Adventures in TLS

Vitaly Shmatikov

What Is SSL / TLS?

- Secure Sockets Layer and Transport Layer Security protocols
  - Same protocol design, different crypto algorithms
- De facto standard for Internet security
  - "The primary goal of the TLS protocol is to provide privacy and data integrity between two communicating applications"
- Deployed in every Web browser; also VoIP, payment systems, distributed systems, etc.

SSL / TLS Guarantees

- End-to-end secure communications in the presence of a network attacker
  - Attacker completely 0wns the network: controls Wi-Fi, DNS, routers, his own websites, can listen to any packet, modify packets in transit, inject his own packets into the network
- Scenario: you are reading your email from an Internet café connected via a r00ted Wi-Fi access point to a dodgy ISP in a hostile authoritarian country

History of the Protocol

- SSL 1.0 – internal Netscape design, early 1994?
  - Lost in the mists of time
- SSL 2.0 – Netscape, Nov 1994
  - Several weaknesses
- SSL 3.0 – Netscape and Paul Kocher, Nov 1996
- TLS 1.0 – Internet standard, Jan 1999
  - Based on SSL 3.0, but not interoperable (uses different cryptographic algorithms)
- TLS 1.1 – Apr 2006
- TLS 1.2 – Aug 2008
- TLS 1.3 – Mar 2016

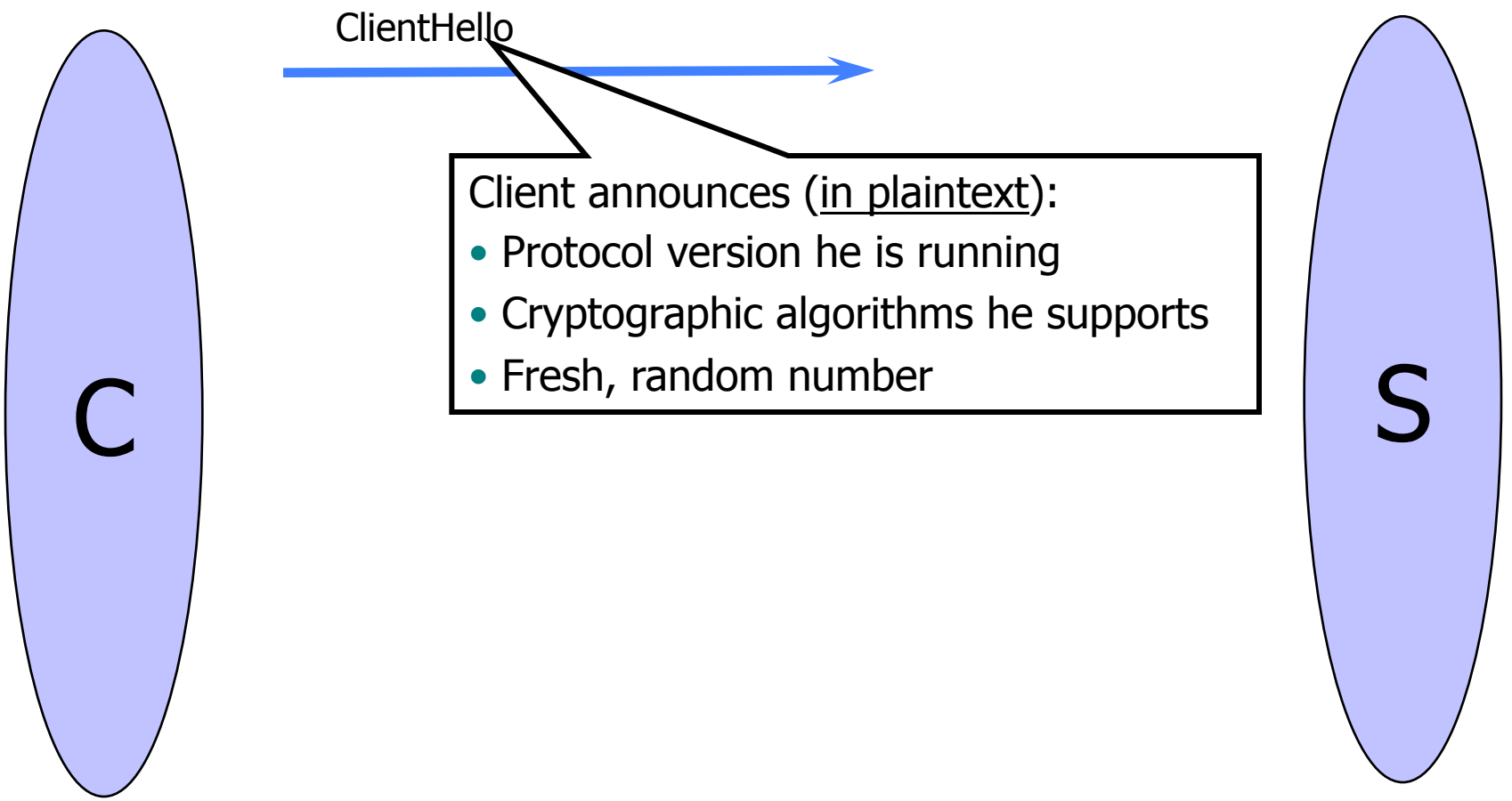
SSL Basics: Two Protocols

- Handshake protocol
  - Uses public-key cryptography to establish several shared secret keys between the client and the server
- Record protocol
  - Uses the secret keys established in the handshake protocol to protect confidentiality, integrity, and authenticity of data exchange between the client and the server

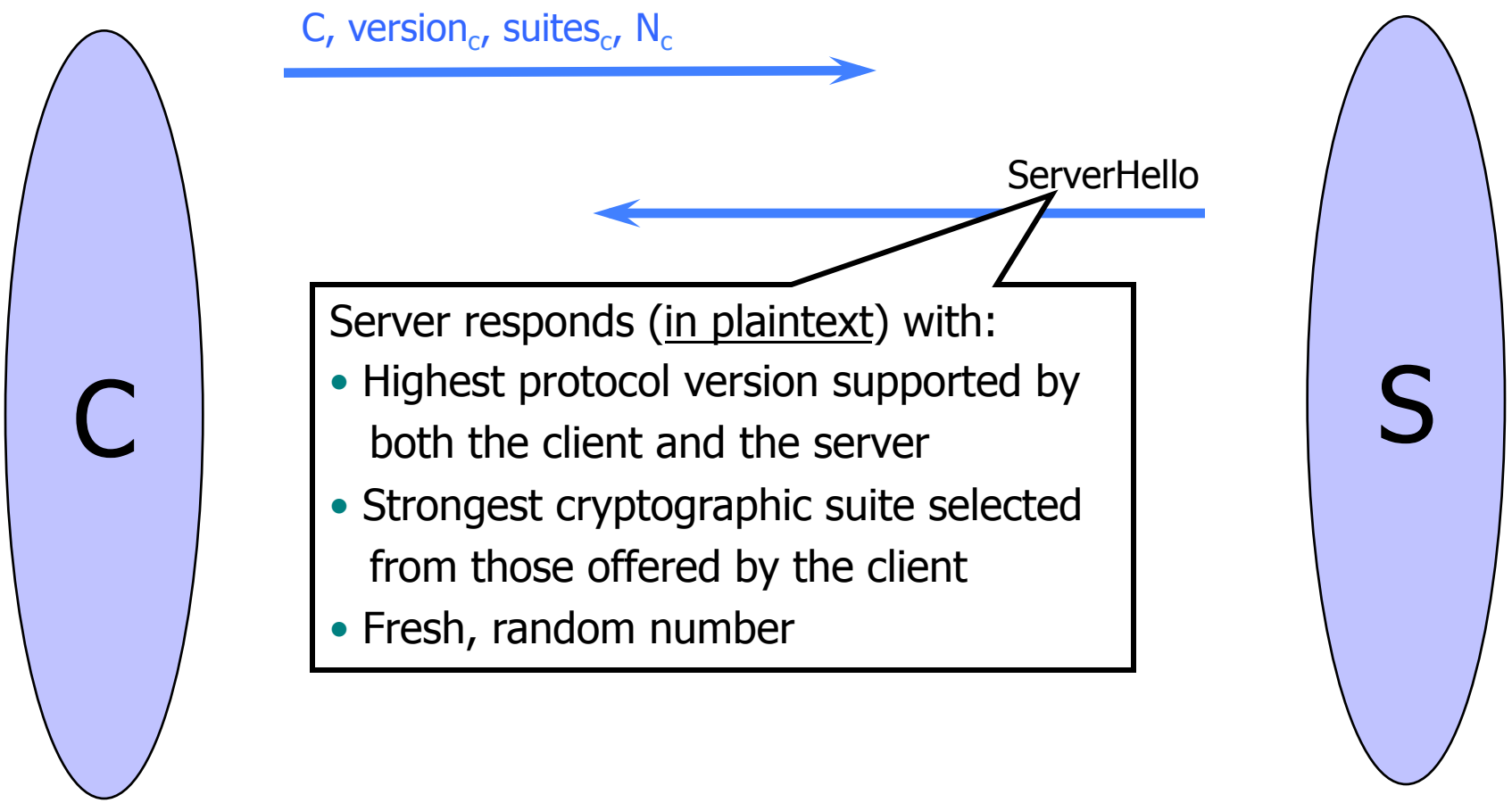
SSL Handshake Protocol

- Runs between a client and a server
  - For example, client = Web browser, server = website
- Negotiate version of the protocol and the set of cryptographic algorithms to be used
  - Interoperability between different implementations
- Authenticate server and client (optional)
  - Use digital certificates to learn each other's public keys and verify each other's identity
  - Often only the server is authenticated
- Use public keys to establish a shared secret

