CSE 484 / CSE M 584: Web Security + Asymmetric Cryptography

Winter 2022

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Announcements

- Today: Return to asymmetric crypto
- Lab 3 will be extra credit
  - Designed to be a fun lab (IoT security)
  - I encourage everyone to try it!
  - But if your schedule is too complicated right now, it is extra credit
- Yoshi's Thursday office hours this week (March 3): canceled
- Physical security lecture: Wednesday, March 9

Begin Review Slides

Cross-Site Request Forgery

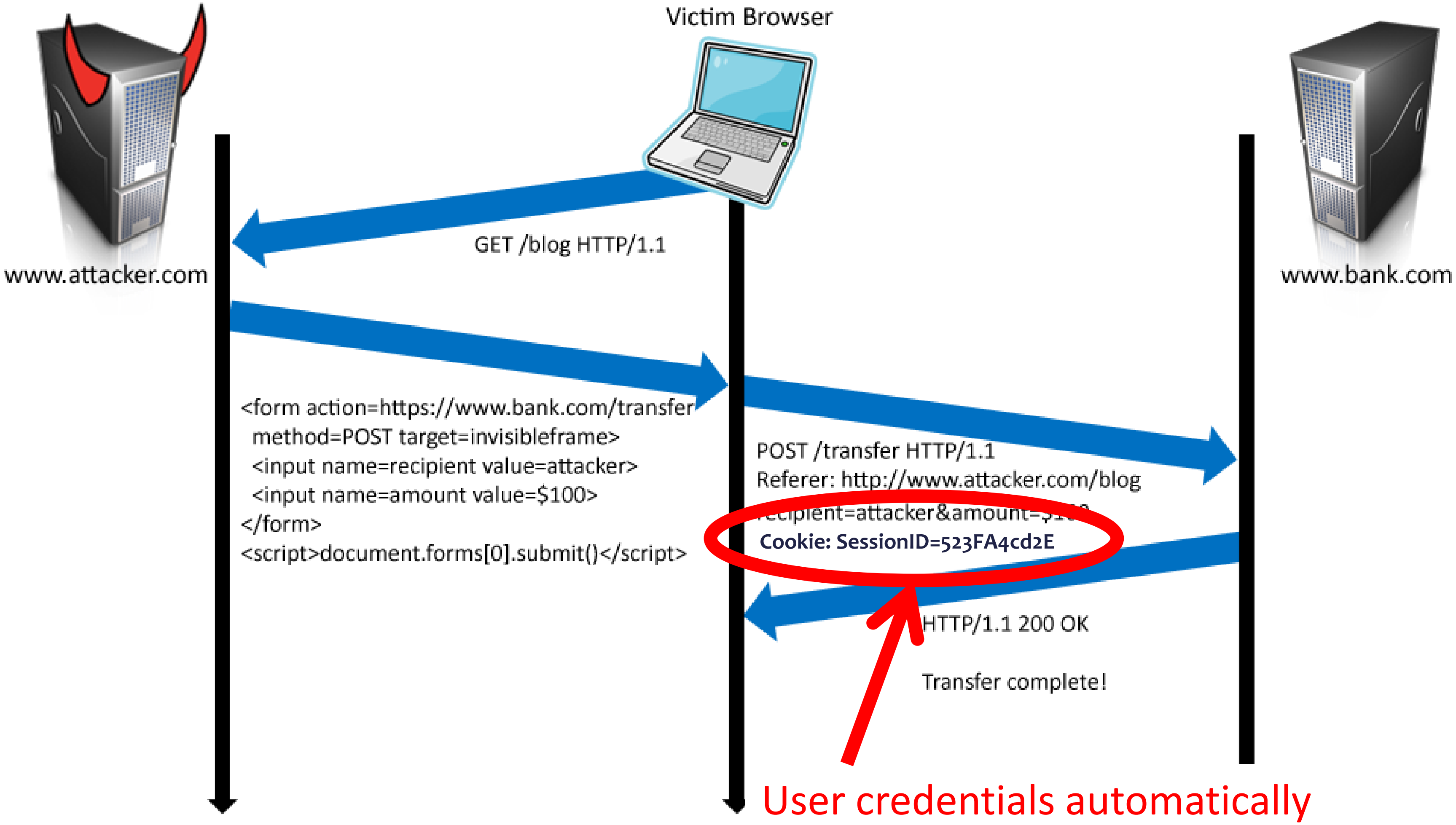
- Users logs into bank.com, forgets to sign off
  - Session cookie remains in browser state
- User then visits a malicious website containing

```
<form  name=BillPayForm
action=http://bank.com/BillPay.php>
<input  name=recipient  value=attacker> …

<script> document.BillPayForm.submit(); </script>
```

- Browser sends cookie, payment request fulfilled!
- Lesson: cookie authentication is not sufficient when side effects can happen

Cookies in Forged Requests



User credentials automatically sent by browser

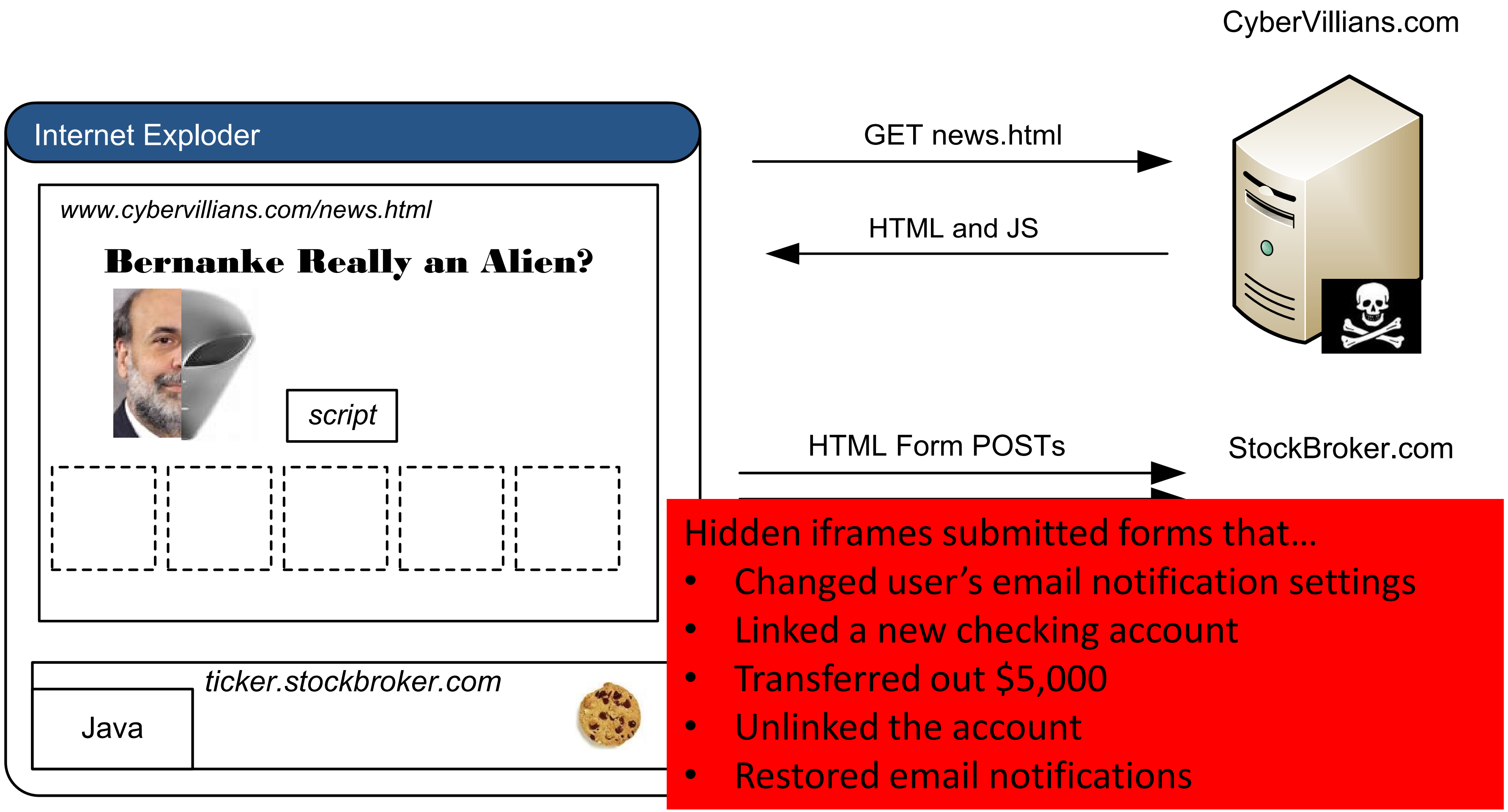
End Review Slides

Impact

- Hijack any ongoing session (if no protection)
  - Netflix: change account settings, Gmail: steal contacts, Amazon: one-click purchase
- Reprogram the user's home router
- Login to the *attacker's* account
  - Why?

