems in Usable Security and Privacy.

Even now we have no good answer.

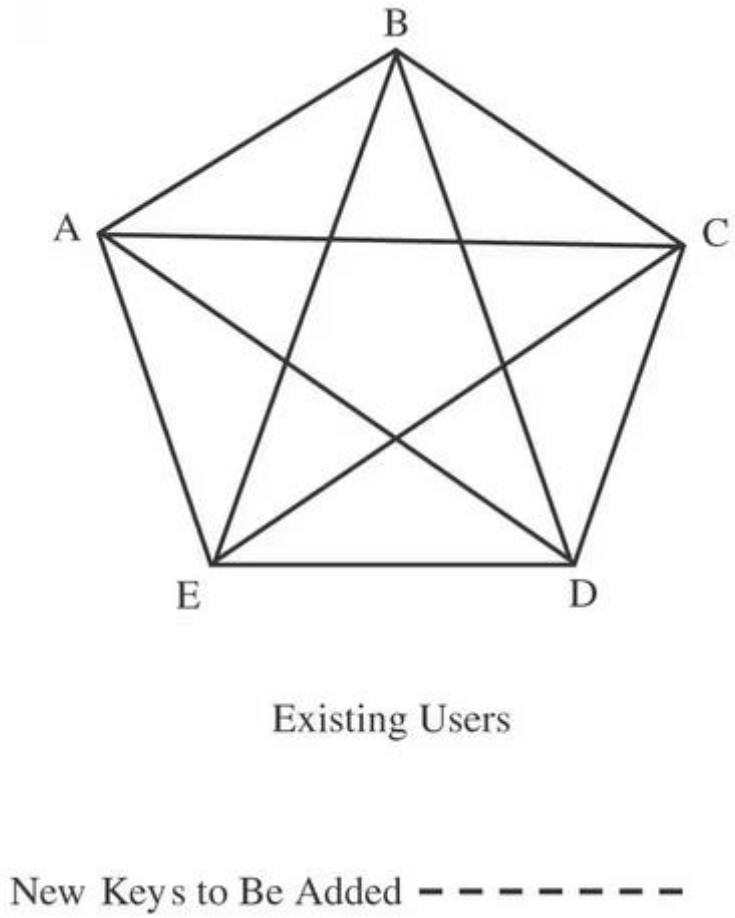
How do we solve the identity problem?

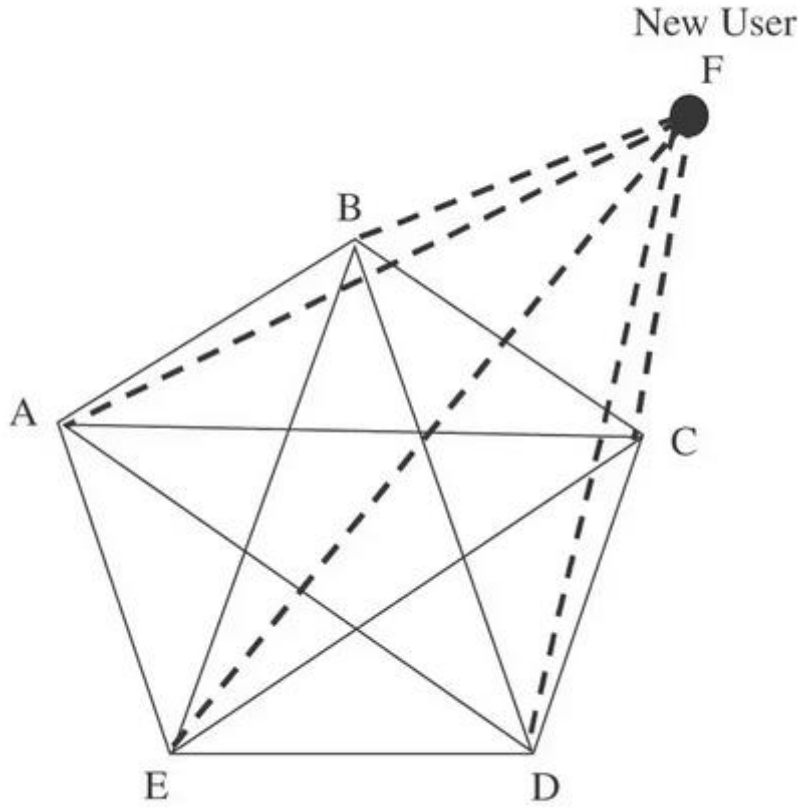
Idea: Have the humans do the linking of identity to cryptographic keys.

Approach scales poorly

An n user system requires n*(n-1)/2 keys

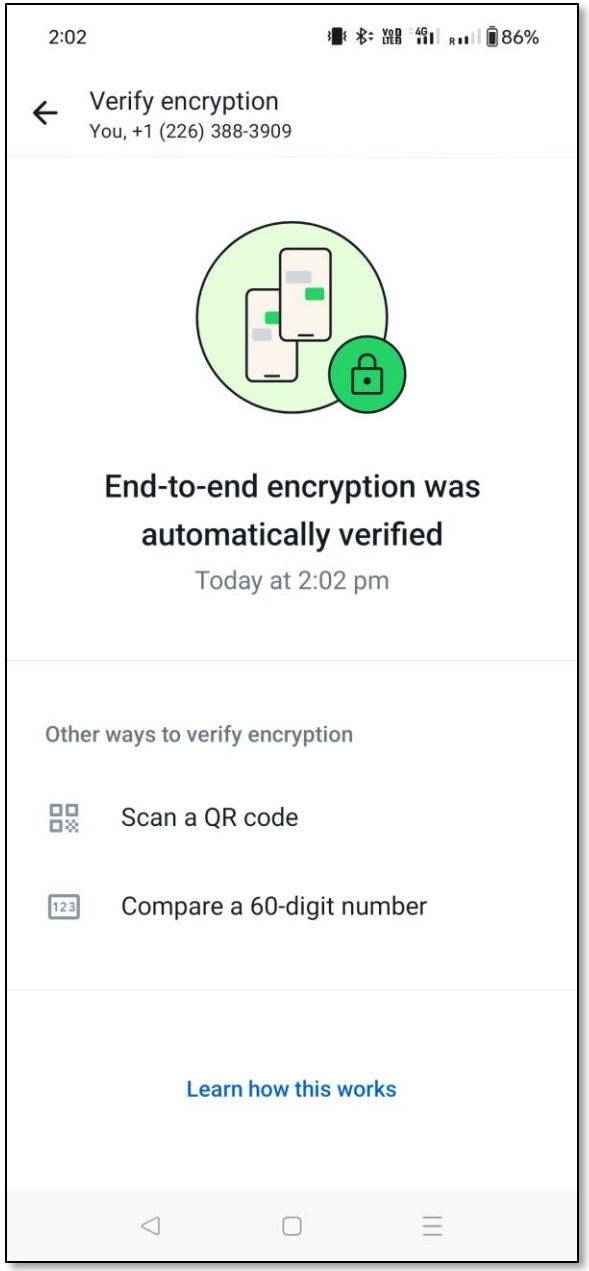
Expecting people to verify that many keys, as well as store and not loose them is unreasonable



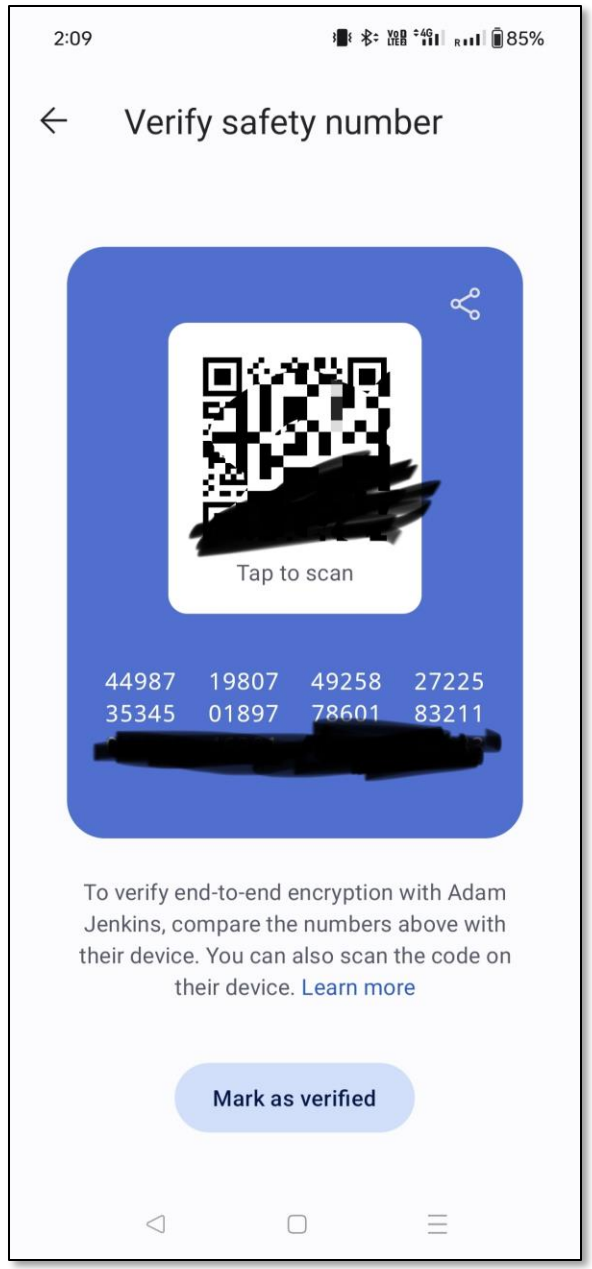


User comparing of keys is still used for verification today by common apps like WhatsApp and Signal.