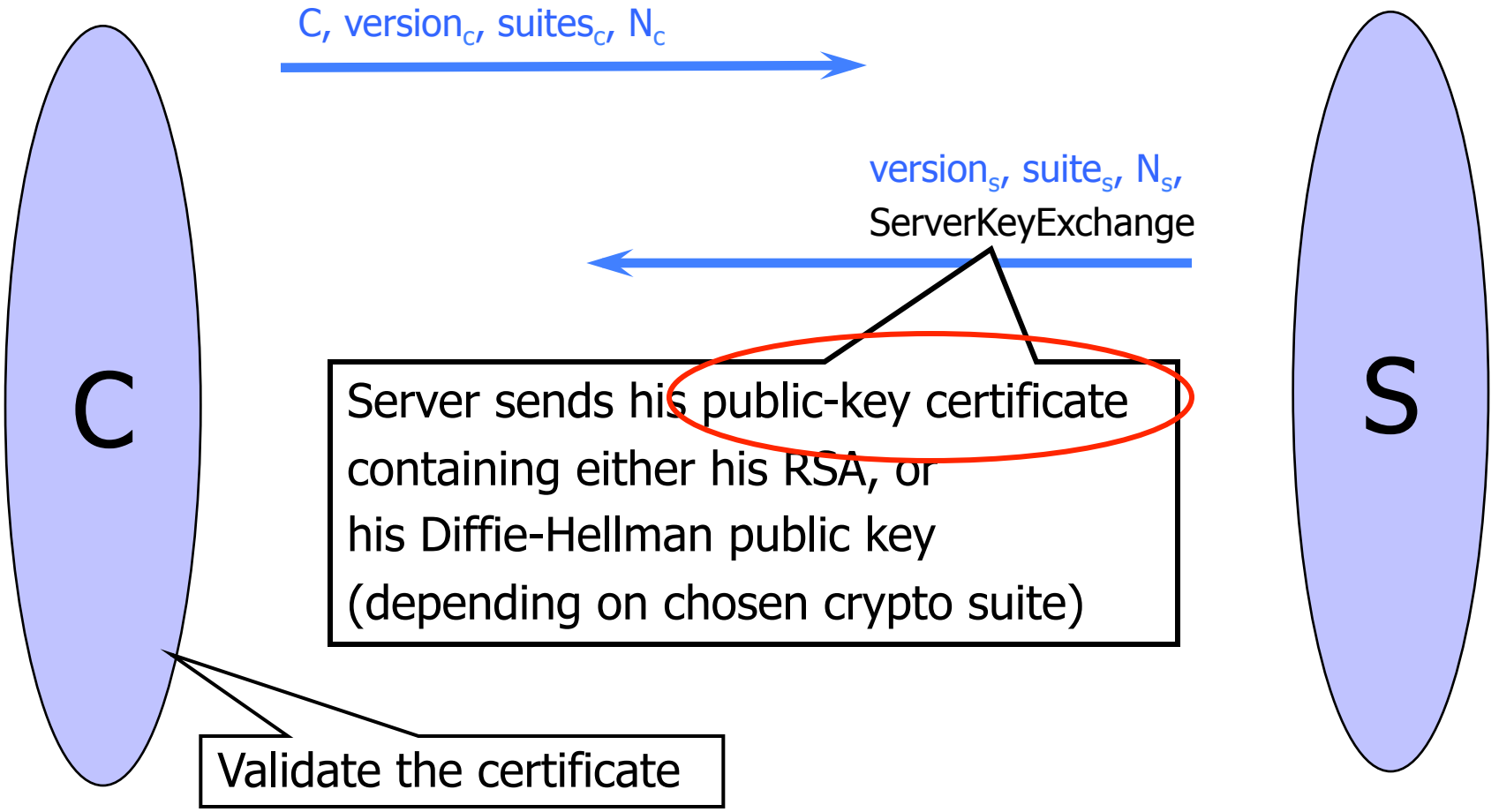
ClientHello



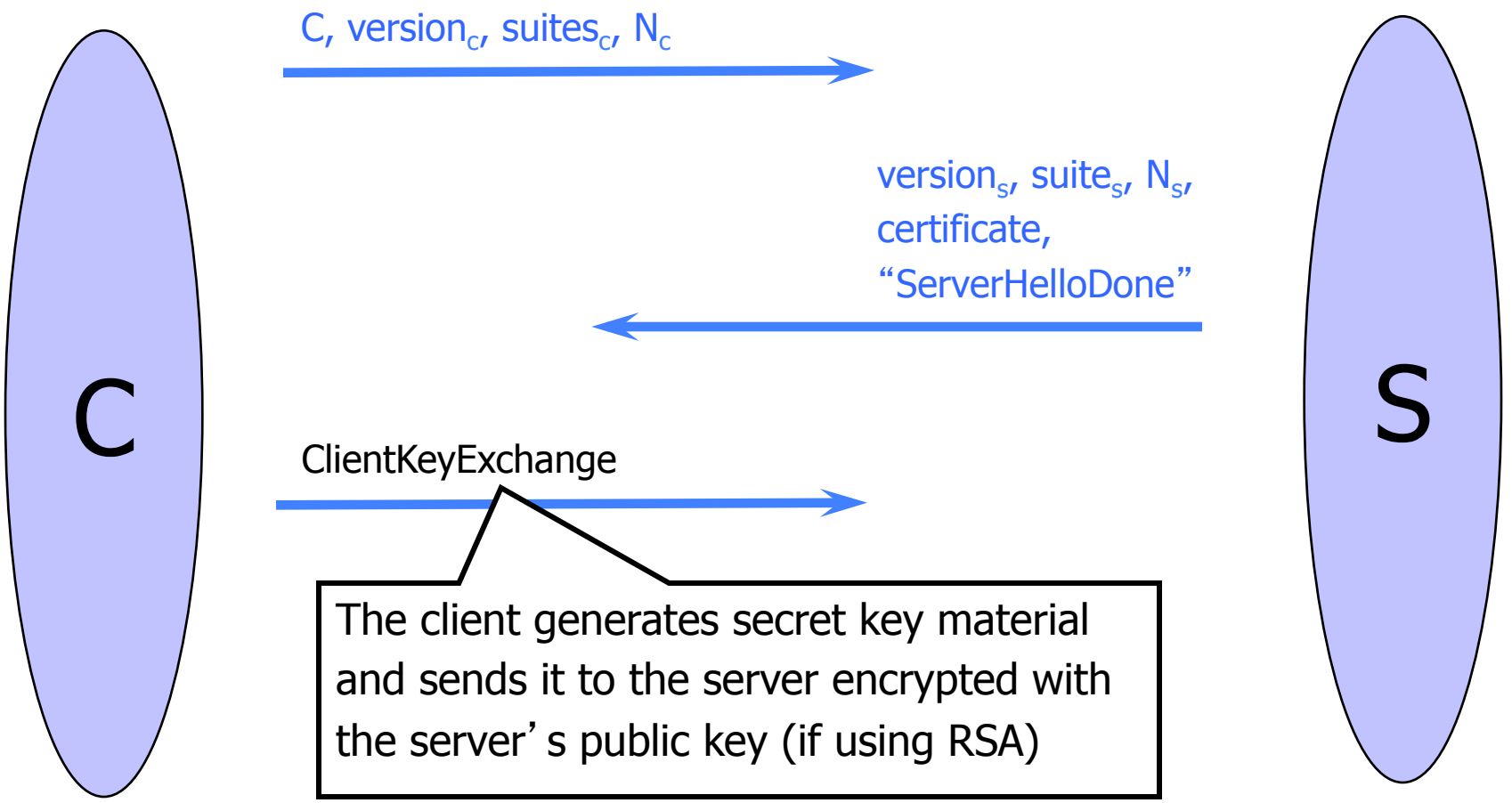
ServerHello



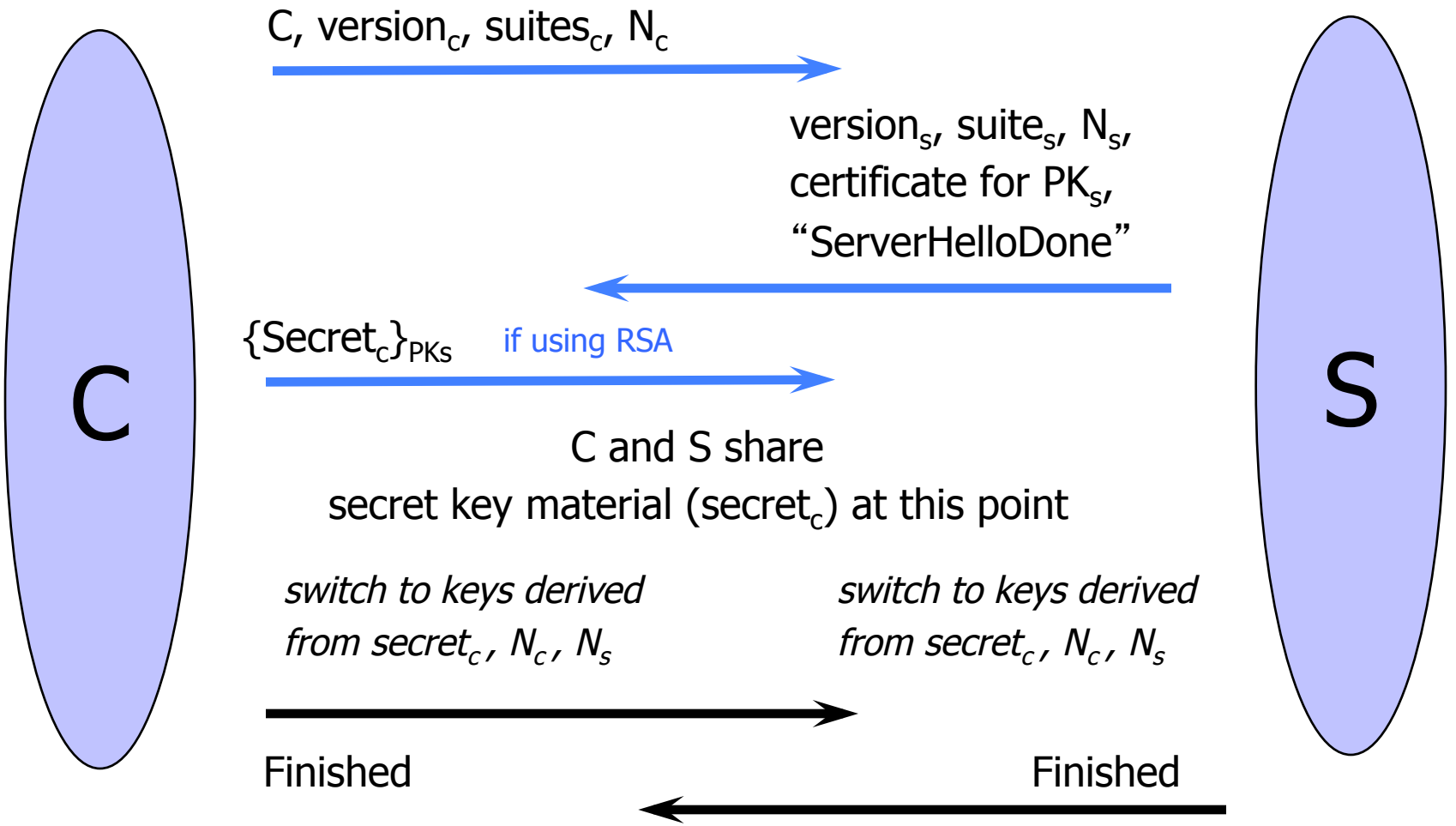
ServerKeyExchange



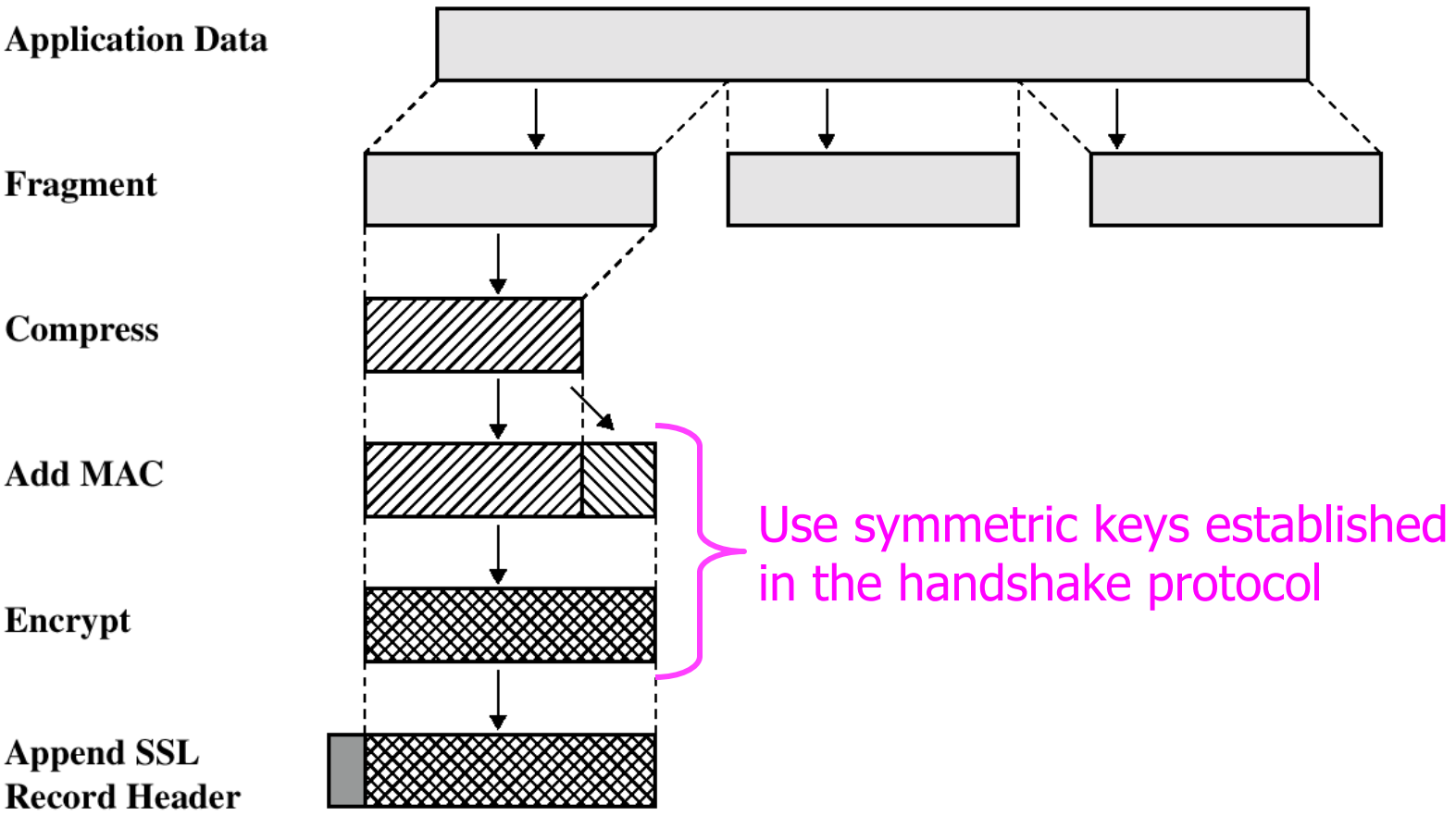
ClientKeyExchange



“Core” SSL Handshake

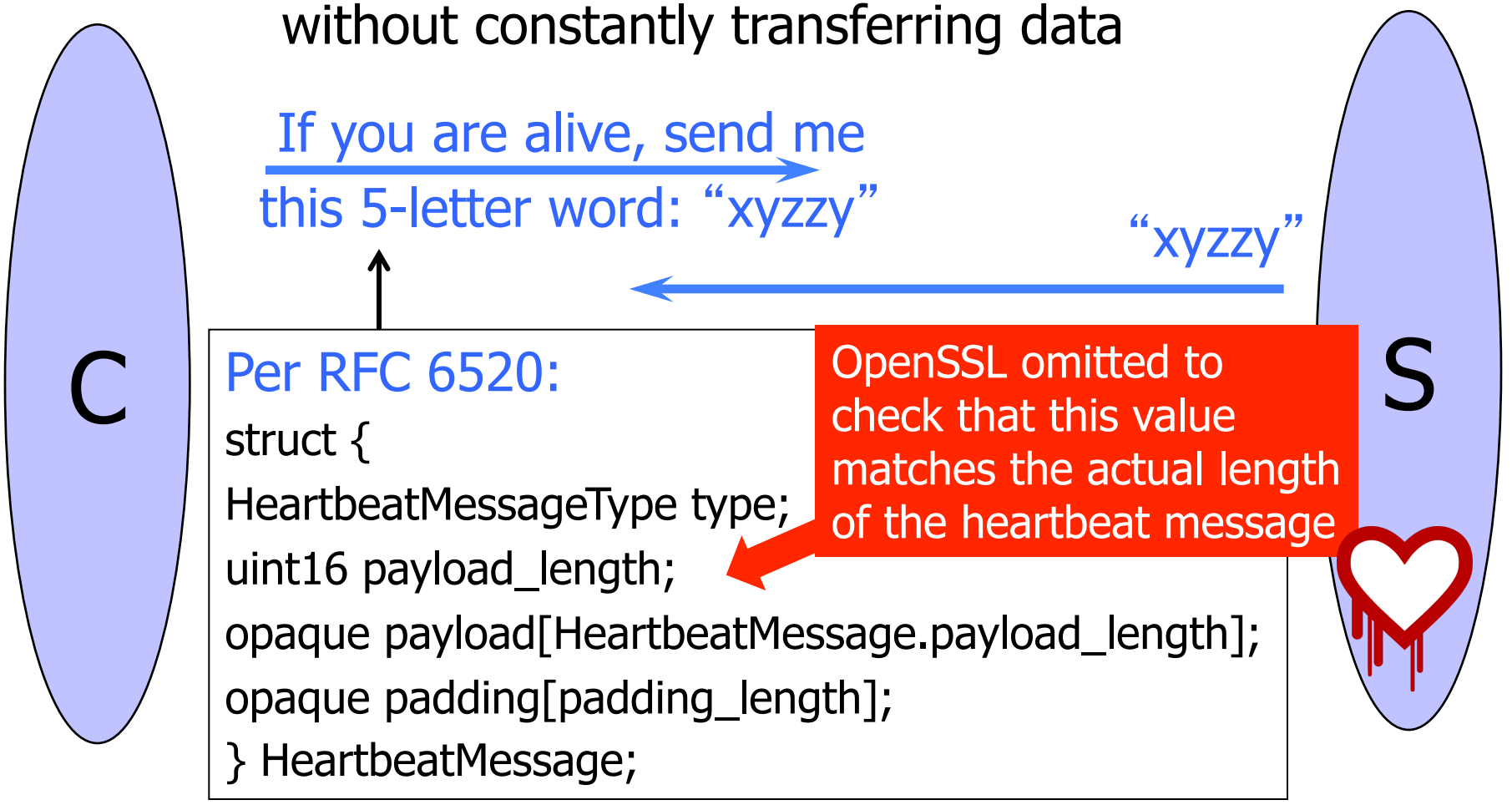


SSL/TLS Record Protection



TLS Heartbeat

A way to keep TLS connection alive
without constantly transferring data

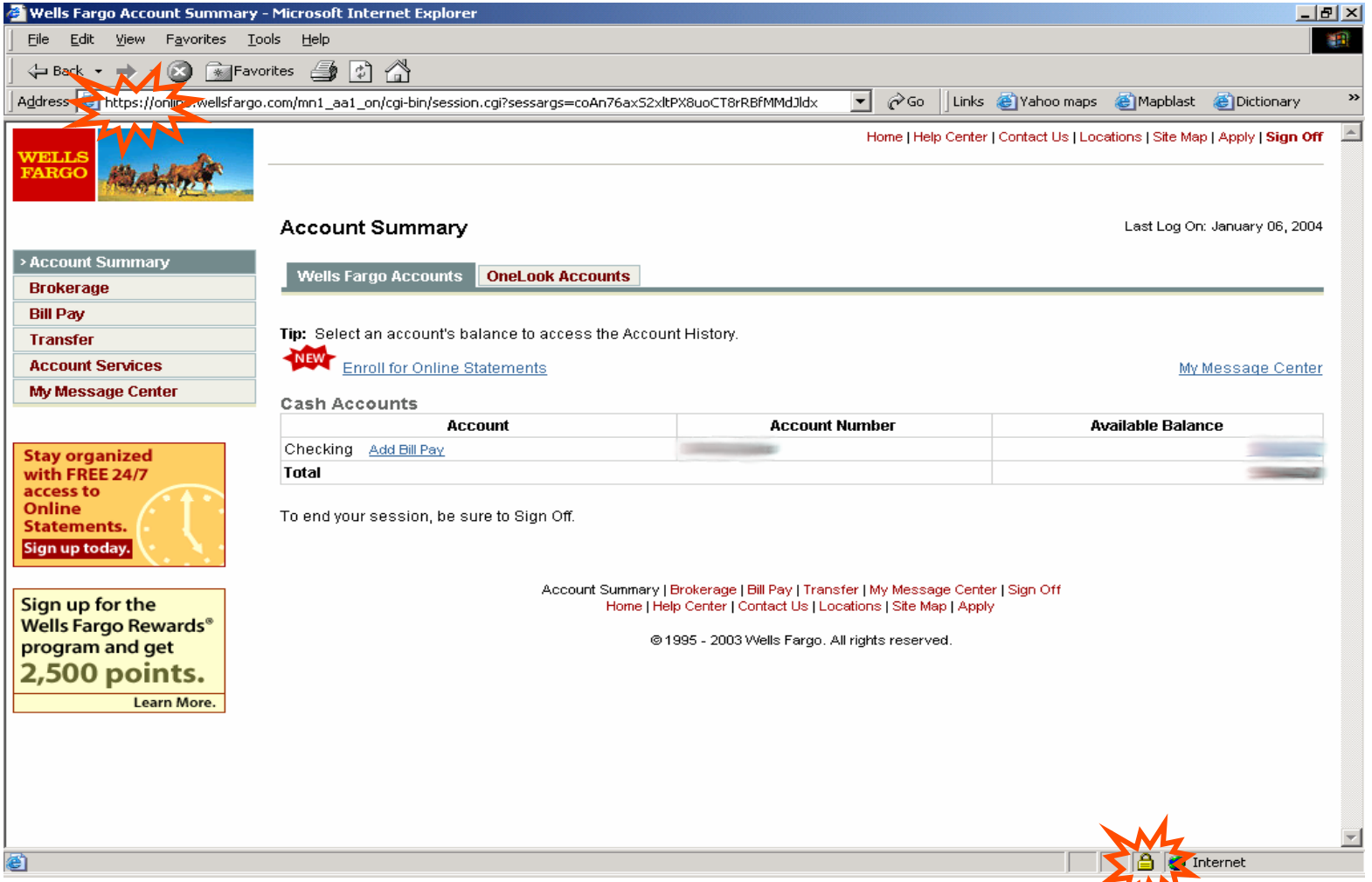


Heartbleed Consequences

- Attacker can obtain chunks of server memory
  - Passwords, contents of other users' communications, even the server's private RSA key
  - Why is the RSA key still in memory?