XSRF True Story

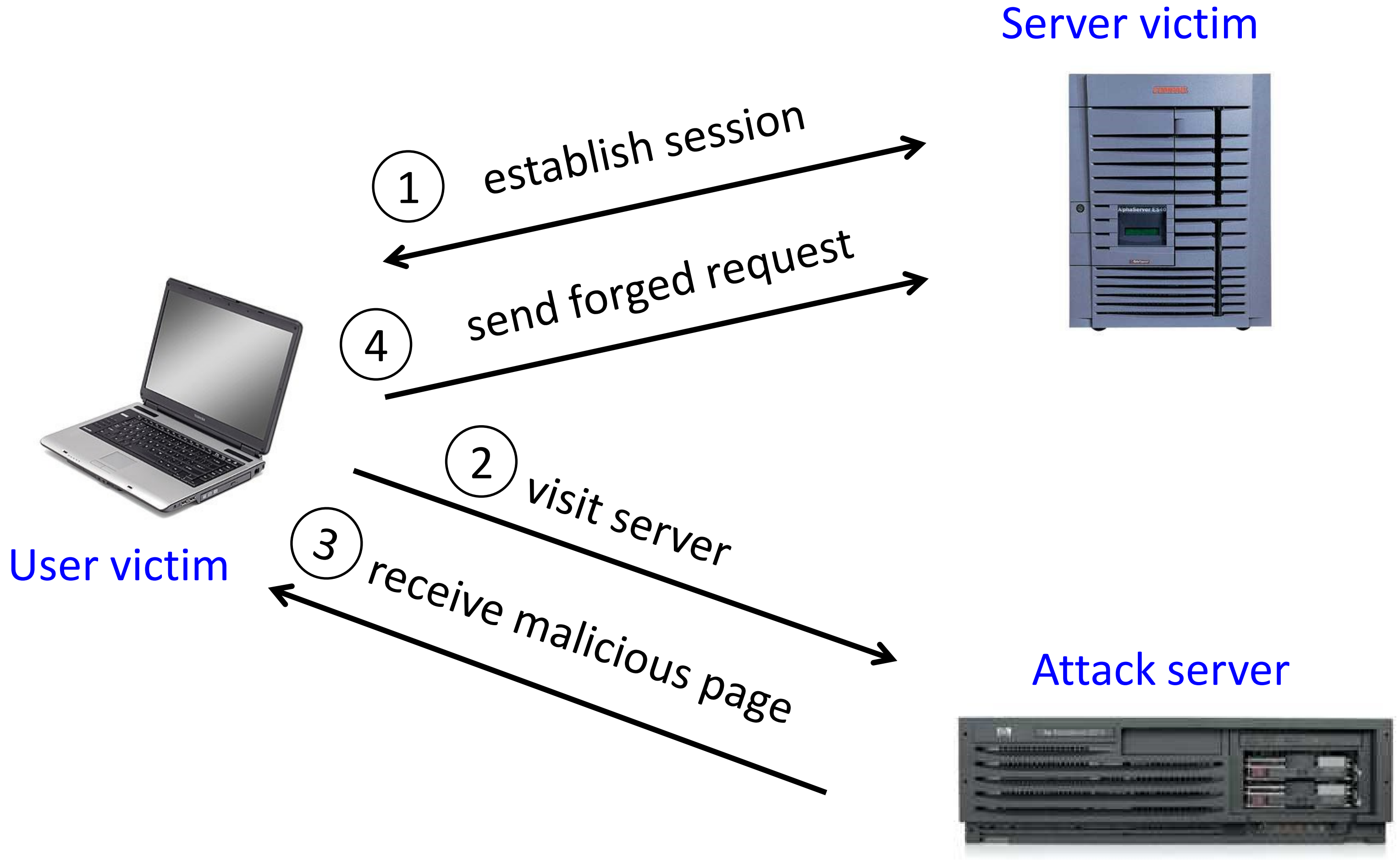
[Alex Stamos]



Hidden iframes submitted forms that…

- Changed user's email notification settings
- Linked a new checking account
- Transferred out $5,000
- Unlinked the account
- Restored email notifications

XSRF (aka CSRF): Summary



Q: how long do you stay logged on to Gmail? Financial sites?

Broader View of XSRF

- Abuse of cross-site data export
  - SOP does not control data export
  - Malicious webpage can initiates requests from the user's browser to an honest server
  - Server thinks requests are part of the established session between the browser and the server (automatically sends cookies)

XSRF Defenses

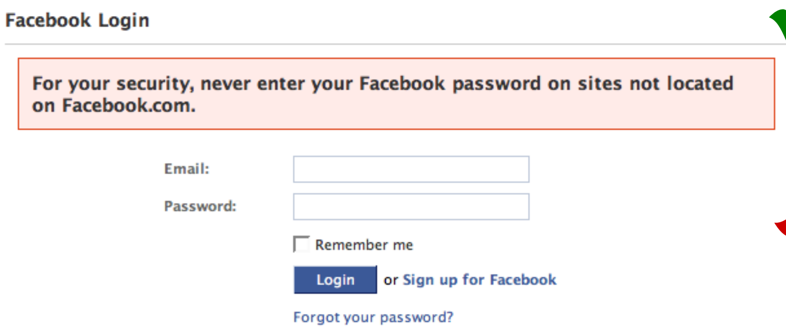
- Secret validation token

<input type=hidden value=23a3af01b>

- Referer validation

Referer:
http://www.facebook.com/home.php

Referer Validation



✓ Referer: http://www.facebook.com/home.php

✗ Referer: http://www.evil.com/attack.html

? Referer:

- Lenient referer checking – header is optional
- Strict referer checking – header is required

Why Not Always Strict Checking?

- Why might the referer header be suppressed?
  - Stripped by the organization's network filter
  - Stripped by the local machine
  - Stripped by the browser for HTTPS $\rightarrow$ HTTP transitions
  - User preference in browser
  - Buggy browser
- Web applications can't afford to block these users
- **Many web application frameworks include CSRF defenses today**

Add Secret Token to Forms

```
<input type=hidden value=23a3af01b>
```

- "Synchronizer Token Pattern"
- Include a secret challenge token as a hidden input in forms
  - Token often based on user's session ID
  - Server must verify correctness of token before executing sensitive operations
- Why does this work?
  - **Same-origin policy:** attacker can't read token out of legitimate forms loaded in user's browser, so can't create fake forms with correct token