WhatsApp



Signal



We could post the public key somewhere highly public and verifiable it came from us.

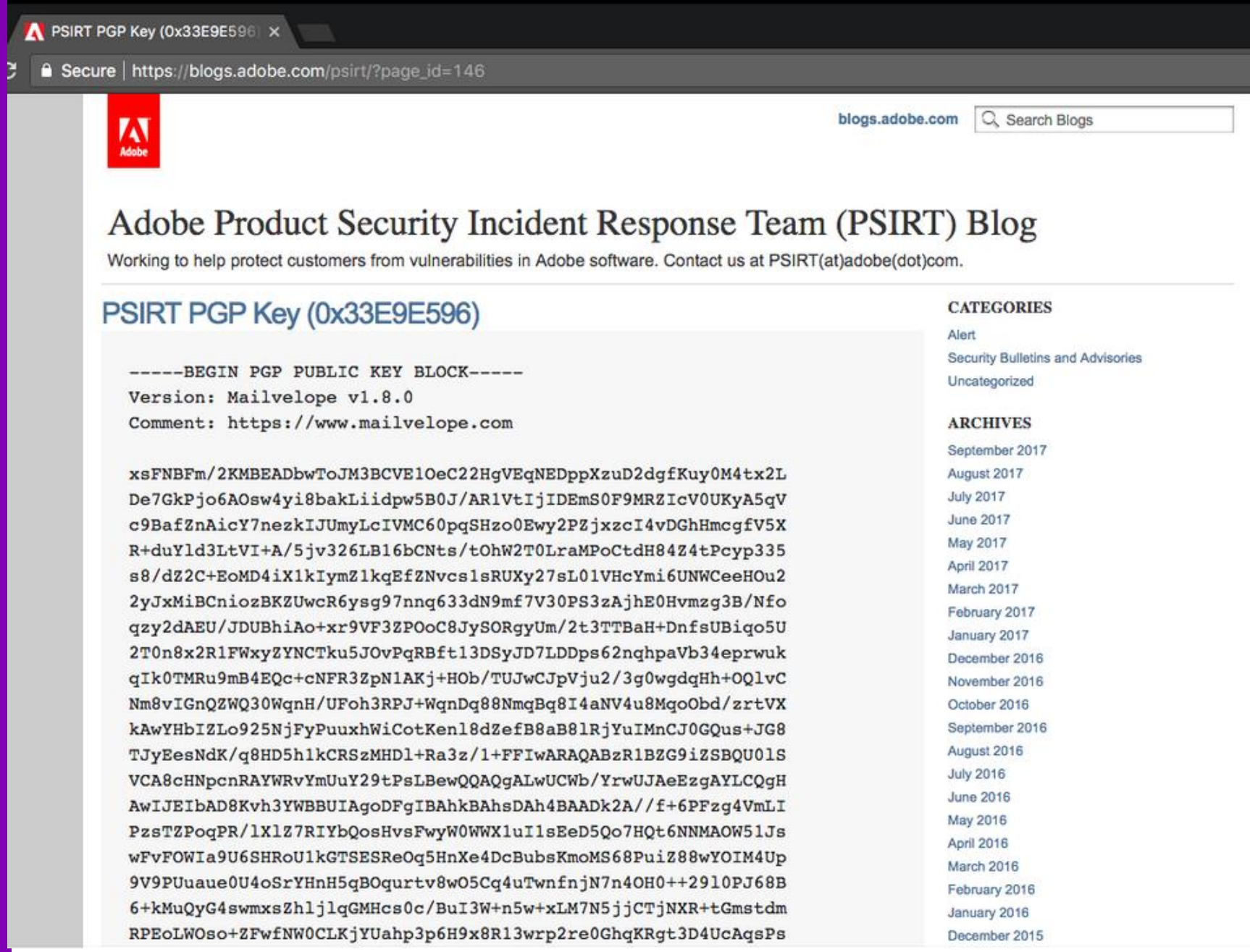


Photo credit: Juho Nurminen @jupenur

Other people can then compare the keys on their computers to the highly visible copy.

xsFNBFm/2KMBEADbwToJM3BCVE1OeC22HgVEqNEDppXzuD2dgfKuy0M4tx2L
De7GkPjo6AOsw4yi8bakLiidpw5B0J/AR1VtIjIDEmS0F9MRZIcV0UKyA5qV
c9BafZnAicY7nezkIJUmyLcIVMC60pqSHzo0Ewy2PZjxzcI4vDGhHmcgfV5X
R+duYld3LtVI+A/5jv326LB16bCNts/tOhW2T0LraMPoCtdH84Z4tPcyp335
s8/dZ2C+EoMD4iX1kIymZ1kqEfZNvcs1sRUXy27sL01VHcYmi6UNWCeeHOu2
2yJxMiBCniozBKZUwcR6ysg97nnq633dN9mf7V30PS3zAjhE0Hvmzg3B/Nfo
qzy2dAEU/JDUBhiAo+xr9VF3ZPOoC8JySORgyUm/2t3TTBaH+DnfsUBiqo5U
2T0n8x2R1FWxyZYNCTku5JOvPqRBft13DSyJD7LDDps62nqhpaVb34eprwuk
qIk0TMRu9mB4EQc+cNFR3ZpN1AKj+HOb/TUJwCJpVju2/3g0wgdqHh+OQlvC
Nm8vIGnQZWQ30WqnH/UFoh3RPJ+WqnDq88NmqBq8I4aNV4u8MqoObd/zrtVX
kAwYHbIZLo925NjFyPuuxhWiCotKenl8dZefB8aB8lRjYuIMnCJ0GQus+JG8
TJyEesNdK/q8HD5h1kCRSzMHDl+Ra3z/1+FFIwARAQABzR1BZG9iZSBQU0lS
VCA8cHNpcnRAYWRvYmUuY29tPsLBewQQAQgALwUCWb/YrwUJAeEzgAYLCQgH
AwIJEIbAD8Kvh3YWBBUIAgoDFgIBAhkBAhsDAh4BAADk2A//f+6PFzg4VmLI
PzsTZPoqPR/lXlZ7RIYbQosHvsFwyW0WWX1uI1sEeD5Qo7HQt6NNMAOW51Js
wFvFOWIa9U6SHRoU1kGTSESReOq5HnXe4DcBubsKmoMS68PuiZ88wYOIM4Up
9V9PUuaue0U4oSrYHnH5qBOqurtv8wO5Cq4uTwnfnjN7n4OH0++29l0PJ68B
6+kMuQyG4swmxsZhljlqGMHcs0c/BuI3W+n5w+xLM7N5jjCTjNXR+tGmstdm
RPEoLWOso+ZFwfNW0CLKjYUahp3p6H9x8R13wrp2re0GhqKRgt3D4UcAqsPs

