CS 6431

SSL/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

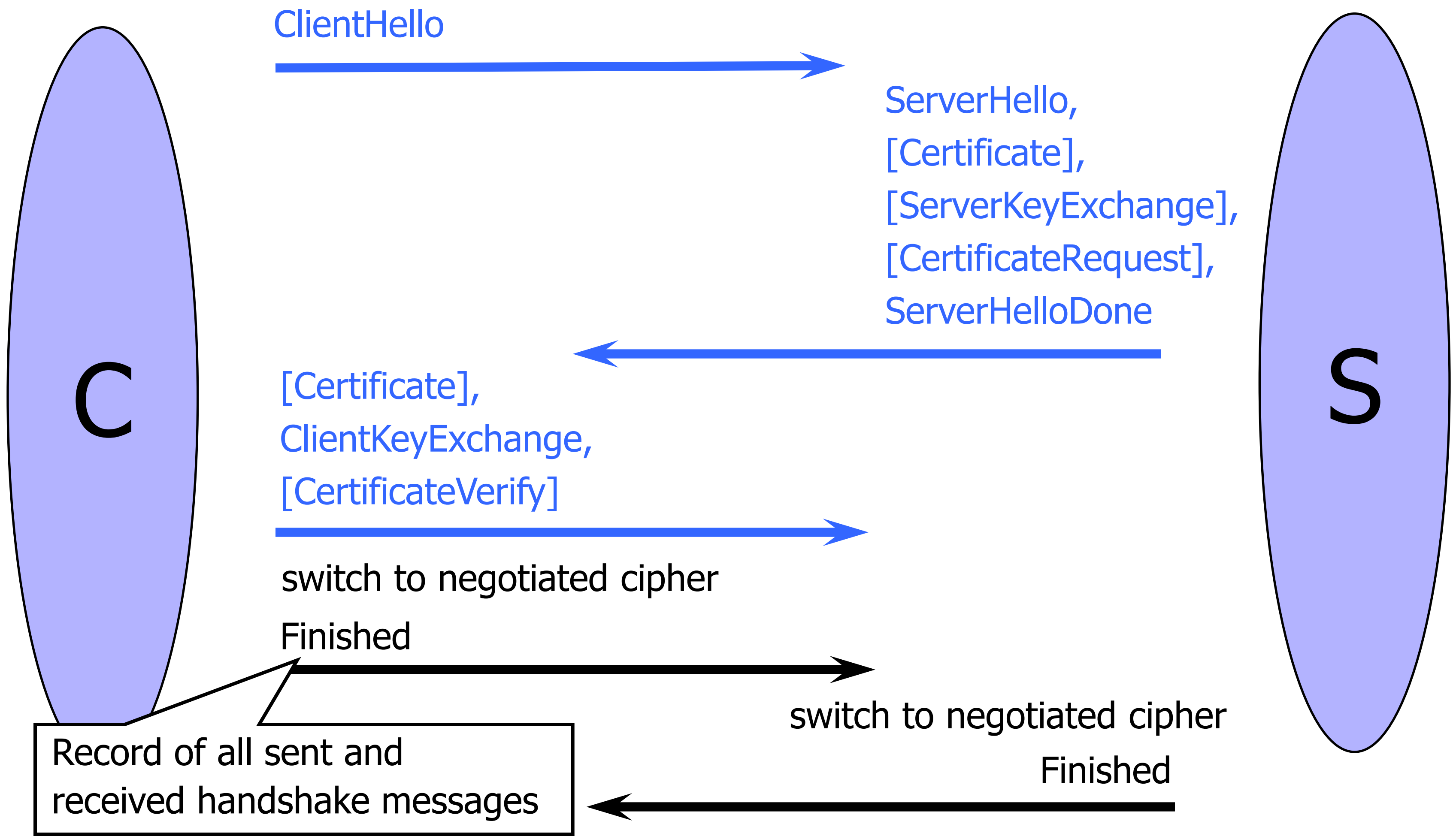
SSL Basics

- SSL consists of 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

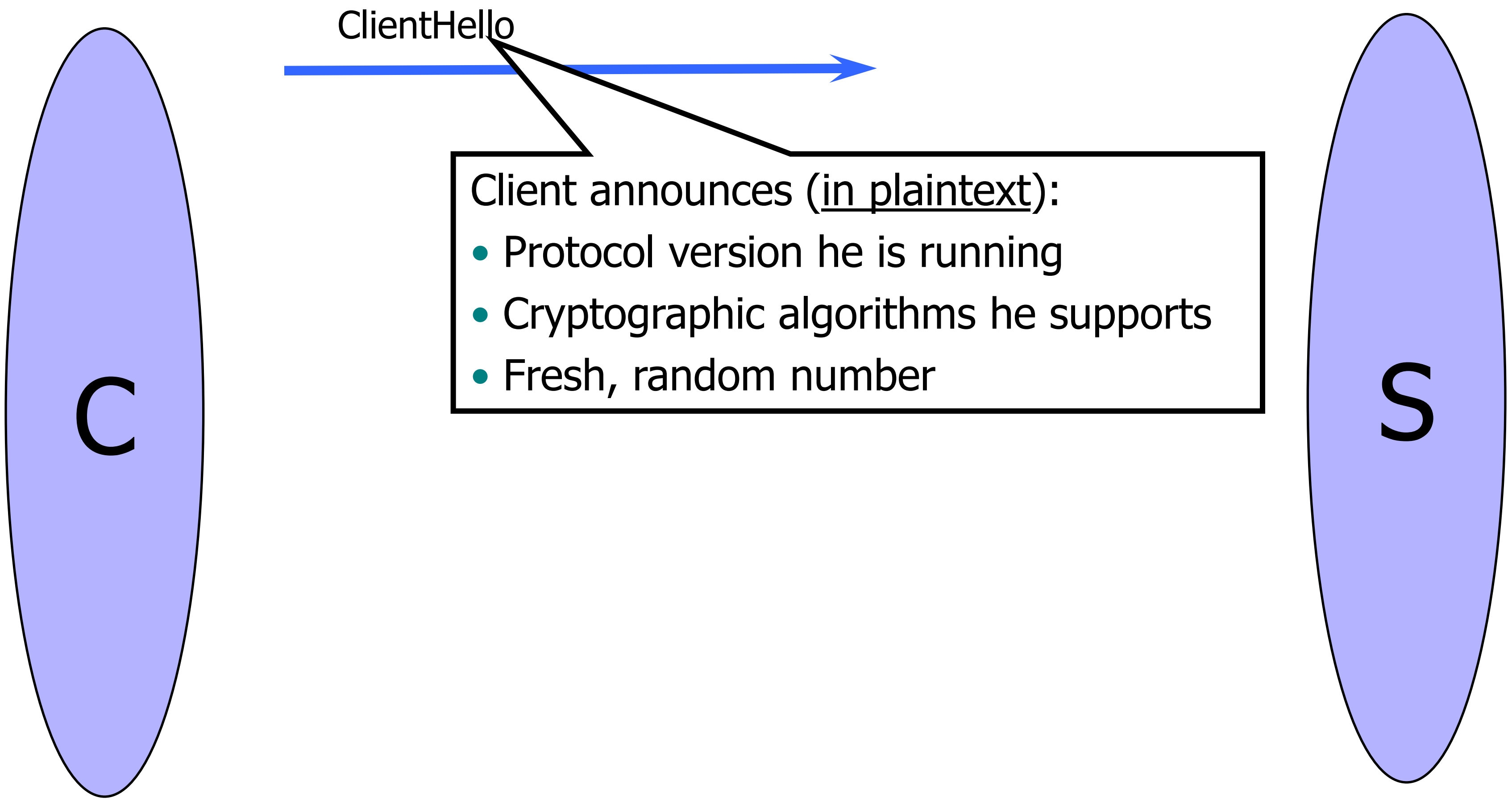
SSL Handshake Protocol

- 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

Handshake Protocol Structure



ClientHello



Client announces (in plaintext):

- Protocol version he is running
- Cryptographic algorithms he supports
- Fresh, random number

ClientHello (RFC)

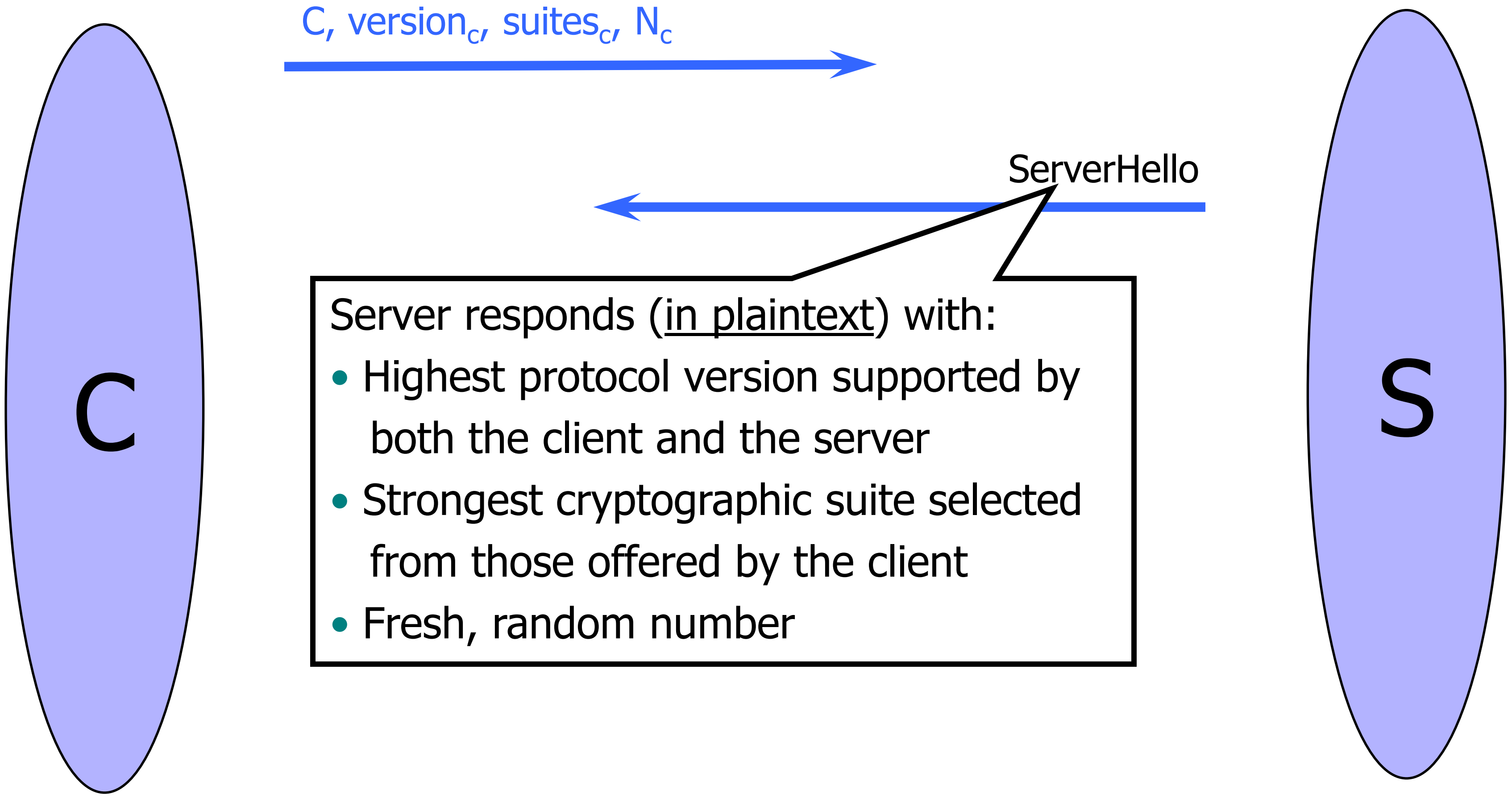
```
struct {
    ProtocolVersion client_version;
    Random random;
    SessionID session_id;
    CipherSuite cipher_suites;
    CompressionMethod compression_methods;
} ClientHello
```

Highest version of the protocol supported by the client

Session id (if the client wants to resume an old session)

Set of cryptographic algorithms supported by the client (e.g., RSA or Diffie-Hellman)