Back to cryptography land

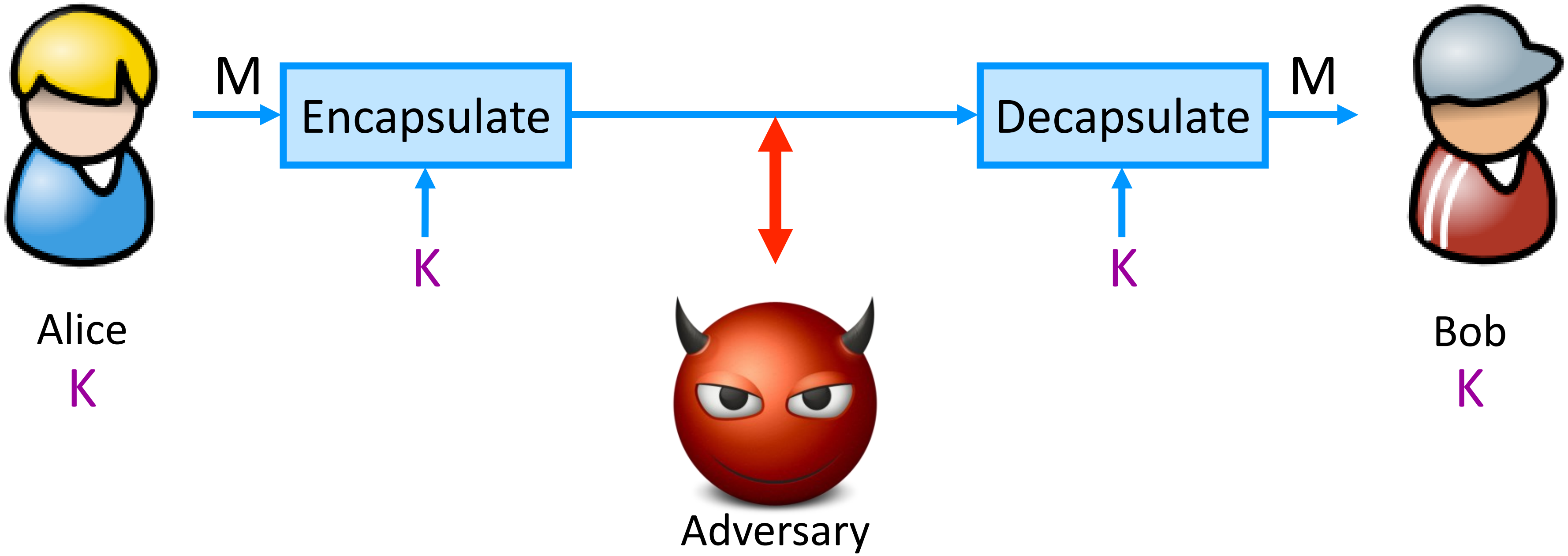
Stepping Back: Flavors of Cryptography

- Symmetric cryptography
  - Both communicating parties have access to a shared random string K, called the key.

- Asymmetric cryptography
  - Each party creates a public key pk and a secret key sk.

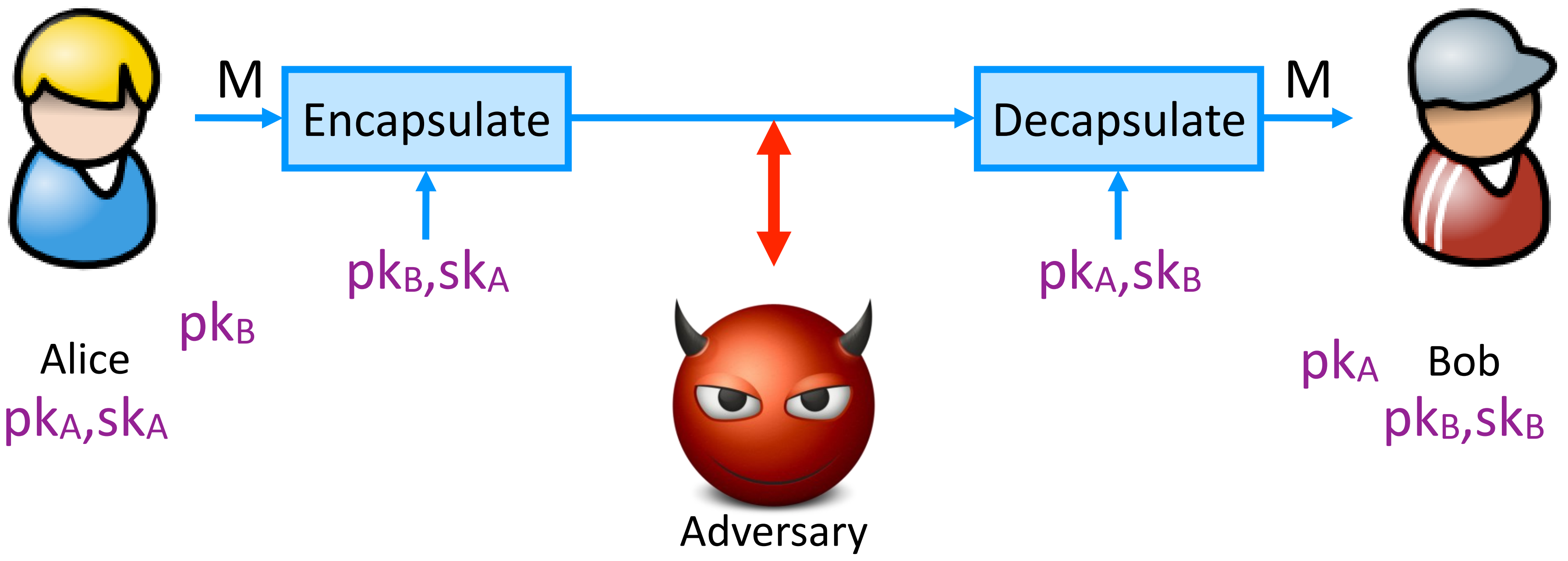
Symmetric Setting

Both communicating parties have access to a shared random string K, called the key.

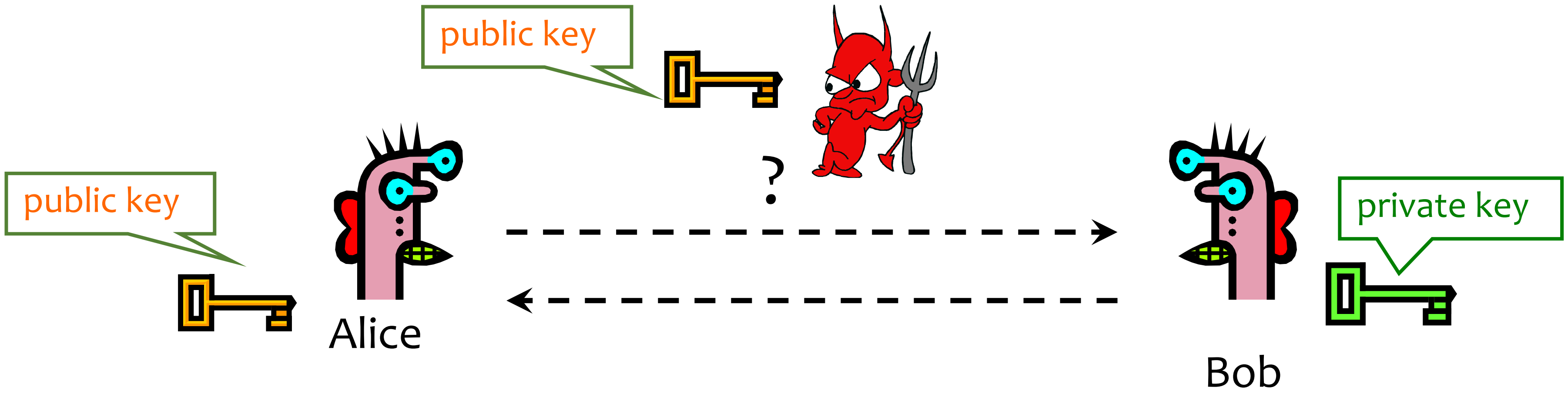


Asymmetric Setting

Each party creates a public key pk and a secret key sk.



Public Key Crypto: Basic Problem



Ignore for now: How do we know it's REALLY Bob's??

Given: Everybody knows Bob's public key
Only Bob knows the corresponding private key

Goals: 1. Alice wants to send a secret message to Bob
2. Bob wants to authenticate themself

Applications of Public Key Crypto

- Encryption for confidentiality
  - Anyone can encrypt a message
    - With symmetric crypto, must know secret key to encrypt
  - Only someone who knows private key can decrypt
  - Key management is simpler (or at least different)
    - Secret is stored only at one site: good for open environments
- Digital signatures for authentication
  - Can "sign" a message with your private key
- Session key establishment
  - Exchange messages to create a secret session key
  - Then switch to symmetric cryptography (why?)