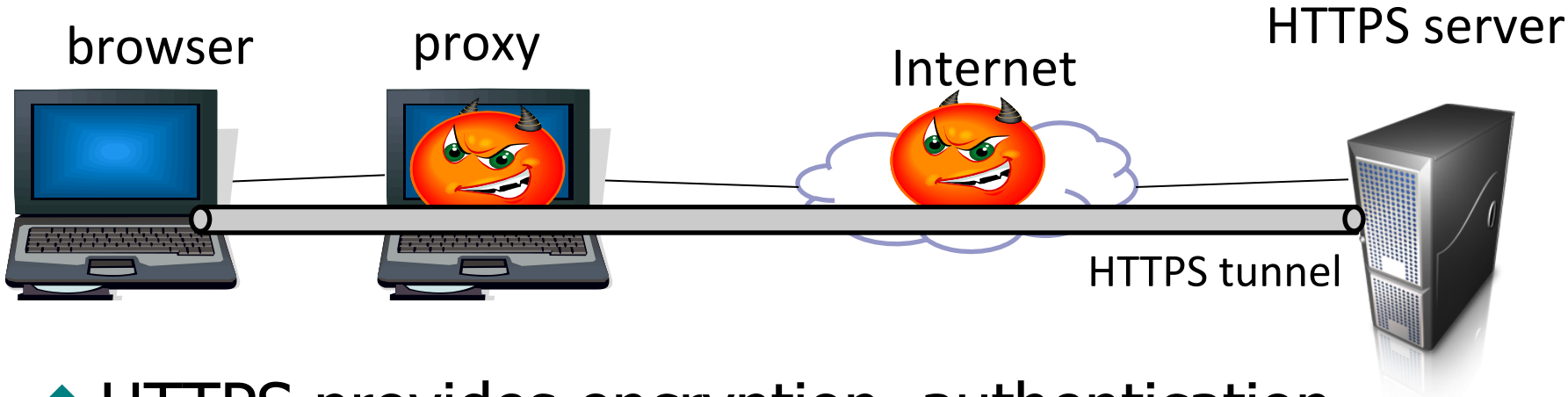
  Long story:
  https://www.lightbluetouchpaper.org/2014/04/25/heartbleed-and-rsa-private-keys/
- Assisted by a custom allocator that does not zero out malloc'd memory (for "performance," natch!)

Most Common Use of SSL/TLS



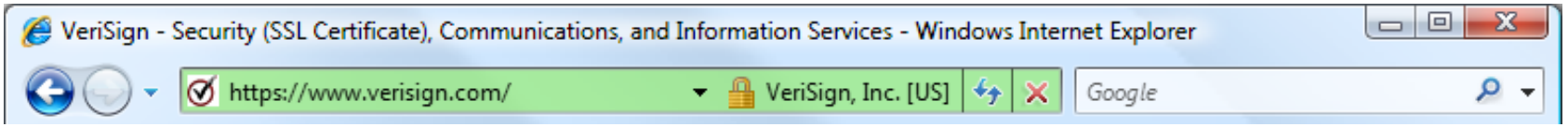
HTTPS and Its Adversary Model

- HTTPS: end-to-end secure protocol for Web
- Designed to be secure against network attackers, including man-in-the-middle (MITM) attacks



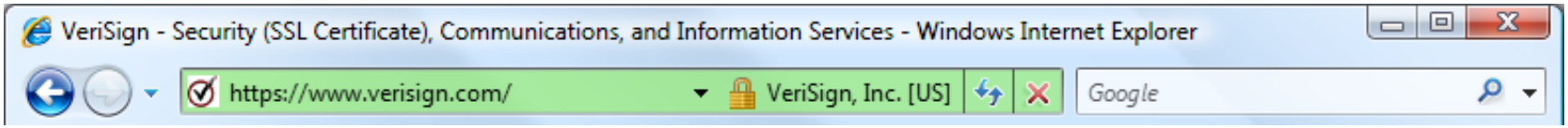
- HTTPS provides encryption, authentication (usually for server only), and integrity checking

The Lock Icon



- Goal: identify secure connection
  - SSL/TLS is being used between client and server to protect against active network attacker
- Lock icon should only be shown when the page is secure against network attacker
  - Semantics subtle and not widely understood by users
  - Problem in user interface design

HTTPS Security Guarantees

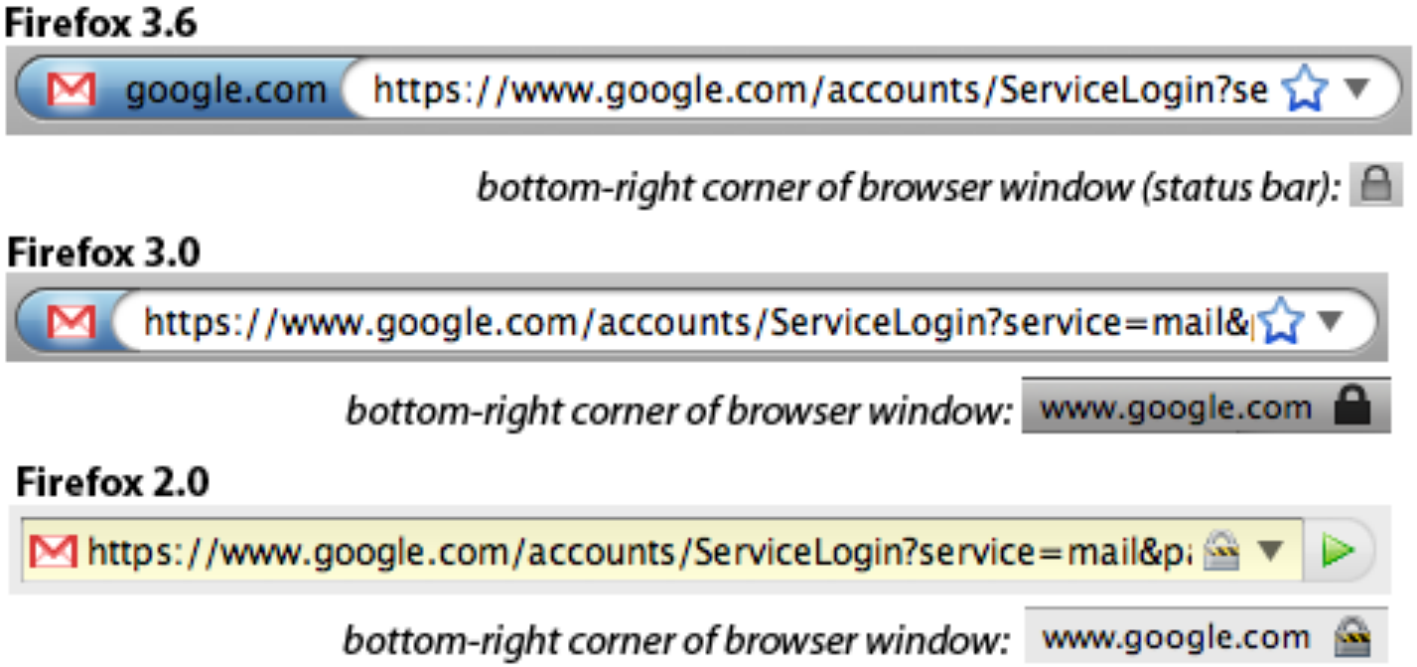


- The origin of the page is what it says in the address bar
  - User must interpret what he sees
- Contents of the page have not been viewed or modified by a network attacker

Evolution of the Lock in Firefox

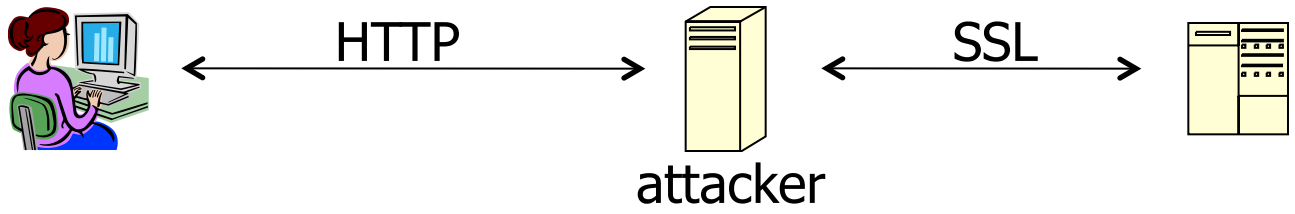
[Schultze]

How about Firefox 4?



HTTP → HTTPS and Back

- Typical pattern: HTTPS upgrade
  - Come to site over HTTP, redirect to HTTPS for login
  - Browse site over HTTP, redirect to HTTPS for checkout
- sslstrip: network attacker downgrades connection

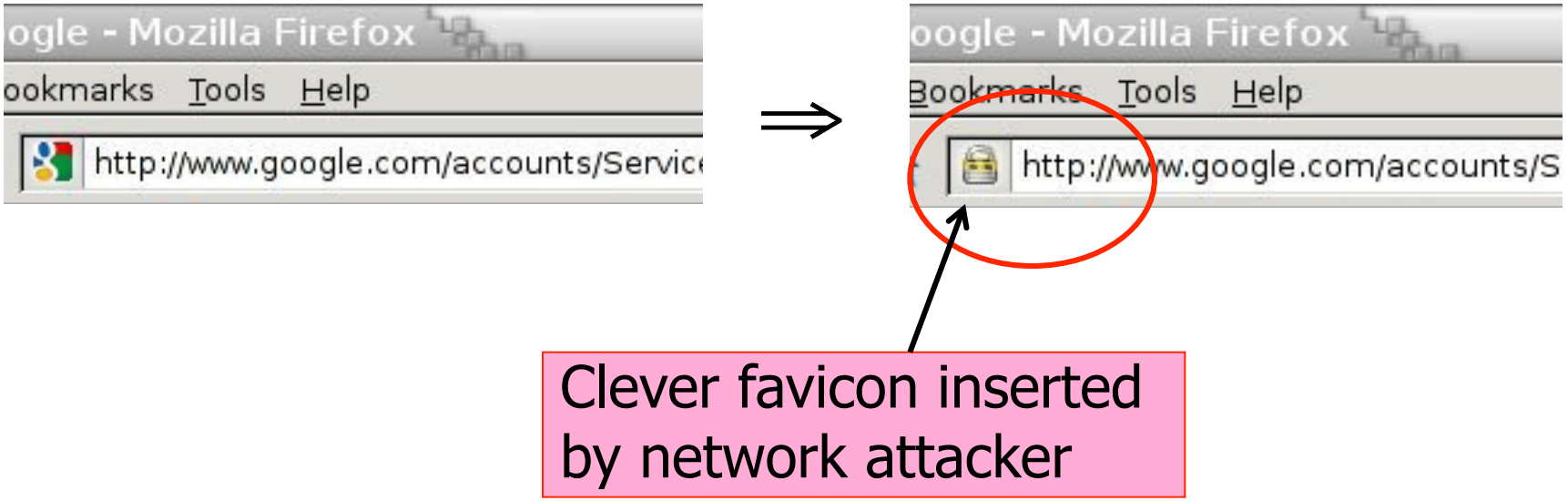


  - Rewrite <a href=https://...> to <a href=http://...>
  - Redirect Location: https://... to Location: http://...
  - Rewrite <form action=https://... > to <form action=http://...>

Can the server detect this attack?

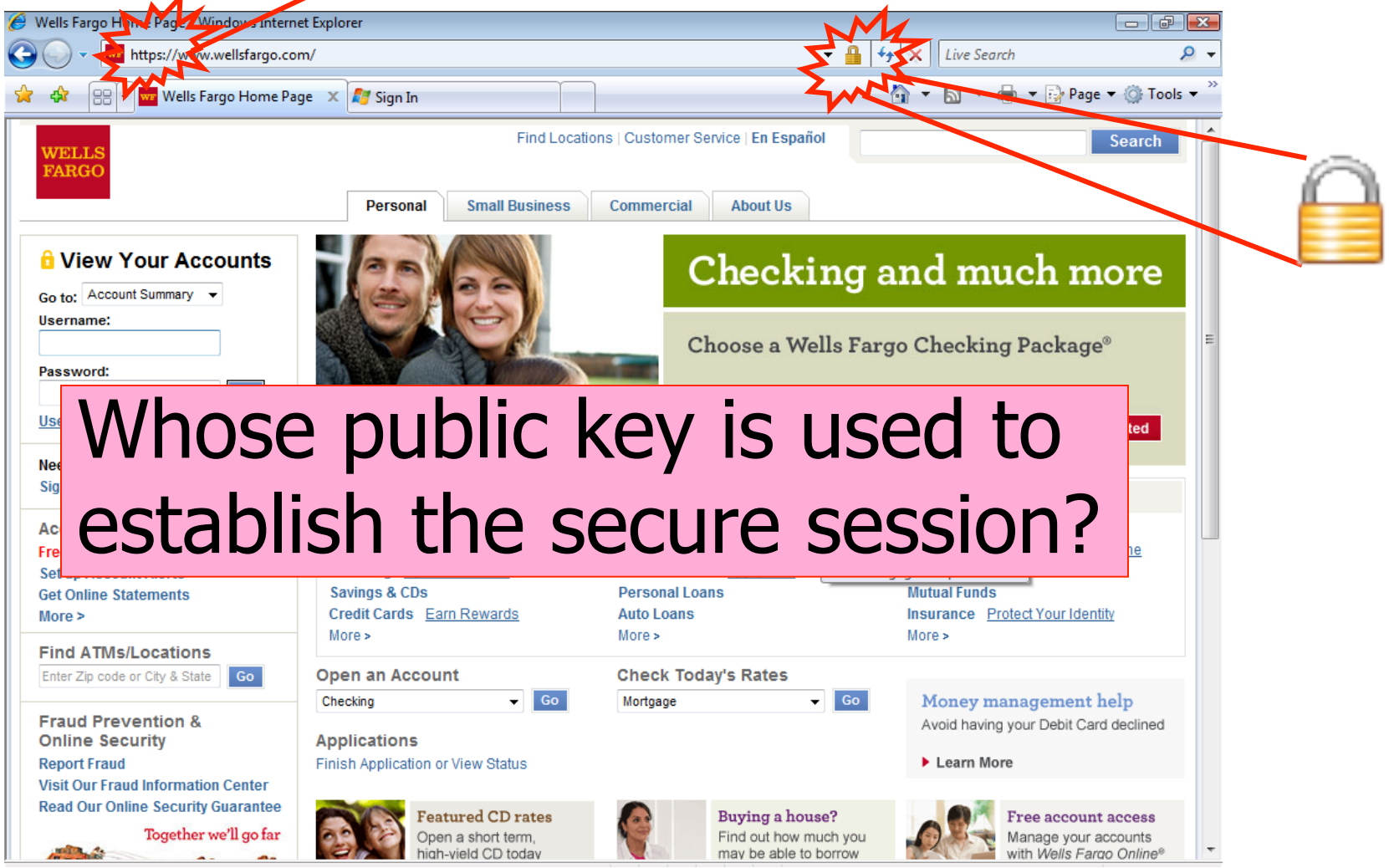
Will You Notice?