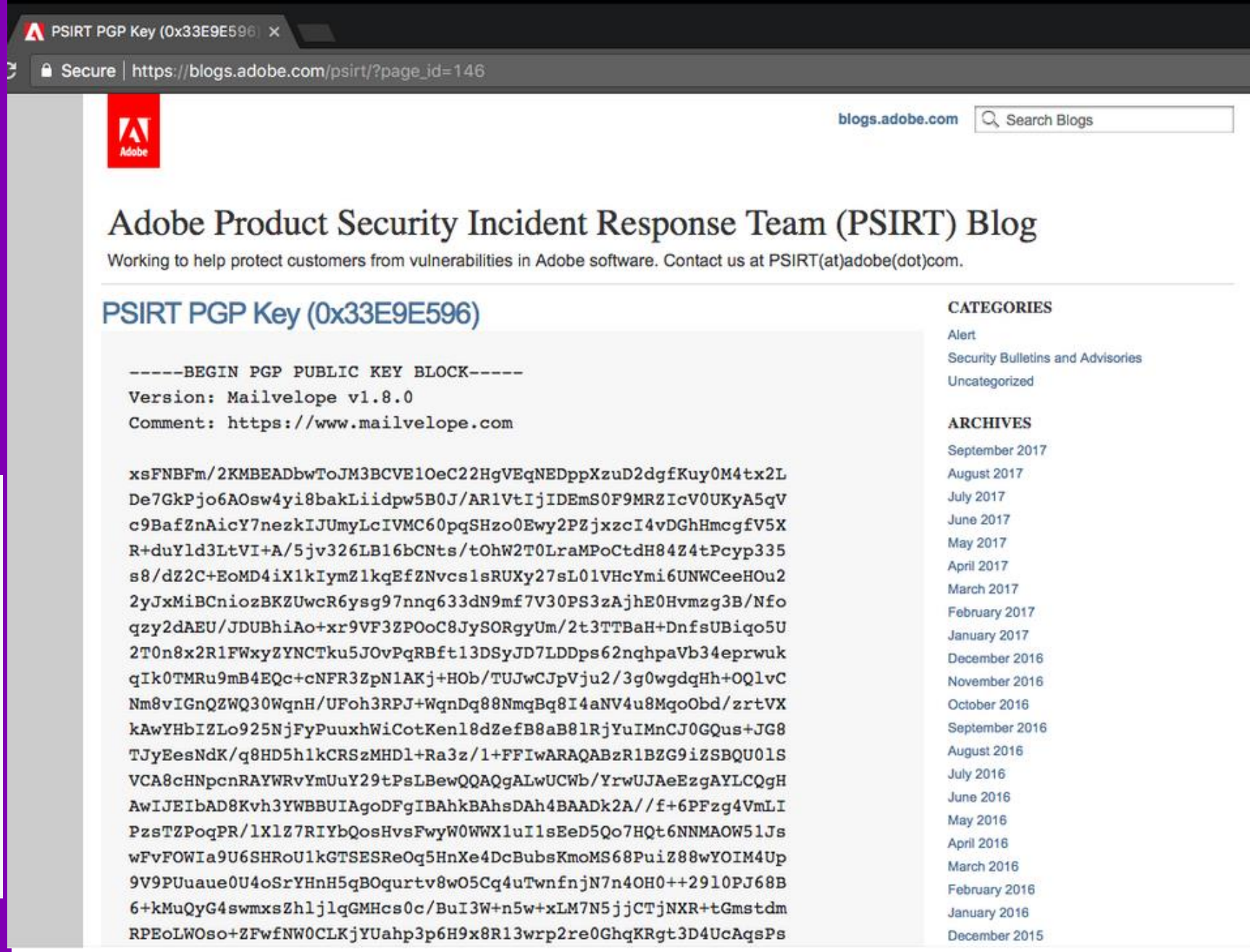
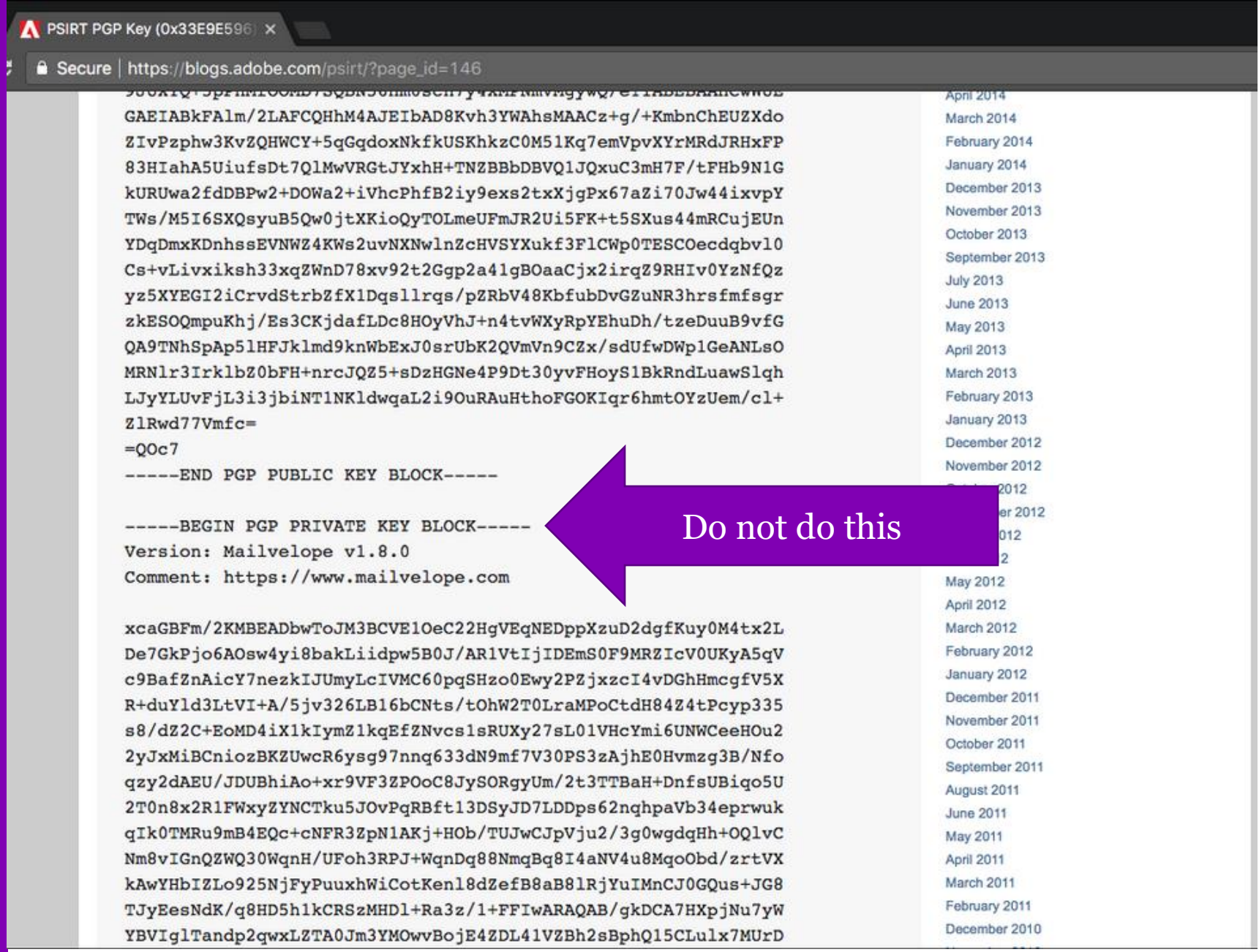


Photo credit: Juho Nurminen @jupenur

Though we must be careful to post ONLY the public key…



Do not do this

Photo credit: Juho Nurminen @jupenur

Nice idea, but it does not scale.

Also a chicken-and-egg problem. How do we find a place guaranteed to be from us without using cryptography?

Idea 2: What if everyone did a few verifications. We could slowly build a web of verifications like:

Alice verified Bob's key
Bob verified Charlie's key
so
Alice can trust Charlie's key

Web of trust

- Alice hand verifies that Bob's public key really does belong to Bob
- Then Alice "signs" the key by encrypting it with her private key.
- Now anyone that has hand verified Alice's key, can also trust Bob's key (if they trust Alice to do verifications).
- Key signing parties 