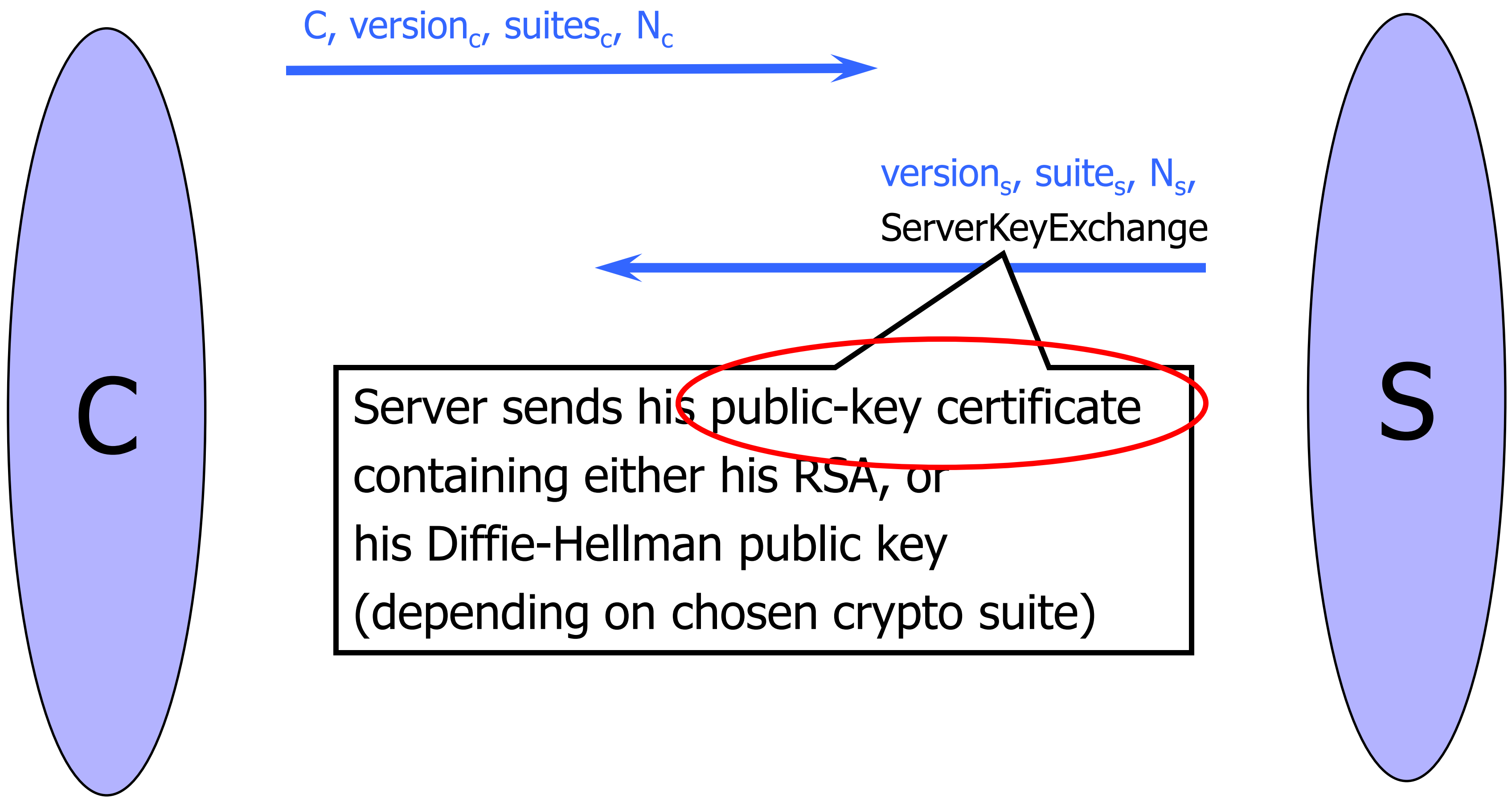
ServerHello



Server responds (<u>in plaintext</u>) with:

- Highest protocol version supported by both the client and the server
- Strongest cryptographic suite selected from those offered by the client
- Fresh, random number

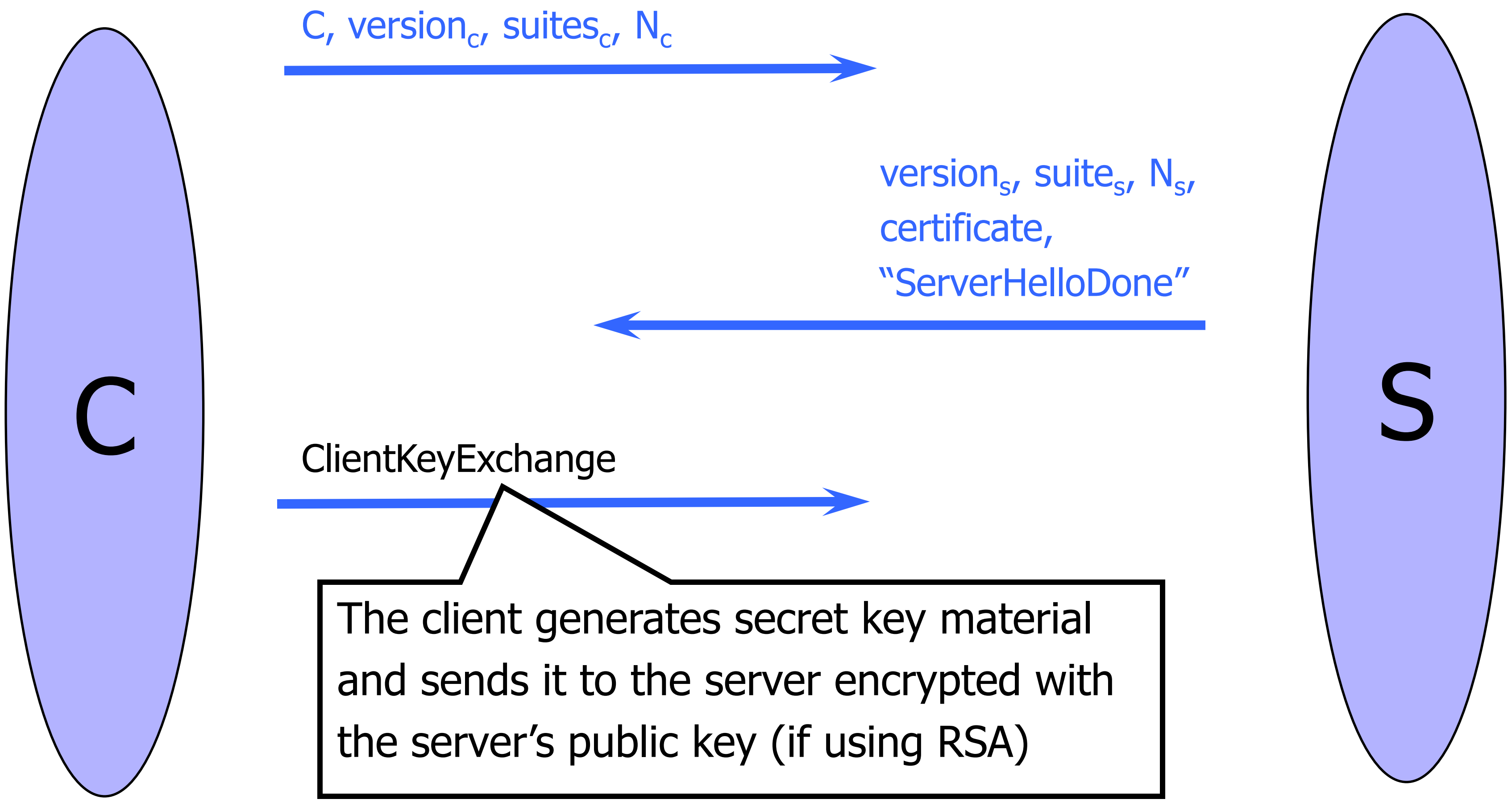
ServerKeyExchange



C
C, version_c, suites_c, N_c
version_s, suite_s, N_s,
ServerKeyExchange
S

Server sends his public-key certificate containing either his RSA, or his Diffie-Hellman public key (depending on chosen crypto suite)

ClientKeyExchange



C, version_c, suites_c, N_c
version_s, suite_s, N_s, certificate, “ServerHelloDone”
ClientKeyExchange
C
S

The client generates secret key material and sends it to the server encrypted with the server’s public key (if using RSA)

ClientKeyExchange (RFC)

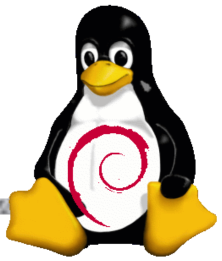
```
struct {
    select (KeyExchangeAlgorithm) {
        case rsa: EncryptedPreMasterSecret;
        case diffie_hellman: ClientDiffieHellmanPublic;
    } exchange_keys
} ClientKeyExchange

struct {
    ProtocolVersion client_version;
    opaque random[46];
} PreMasterSecret
```

Where do random bits come from?

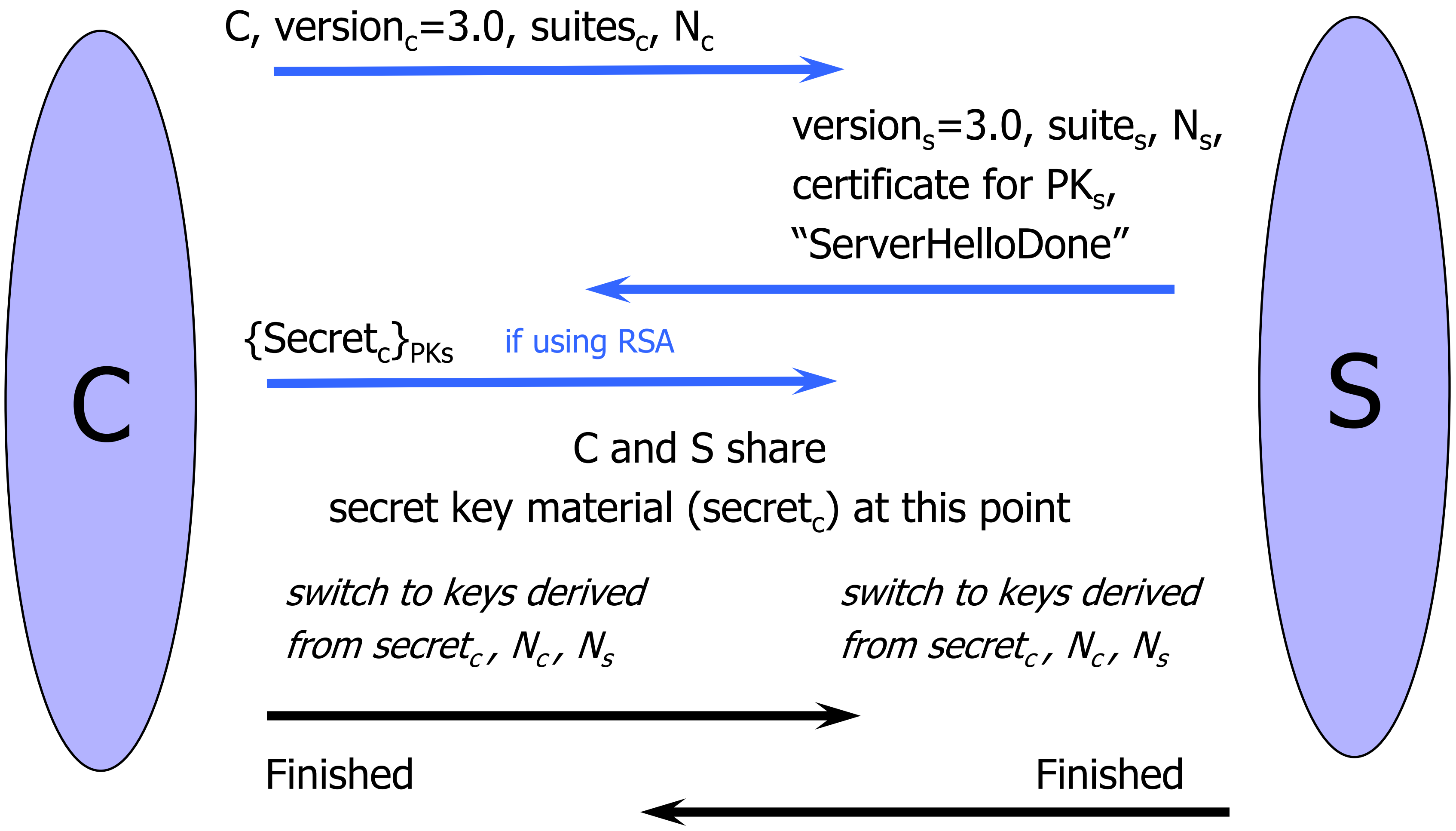
Random bits from which symmetric keys will be derived (by hashing them with nonces)

Debian Linux (2006-08)



- A line of code commented out from md_rand
  - MD_Update(&m,buf,j); /* purify complains */
- Without this line, the seed for the pseudo-random generator is derived only from process ID
  - Default maximum on Linux = 32768
- Result: all keys generated using Debian-based OpenSSL package in 2006-08 are predictable
  - "Affected keys include SSH keys, OpenVPN keys, DNSSEC keys, and key material for use in X.509 certificates and session keys used in SSL/TLS connections"