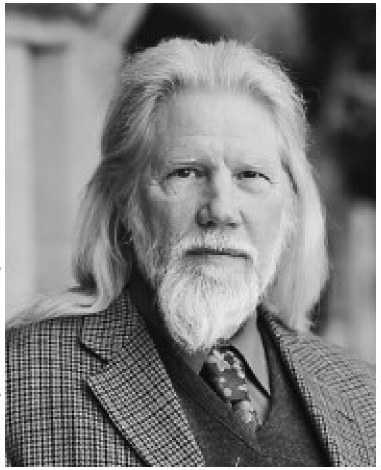
Session Key Establishment

Modular Arithmetic

- Given g and prime p, compute: g^1 mod p, g^2 mod p, … g^{100} mod p
  - For p=11, g=10
    - 10^1 mod 11 = 10, 10^2 mod 11 = 1, 10^3 mod 11 = 10, …
    - Produces cyclic group {10, 1} (order=2)
  - For p=11, g=7
    - 7^1 mod 11 = 7, 7^2 mod 11 = 5, 7^3 mod 11 = 2, …
    - Produces cyclic group {7,5,2,3,10,4,6,9,8,1} (order = 10)
    - g=7 is a "generator" of Z_{11}^*

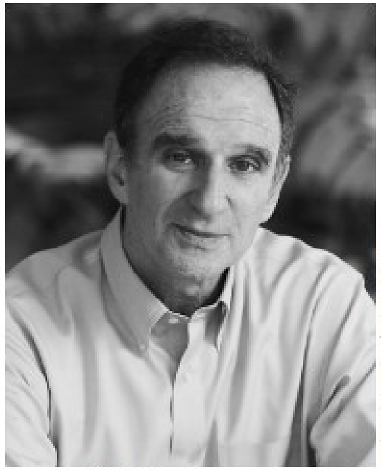
Diffie-Hellman Protocol (1976)

Diffie and Hellman Receive 2015 Turing Award



Rod Searcey/Stanford University.

Whitfield Diffie

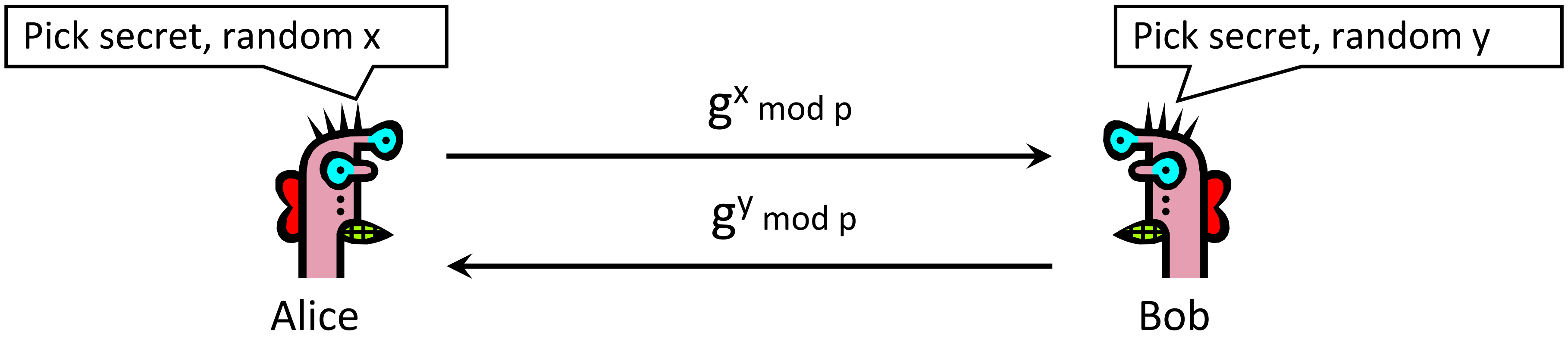


Linda A. Cicero/Stanford News Service.

Martin E. Hellman

Diffie-Hellman Protocol (1976)

- Alice and Bob never met and share no secrets
- Public info: p and g
  - p is a large prime, g is a **generator** of Z_p*
    - Z_p*={1, 2 … p-1}; a is in Z_p* if there is an i such that $a=g^i$ mod p
    - Modular arithmetic: numbers “wrap around” after they reach p



Compute $k=(g^y)^x=g^{xy}$ mod p

Compute $k=(g^x)^y=g^{xy}$ mod p

Example Diffie Hellman Computation

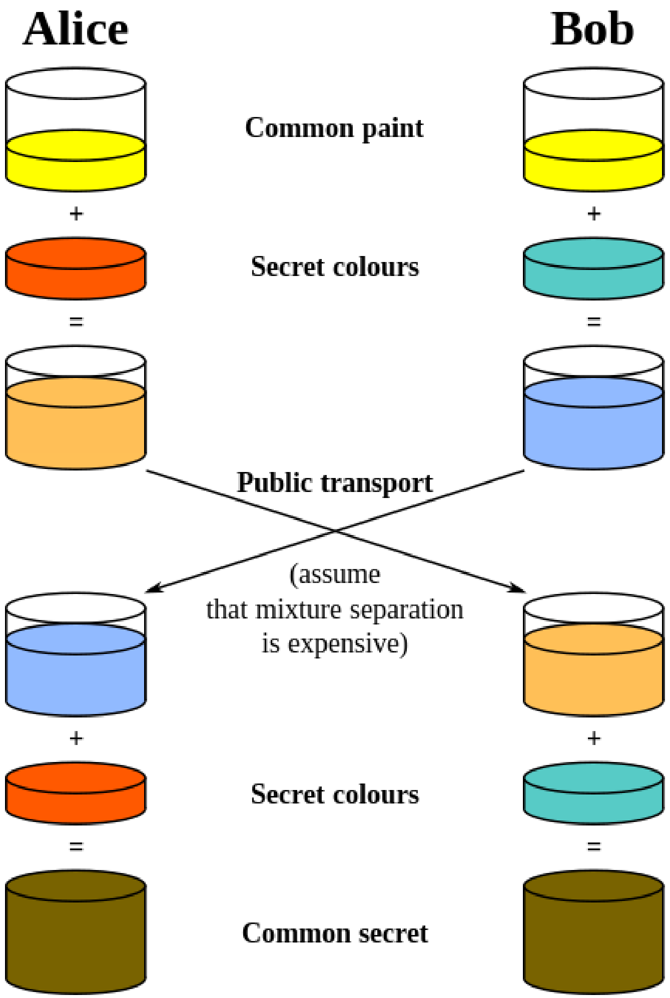
- PUBLIC
  - p = 11
  - g = 2
  - (g is a generator for group mod p)

- Alice: x=9, sends 6 (g^x mod p = 2^9 mod 11 = 6)
- Bob: y=4, send 5 (g^y mod p = 2^4 mod 11 = 5)

- A compute: 5^x mod 11 (5^9 mod 11 = 9)
- B compute 6^y mod 11 (6^4 mod 11 = 9)
- Both get 9

- All computations modulo 11

Diffie-Hellman: Conceptually



Common paint: p and g

Secret colors: x and y

Send over public transport:
$g^x \bmod p$
$g^y \bmod p$

Common secret: $g^{xy} \bmod p$

[from Wikipedia]

Why is Diffie-Hellman Secure?

- Discrete Logarithm (DL) problem:

  given $g^x \bmod p$, it's hard to extract x
  - There is no known <u>efficient</u> algorithm for doing this
  - This is <u>not</u> enough for Diffie-Hellman to be secure!
- Computational Diffie-Hellman (CDH) problem:

  given g^x and g^y, it's hard to compute $g^{xy} \bmod p$
  - … unless you know x or y, in which case it's easy
- Decisional Diffie-Hellman (DDH) problem:

  given g^x and g^y, it's hard to tell the difference between $g^{xy} \bmod p$ and $g^r \bmod p$ where r is random

More on Diffie-Hellman Key Exchange

- Important Note:
  - We have discussed discrete logs modulo integers
  - Significant advantages in using elliptic curve groups
    - Groups with some similar mathematical properties (i.e., are "groups") but have better security and performance (size) properties

Diffie-Hellman Caveats

- Assuming DDH problem is hard (depends on choice of parameters!), Diffie-Hellman protocol is a secure key establishment protocol against passive attackers
  - Common recommendation:
    - Choose p=2q+1, where q is also a large prime
    - Choose g that generates a subgroup of order q in Z_p*
    - DDH is hard in this group
  - Eavesdropper can't tell the difference between the established key and a random value
  - In practice, often hash $g^{xy} \bmod p$, and use the hash as the key
  - Can use the new key for symmetric cryptography
- Diffie-Hellman protocol (by itself) does not provide authentication (against active attackers)
  - Person in the middle attack (also called "man in the middle attack")