My public key

-----BEGIN PGP PUBLIC KEY BLOCK-----
Version: GnuPG v2

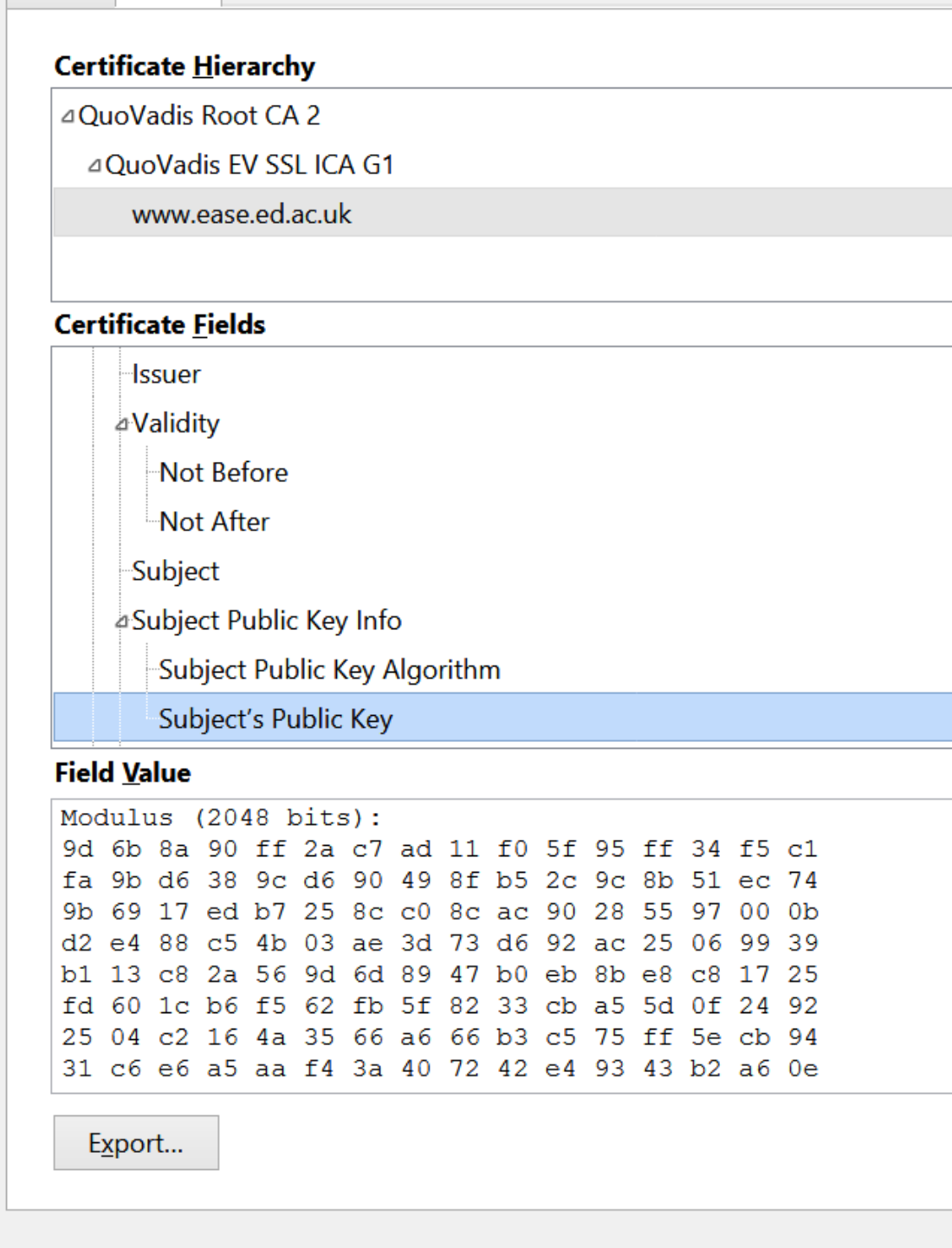
mQENBFHMcgABCAC9WrYDO6K2L3VHyi4eHN6suHLqMpJ+SO+IUTuLEVnUzIoXAUXH
KozHejfV/9XoG8j933ZtszXKCog3aMESe0E0z6fNGfolvaCe5B4jwq0Jt8NHwb5L
B2dnq0CplgXcN2GJxfEHHUaf27COSobCJxPMeshUh4ZHke+g6DatmiEtBpVp41Ot
1zgxdMQkgb2H2xw28RYfYkdDoueteIkOrFLrCy9ZF9KdMhA1eBH94KnwIQshdiZR
QYEX25+M8cKCb++Rc9H6an7EG9WHOFRW40UsY52OfveOyfQPzkkRto7u2339hvHo
B/h+7xLM6FQbOUZQ9BD5w7IQHgYtXJVsUjodABEBAAG0IkthbWkgVmFuaWVhIDxr
dmFuaWVhQGluZi5lZC5hYy51az6JAT8EEwEIACkFAlYKYvECGyMFCQlmAYAHCwkI
BwMCAQYVCAIJCgsEFgIDAQIeAQIXgAAKCRCTdsxl9/HZffG+CACShuKxje3QAqew
GWh8K4gCdiYoxDqJwq3PHxmyhZmQeN/1a1KcOrIjI2b+Q75/5t+EgXOHpR0PIxfG
lZ6zOEpf6A18iFXx3JgQZdwPD0jtBiWNpOyMeBGTgIvEYG3so2VueQoeXcq3dbYp
5vstVxtD+TKHQ5CioIT75P2bzYq/XLT5aIbNQhQDPcTo0DgbRH+FvqsRXr7yeaef
JaPnxX0+1L33t2QY9zctiGyebwrvHMrIPBJ2VYCDzQkJ7uQ5eFh4ZhsMgOmzLQD4
YiGr5weIMFwAvxZOaRxEa9Vf48jiWvrxuJ8YfHWS0hEScNOcYC2P8q20lJwwE26T
lpdtrwCqtB1LYW1pIFZhbmllYSA8a2FtaUB2YW5pZWEuY29tPokBQgQTAQIALAIb
IwUJCWYBgAcLCQgHAwIBBhUIAgkKCwQWAgMBAh4BAheABQJWCmMeAhkBAAoJEJN2
zGX38dl9JJAIAIW0rxrlYsrmKS6CbW8MgTxxTDOXaCt1b7F0W0QZHskIUQhEcE+a
XBYib1A5uHaatLfyjeXaD3qMEoZnQHoYMGE0GKu00wWsbhfoQzHPgwzRLkD1i75M
BIbaww0KW0VB9e4AkMakXJCnF5BXe06AHRL2v15V205DikVnlCRXocKtu8b7LnkM
cLn70Lobr1de1uyKoNzbSnO/vpKDJp0/EY5yUeV90IypZy/6wFQBehg1sXye6zn0
9wb9uUsu9+/P8pz4JILMDSevjfT7zSRSl/YP3fOfZ6N4bc+KOdwPM7u5Iyoeu9zh
pzibv3ge7VhH2xIWz8vYZ/2xT1345tWRRMOJAhwEEwECAAYFAlTnSpEACgkQjyxM
p99tBt2B8A/+OpIzOsQbQJB8yxti4I7PpD1weJDf3a81Vhm7JyXE/Xy66ypfdt3w
XmFRUuIrwezY1NebWNCRQHzQvRv/VJwjbTUx+Q3HsjIkKlHbE7iCiQXXtTRkoEny
2nudcjGI2v03C3B2JCucEw6esF1x79PI/lPv2+6tgUBKmDfOpsB2vbtqrHnmAYKL
4lQBFH1YSJgnzwo2Jkh0hcHdF90Zem1eMeiDEeVkH63893N8Swk5fBKdTj+SKZ/L
rQElBBlpMR9BmeY6bPvWRuycVKonIMR80G9iFABxjTpWBL8aGk6EeVK5EqYDGvkd
ZIarK84r+KU1KD5IfgOCN7nhwgy7VImE68caZHSRiPWZP1fVVMhydiRJv8WsoUs6
INfVU3nxH+ZYthPbY0T86leGSchBT5K/fBQvbjhrRTbTFwvjzSifb9efWylDi994
nzP6cNorir3GIpsT8gPgBB2/NjxaWiM6y3X1az1vRnsunQHuyKkFWPZwnEvDJYaC
NN/3jWcbhLFwKBDsaHps2+1meFP0oJFvNetzp2bjT9a9pXaQ6KhOmo5DnhLcaV97
bFBpsUuBGaYZTSS05x1RdXHqpEbgap8dtuHhVvJw9QYDQBJr0K4aKyG9qqMD8cta
Pl/FAdyAqwH8Nw9efqAK+RQxSVUaue9BYEnbIRpsDK6MkP3YMFmu5ki5AQ0EUcxy
AAEIALyXYy8G2ZaTDJpdGcRhmIqOOSUlzPV7/5E5BbYKBNu4KU3nX+JLVcF5jxPQ
42c7i/WRVxE1BJTiarKGsEvCi94TTXSIUKAt3T10GBtXmGvqbGBq8ljSGl1UTwdF
5yu50JyRSf2fqRND6P/2eHNXejDUtdvhUXIUt8h9MuUO/ipD0DnwIvMnAATJHA+R
Zqw60NpyjRGzvr3iuWUwe4PtyJDI3ELAFkbp/NAc5TIuVHRHNOWNplcIJhM5zHuB
QQb3G/EsCn2PQZ5w5SDzavF2SpvQfDqxYpDaTLAXtF+wsJL5iaUjxwRgJPOdbCZf
2Tozd7h9MXtGJDlPKJ8eLG80gcMAEQEAAYkBJQQYAQIADwUCUcxyAAIbDAUJCWYB
gAAKCRCTdsxl9/HZfS+hB/9BJqSmIgcoHFXnb1PVIKxekzL8+WVm5Pk/EgMQSLZ2
HX4p3ial5PEPcYgUw9YnaG4i00dwJGw5/daTWRrTzcnKd8Yq0P+DU0t96HZDSu3m
mCzE9NVAQYboFbVmGOx0eo627UBSvFqaXvAxBDYkoR8B0TnKhrQFwXkZVb30hKwD
TgAFjOGlZiE6uAdST231tFaq0bizYfe5AVXRqro20xBqNbaJNqs3SW0D831Syvdv
llOBx83/R0gg7hUkI6F2vzXicWmUwFSXRrggCSbLosHsP6isBWwvlHeRmna/aQab
YKG3gbV9iyczAS31gbogVLAZqNSWhp8vVIEE28Fyf/Ed
=x5FK
-----END PGP PUBLIC KEY BLOCK-----

Wonderful idea in theory. But verifying those long keys is hard… also I don’t trust most people to do a thorough job of it….

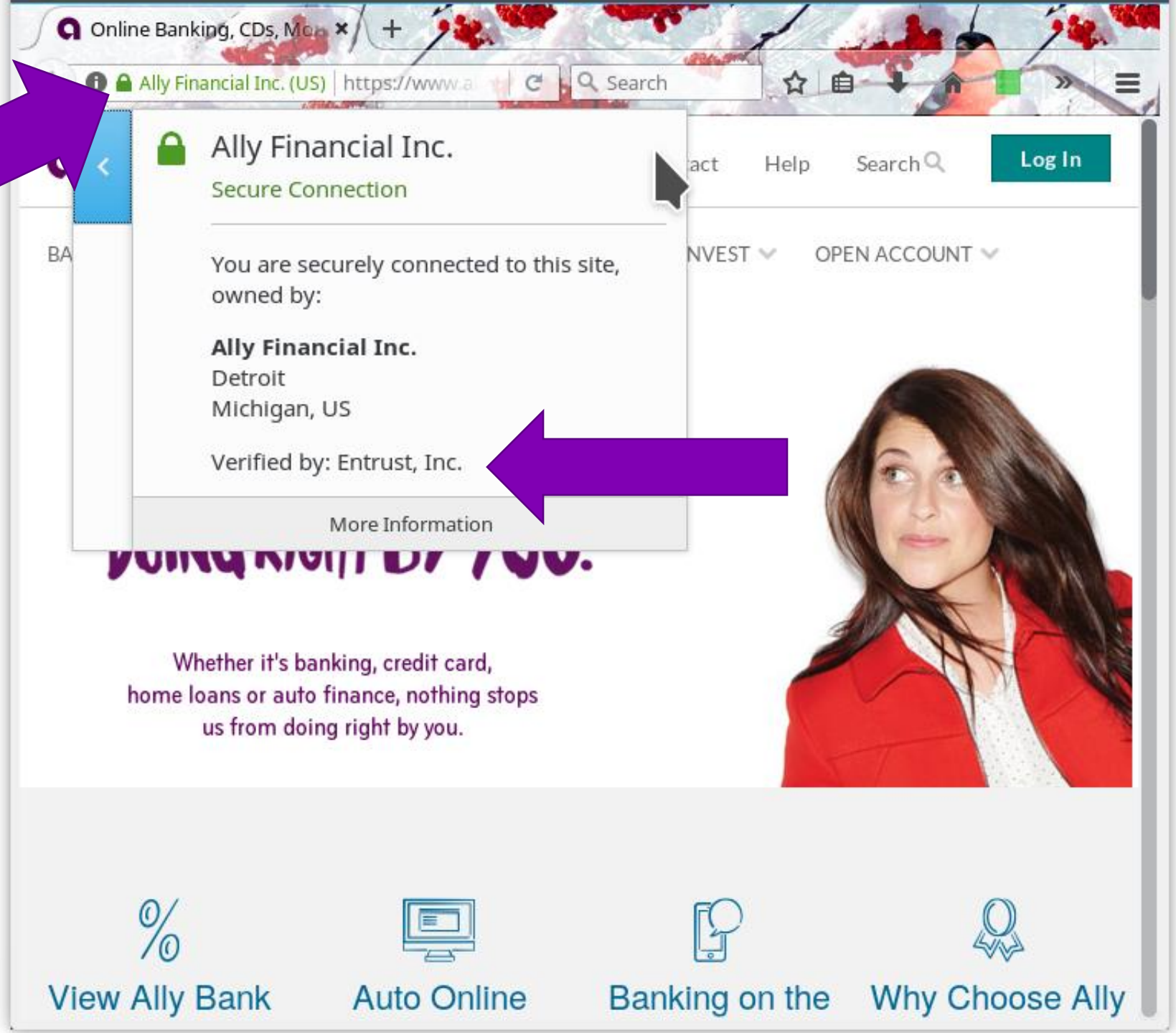
Idea 3: What if a couple of trusted groups did the verifications. Then they could have high standards and everyone could just trust them.