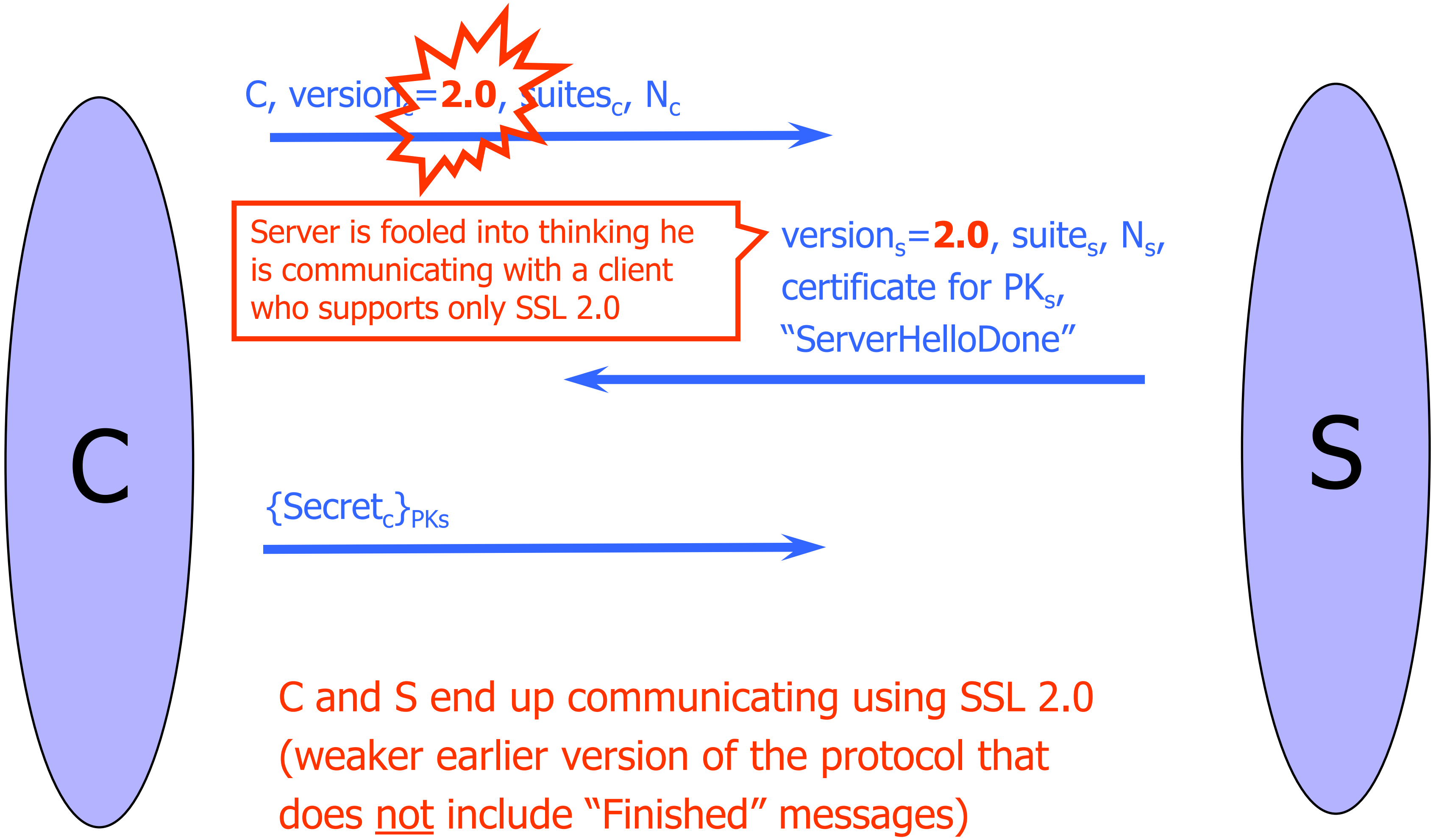
"Core" SSL Handshake


C, version$_c$=3.0, suites$_c$, N$_c$
version$_s$=3.0, suite$_s$, N$_s$,
certificate for PK$_s$,
"ServerHelloDone"
{Secret$_c$}$_{PKs}$
if using RSA
C and S share
secret key material (secret$_c$) at this point
switch to keys derived from secret$_c$, N$_c$, N$_s$
switch to keys derived from secret$_c$, N$_c$, N$_s$
Finished
Finished
C
S

SSL 2.0 Weaknesses (Fixed in 3.0)

- Cipher suite preferences are not authenticated
  - "Cipher suite rollback" attack is possible
- Weak MAC construction, MAC hash uses only 40 bits in export mode
- SSL 2.0 uses padding when computing MAC in block cipher modes, but padding length field is not authenticated
  - Attacker can delete bytes from the end of messages
- No support for certificate chains or non-RSA algorithms

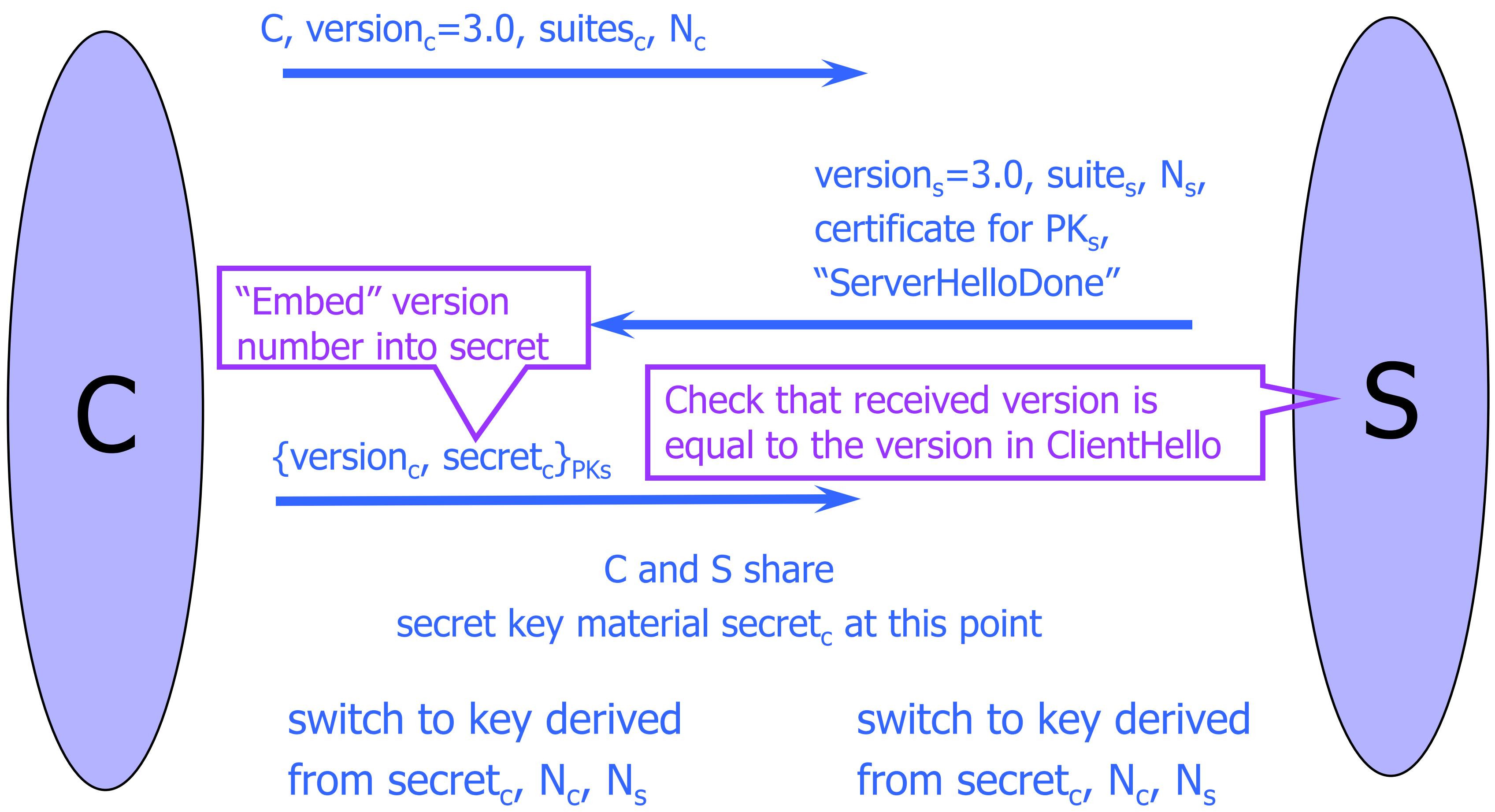
Version Rollback Attack


C, version$_c$=**2.0**, suites$_c$, N$_c$
version$_s$=**2.0**, suite$_s$, N$_s$,
certificate for PK$_s$,
"ServerHelloDone"
{Secret$_c$}$_{PKs}$
C
S

Server is fooled into thinking he is communicating with a client who supports only SSL 2.0

C and S end up communicating using SSL 2.0 (weaker earlier version of the protocol that does not include "Finished" messages)

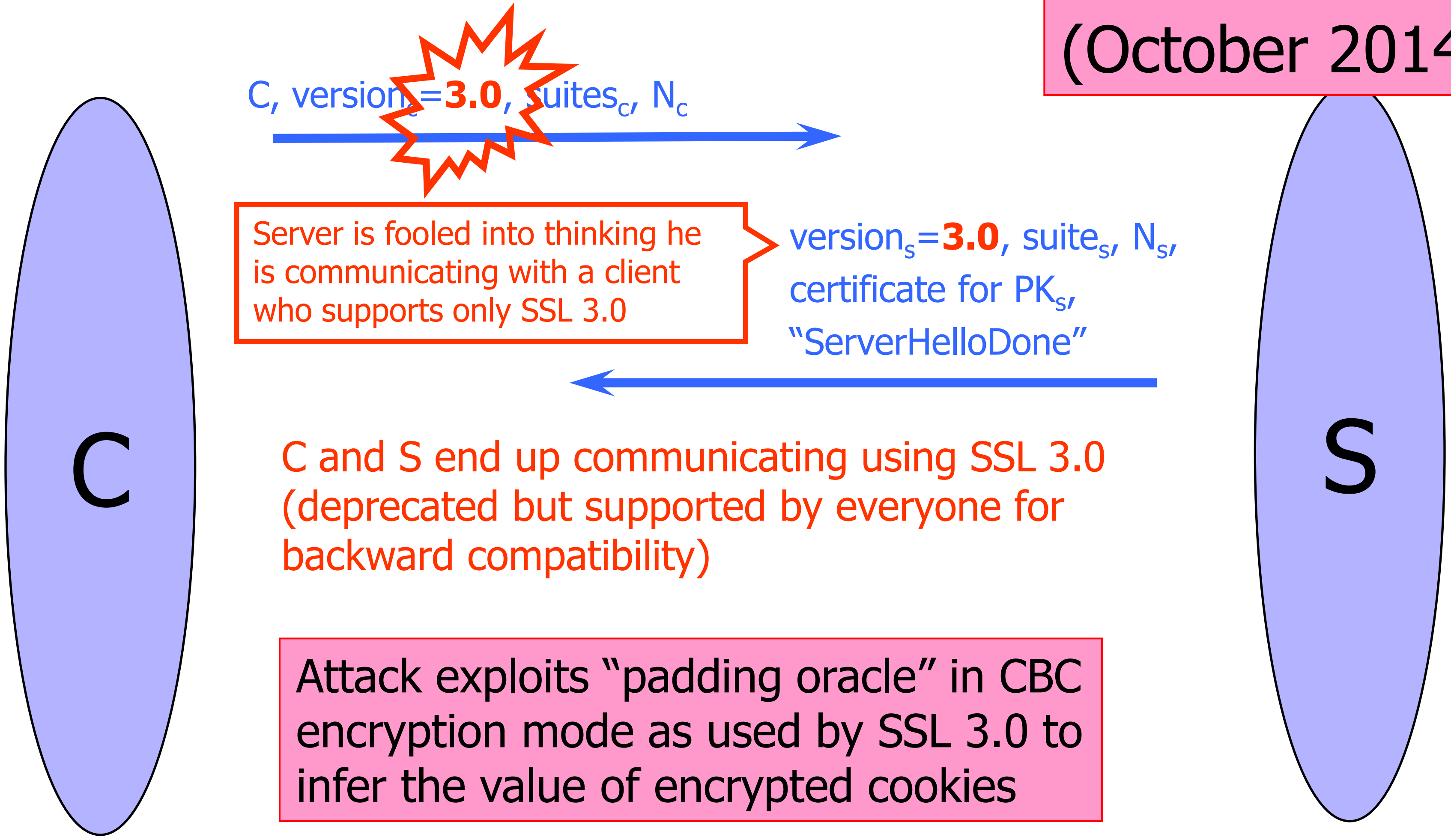
Version Check in SSL 3.0



C, version_c=3.0, suites_c, N_c
version_s=3.0, suite_s, N_s,
certificate for PK_s,
"ServerHelloDone"
"Embed" version number into secret
Check that received version is equal to the version in ClientHello
$\{\text{version}_c, \text{secret}_c\}_{PKs}$
C
S
C and S share secret key material secret_c at this point
switch to key derived from secret_c, N_c, N_s
switch to key derived from secret_c, N_c, N_s

TLS Version Rollback

POODLE attack (October 2014)