Example from Earlier

- Given g and prime p, compute: g^1 mod p, g^2 mod p, … g^{100} mod p
  - For p=11, g=10
    - 10^1 mod 11 = 10, 10^2 mod 11 = 1, 10^3 mod 11 = 10, …
    - Produces cyclic group {10, 1} (order=2)
  - For p=11, g=7
    - 7^1 mod 11 = 7, 7^2 mod 11 = 5, 7^3 mod 11 = 2, …
    - Produces cyclic group {7,5,2,3,10,4,6,9,8,1} (order = 10)
    - g=7 is a "generator" of Z_{11}*
  - For p=11, g=3
    - 3^1 mod 11 = 3, 3^2 mod 11 = 9, 3^3 mod 11 = 5, …
    - Produces cyclic group {3,9,5,4,1} (order = 5) (5 is a prime)
    - g=3 generates a group of prime order

Stepping Back: Asymmetric Crypto

- We've just seen session key establishment
  - Can then use shared key for symmetric crypto
- Next: public key encryption
  - For confidentiality
- Then: digital signatures
  - For authenticity

Requirements for Public Key Encryption

- Key generation: computationally easy to generate a pair (public key PK, private key SK)
- Encryption: given plaintext M and public key PK, easy to compute ciphertext $C=E_{PK}(M)$
- Decryption: given ciphertext $C=E_{PK}(M)$ and private key SK, easy to compute plaintext M
  - Infeasible to learn anything about M from C without SK
  - Trapdoor function: Decrypt(SK,Encrypt(PK,M))=M

Some Number Theory Facts

- Euler totient function $\varphi(n)$ ($n \geq 1$) is the number of integers in the [1,n] interval that are relatively prime to n
  - Two numbers are relatively prime if their greatest common divisor (gcd) is 1
  - Easy to compute for primes: $\varphi(p) = p-1$
  - Note that $\varphi(ab) = \varphi(a)\,\varphi(b)$ if a & b are relatively prime

RSA Cryptosystem [Rivest, Shamir, Adleman 1977]

- Key generation:
  - Generate large primes p, q
    - Say, 2048 bits each (need primality testing, too)
  - Compute **n**=pq and **φ(n)**=(p-1)(q-1)
  - Choose small **e**, relatively prime to φ(n)
    - Typically, **e=3** or **$e=2^{16}+1=65537$**
  - Compute unique **d** such that ed ≡ 1 mod φ(n)
    - Modular inverse: $d \equiv e^{-1} \bmod \varphi(n)$
  - Public key = (e,n); private key = (d,n)
- Encryption of m: $c = m^e \bmod n$
- Decryption of c: $c^d \bmod n = (m^e)^d \bmod n = m$

How to compute?

Why is RSA Secure?

- RSA problem: given c, $n=pq$, and e such that $\gcd(e, \varphi(n))=1$, find m such that $m^e=c \bmod n$
  - In other words, recover m from ciphertext c and public key (n,e) by taking e^{th} root of c modulo n
  - There is no known efficient algorithm for doing this *without* knowing p and q
- Factoring problem: given positive integer n, find primes $p_1, \ldots, p_k$ such that $n=p_1^{e_1}p_2^{e_2}\ldots p_k^{e_k}$

- If factoring is easy, then RSA problem is easy (knowing factors means you can compute d = inverse of e mod (p-1)(q-1))
  - It may be possible to break RSA without factoring n -- but if it is, we don't know how

RSA Encryption Caveats

- Encrypted message needs to be interpreted as an integer less than n
- Don't use RSA **directly** for privacy – output is deterministic! Need to pre-process input somehow
- Plain RSA also does not provide integrity
  - Can tamper with encrypted messages

In practice, OAEP is used: instead of encrypting M, encrypt
$M \oplus G(r) \,||\, r \oplus H(M \oplus G(r))$

- r is random and fresh, G and H are hash functions

RSA OAEP

$M \oplus G(r) \, || \, r \oplus H(M \oplus G(r))$

Review: RSA Cryptosystem [Rivest, Shamir, Adleman 1977]

- Key generation:
  - Generate large primes p, q
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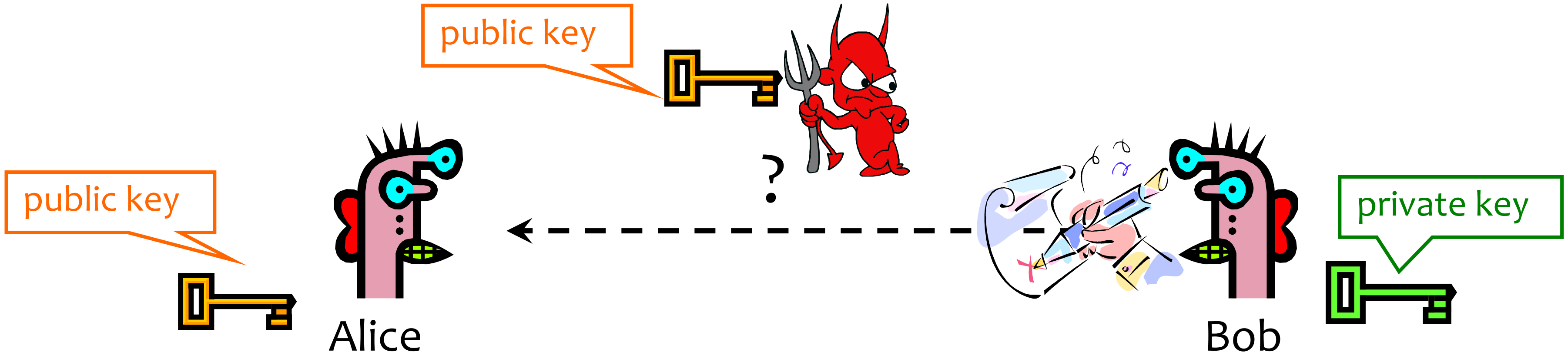
How to compute?

Digital Signatures: Basic Idea



Given: Everybody knows Bob's public key
Only Bob knows the corresponding private key

Goal: Bob sends a "digitally signed" message

1. To compute a signature, must know the private key
2. To verify a signature, only the public key is needed

RSA Signatures

- Public key is **(n,e)**, private key is **(n,d)**
- To sign message m: $s = m^d \bmod n$
  - Signing & decryption are same **underlying** operation in RSA
  - It's infeasible to compute **s** on **m** if you don't know **d**
- To verify signature s on message m:

  verify that $s^e \bmod n = (m^d)^e \bmod n = m$
  - Just like encryption (for RSA primitive)
  - Anyone who knows **n** and **e** (public key) can verify signatures produced with d (private key)
- In practice, also need padding & hashing
  - Without padding and hashing: Consider multiplying two signatures together
  - Standard padding/hashing schemes exist for RSA signatures

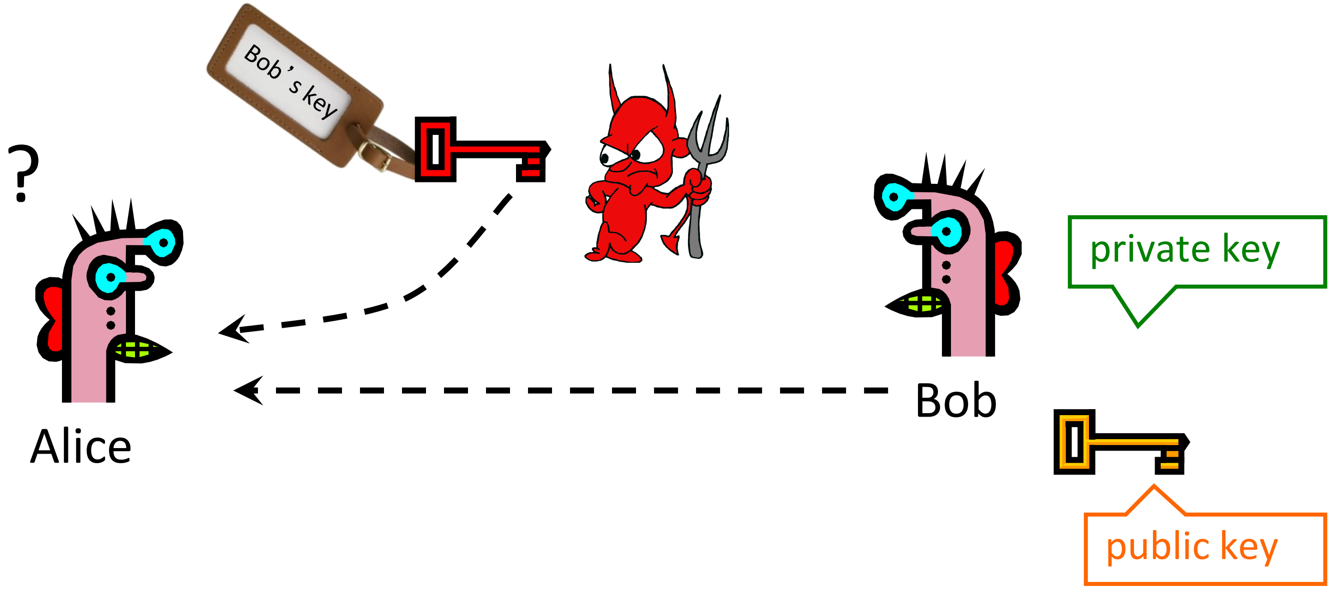
DSS Signatures

- Digital Signature Standard (DSS)
  - U.S. government standard (1991, most recent rev. 2013)
- Public key: $(p, q, g, y=g^x \bmod p)$, private key: x
- Each signing operation picks a new random value, to use during signing. Security breaks if two messages are signed with that same value.
- Security of DSS requires hardness of discrete log
  - If could solve discrete logarithm problem, would extract x (private key) from g^x mod p (public key)
- Again: We've discussed discrete logs modulo integers; significant advantages to using elliptic curve groups instead.