Certificate Authorities

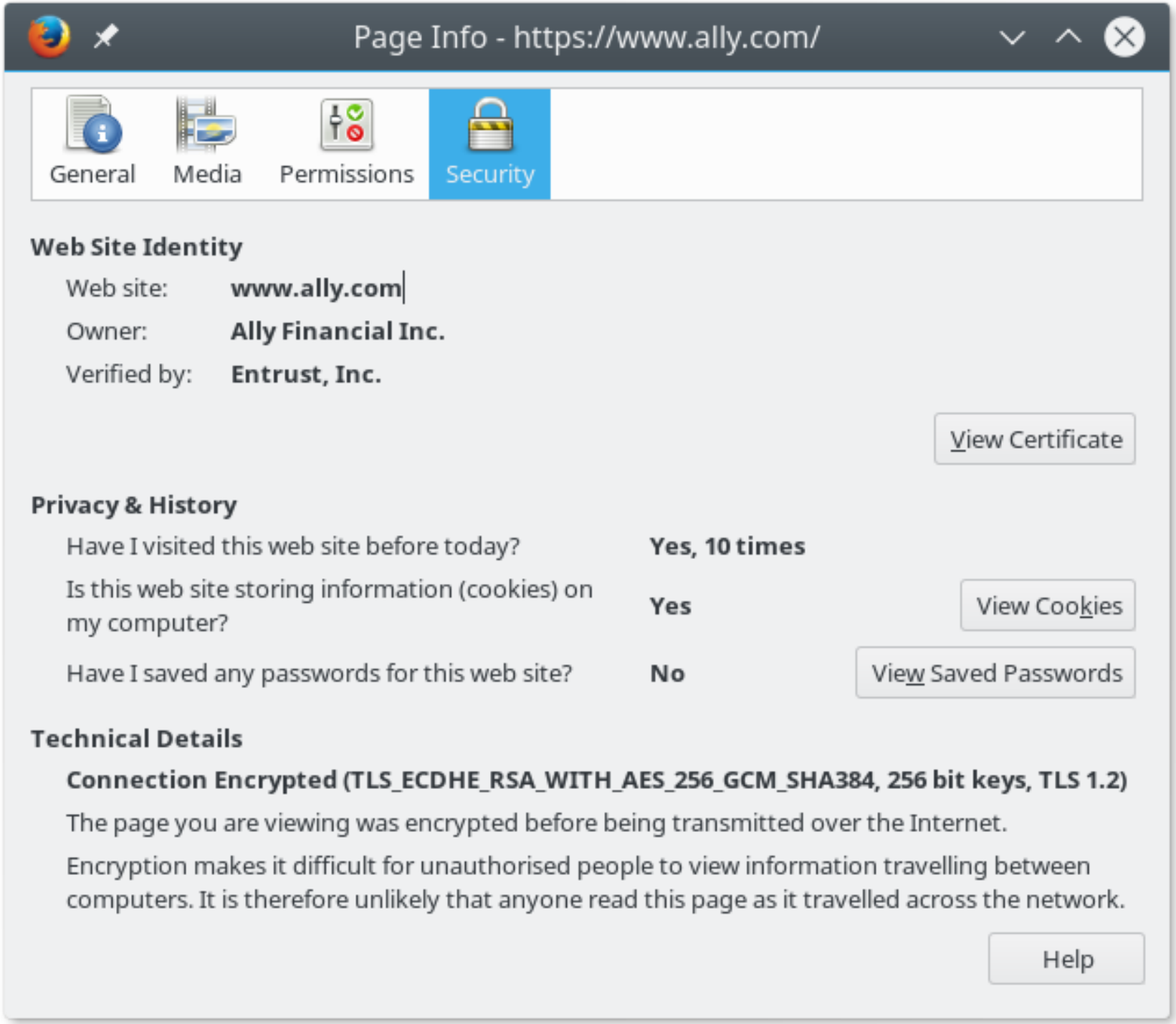
- A certificate authority verifies some properties of a person/organization and issues a “certificate” signed by their private key.
- Certificates can be quite detailed about what has been verified, and what they have been verified to do.

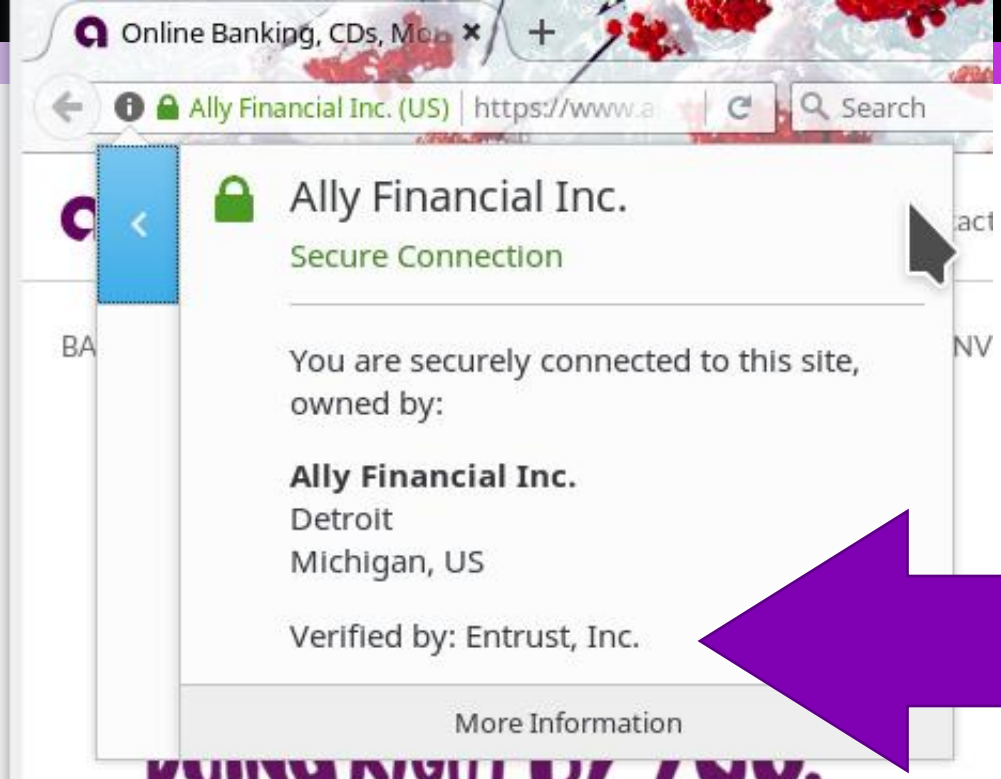


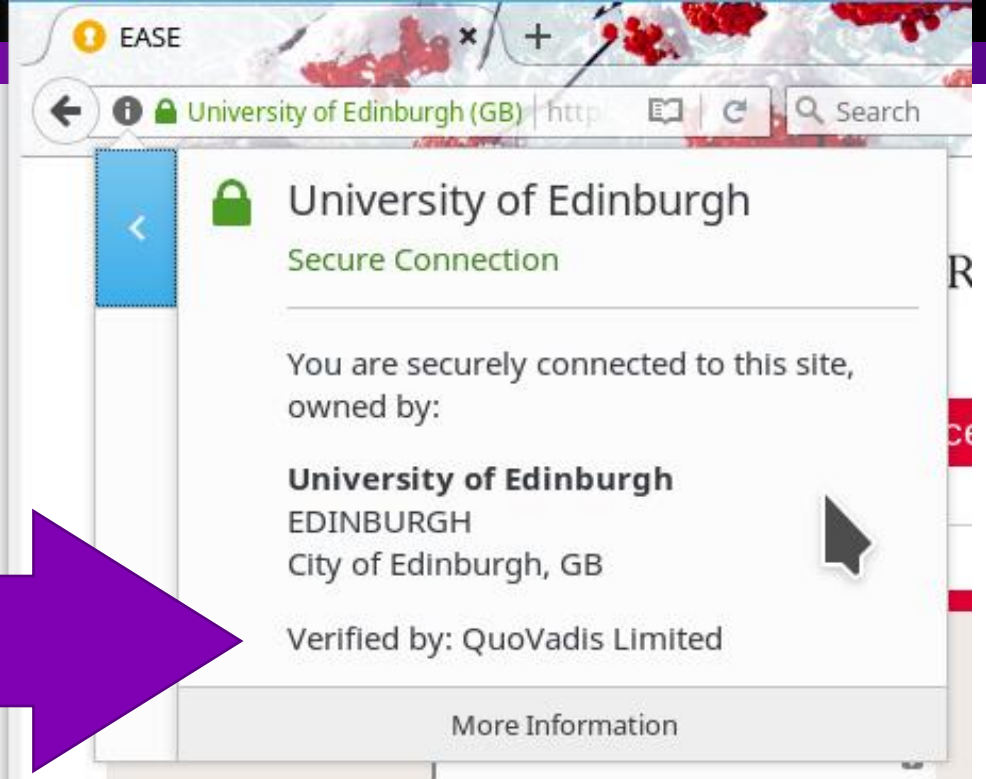
Certificate Authorities are used by browsers to verify identity



You can see lots of details about any encrypted connection.