C, version_c=**3.0**, suites_c, N_c
version_s=**3.0**, suite_s, N_s,
certificate for PK_s,
"ServerHelloDone"
C
S

Server is fooled into thinking he is communicating with a client who supports only SSL 3.0

C and S end up communicating using SSL 3.0 (deprecated but supported by everyone for backward compatibility)

Attack exploits "padding oracle" in CBC encryption mode as used by SSL 3.0 to infer the value of encrypted cookies

Many "padding oracle" attacks over the years: BEAST, CRIME, …

“Chosen-Protocol” Attacks

- Why do people release new versions of security protocols? Because the old version got broken!
- New version must be backward-compatible
  - Not everybody upgrades right away
- Attacker can fool someone into using the old, broken version and exploit known vulnerabilities
  - Similar: fool victim into using weak crypto algorithms
- Defense is hard: must authenticate version early
- Many protocols had “version rollback” attacks
  - SSL, SSH, GSM (cell phones)

Exploiting SSL for Denial of Service

https://www.thc.org/thc-ssl-dos/

2 simple commands in bash:

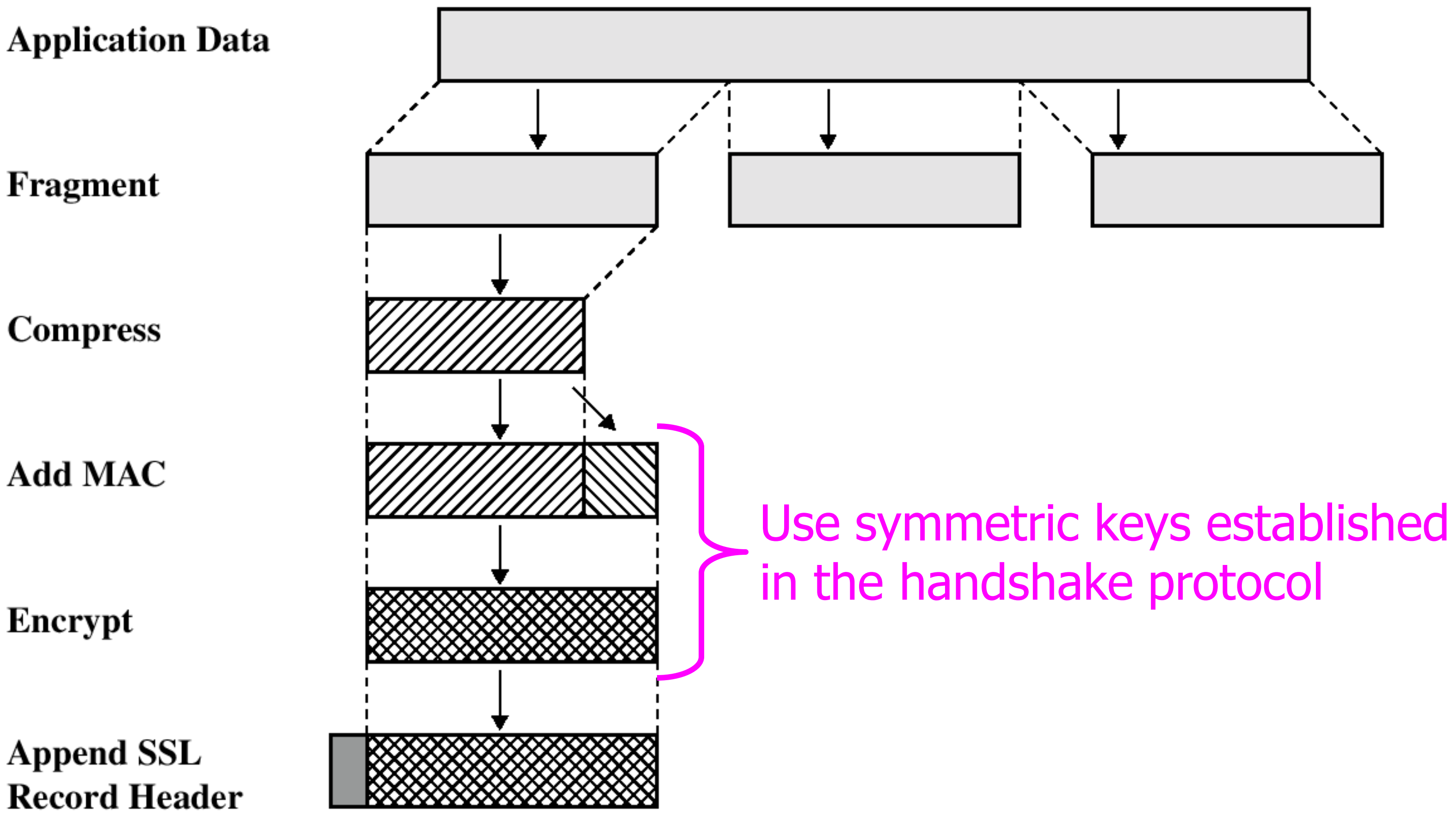
```
-----BASH SCRIPT BEGIN-----
thc-ssl-dosit() { while :; do (while :; do echo R; done) | openssl s_client
-connect 127.0.0.1:443 2>/dev/null; done }
for x in `seq 1 100`; do thc-ssl-dosit & done
-----BASH SCRIPT END-------
```

THC-SSL-DOS is a tool to verify the performance of SSL

Establishing a secure SSL connection requires 15x more processing power on the server than on the client

"THC-SSL-DOS exploits this asymmetric property by overloading the server and knocking it off the Internet"

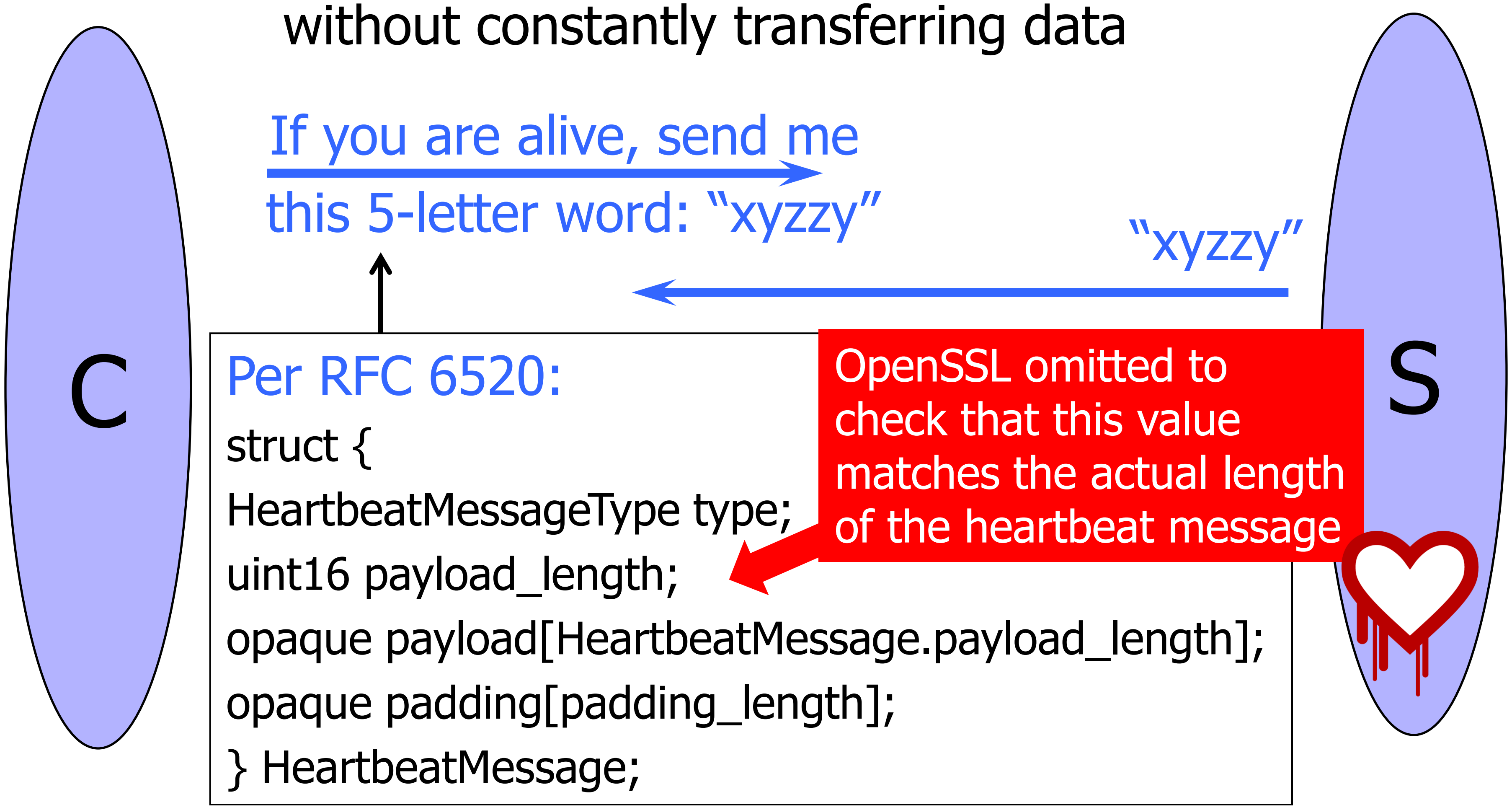
SSL/TLS Record Protection



Use symmetric keys established in the handshake protocol

TLS Heartbeat

A way to keep TLS connection alive without constantly transferring data



Per RFC 6520:

```
struct {
HeartbeatMessageType type;
uint16 payload_length;
opaque payload[HeartbeatMessage.payload_length];
opaque padding[padding_length];
} HeartbeatMessage;
```

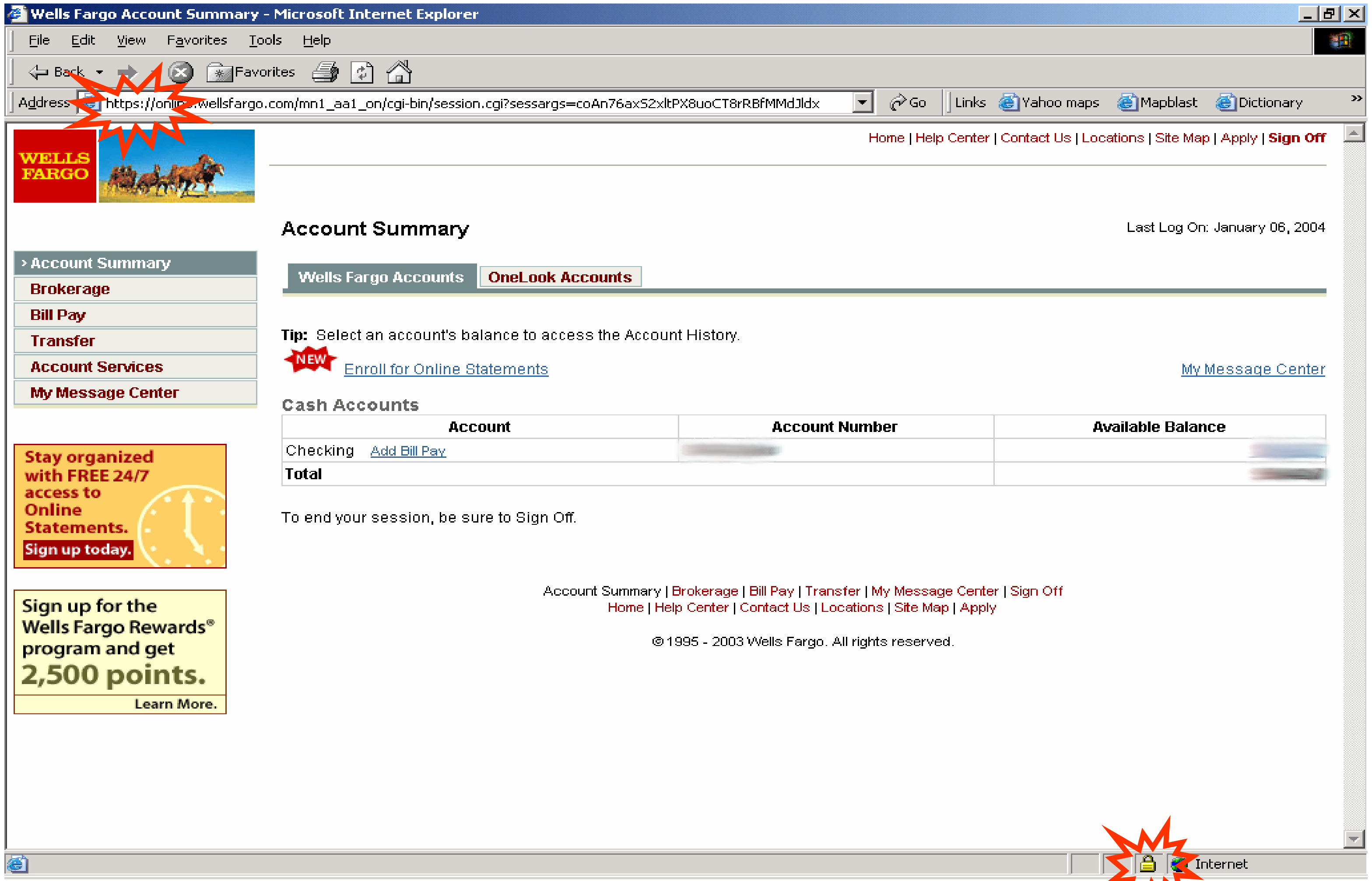
OpenSSL omitted to check that this value matches the actual length of the heartbeat message

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



Wells Fargo Account Summary - Microsoft Internet Explorer

https://online.wellsfargo.com/mn1_aa1_on/cgi-bin/session.cgi?sessargs=coAn76axS2xltPX8uoCT8rRBfMMdJldx

Home | Help Center | Contact Us | Locations | Site Map | Apply | **Sign Off**

› Account Summary
Brokerage
Bill Pay
Transfer
Account Services
My Message Center

Stay organized with FREE 24/7 access to Online Statements. Sign up today.