[Moxie Marlinspike]



Motivation

https://

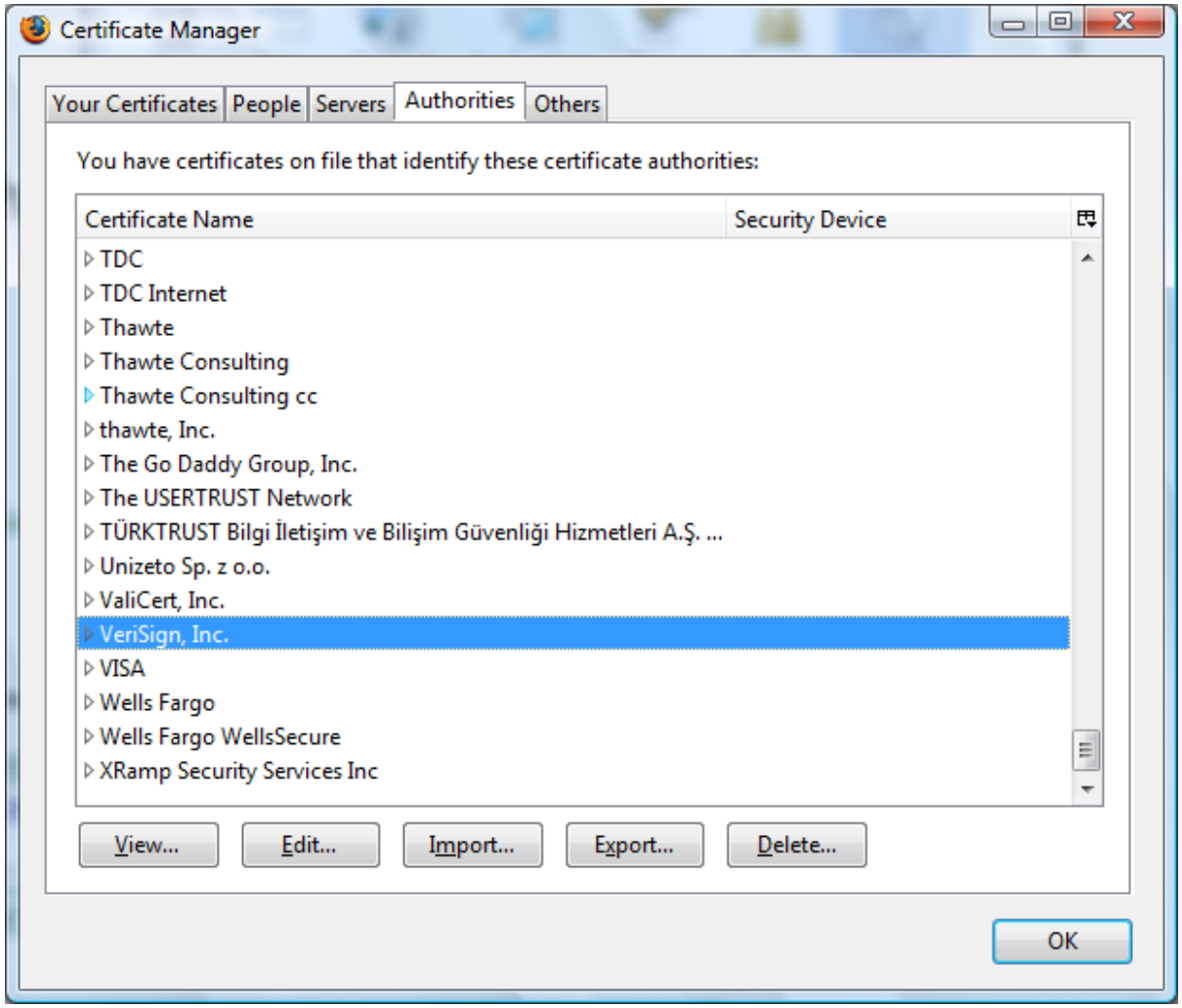


Whose public key is used to establish the secure session?

Distribution of Public Keys

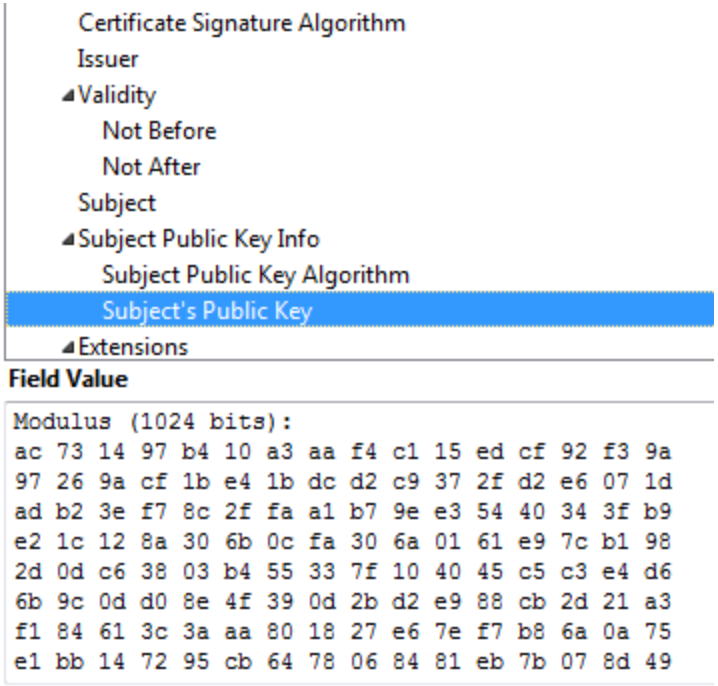
- Public announcement or public directory
  - Risks: forgery and tampering
- Public-key certificate
  - Signed statement specifying the key and identity
    - sig_{Alice}(“Bob”, PK_B)
- Common approach: certificate authority (CA)
  - An agency responsible for certifying public keys
  - Browsers are pre-configured with 100+ of trusted CAs
  - A public key for any website in the world will be accepted by the browser if certified by one of these CAs

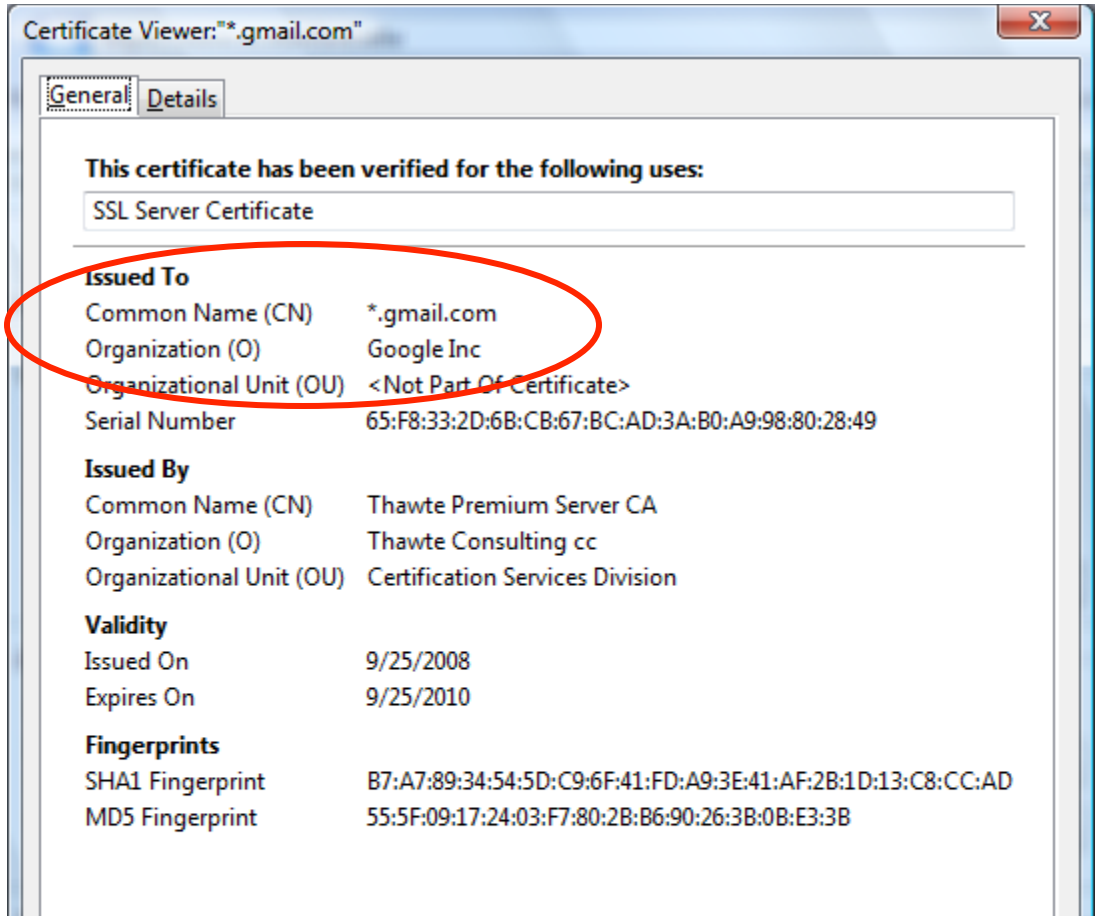
Trusted Certificate Authorities



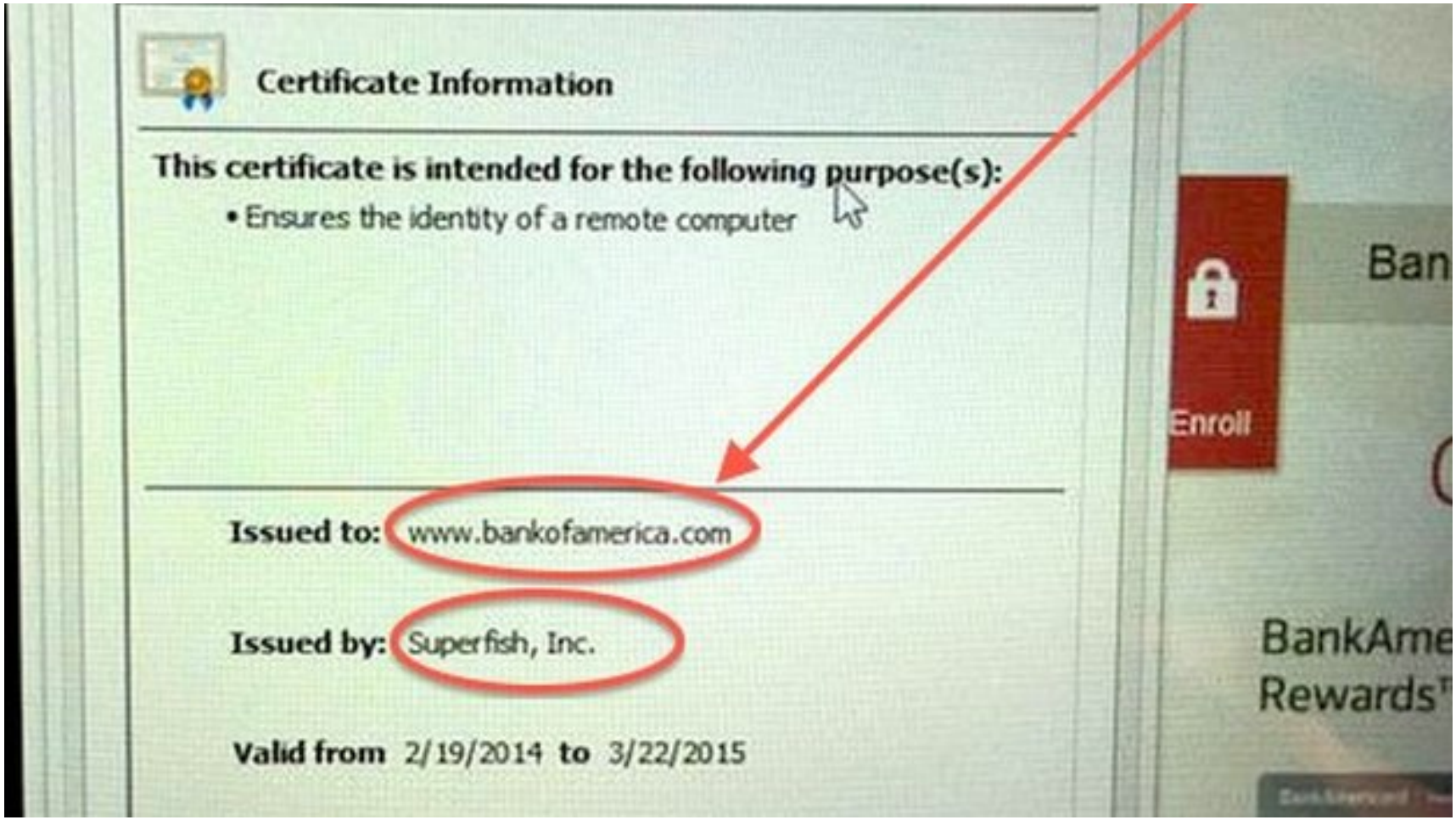
Example of a Certificate

Important fields





Another Example of a Certificate



Root Certificates in Lenovo

In the news

Lenovo hit by lawsuit over Superfish adware
CNET - 3 days ago
Sarah Tew/CNET. **Lenovo** may find itself in a courtroom over its **Superfish adware** fiasco.

Interview with Lenovo's CTO will scare anyone still thinking of buying a Lenovo product
BGR - 2 days ago

Lenovo's Chief Technology Officer Discusses the Superfish Adware Fiasco - NYTimes.com
Bits - The New York Times - 3 days ago

More news for lenovo superfish adware

Lenovo Sued Over Superfish Adware : NPR
www.npr.org › News › Business NPR
2 days ago - Renee Montagne talks to Jordan Robertson of Bloomberg News about computer maker **Lenovo**, which allowed controversial spyware to be ...

Lenovo users lawyer up over hole-filled, HTTPS-breaking ...
arstechnica.com/.../**lenovo**-users-lawyer-up-over-hole-filled... Ars Technica
4 days ago - In the wake of last week's **Lenovo's Superfish** debacle, at least one ... and that **Superfish adware** "does not present a security risk," despite ...

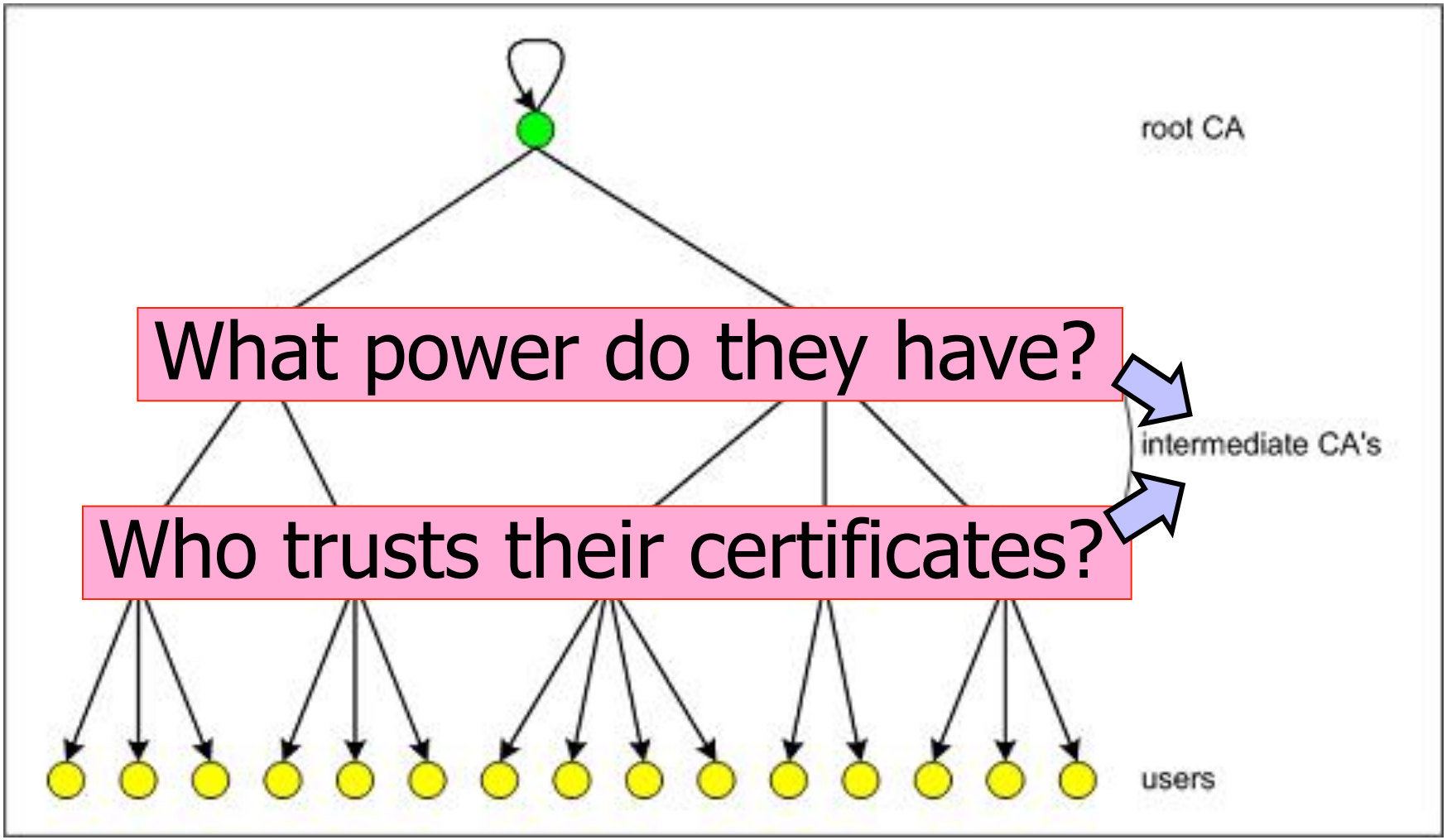
Lenovo's Chief Technology Officer Discusses the Superfish ...
bits.blogs.nytimes.com/.../**lenovos**-chief-technology-officer-discusses-the...
3 days ago - The **adware** was intended to serve **Lenovo** users targeted ads, but the company **Lenovo** partnered with to do this, **Superfish**, did so by hijacking ...