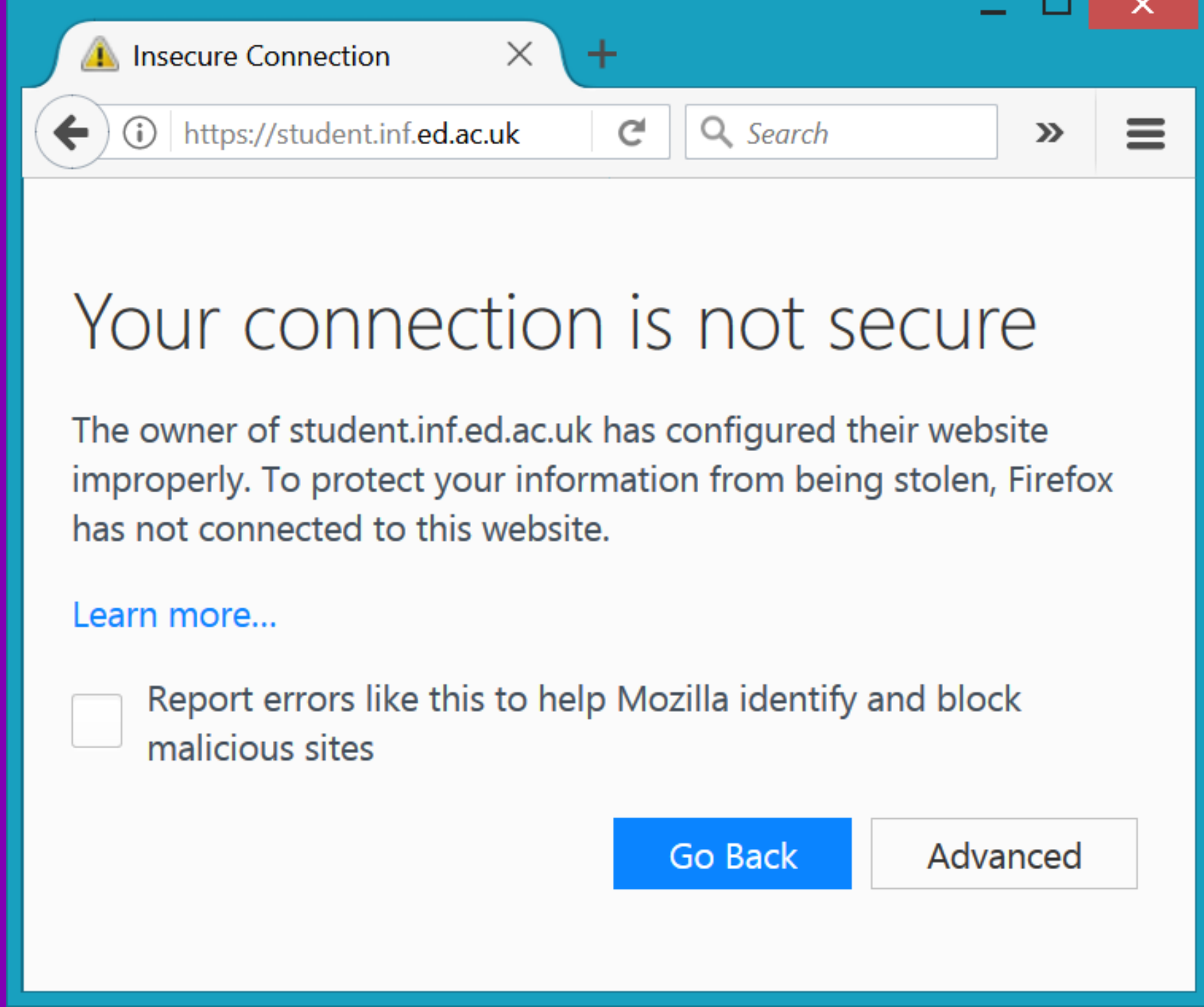




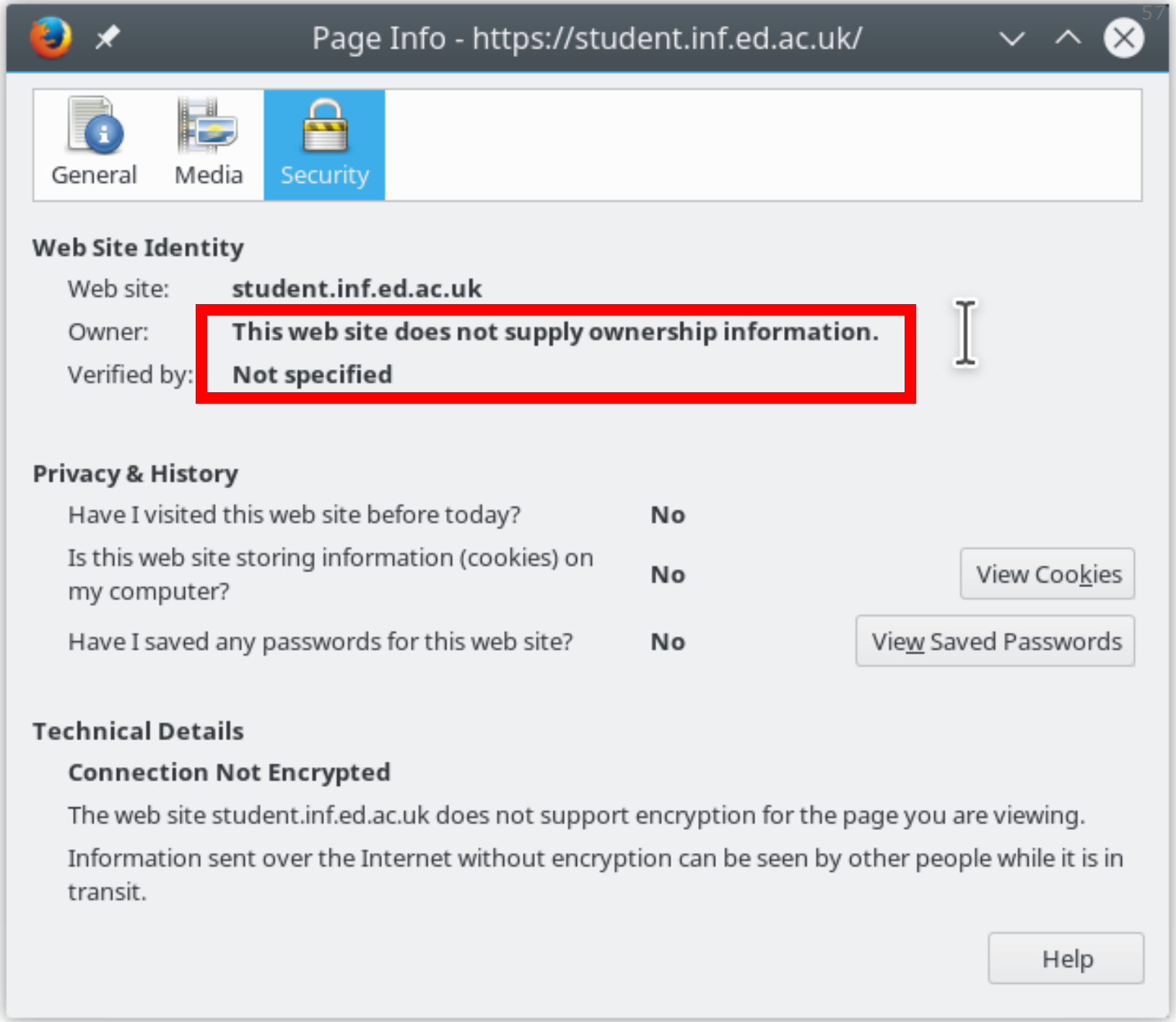
But now don't we just have the same problem again?

How does the browser know which Certificate Authorities to trust?

Clearly some Certificate Authorities are trusted and some are not.