Sign up for the Wells Fargo Rewards® program and get 2,500 points. Learn More.

Account Summary

Last Log On: January 06, 2004

Wells Fargo Accounts | OneLook Accounts

Tip: Select an account's balance to access the Account History.

NEW Enroll for Online Statements

My Message Center

Cash Accounts

Account	Account Number	Available Balance
Checking Add Bill Pay	[redacted]	[redacted]
Total		[redacted]

To end your session, be sure to Sign Off.

Account Summary | Brokerage | Bill Pay | Transfer | My Message Center | Sign Off
Home | Help Center | Contact Us | Locations | Site Map | Apply

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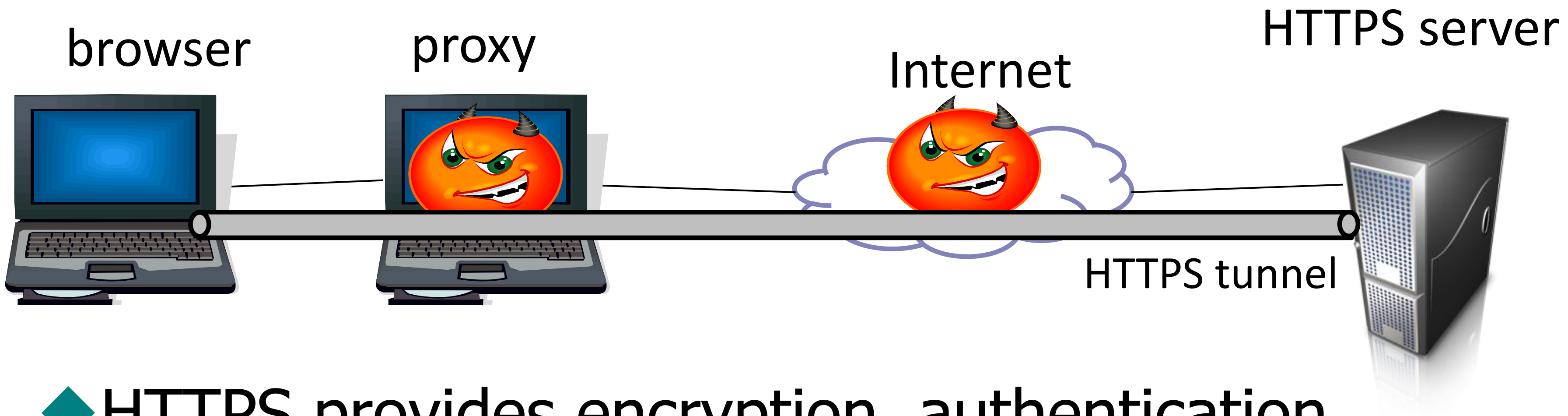
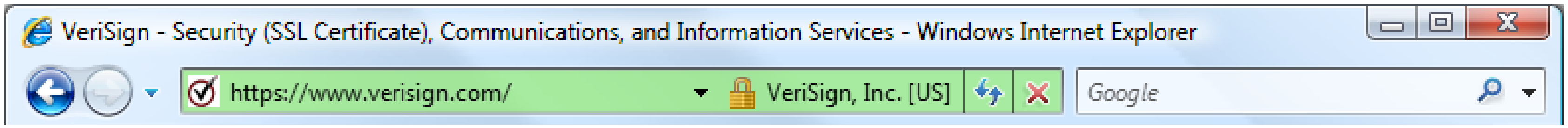
HTTPS and Its Adversary Model

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



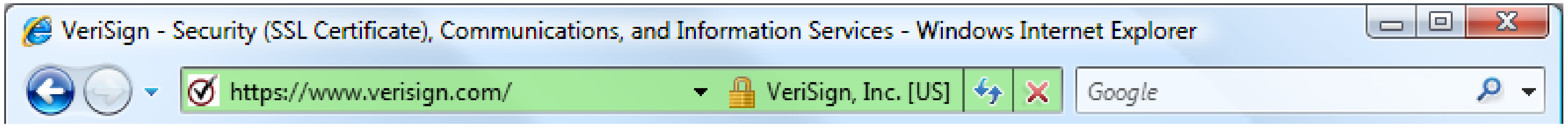
- HTTPS provides encryption, authentication (usually for server only), and integrity checking

The Lock Icon


VeriSign - Security (SSL Certificate), Communications, and Information Services - Windows Internet Explorer
https://www.verisign.com/
VeriSign, Inc. [US]
Google

- 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


VeriSign - Security (SSL Certificate), Communications, and Information Services - Windows Internet Explorer

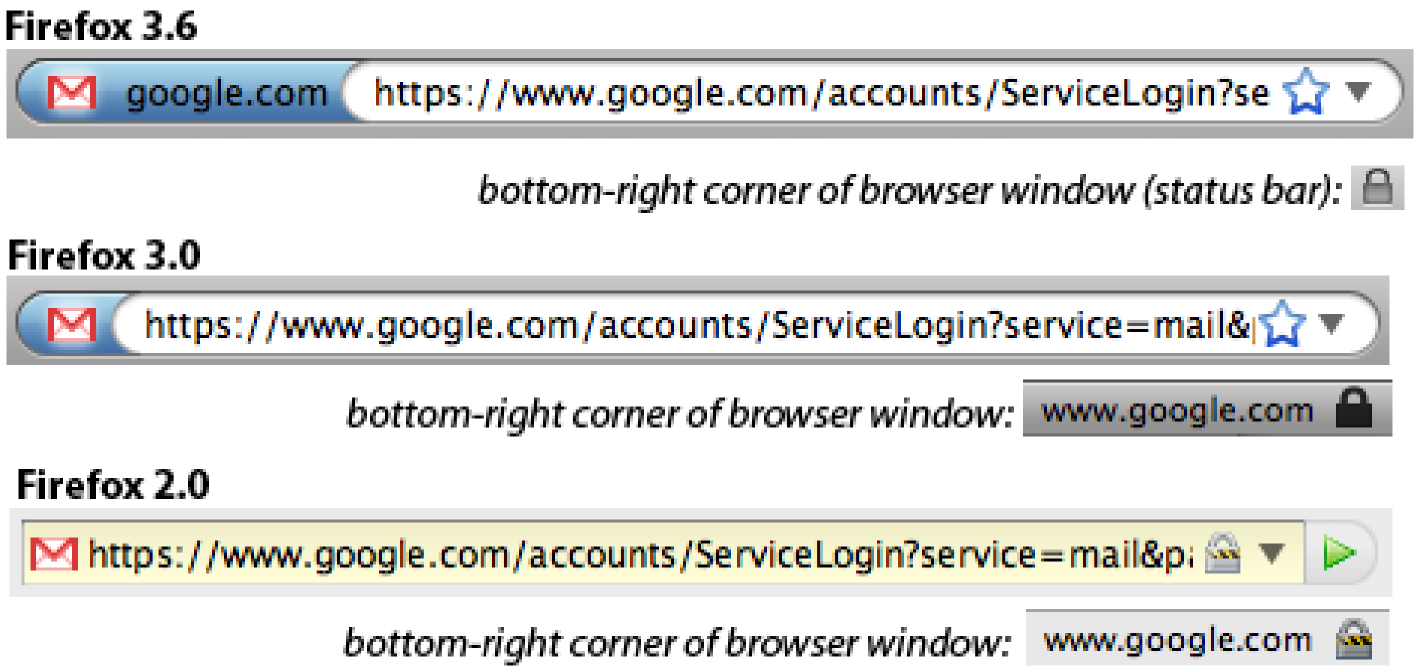
https://www.verisign.com/ VeriSign, Inc. [US]

- 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?


Firefox 3.6

google.com https://www.google.com/accounts/ServiceLogin?se

bottom-right corner of browser window (status bar):

Firefox 3.0

https://www.google.com/accounts/ServiceLogin?service=mail&

bottom-right corner of browser window: www.google.com

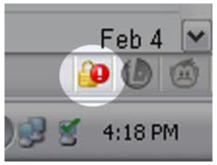
Firefox 2.0

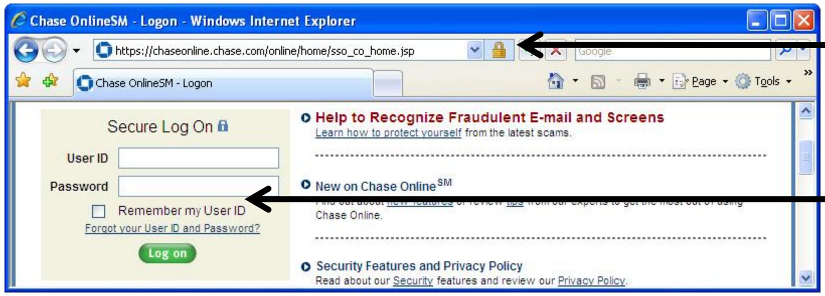
https://www.google.com/accounts/ServiceLogin?service=mail&p

bottom-right corner of browser window: www.google.com

Combining HTTPS and HTTP

- Page served over HTTPS but contains HTTP
  - IE 7: no lock, "mixed content" warning
  - Firefox: "!" over lock, no warning by default
  - Safari: does not detect mixed content




Chase OnlineSM - Logon - Windows Internet Explorer
https://chaseonline.chase.com/online/home/sso_co_home.jsp
Chase OnlineSM - Logon
Page
Tools
Secure Log On
User ID
Password
Remember my User ID
Forgot your User ID and Password?
Log on
Help to Recognize Fraudulent E-mail and Screens
Learn how to protect yourself from the latest scams.
New on Chase Online SM
Chase Online.
Security Features and Privacy Policy
Read about our Security features and review our Privacy Policy.

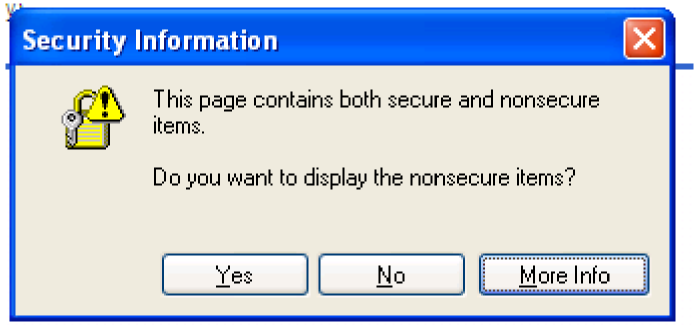
Lock icon

Flash file served over HTTP

Can script embedding page!