Post-Quantum

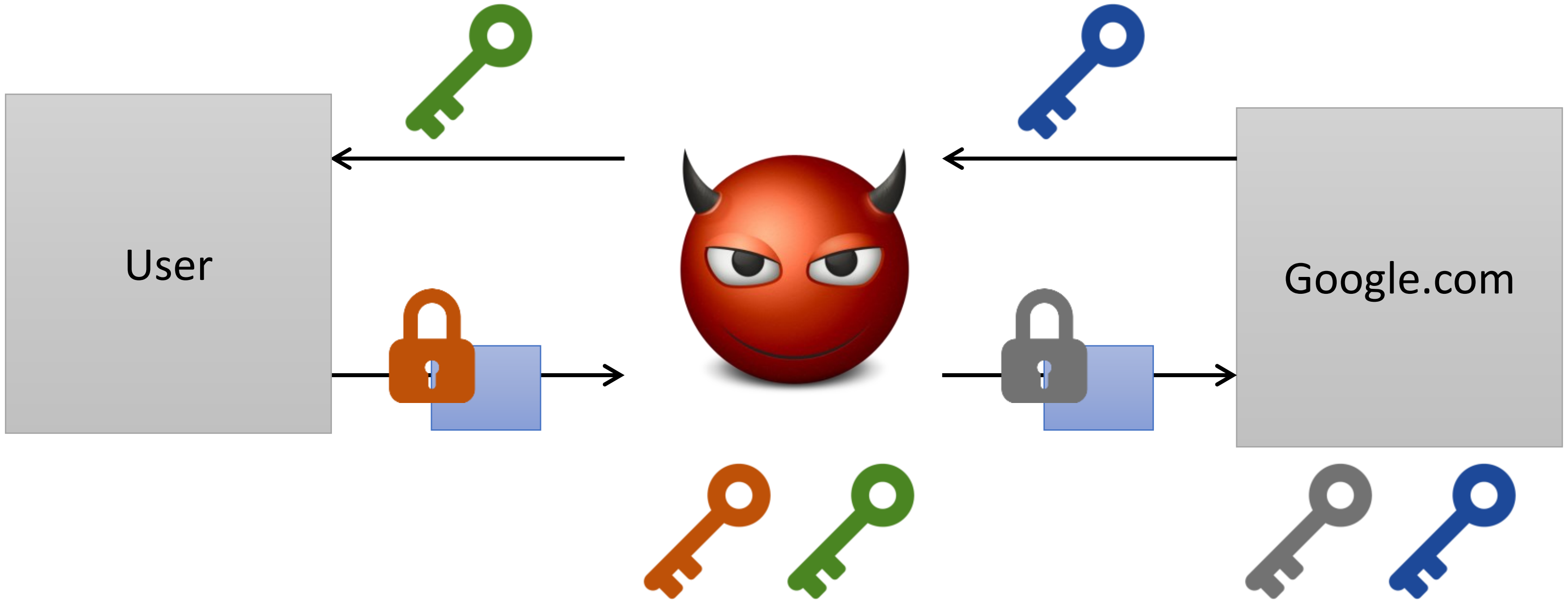
- If quantum computer become a reality
  - It becomes much more efficient to break conventional asymmetric encryption schemes (e.g., factoring becomes “easy”)
  - For block ciphers (symmetric encryption), use 128-bit keys for 256-bits of security
- There exists efforts to make quantum-resilient asymmetric encryption schemes

Authenticity of Public Keys



Problem: How does Alice know that the public key they received is really Bob's public key?

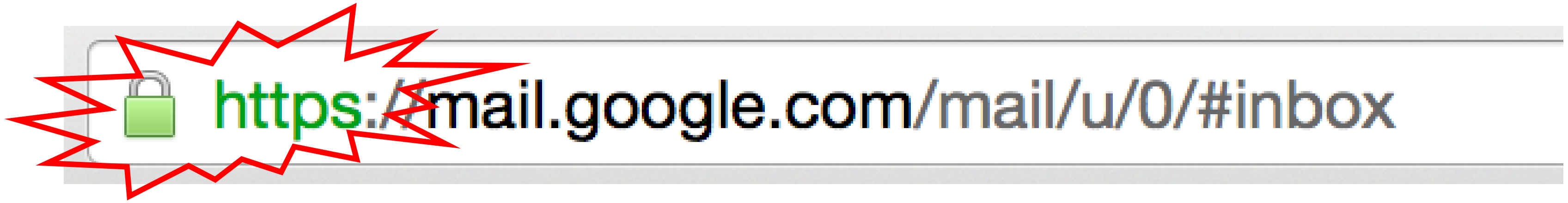
Threat: Person-in-the Middle



Distribution of Public Keys

- Public announcement or public directory
  - Risks: forgery and tampering
- Public-key certificate
  - Signed statement specifying the key and identity
    - sig_{CA}(“Bob”, PK_B)
    - Additional information often signed as well (e.g., expiration date)
- Common approach: certificate authority (CA)
  - Single agency responsible for certifying public keys
  - After generating a private/public key pair, user proves their identity and knowledge of the private key to obtain CA’s certificate for the public key (offline)
  - Every computer is <u>pre-configured</u> with CA’s public key