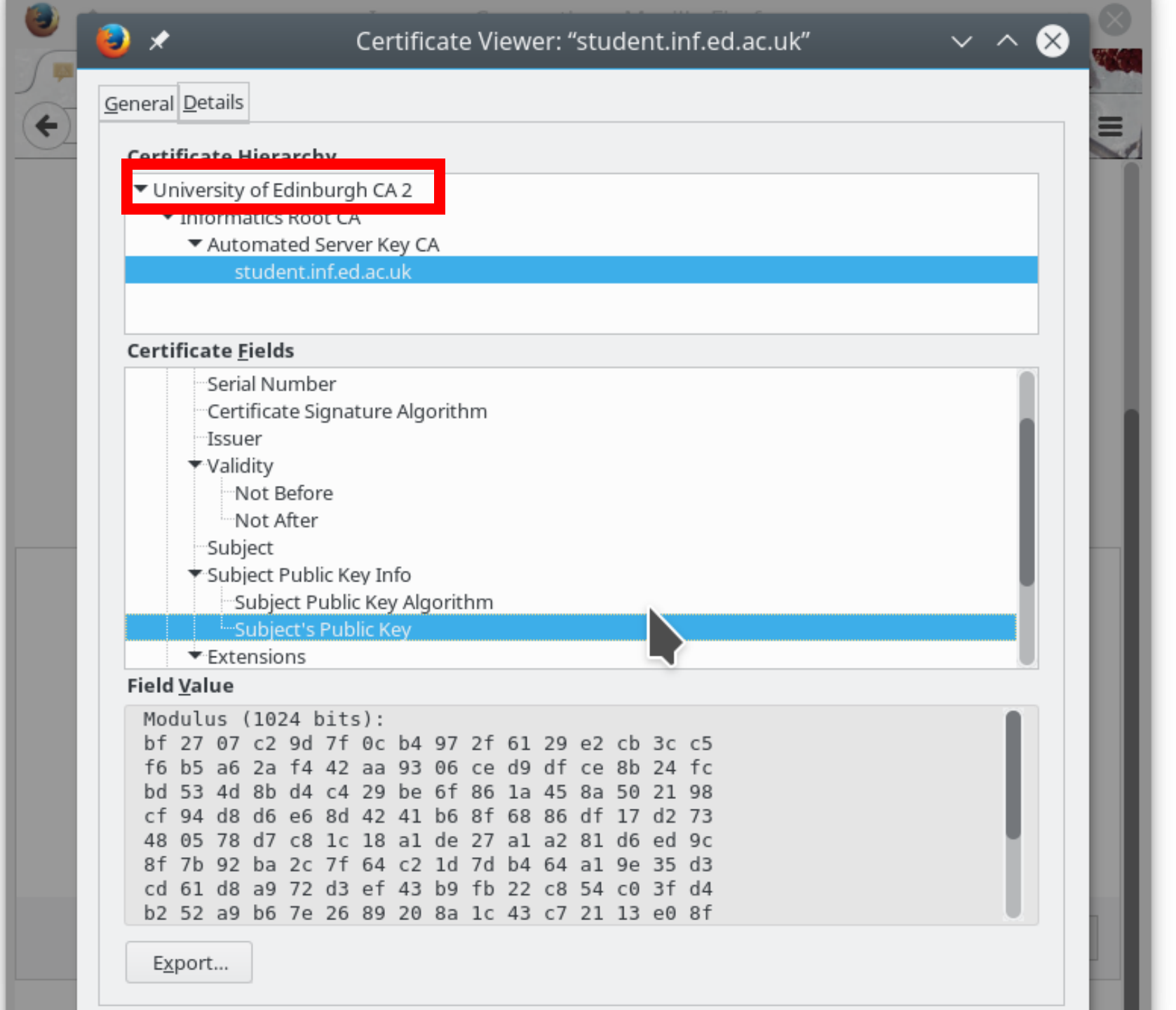


Errors on student.inf.ed.ac.uk are a bit easier to understand though, identity information is missing...



This site is “self signed” which means that the University created its own Certificate Authority and used it to sign all the sites keys.

Why? It costs money to get a signed certificate.



Your operating system and your browser both maintain lists of Certificate Authorities that they trust.

These lists differ between operating systems, browsers, and organizations.

Each organization makes its own trust decisions about Certificate Authorities

INFOWORLD TECH WATCH

By Fahmida Y. Rashid, Senior Writer, InfoWorld | MAR 24, 2017

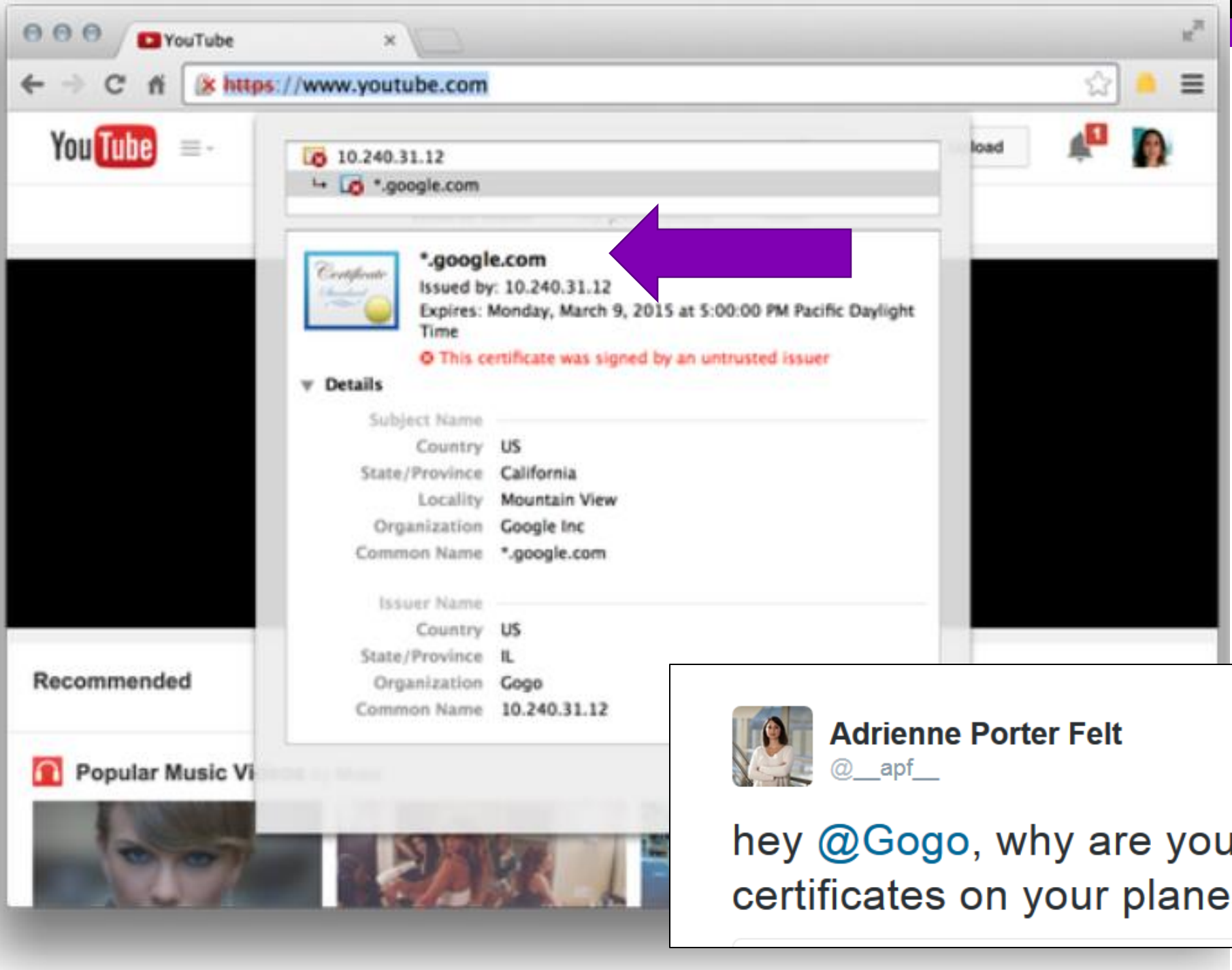
Google to Symantec: We don't trust you anymore

Admins need to consider whether they still want to use Symantec after its repeated mistakes with issuing TLS certificates

geralt via pixabay

Security teams, network administrators, and operations teams have busy days ahead. Google's Chrome development team is fed up with Symantec as a certificate authority and has announced plans to no longer trust current Symantec certificates.

In the past 18 months, Google has tangled repeatedly with Symantec over the way it issues transport layer security (TLS) certificates, with Symantec promising to do better. The latest incident—an investigation into 127 mis-issued certificates—ballooned into "at least 30,000, issued over a period spanning several years," Ravi Sleevi, a software engineer on the Google