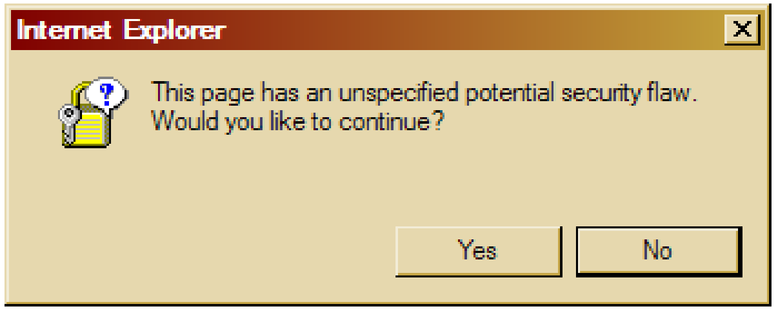
  - Flash does not trigger warning in IE7 and FF
- Network attacker can now inject scripts, hijack session

Mixed Content: UI Challenges

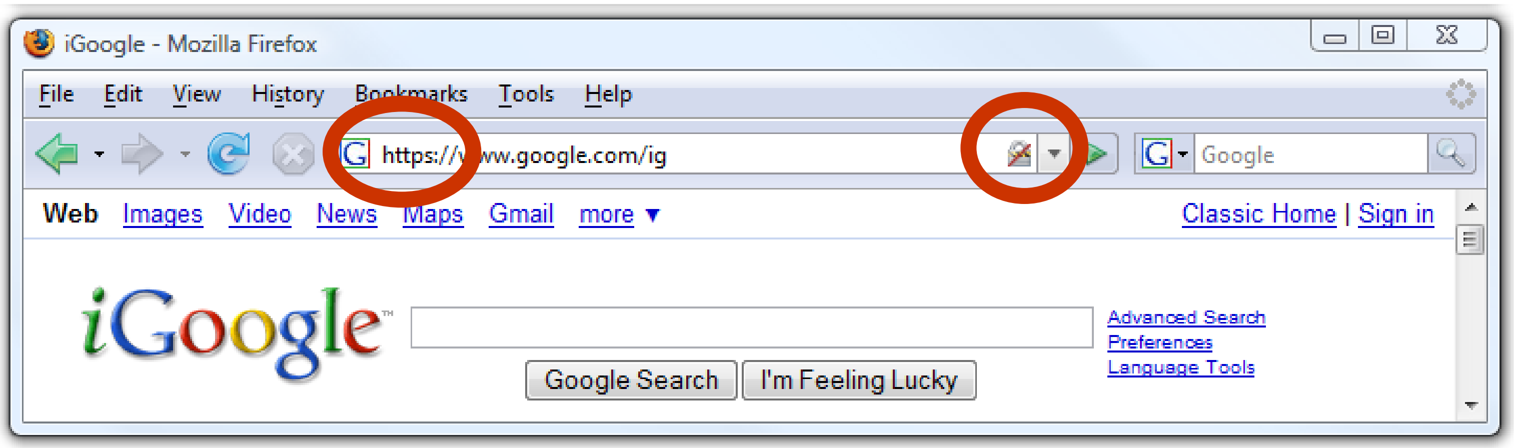

Security Information

This page contains both secure and nonsecure items.

Do you want to display the nonsecure items?


Internet Explorer

This page has an unspecified potential security flaw. Would you like to continue?



Mixed Content and Network Attacks

- Banks: after login, all content served over HTTPS
- Developer error: somewhere on bank site write

```
<script src=http://www.site.com/script.js> </script>
```

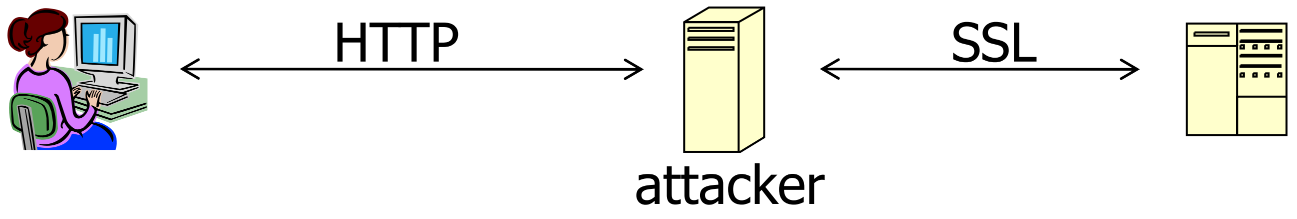
  - Active network attacker can now hijack any session (how?)
- Better way to include content:

```
<script src=//www.site.com/script.js> </script>
```

  - Served over the same protocol as embedding page

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

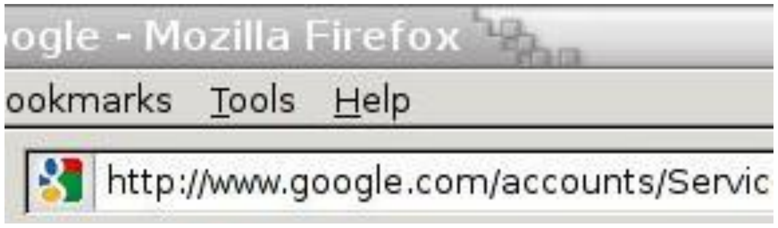


  - Rewrite <a href=https://…> to <a href=http://…>
  - Redirect Location: https://... to Location: http://...
  - Rewrite <form action=https://… > to <form action=http://…>

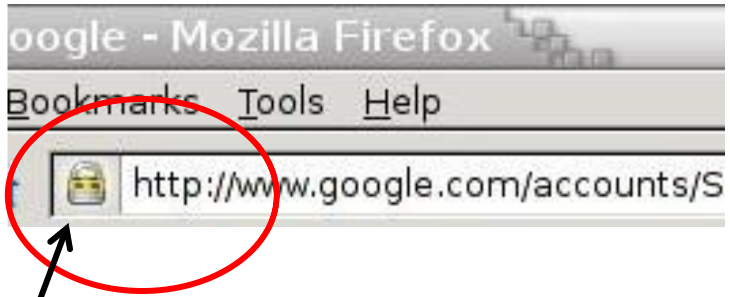
Can the server detect this attack?

Will You Notice?

[Moxie Marlinspike]



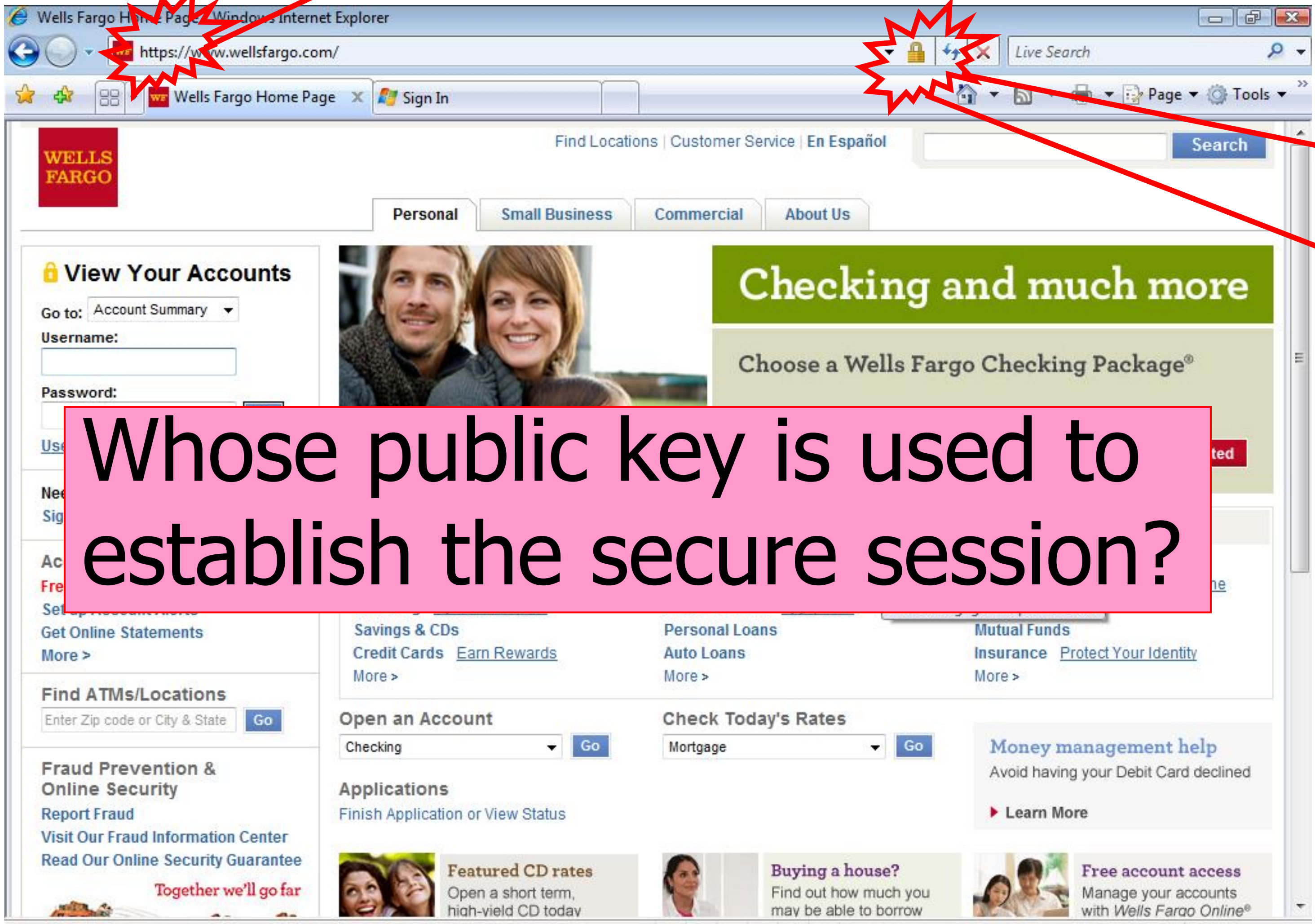
$\Rightarrow$



Clever favicon inserted by network attacker

Motivation

https://



Wells Fargo Home Page - Windows Internet Explorer

https://www.wellsfargo.com/

Live Search

Wells Fargo Home Page | Sign In

Page | Tools

WELLS FARGO

Find Locations | Customer Service | En Español

Search

Personal | Small Business | Commercial | About Us

View Your Accounts

Go to: Account Summary

Username:

Password:

Checking and much more

Choose a Wells Fargo Checking Package®

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More >

Savings & CDs
Credit Cards Earn Rewards
More >

Personal Loans
Auto Loans
More >

Mutual Funds
Insurance Protect Your Identity
More >

Find ATMs/Locations
Enter Zip code or City & State Go

Open an Account
Checking Go

Check Today's Rates
Mortgage Go

Money management help
Avoid having your Debit Card declined
Learn More

Applications
Finish Application or View Status

Fraud Prevention & Online Security
Report Fraud
Visit Our Fraud Information Center
Read Our Online Security Guarantee

Together we'll go far

Featured CD rates
Open a short term, high-yield CD today

Buying a house?
Find out how much you may be able to borrow

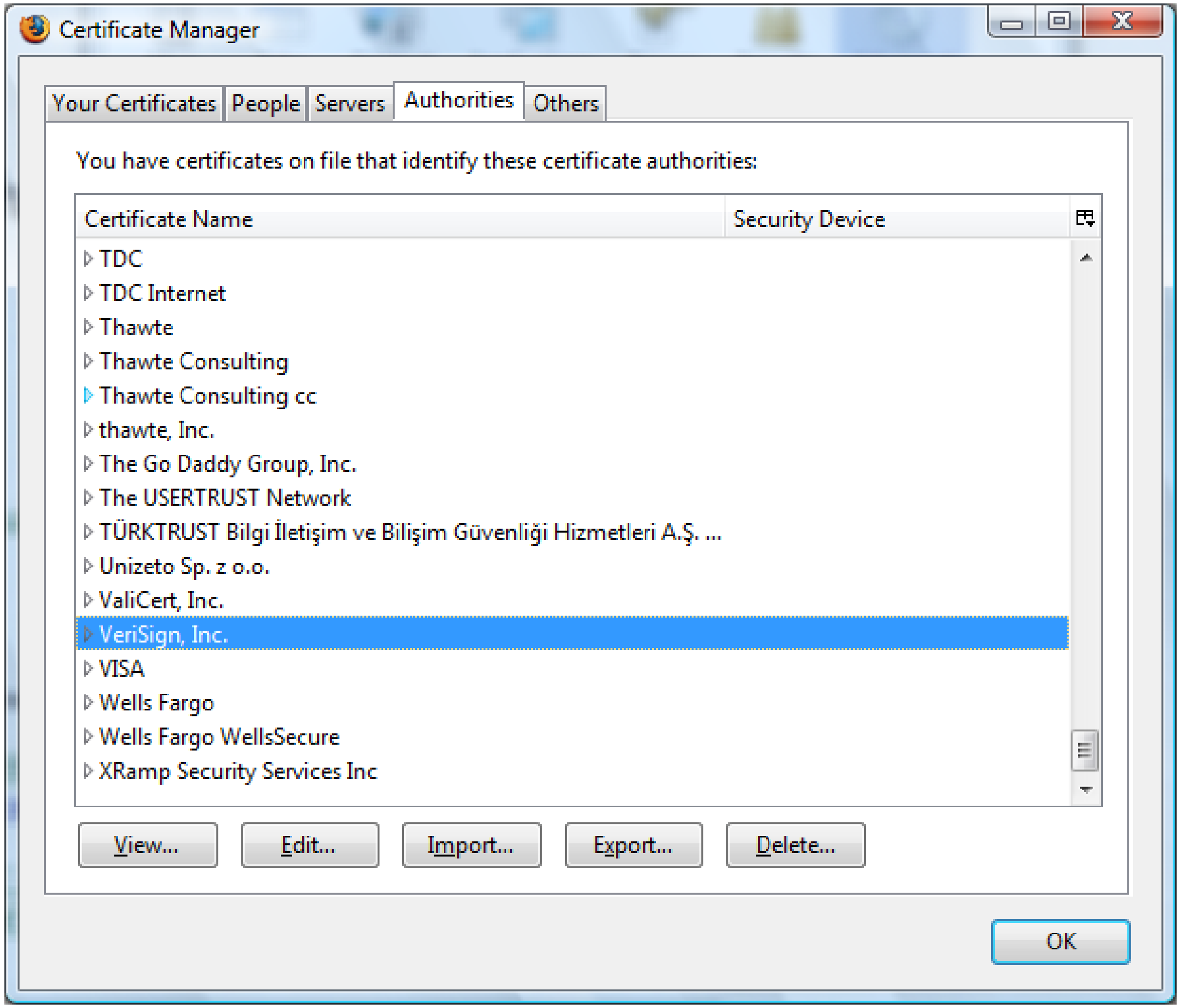
Free account access
Manage your accounts with Wells Fargo Online®