You encounter this every day…

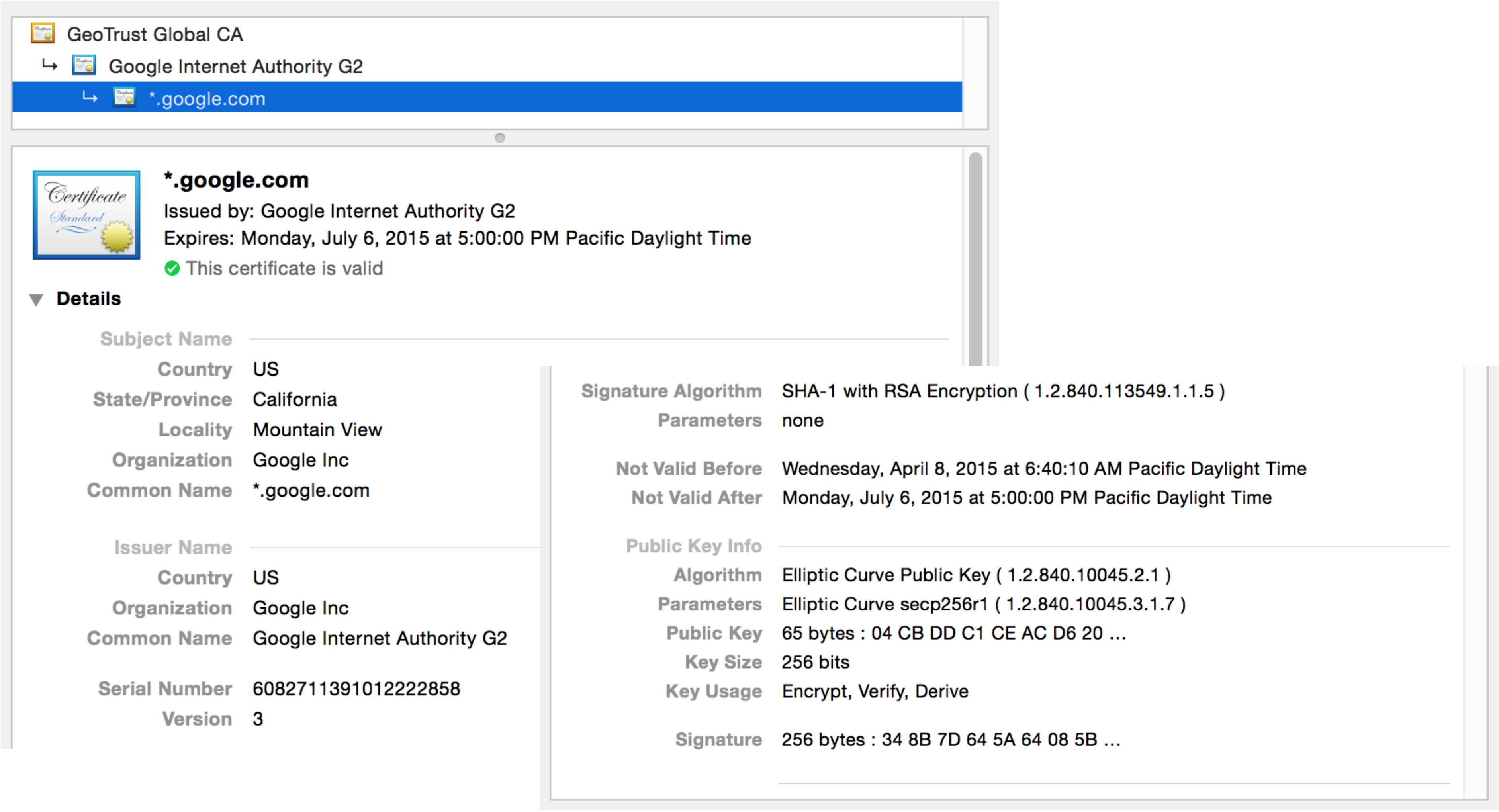


SSL/TLS: Encryption & authentication for connections

SSL/TLS High Level

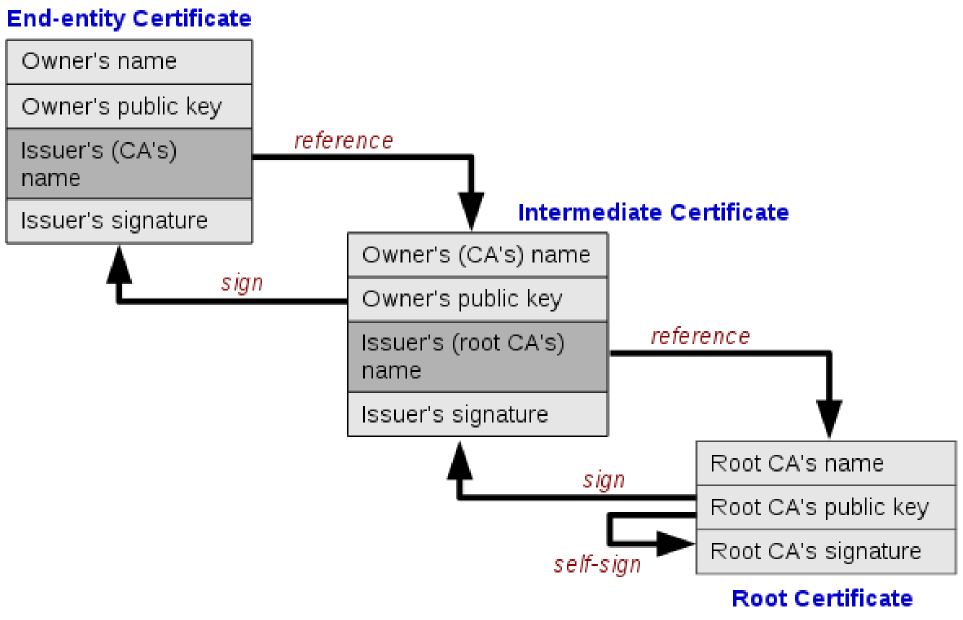
- SSL/TLS consists of two protocols
  - Familiar pattern for key exchange protocols
- Handshake protocol
  - Use public-key cryptography to establish a shared secret key between the client and the server
- Record protocol
  - Use the secret symmetric key established in the handshake protocol to protect communication between the client and the server

Example of a Certificate



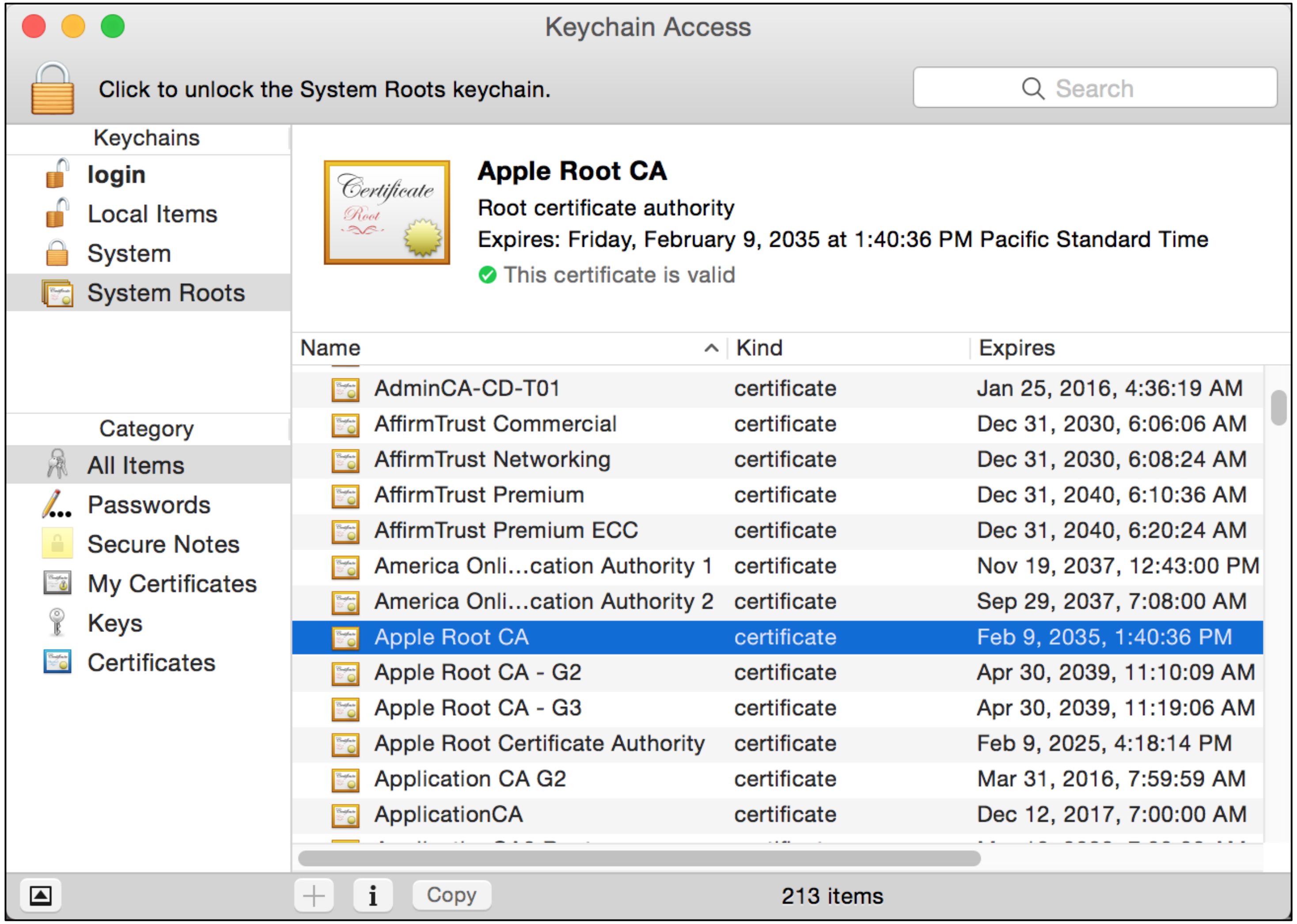
Hierarchical Approach

- Single CA certifying every public key is impractical
- Instead, use a trusted root authority (e.g., Verisign)
  - Everybody must know the root's public key
  - Instead of single cert, use a certificate chain
    - $sig_{Verisign}$(“AnotherCA”, $PK_{AnotherCA}$), $sig_{AnotherCA}$(“Alice”, PK_A)
  - Not shown in figure but important:
    - Signed as part of each cert is whether party is a CA or not



- What happens if root authority is ever compromised?