Lenovo Sued Over Superfish Adware | News & Opinion ...
www.pcmag.com › Reviews › Software › Security PC Magazine
4 days ago - Not surprisingly, the controversy over **Lenovo** installing **Superfish adware** into its consumer PCs has resulted in a lawsuit. According to the suit, ...

CA Hierarchy

- Browsers, operating systems, etc. have trusted root certificate authorities
  - My Chrome includes certificates of 195 trusted root CAs
- A Root CA signs certificates for intermediate CAs, they sign certificates for lower-level CAs, etc.
  - Certificate "chain of trust"
    - $sig_{Verisign}$("Cornell", $PK_{Cornell}$), $sig_{Cornell}$("Vitaly S.", PK_{Vitaly})
- CA is responsible for verifying the identities of certificate requestors, domain ownership

Certificate Hierarchy



Common Name

- Explicit name: www.foo.com
- Wildcard: *.foo.com or www*.foo.com
- Matching rules
  - Firefox: * matches anything
  - Internet Explorer: * must occur in the leftmost component, does not match '.'
    - *.foo.com matches a.foo.com, but not a.b.foo.com

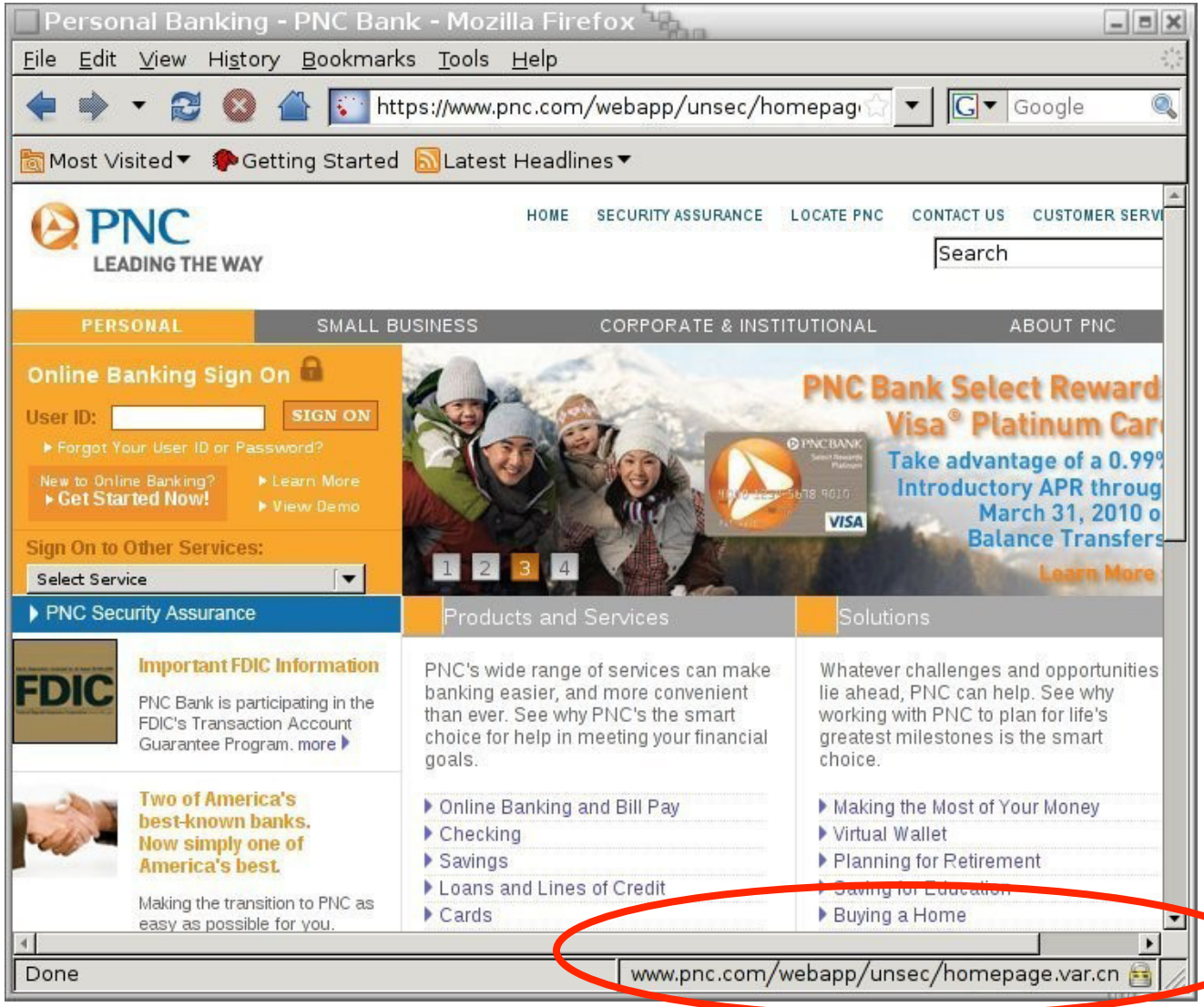
International Domain Names

- Rendered using international character set
- Chinese character set contains characters that look like / ? = .
  - What could go wrong?
- Can buy a certificate for *.foo.cn, create any number of domain names that look like

  www.bank.com/accounts/login.php?q=me.foo.cn
  - What does the user see?
  - *.foo.cn certificate works for all of them!

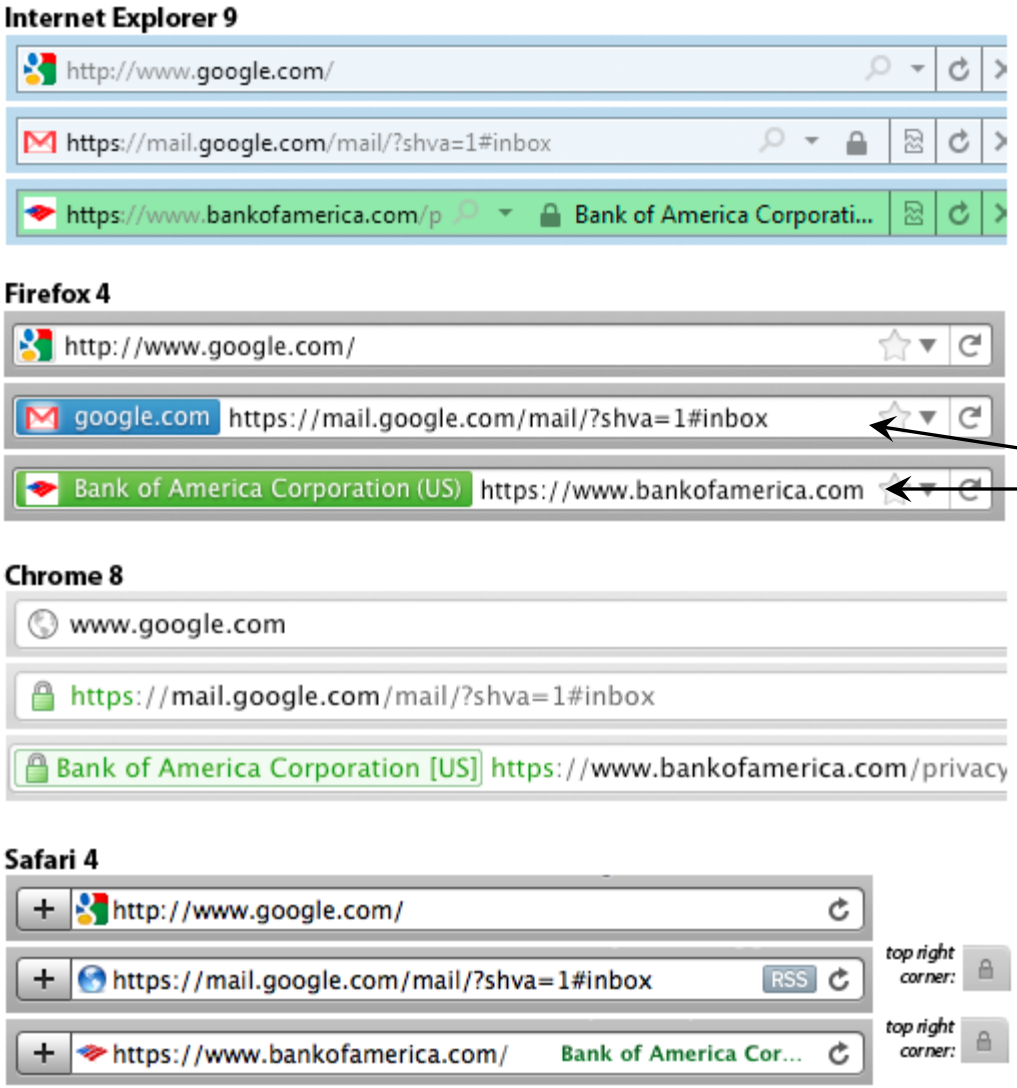
Example

[Moxie Marlinspike]



Meaning of Color

[Schultze]



What is the difference?

Domain Validation (DV) certificate

vs.

Extended Validation (EV) certificate

Means what?

Mobile Browsing

[Schultze]

Same lock for DV and EV

Windows Phone 7: same behavior

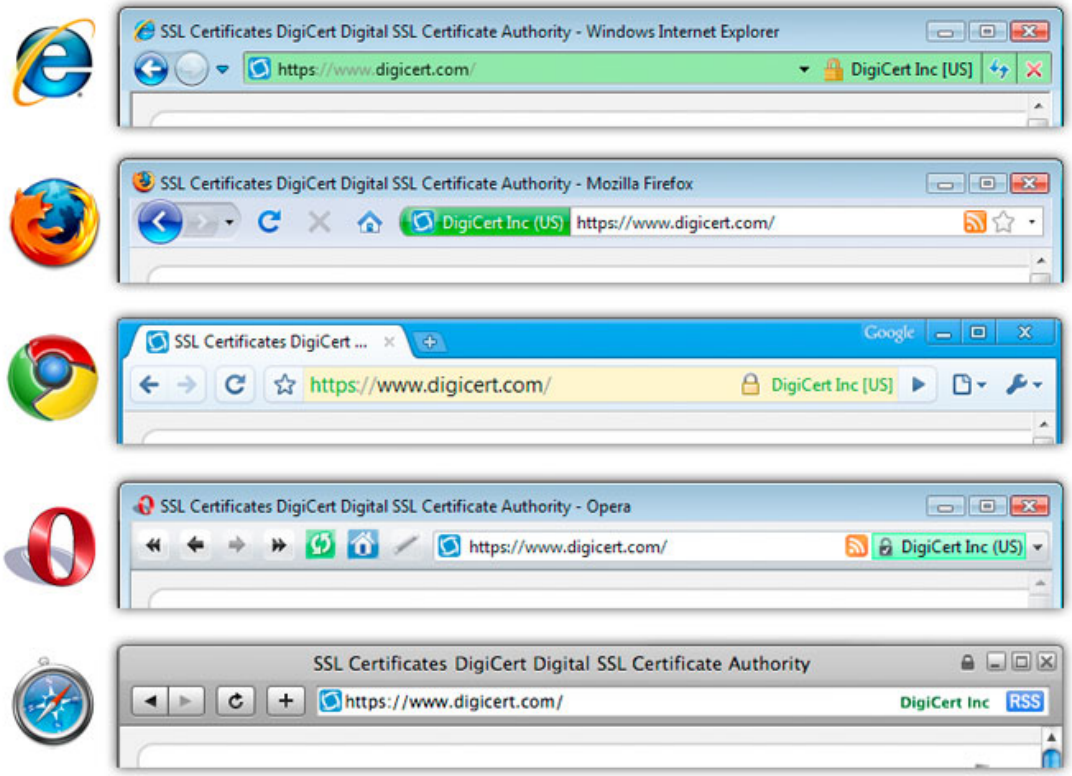
… but only when URL bar present

… landscape mode: no URL bar

http://www.freedom-to-tinker.com/blog/sjs/web-browser-security-user-interfaces-hard-get-right-and-increasingly-inconsistent

Extended Validation (EV) Certificates

- Certificate request must be approved by a human lawyer at the certificate authority



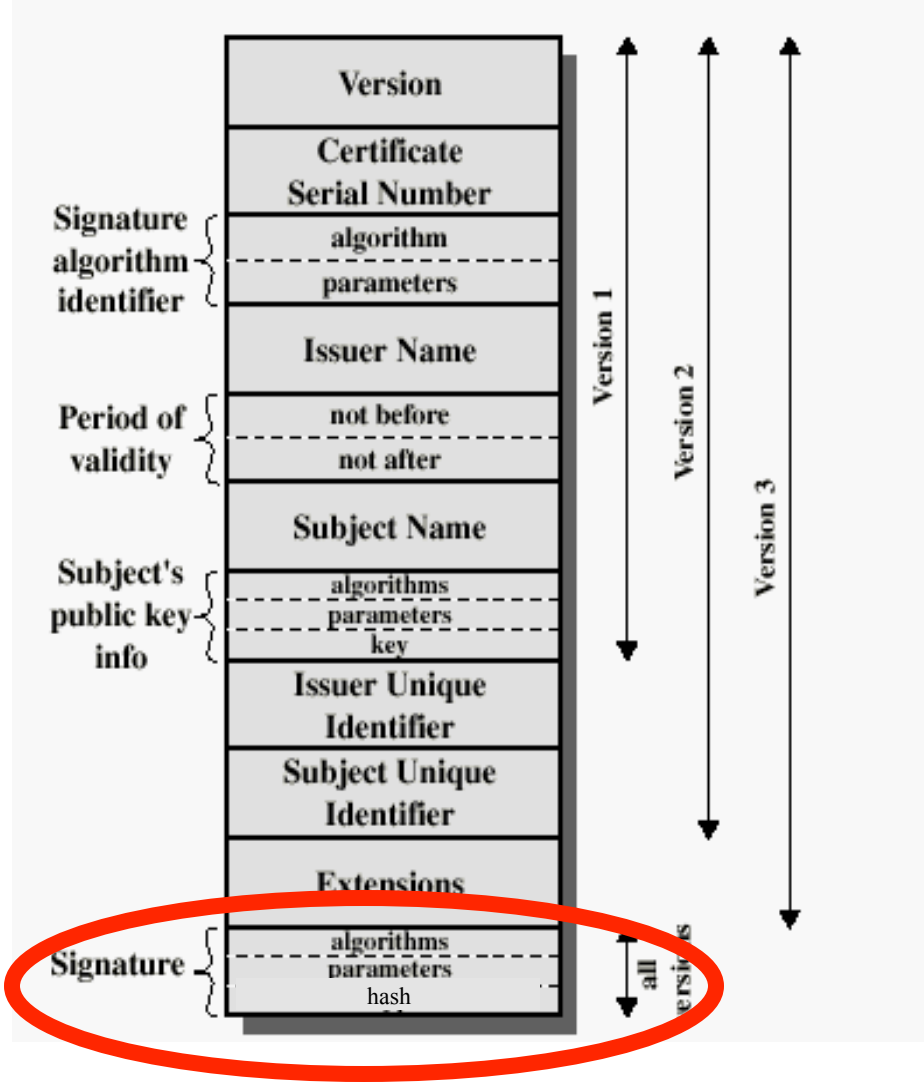
Questions about EV Certificates

- What does EV certificate mean?
- What is the difference between an HTTPS connection that uses a regular certificate and an HTTPS connection that uses an EV certificate?
- If an attacker has somehow obtained a non-EV certificate for bank.com, can he inject a script into https://bank.com content?
  - What is the origin of the script? Can it access or modify content that arrived from actual bank.com via HTTPS?
- What would the browser show – blue or green?