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
    - $\mathrm{sig}_{\mathrm{Alice}}(\text{“Bob”}, PK_B)$
- 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



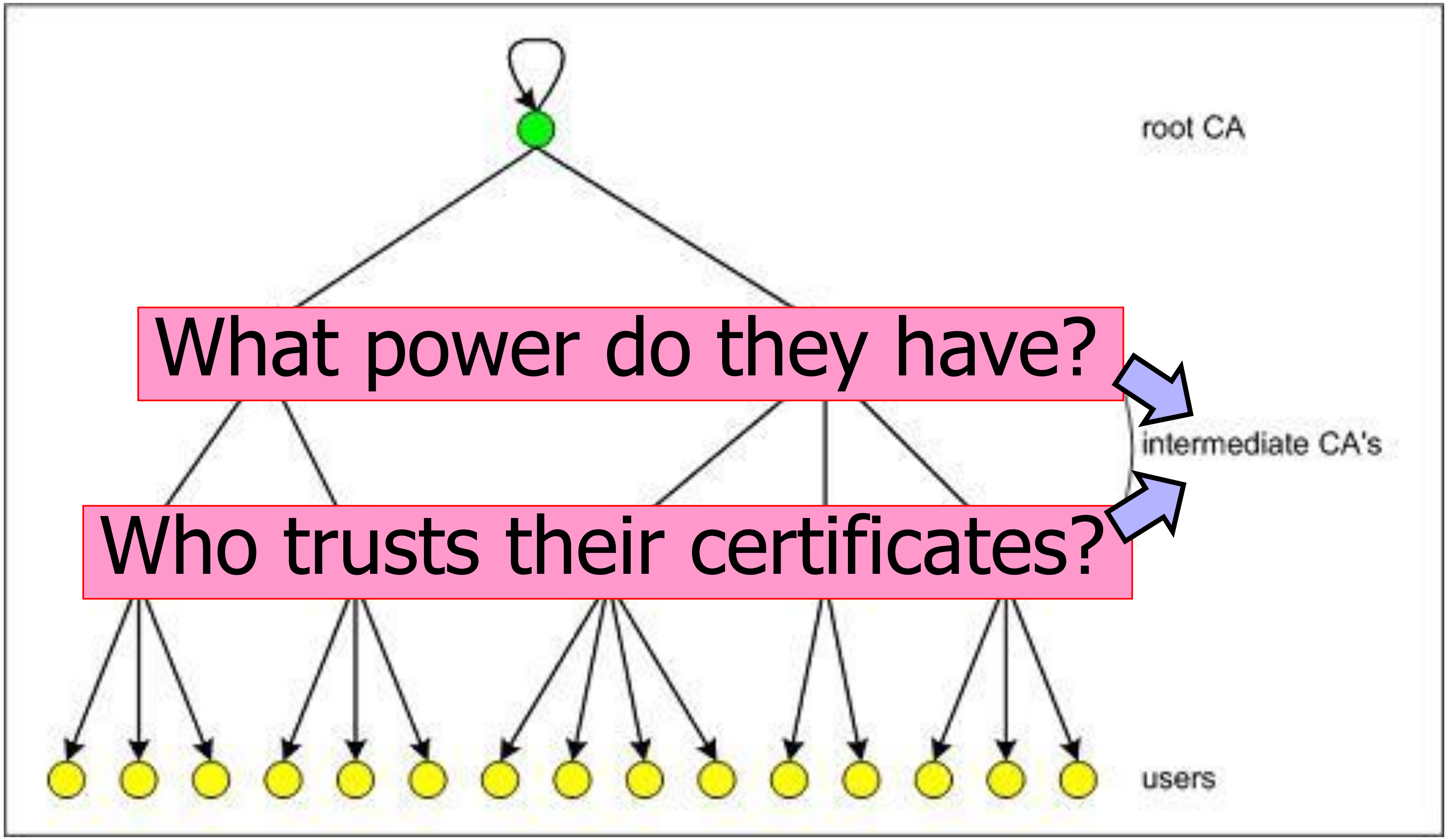
You have certificates on file that identify these certificate authorities:

Certificate Name	Security Device
TDC	
TDC Internet	
Thawte	
Thawte Consulting	
Thawte Consulting cc	
thawte, Inc.	
The Go Daddy Group, Inc.	
The USERTRUST Network	
TÜRKTRUST Bilgi İletişim ve Bilişim Güvenliği Hizmetleri A.Ş. ...	
Unizeto Sp. z o.o.	
ValiCert, Inc.	
VeriSign, Inc.	
VISA	
Wells Fargo	
Wells Fargo WellsSecure	
XRamp Security Services Inc	

CA Hierarchy

- Browsers, operating systems, etc. have trusted root certificate authorities
  - Firefox 3 includes certificates of 135 trusted root CAs
- A Root CA signs certificates for intermediate CAs, they sign certificates for lower-level CAs, etc.
  - Certificate "chain of trust"
    - $sig_{Verisign}$("UT Austin", PK_{UT}), sig_{UT}("Vitaly S.", PK_{Vitaly})
- CA is responsible for verifying the identities of certificate requestors, domain ownership

Certificate Hierarchy

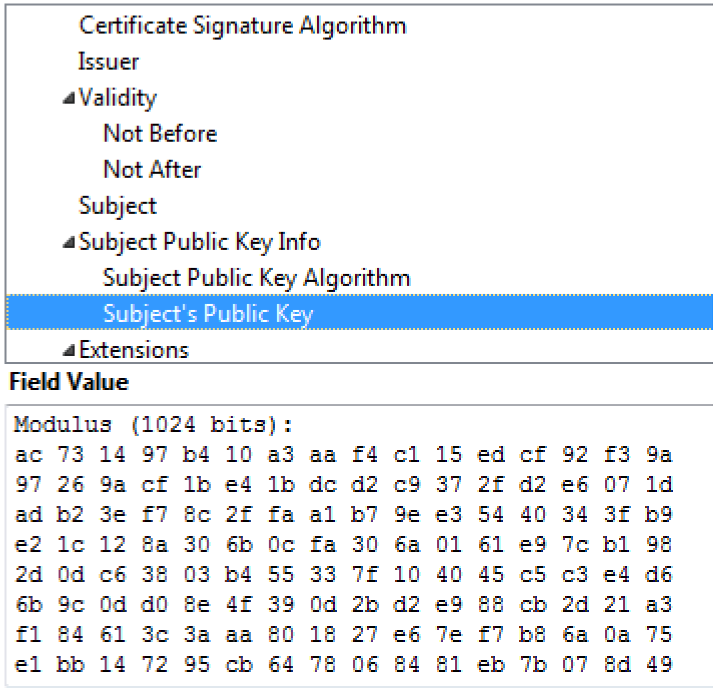


What power do they have?

Who trusts their certificates?

Example of a Certificate

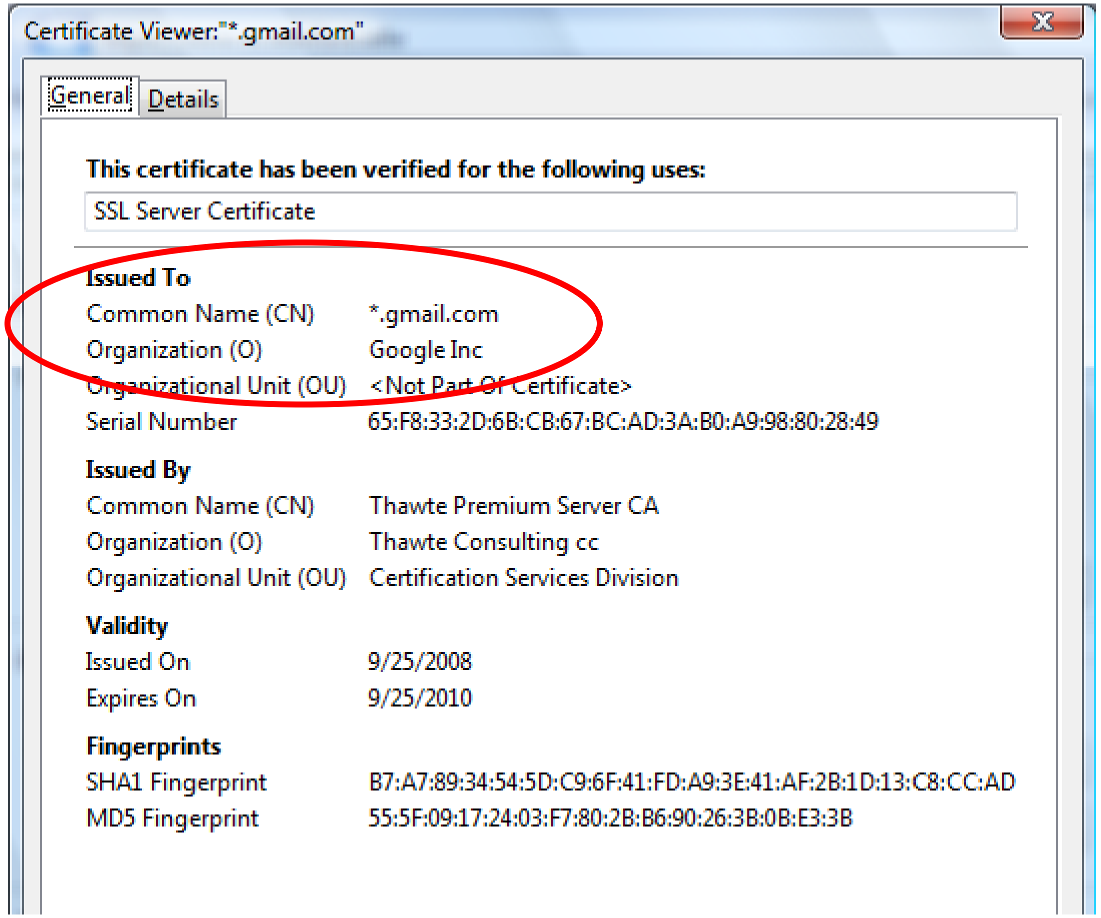
Important fields



Certificate Signature Algorithm
Issuer
◢Validity
Not Before
Not After
Subject
◢Subject Public Key Info
Subject Public Key Algorithm
Subject's Public Key
◢Extensions

Field Value

```
Modulus (1024 bits):
ac 73 14 97 b4 10 a3 aa f4 c1 15 ed cf 92 f3 9a
97 26 9a cf 1b e4 1b dc d2 c9 37 2f d2 e6 07 1d
ad b2 3e f7 8c 2f fa a1 b7 9e e3 54 40 34 3f b9
e2 1c 12 8a 30 6b 0c fa 30 6a 01 61 e9 7c b1 98
2d 0d c6 38 03 b4 55 33 7f 10 40 45 c5 c3 e4 d6
6b 9c 0d d0 8e 4f 39 0d 2b d2 e9 88 cb 2d 21 a3
f1 84 61 3c 3a aa 80 18 27 e6 7e f7 b8 6a 0a 75
e1 bb 14 72 95 cb 64 78 06 84 81 eb 7b 07 8d 49
```



Certificate Viewer:"*.gmail.com"

General | Details

This certificate has been verified for the following uses:

SSL Server Certificate

Issued To

Common Name (CN)	*.gmail.com
Organization (O)	Google Inc
Organizational Unit (OU)	<Not Part Of Certificate>
Serial Number	65:F8:33:2D:6B:CB:67:BC:AD:3A:B0:A9:98:80:28:49

Issued By

Common Name (CN)	Thawte Premium Server CA
Organization (O)	Thawte Consulting cc
Organizational Unit (OU)	Certification Services Division

Validity

Issued On	9/25/2008
Expires On	9/25/2010

Fingerprints

SHA1 Fingerprint	B7:A7:89:34:54:5D:C9:6F:41:FD:A9:3E:41:AF:2B:1D:13:C8:CC:AD
MD5 Fingerprint	55:5F:09:17:24:03:F7:80:2B:B6:90:26:3B:0B:E3:3B

Common Name

- Explicit name: www.foo.com
- Wildcard: *.foo.com or www*.foo.com
- Matching rules
  - Firefox 3: * matches anything
  - Internet Explorer 7: * must occur in the leftmost component, does not match '.'
    - *.foo.com matches a.foo.com, but not a.b.foo.com