Adrienne Porter Felt
@__apf__

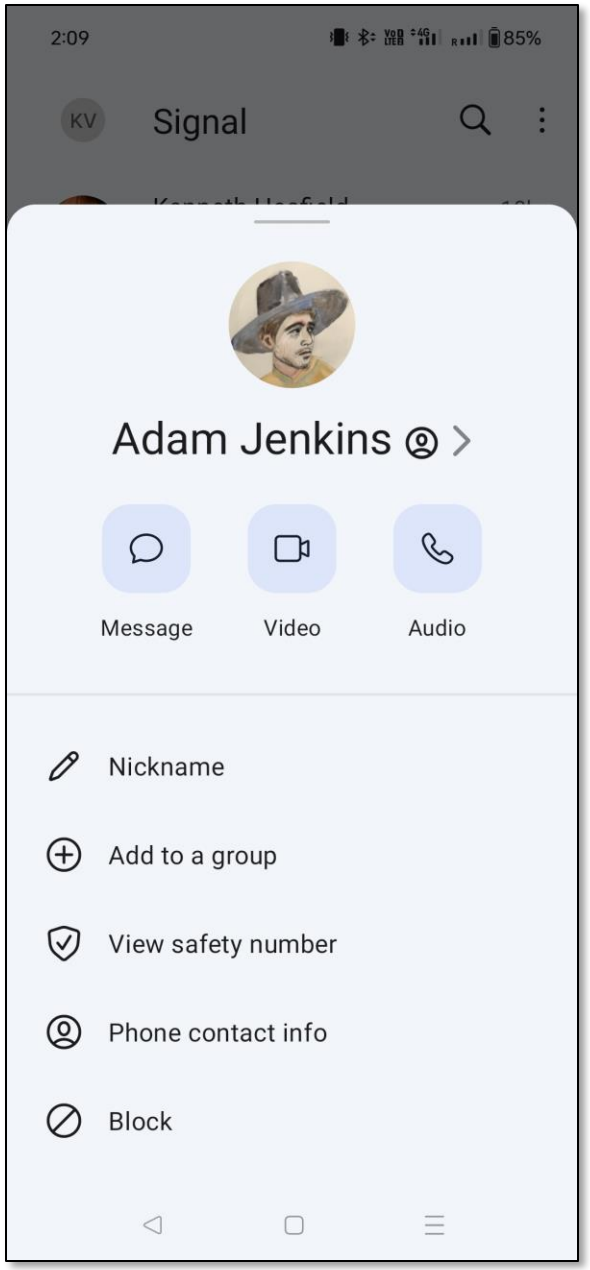
Following

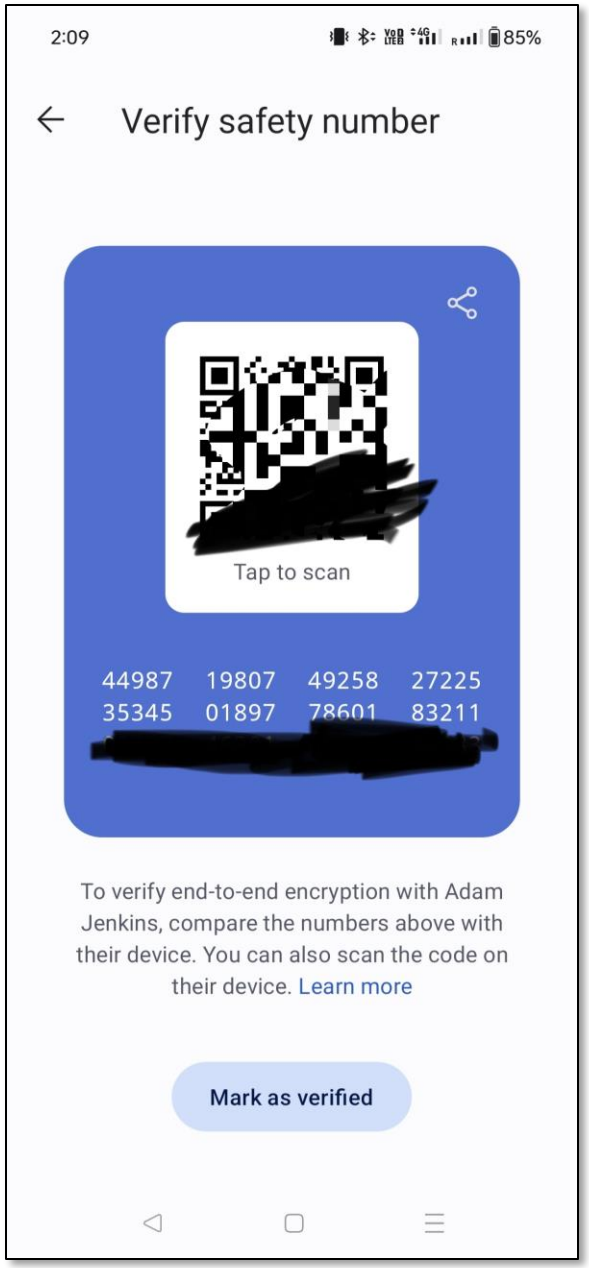
hey @Gogo, why are you issuing *.google.com certificates on your planes?

END-TO-END MESSAGING

Signal

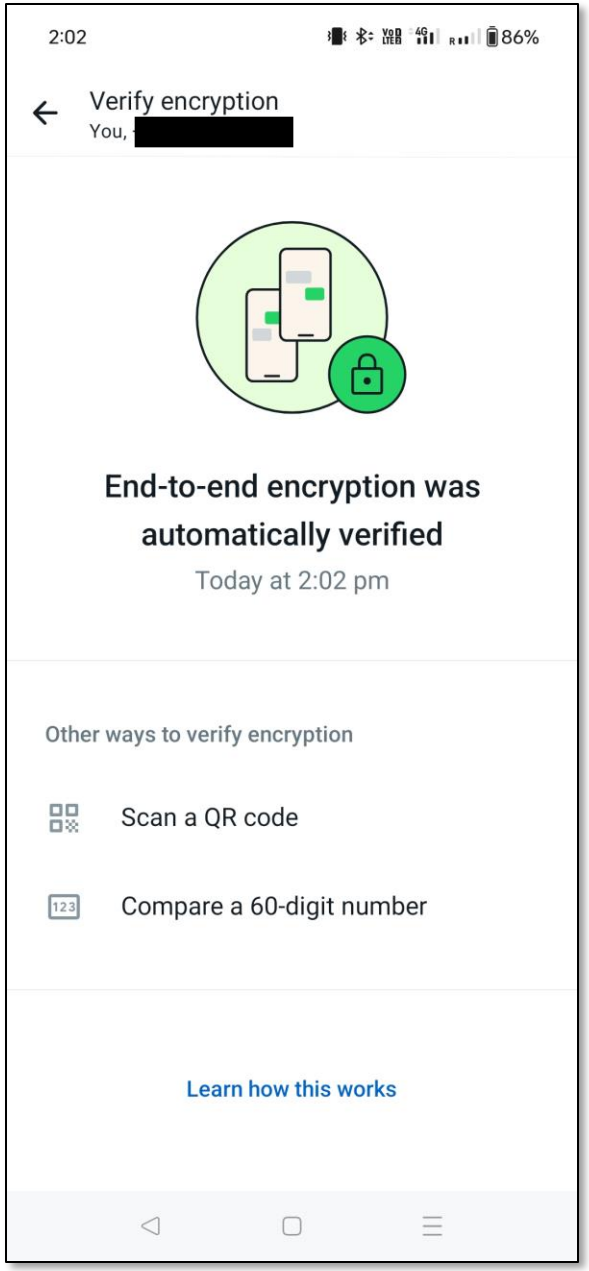
- End to end encrypted
- The “ends” are the apps on both sides





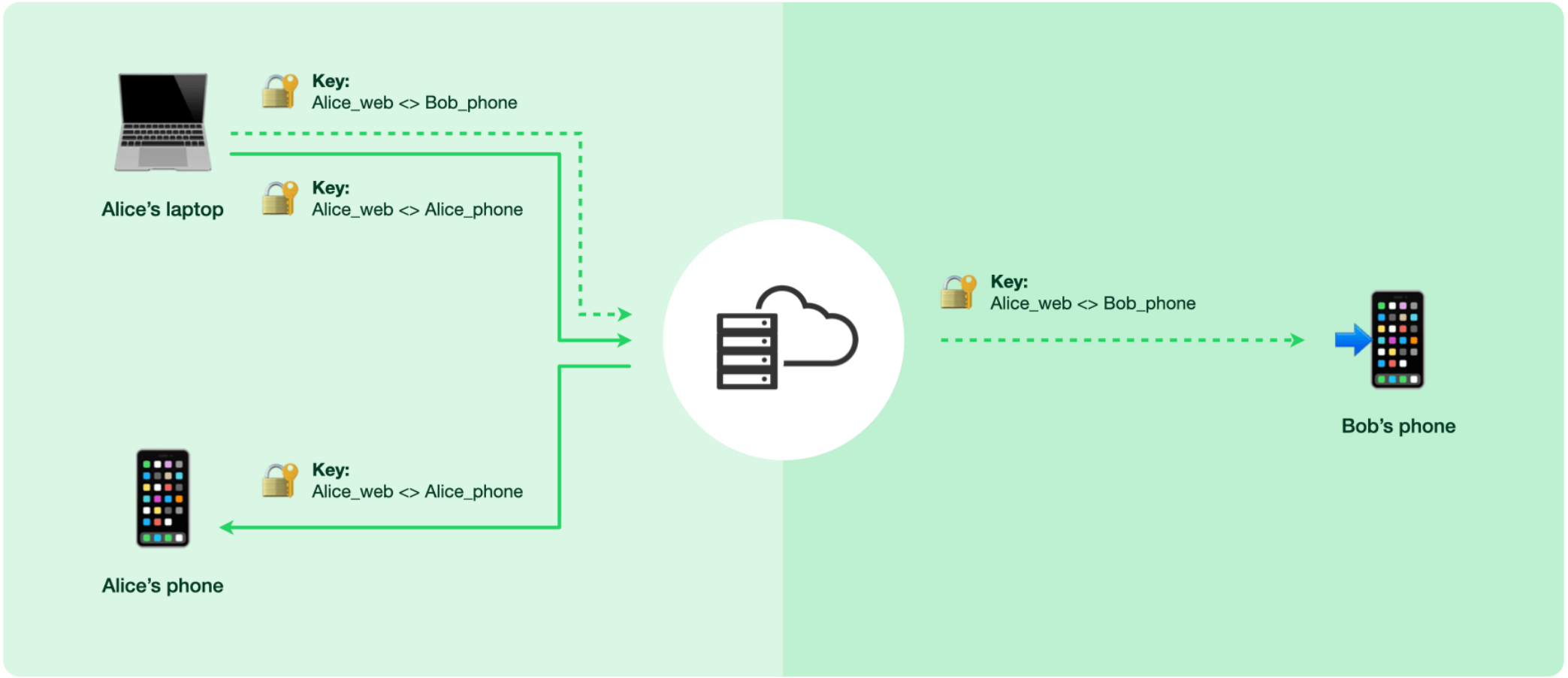
WhatsApp

- All messages, including group chats, are end-to-end encrypted
- The “ends” are the WhatsApp app on both devices
- Keys are managed by WhatsApp itself and shared with the devices as needed



WhatsApp: syncing chats

Life of a message: Multi-Device (new)



https://engineering.fb.com/2021/07/14/security/whatsapp-multi-device/

QUESTIONS