X.509 Authentication Service

- Internet standard (1988-2000)
- Specifies certificate format
  - X.509 certificates are used in IPsec and SSL/TLS
- Specifies certificate directory service
  - For retrieving other users' CA-certified public keys
- Specifies a set of authentication protocols
  - For proving identity using public-key signatures
- Can use with any digital signature scheme and hash function, but must hash before signing

X.509 Certificate



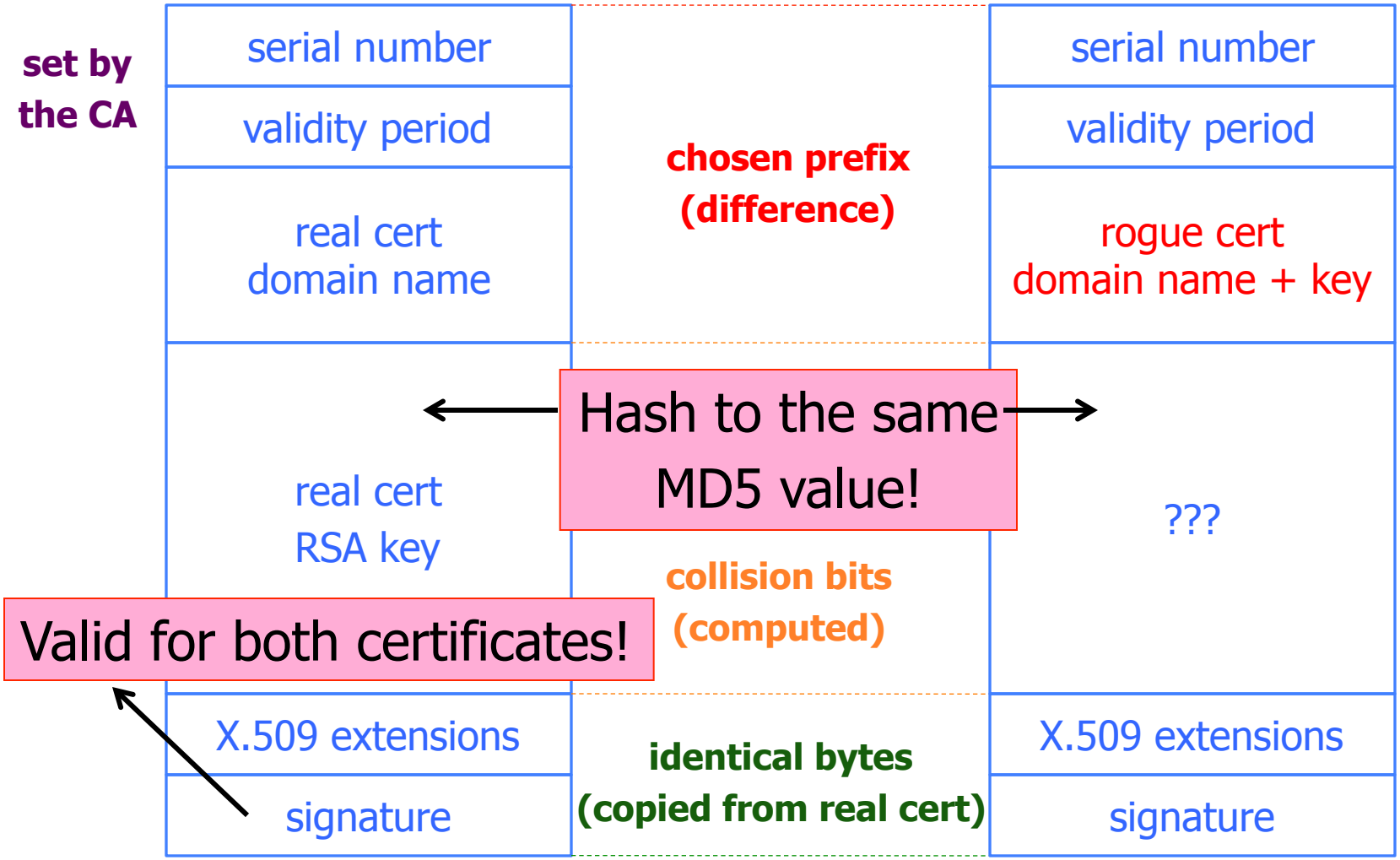
Back in 2008

[Sotirov et al. “MD5 Considered Harmful Today: Creating a Rogue CA Certificate”]

- Many CAs still used MD5
  - RapidSSL, FreeSSL, TrustCenter, RSA Data Security, Thawte, verisign.co.jp
- Sotirov et al. collected 30,000 website certificates
- 9,000 of them were signed using MD5 hash
- 97% of those were issued by RapidSSL

Colliding Certificates

[Sotirov et al.]



Generating Collisions Back in '08

[Sotirov et al.]

1-2 days on a cluster of 200 PlayStation 3s

Equivalent to 8000 desktop CPU cores or $20,000 on Amazon EC2

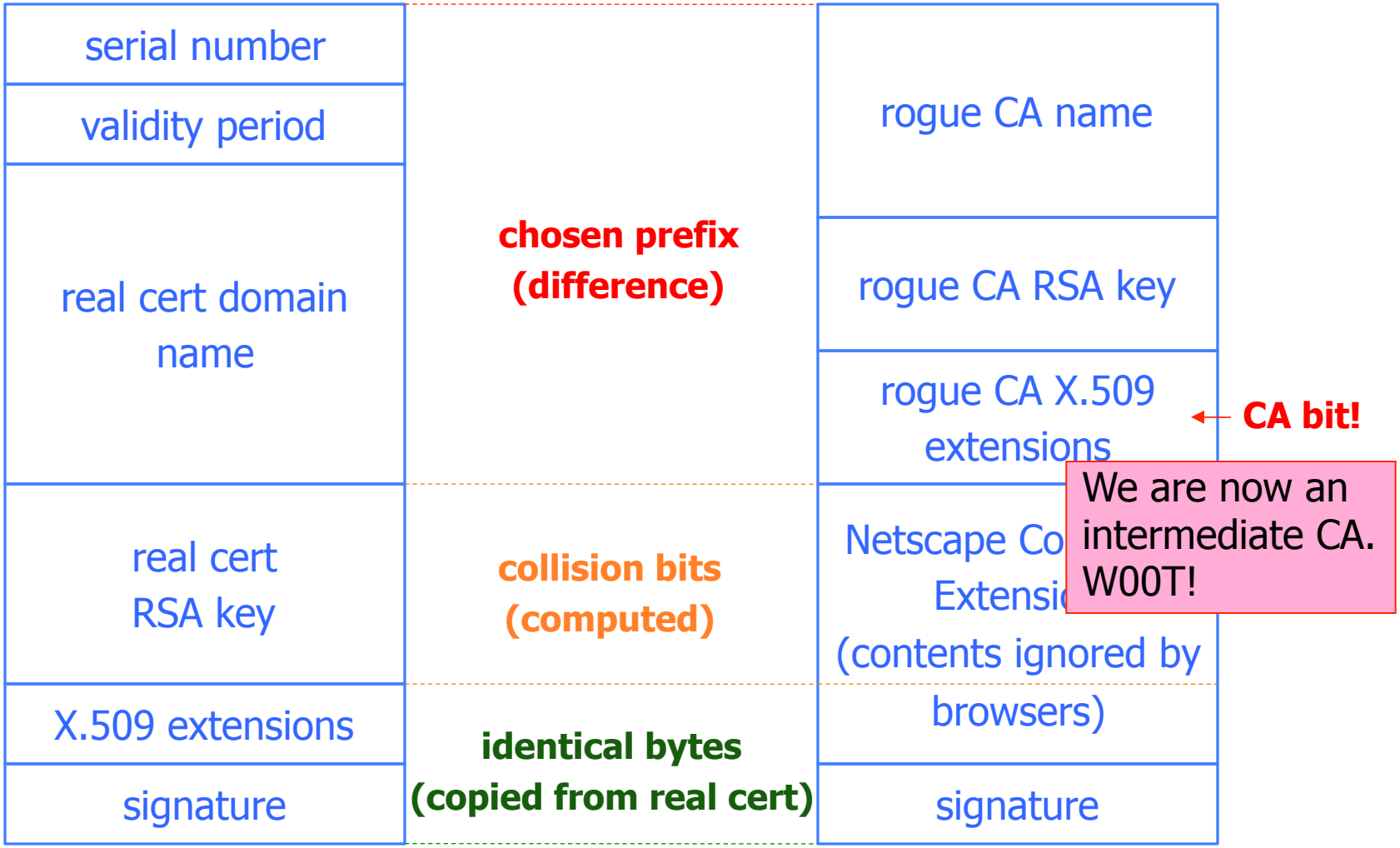
Generating Colliding Certificates

[Sotirov et al.]

- RapidSSL uses a fully automated system
  - $69 for a certificate, issued in 6 seconds
  - Sequential serial numbers
- Technique for generating colliding certificates
  - Get a certificate with serial number S
  - Predict time T when RapidSSL's counter goes to S+1000
  - Generate the collision part of the certificate
  - Shortly before time T buy enough (non-colliding) certificates to increment the counter to S+999
  - Send colliding request at time T and get serial number S+1000

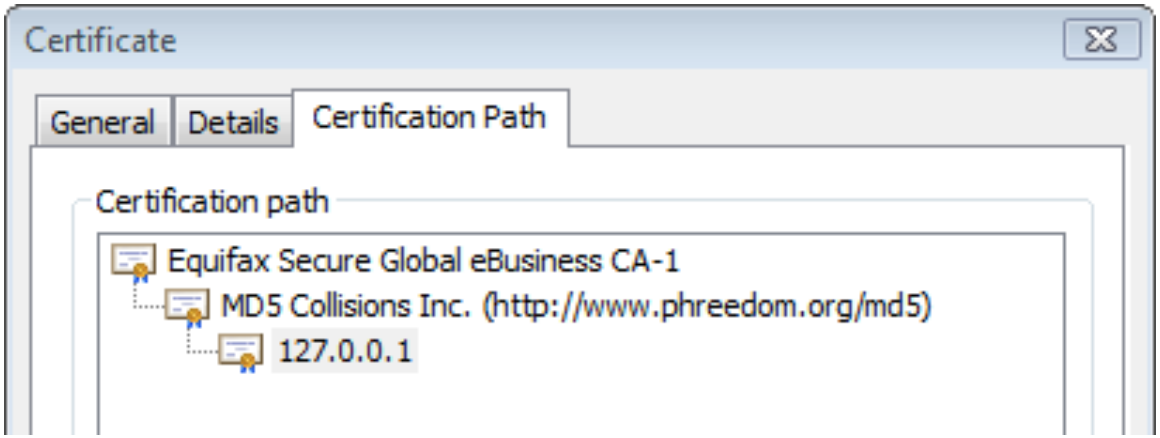
Creating a Fake Intermediate CA

[Sotirov et al.]



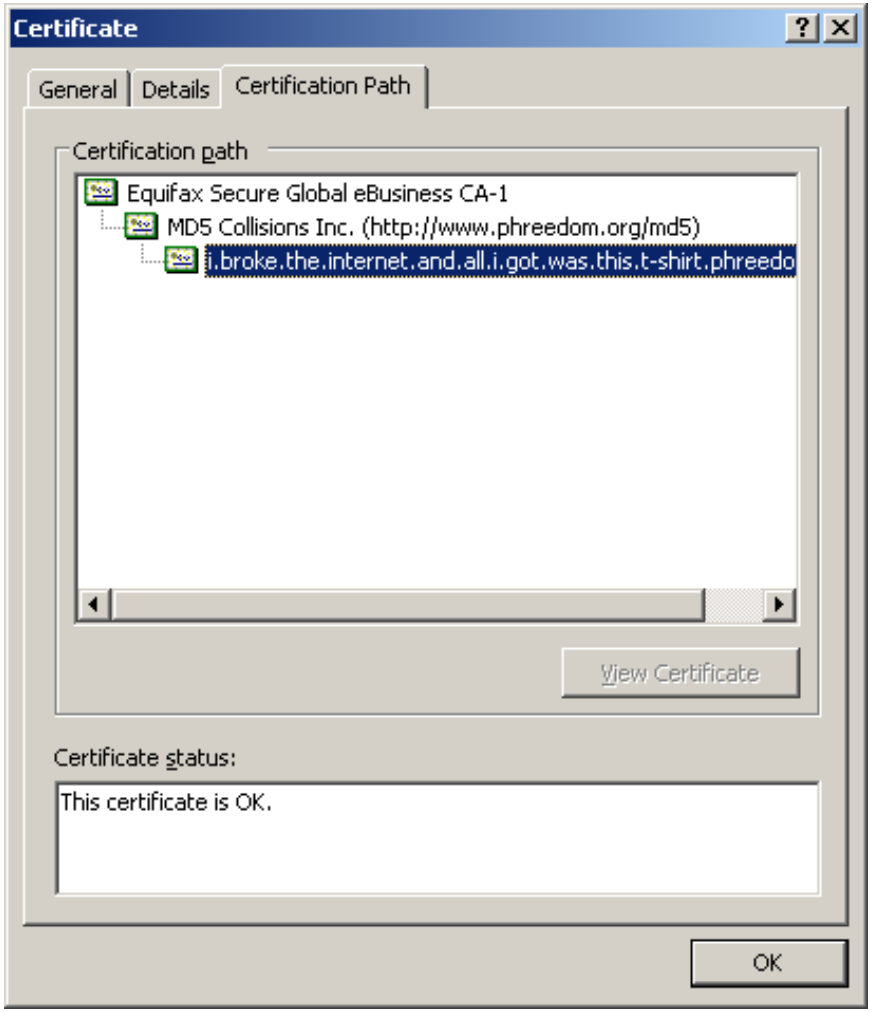
Result: Perfect Man-in-the-Middle

- This is a "skeleton key" certificate: it can issue fully trusted certificates for any site (why?)



- To take advantage, need a network attack
  - Insecure wireless, DNS poisoning, proxy auto-discovery, hacked routers, etc.

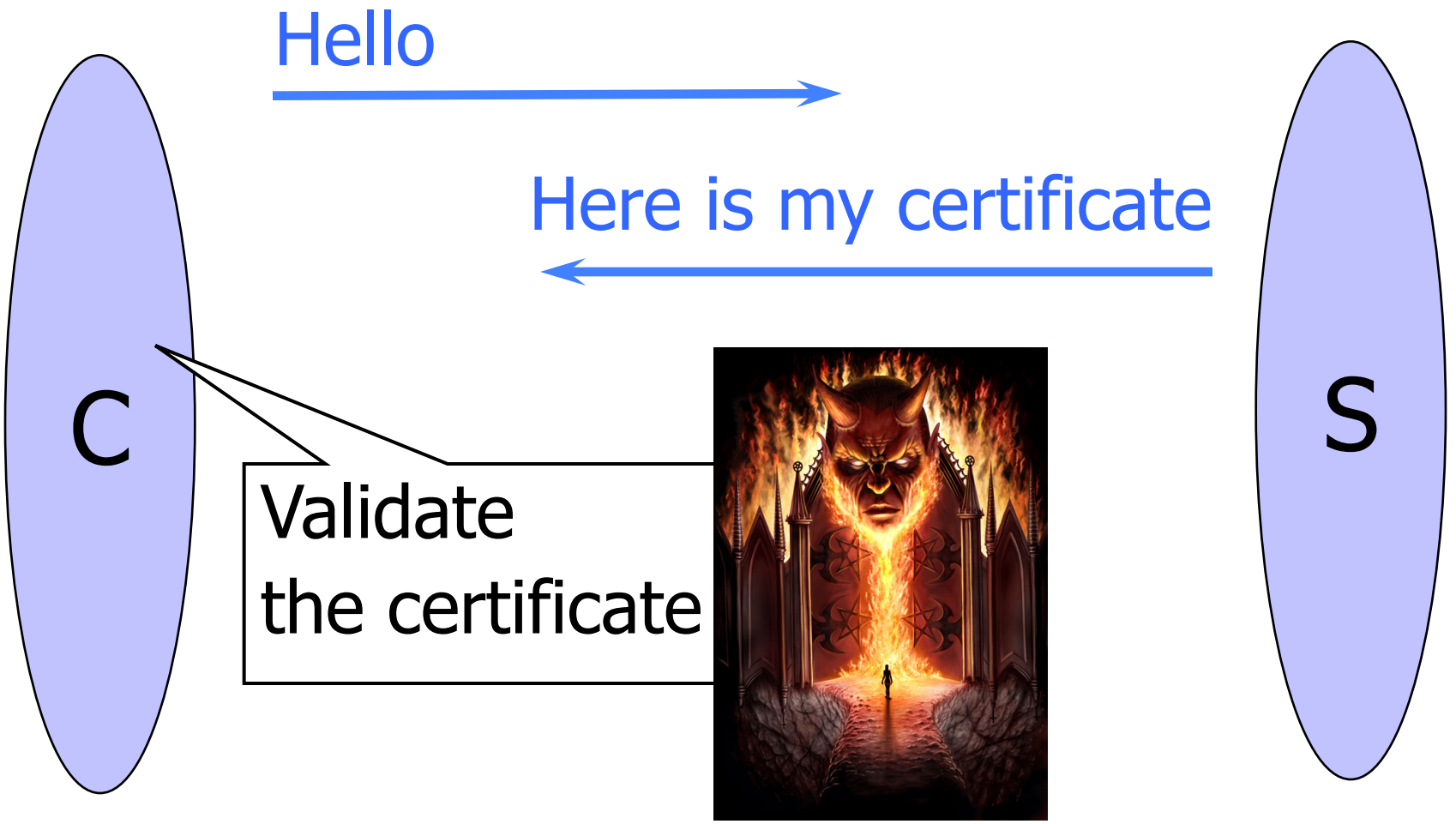
A Rogue Certificate



Flame

- Cyber-espionage virus (2010-2012)
- Signed with a fake intermediate CA certificate accepted by any Windows Update service
  - Fake intermediate CA certificate was created using an MD5 chosen-prefix collision against an obscure Microsoft Terminal Server Licensing Service certificate that was enabled for code signing and still used MD5
- MD5 collision technique possibly pre-dates Sotirov et al.'s work
  - Evidence of state-level cryptanalysis?