Trusted(?) Certificate Authorities



Turtles All The Way Down…

The saying holds that the world is supported by a chain of increasingly large turtles. Beneath each turtle is yet another: it is "turtles all the way down".

[Image from Wikipedia]

Corporate CAs?

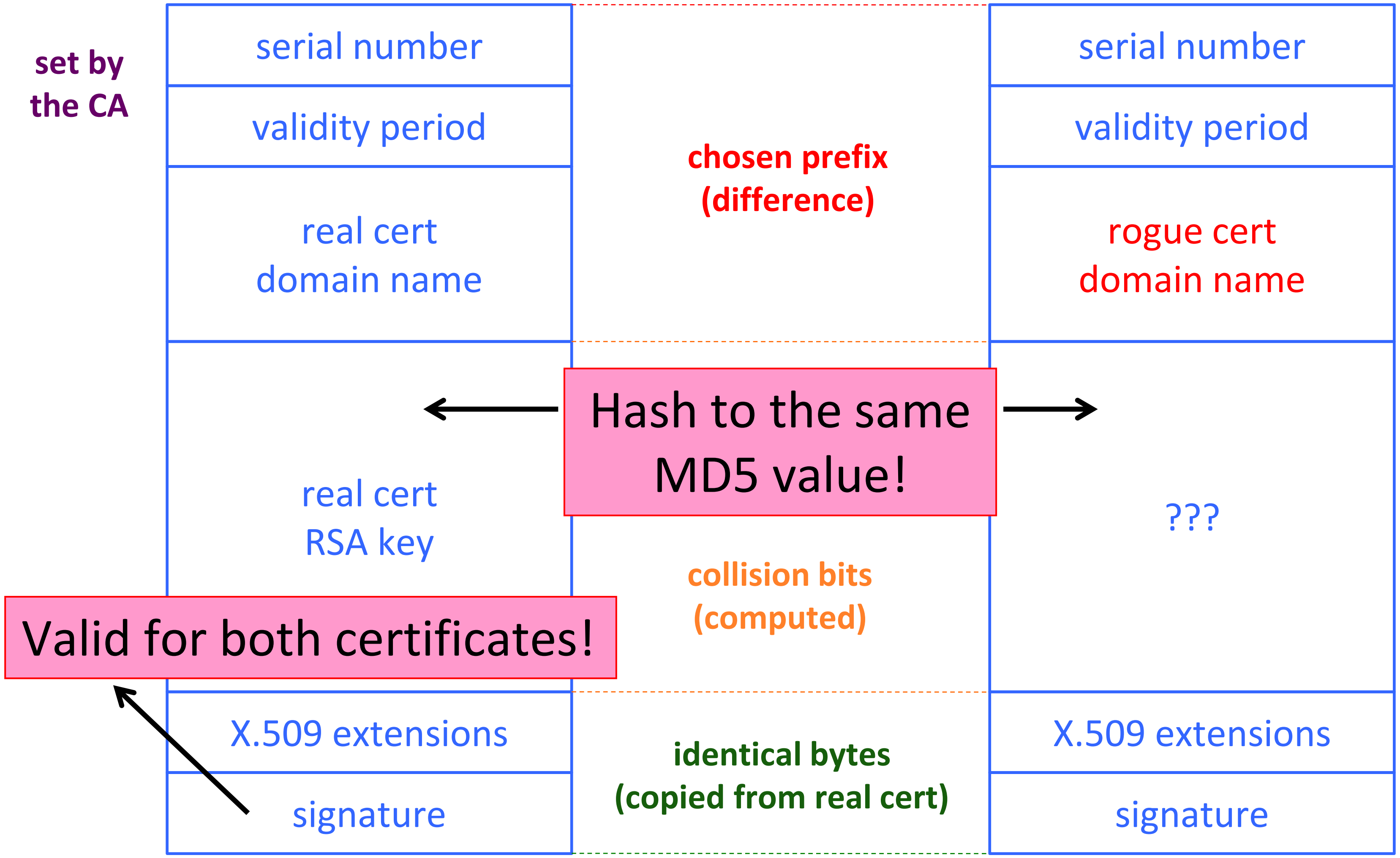
- Canvas!

Many Challenges…

- Hash collisions
- Weak security at CAs
  - Allows attackers to issue rogue certificates
- Users don’t notice when attacks happen
  - We’ll talk more about this later in the course
- How do you revoke certificates?

[Sotirov et al. “Rogue Certificates”]

Colliding Certificates



Attacking CAs

DigiNotar Hacked by Black.Spook and Iranian Hackers

Posted by Mikko @ 09:05 GMT | Comments

DigiNotar is a Dutch Certificate Authority. They sell SSL certificates.

Somehow, somebody managed to get a rogue SSL certificate from them on **July 10th, 2011**. This certificate was issued for domain name **.google.com**.

What can you do with such a certificate? Well, you can impersonate Google — assuming you can first reroute Internet traffic for google.com to you. This is something that can be done by a government or by a rogue ISP. Such a reroute would only affect users within that country or under that ISP.

<u>Security of DigiNotar servers:</u>

- All core certificate servers controlled by a single admin password (Pr0d@dm1n)
- Software on public-facing servers out of date, unpatched
- No anti-virus (could have detected attack)

Consequences

- Attacker needs to first divert users to an attacker-controlled site instead of Google, Yahoo, Skype, but then…
  - For example, use DNS to poison the mapping of mail.yahoo.com to an IP address
- … “authenticate” as the real site
- … decrypt all data sent by users
  - Email, phone conversations, Web browsing

More Rogue Certs

- In Jan 2013, a rogue *.google.com certificate was issued by an intermediate CA that gained its authority from the Turkish root CA TurkTrust
  - TurkTrust accidentally issued intermediate CA certs to customers who requested regular certificates
  - Ankara transit authority used its certificate to issue a fake *.google.com certificate in order to filter SSL traffic from its network
- This rogue *.google.com certificate was trusted by every browser in the world

Bad CAs

- DarkMatter (https://groups.google.com/g/mozilla.dev.security.policy/c/nnLVNfqgz7g/m/TseYqDzaDAAJ and https://bugzilla.mozilla.org/show_bug.cgi?id=1427262)
  - Security company wanted to get CA status
  - Questionable practices
- Symantec! (https://wiki.mozilla.org/CA:Symantec_Issues)
  - Major company, regular participant in standards
  - Poor practices, mismanagement 2013-2017
  - CA distrusted in Oct 2018
- Recall: Turtles all the way down. How can we trust the CAs? What happens if we can't?

Certificate Revocation

- Revocation is very important
- Many valid reasons to revoke a certificate
  - Private key corresponding to the certified public key has been compromised
  - User stopped paying their certification fee to this CA and CA no longer wishes to certify them
  - CA's private key has been compromised!
- Expiration is a form of revocation, too
  - Many deployed systems don't bother with revocation
  - Re-issuance of certificates is a big revenue source for certificate authorities

Certificate Revocation Mechanisms

- Certificate revocation list (CRL)
  - CA periodically issues a signed list of revoked certificates
    - Credit card companies used to issue thick books of canceled credit card numbers
  - Can issue a "delta CRL" containing only updates
- Online revocation service
  - When a certificate is presented, recipient goes to a special online service to verify whether it is still valid
    - Like a merchant dialing up the credit card processor

Attempt to Fix CA Problems:
Certificate Transparency

- **Problem:** browsers will think nothing is wrong with a rogue certificate until revoked
- **Goal:** make it impossible for a CA to issue a bad certificate for a domain *without the owner of that domain knowing*
- **Approach:** auditable certificate logs
    - Certificates published in public logs
    - Public logs checked for unexpected certificates

www.certificate-transparency.org

Attempt to Fix CA Problems:
Certificate Pinning

- Trust on first access: tells browser how to act on subsequent connections
- HPKP – HTTP Public Key Pinning
  - Use these keys!
  - HTTP response header field "`Public-Key-Pins`"
- HSTS – HTTP Strict Transport Security
  - Only access server via HTTPS
  - HTTP response header field "`Strict-Transport-Security`"