SSL/TLS Handshake



SSL/TLS Handshake

Hello

I am Chase.com
Here is my certificate

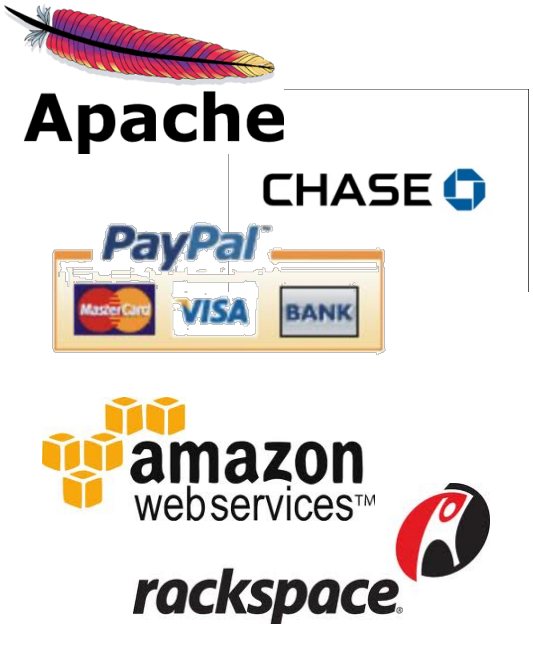
Issued by GoDaddy to
AllYourSSLAreBelongTo.us

CHASE

Android app

Ok!

Failing to Check Hostname



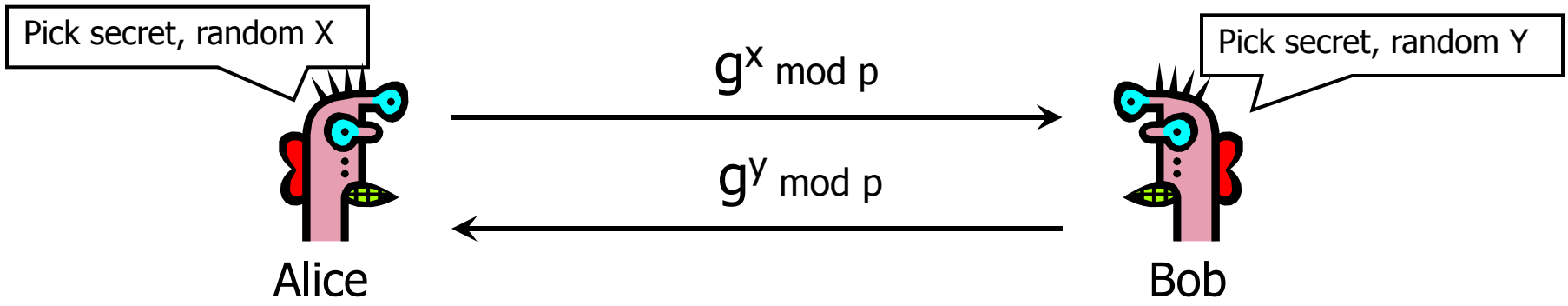
"Researchers at the University of Texas at Austin and Stanford University have discovered that poorly designed APIs used in SSL implementations are to blame for vulnerabilities in many critical non-browser software packages. Serious security vulnerabilities were found in programs such as Amazon's EC2 Java library, Amazon's and PayPal's merchant SDKs, Trillian and AIM instant messaging software, popular integrated shopping cart software packages, Chase mobile banking software, and several Android applications and libraries. SSL connections from these programs and many others are vulnerable to a man in the middle attack..."

- Threatpost (Oct 2012)

Major payment processing gateways, client software for cloud computing, integrated e-commerce software, etc.

Diffie-Hellman Key Establishment

- Alice and Bob never met and share no secrets
- Public information: p and g, where p is a large prime number, g is a generator of Z^*_p
  - $Z^*_p=\{1, 2 \ldots p-1\}$; $\forall a \in Z^*_p \; \exists i$ such that $a=g^i \bmod p$



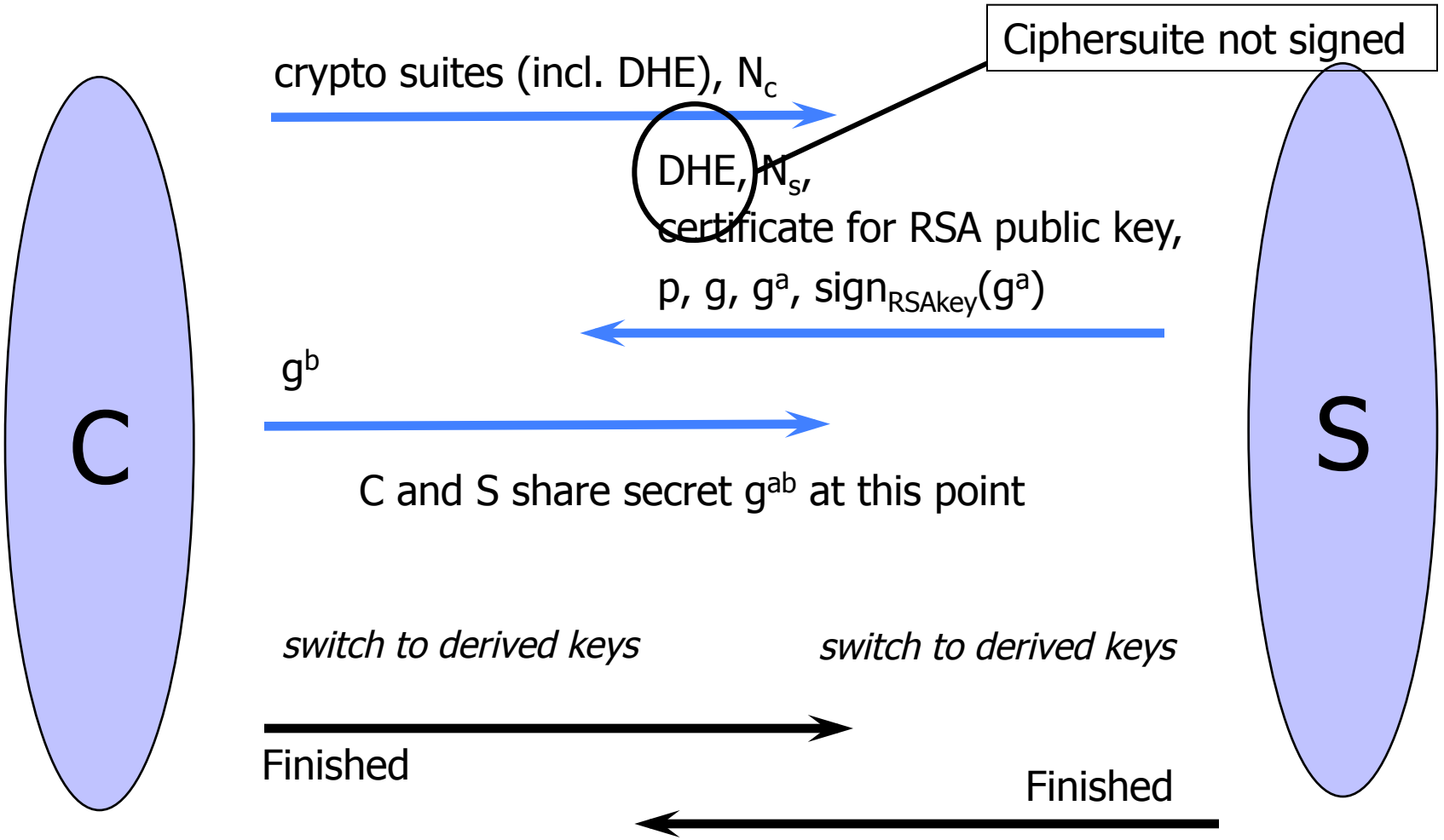
Compute $k=(g^y)^x=g^{xy} \bmod p$

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

Security of Diffie-Hellman Protocol

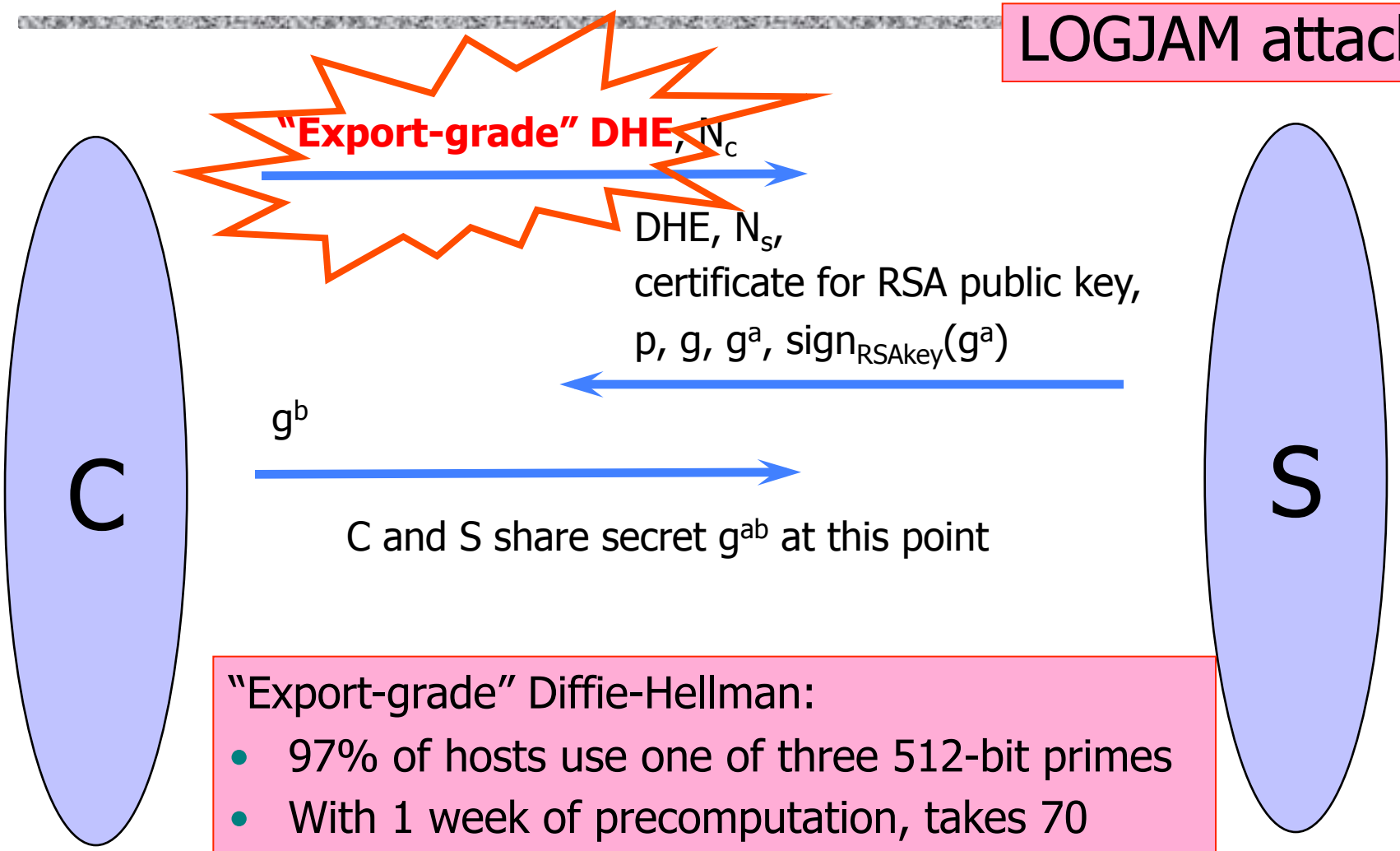
- Under certain cryptographic assumptions, Diffie-Hellman protocol is a secure key establishment protocol against passive attackers
  - Eavesdropper can't tell the difference between the new key and a random value
- Basic Diffie-Hellman protocol is not secure against an active, man-in-the-middle attacker
  - Need signatures or another authentication mechanism

TLS/SSL with Diffie-Hellman



DH Downgrade by MITM

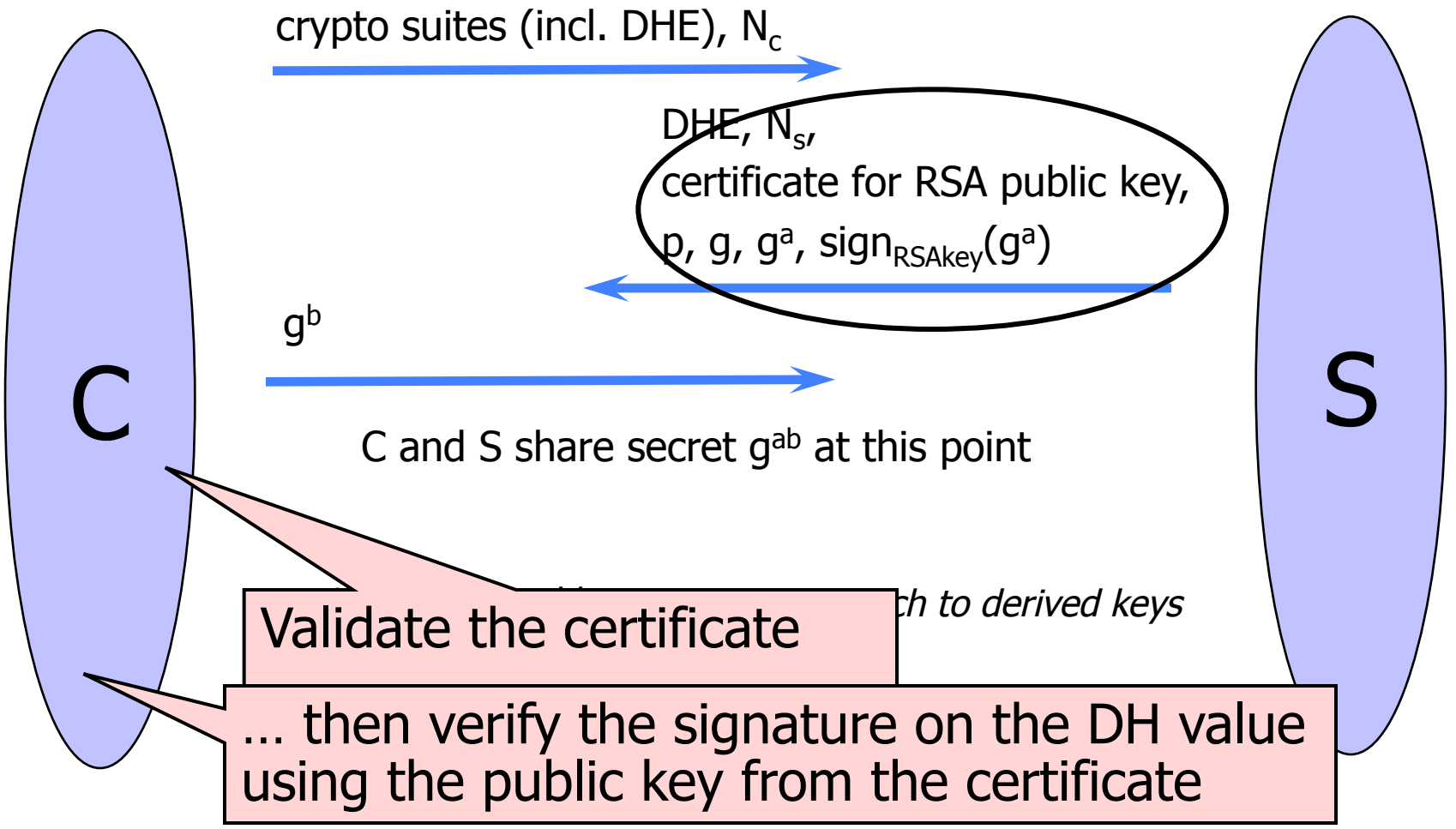
LOGJAM attack



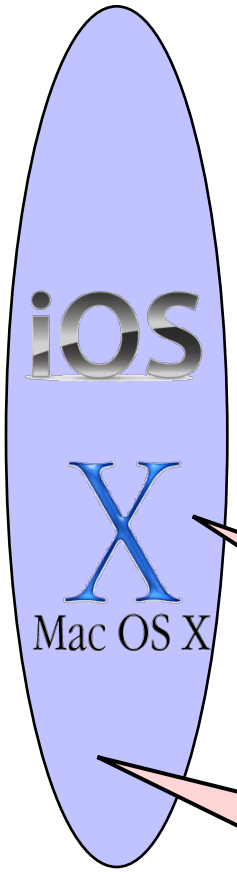
"Export-grade" Diffie-Hellman:

- 97% of hosts use one of three 512-bit primes
- With 1 week of precomputation, takes 70 seconds of real time to compute discrete log

More Fun With Diffie-Hellman



MITM Presenting Valid Certificate



Hello

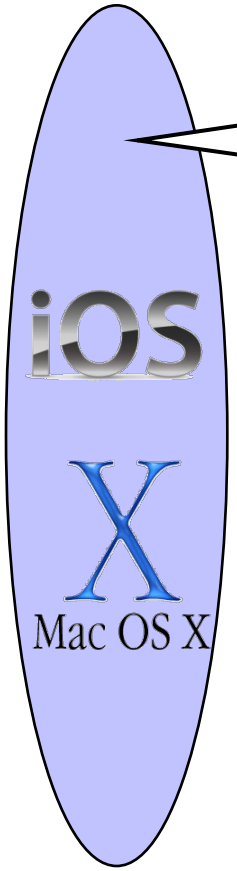
I am PayPal.com
(or whoever you want me to be)
Here is PayPal's certificate for
its RSA signing key
And here is my signed Diffie-Hellman value

Validate the certificate

… then verify the signature on the DH value using the public key from the certificate

Goto Fail

Here is PayPal's certificate
And here is my signed Diffie-Hellman value



… verify the signature on the DH value using the public key from the certificate

```
if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
   goto fail;
if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
   goto fail;
if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
    goto fail;
    goto fail;
if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
    goto fail; …
err = sslRawVerify(...);
…
fail: … return err …
```

???

Signature is verified here

Complete Fail Against MITM

- Discovered in February 2014
- All OS X and iOS software vulnerable to man-in-the-middle attacks
  - Broken TLS implementation provides no protection against the very attack it was supposed to prevent
- What does this tell you about quality control for security-critical software?

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 his certification fee to the CA and the CA no longer wishes to certify him
  - CA 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

- Online revocation service
  - When a certificate is presented, recipient goes to a special online service to verify whether it is still valid
- Certificate revocation list (CRL)
  - CA periodically issues a signed list of revoked certificates
  - Can issue a "delta CRL" containing only updates

Q: Does revocation protect against forged certificates?

Comodo

COMODO
Creating Trust Online®

- Comodo is one of the trusted root CAs
  - Its certificates for any website in the world are accepted by every browser
- Comodo accepts certificate orders submitted through resellers
  - Reseller uses a program to authenticate to Comodo and submit an order with a domain name and public key, Comodo automatically issues a certificate for this site

Comodo Break-In

COMODO
Creating Trust Online®

- An Iranian hacker broke into instantSSL.it and globalTrust.it resellers, decompiled their certificate issuance program, learned the credentials of their reseller account and how to use Comodo API
  - username: gtadmin, password: globaltrust
- Wrote his own program for submitting orders and obtaining Comodo certificates
- On March 15, 2011, got Comodo to issue 9 rogue certificates for popular sites
  - mail.google.com, login.live.com, login.yahoo.com, login.skype.com, addons.mozilla.org, “global trustee"

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

Q: Does HTTPS help? How about EV certificates?

Message from the Attacker

http://pastebin.com/74KXCaEZ

I'm single hacker with experience of 1000 hacker, I'm single programmer with experience of 1000 programmer, I'm single planner/project manager with experience of 1000 project managers …

When USA and Isarel could read my emails in Yahoo, Hotmail, Skype, Gmail, etc. without any simple little problem, when they can spy using Echelon, I can do anything I can. It's a simple rule. You do, I do, that's all. You stop, I stop. It's rule #1 …

Rule#2: So why all the world got worried, internet shocked and all writers write about it, but nobody writes about Stuxnet anymore?... So nobody should write about SSL certificates.

Rule#3: I won't let anyone inside Iran, harm people of Iran, harm my country's Nuclear Scientists, harm my Leader (which nobody can), harm my President, as I live, you won't be able to do so. as I live, you don't have privacy in internet, you don't have security in digital world, just wait and see...

DigiNotar Break-In

- In June 2011, the same “ComodoHacker” broke into a Dutch certificate authority, DigiNotar
  - Message found in scripts used to generate fake certificates:

    “THERE IS NO ANY HARDWARE OR SOFTWARE IN THIS WORLD EXISTS WHICH COULD STOP MY HEAVY ATTACKS MY BRAIN OR MY SKILLS OR MY WILL OR MY EXPERTISE"
- Security of DigiNotar servers
  - All core certificate servers in a single Windows domain, controlled by a single admin password (Pr0d@dm1n)
  - Software on public-facing servers out of date, unpatched
  - Tools used in the attack would have been easily detected by an antivirus… if it had been present

Consequences of DigiNotar Hack

- Break-in not detected for a month
- Rogue certificates issued for *.google.com, Skype, Facebook, www.cia.gov, and 527 other domains
- 99% of revocation lookups for these certificates originated from Iran
  - Evidence that rogue certificates were being used, most likely by Iranian government or Iranian ISPs to intercept encrypted communications
    - Textbook man-in-the-middle attack
  - 300,000 users were served rogue certificates

Another Message from the Attacker

http://pastebin.com/u/ComodoHacker

Most sophisticated hack of all time … I'm really sharp, powerful, dangerous and smart!

My country should have control over Google, Skype, Yahoo, etc. […] I'm breaking all encryption algorithms and giving power to my country to control all of them.

You only heards Comodo (successfully issued 9 certs for me -thanks by the way-), DigiNotar (successfully generated 500+ code signing and SSL certs for me -thanks again-), StartCOM (got connection to HSM, was generating for twitter, google, etc. CEO was lucky enough, but I have ALL emails, database backups, customer data which I'll publish all via cryptome in near future), GlobalSign (I have access to their entire server, got DB backups, their linux / tar gzipped and downloaded, I even have private key of their OWN globalsign.com domain, hahahaa)… BUT YOU HAVE TO HEAR SO MUCH MORE! SO MUCH MORE! At least 3 more, AT LEAST!

TurkTrust

- 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 intercept and filter SSL traffic from its network
- This rogue *.google.com certificate was trusted by every browser in the world

TrustWave

- In Feb 2012, admitted issuing an intermediate CA certificate to a corporate customer
  - Purpose: “re-sign” certificates for “data loss prevention”
  - Translation: forge certificates of third-party sites in order to spy on employees’ encrypted communications with the outside world
- Customer can now forge certificates for any site in world… and they will be accepted by any browser!
  - What if a “re-signed” certificate leaks out?
- Do other CAs do this?

Komodia

- Israeli startup
- From their website: “Our advanced SSL hijacker SDK is a brand new technology that allows you to access data that was encrypted using SSL and perform on the fly SSL decryption.”
  - Installs its own root certificate
  - Goal: re-sign SSL certificates, proxy/MITM connections
- Same private key on all machines, easily extracted
  - Anyone can issue fake Komodia certificates, do man-in-the-middle attacks on any machine with Komodia

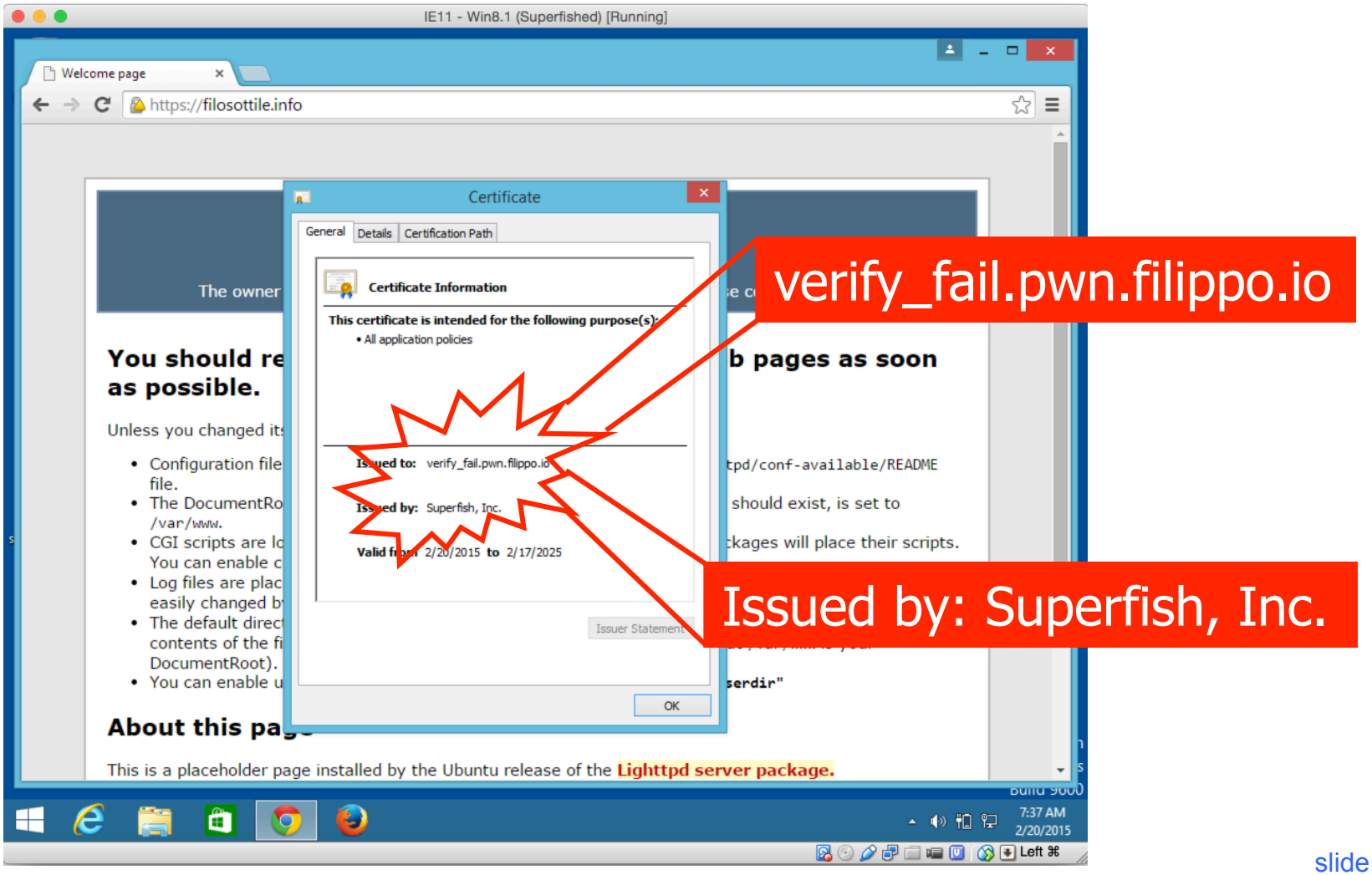
It Gets Worse

https://blog.filippo.io/komodia-superfish-ssl-validation-is-broken/

- What happens if a MITM attacker serves a self-signed certificate to a Komodia client?
- Komodia re-signs and turns it into a trusted certificate
  - But it will also change the name in the certificate, which won't match what the browser is expecting and user will see a warning - maybe not so bad
- But if attacker puts target domain into "alternate name" field, Komodia won't touch it and browser will think the certificate is completely valid

Complete SSL Fail

https://blog.filippo.io/komodia-superfish-ssl-validation-is-broken/



Software based on Komodia SDK

- Superfish
- CartCrunch Israel LTD
- WiredTools LTD
- Say Media Group LTD
- Over the Rainbow Tech
- System Alerts
- ArcadeGiant
- Objectify Media Inc
- Catalytix Web Services
- OptimizerMonitor

Statement from Superfish CEO

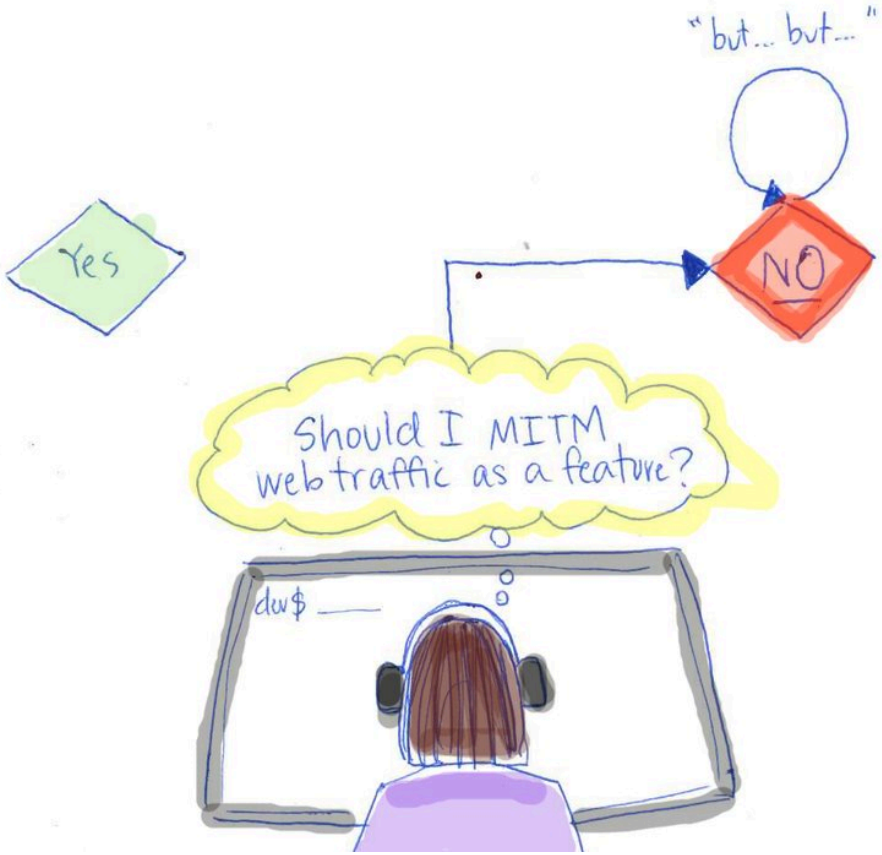
There has been significant misinformation circulating about Superfish software that was pre-installed on certain Lenovo laptops. The software shipped on a limited number of computers in 2014 in an effort to enhance the online shopping experience for Lenovo customers. Superfish's software utilizes visual search technology to help users achieve more relevant search results based on images of products they have browsed.

Despite the false and misleading statements made by some media commentators and bloggers, the Superfish software does not present a security risk. In no way does Superfish store personal data or share such data with anyone. Unfortunately, in this situation a vulnerability was introduced unintentionally by a 3rd party. Both Lenovo and Superfish did extensive testing of the solution but this issue wasn't identified before some laptops shipped. Fortunately, our partnership with Lenovo was limited in scale. We were able to address the issue quickly. The software was disabled on the server side (i.e., Superfish's search engine) in January 2015.

Not Just Komodia

- PrivDog
  - "Your privacy is under attack!"
- Provides "private Web browsing"
  - Translation: replaces ads on webpages with other ads from "trusted sources"
- Re-signs certificates to MITM SSL connections
- Accepts self-signed certificates and turns them into trusted certificates
- Founded by the CEO of Comodo CA

Just Say No



Credit: Adrienne Porter Felt (Google)