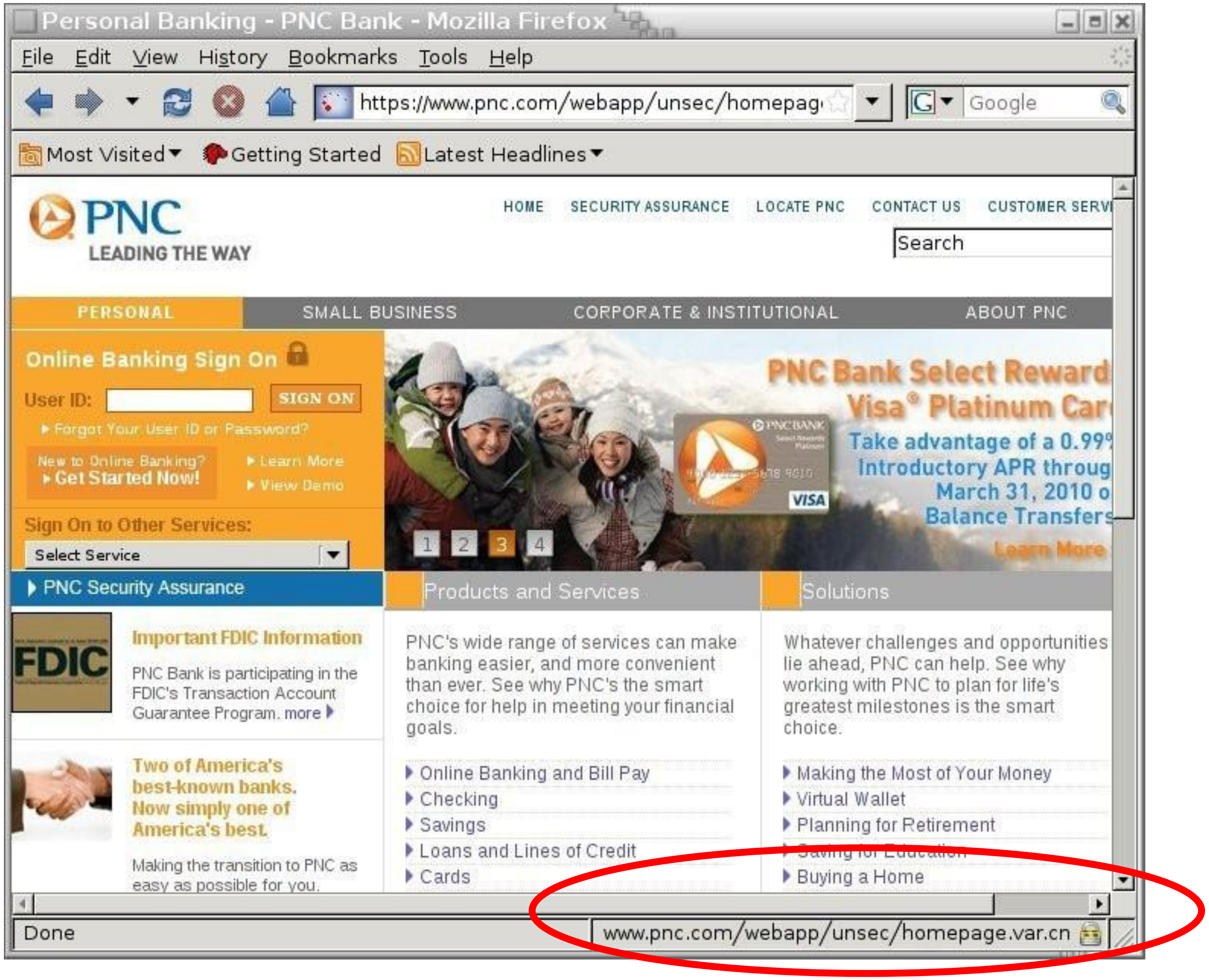
International Domain Names

- 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]



Personal Banking - PNC Bank - Mozilla Firefox

File Edit View History Bookmarks Tools Help

https://www.pnc.com/webapp/unsec/homepag

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PNC LEADING THE WAY

HOME SECURITY ASSURANCE LOCATE PNC CONTACT US CUSTOMER SERVI

PERSONAL SMALL BUSINESS CORPORATE & INSTITUTIONAL ABOUT PNC

Online Banking Sign On

User ID: SIGN ON

Forgot Your User ID or Password?

New to Online Banking? Get Started Now! Learn More View Demo

Sign On to Other Services: Select Service

PNC Security Assurance

PNC Bank Select Reward Visa® Platinum Car

Take advantage of a 0.99 Introductory APR throug March 31, 2010 o Balance Transfers

Learn More

Important FDIC Information

PNC Bank is participating in the FDIC's Transaction Account Guarantee Program. more

Two of America's best-known banks. Now simply one of America's best.

Making the transition to PNC as easy as possible for you.

Products and Services

PNC's wide range of services can make banking easier, and more convenient than ever. See why PNC's the smart choice for help in meeting your financial goals.

- Online Banking and Bill Pay
- Checking
- Savings
- Loans and Lines of Credit
- Cards

Solutions

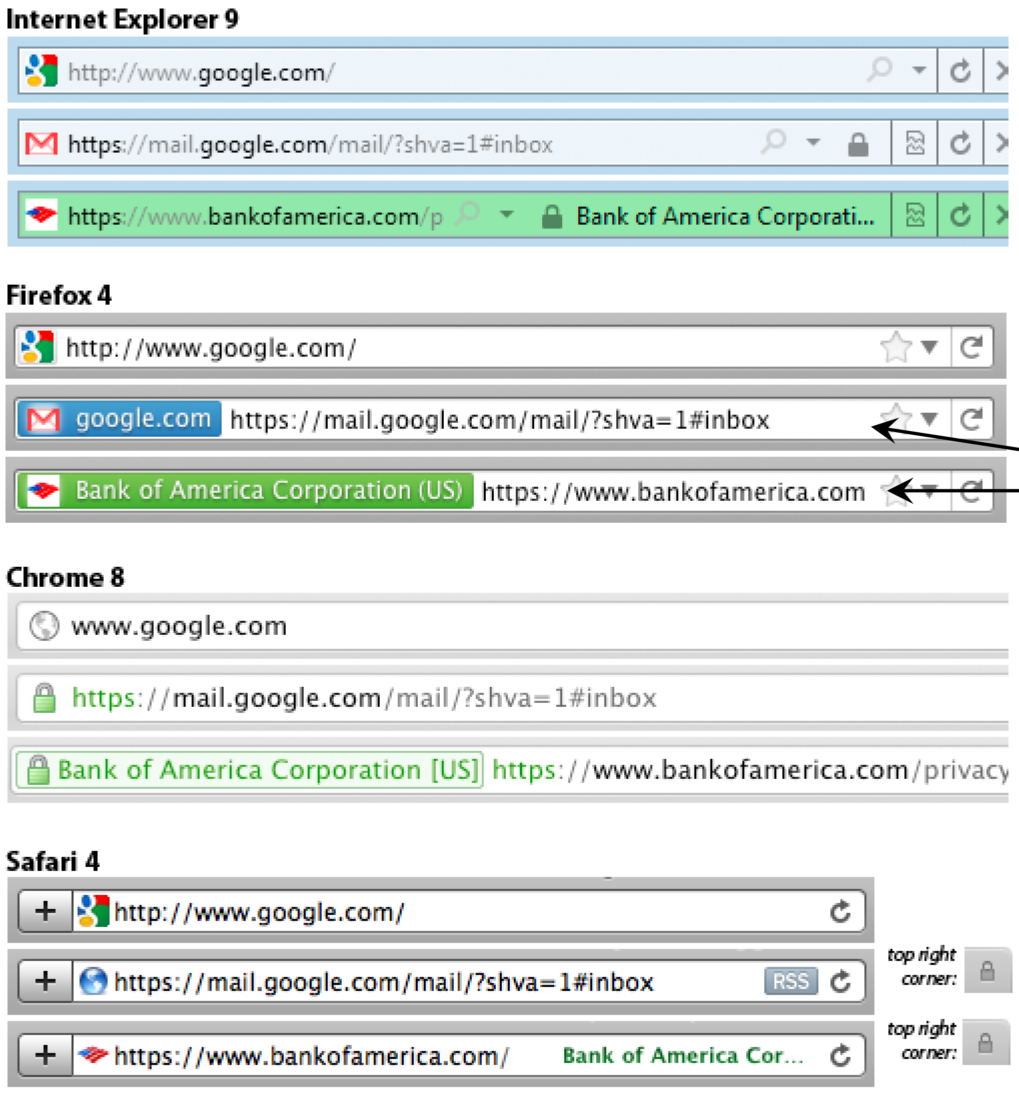
Whatever challenges and opportunities lie ahead, PNC can help. See why working with PNC to plan for life's greatest milestones is the smart choice.

- Making the Most of Your Money
- Virtual Wallet
- Planning for Retirement
- Saving for Education
- Buying a Home

Done www.pnc.com/webapp/unsec/homepage.var.cn

Meaning of Color

[Schultze]



Internet Explorer 9

http://www.google.com/

https://mail.google.com/mail/?shva=1#inbox

https://www.bankofamerica.com/p Bank of America Corporati...

Firefox 4

http://www.google.com/

google.com https://mail.google.com/mail/?shva=1#inbox

Bank of America Corporation (US) https://www.bankofamerica.com

Chrome 8

www.google.com

https://mail.google.com/mail/?shva=1#inbox

Bank of America Corporation [US] https://www.bankofamerica.com/privacy

Safari 4

http://www.google.com/

https://mail.google.com/mail/?shva=1#inbox RSS

top right corner:

https://www.bankofamerica.com/ Bank of America Cor...

top right corner:

What is the difference?

Domain Validation (DV) certificate

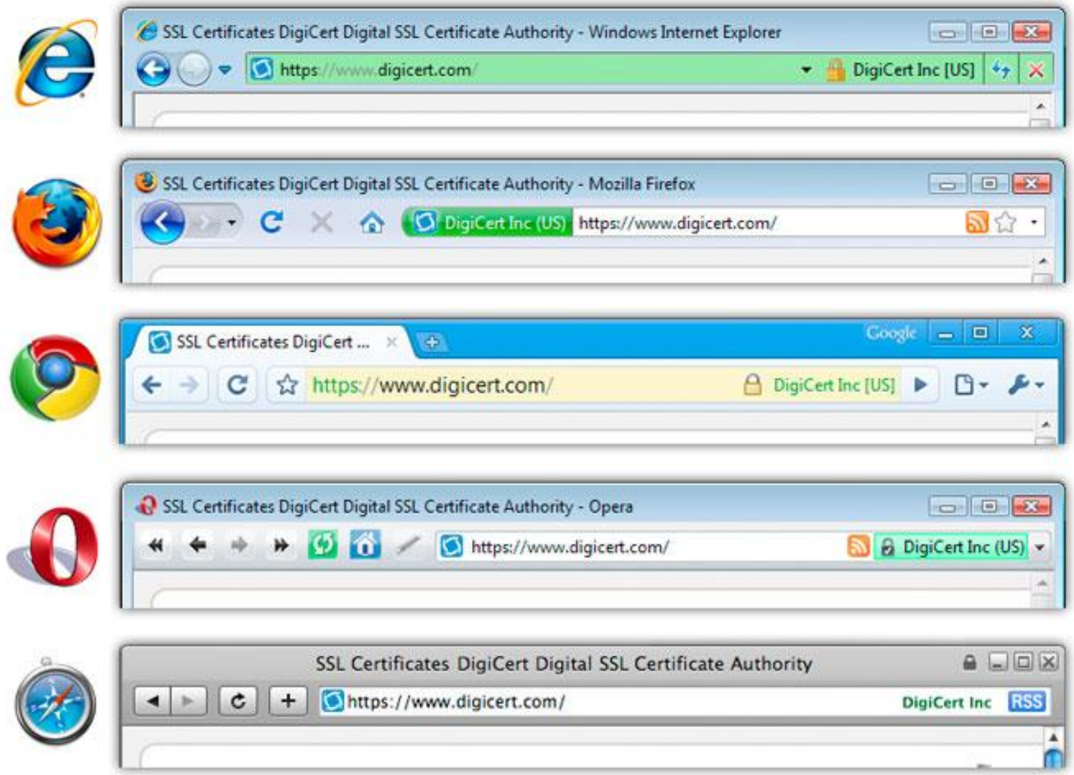
vs.

Extended Validation (EV) certificate

Means what?

Extended Validation (EV) Certificates

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


SSL Certificates DigiCert Digital SSL Certificate Authority - Windows Internet Explorer
https://www.digicert.com/
DigiCert Inc [US]
SSL Certificates DigiCert Digital SSL Certificate Authority - Mozilla Firefox
DigiCert Inc (US)
https://www.digicert.com/
SSL Certificates DigiCert ...
Google
https://www.digicert.com/
DigiCert Inc [US]
SSL Certificates DigiCert Digital SSL Certificate Authority - Opera
https://www.digicert.com/
DigiCert Inc (US)
SSL Certificates DigiCert Digital SSL Certificate Authority
https://www.digicert.com/
DigiCert Inc
RSS

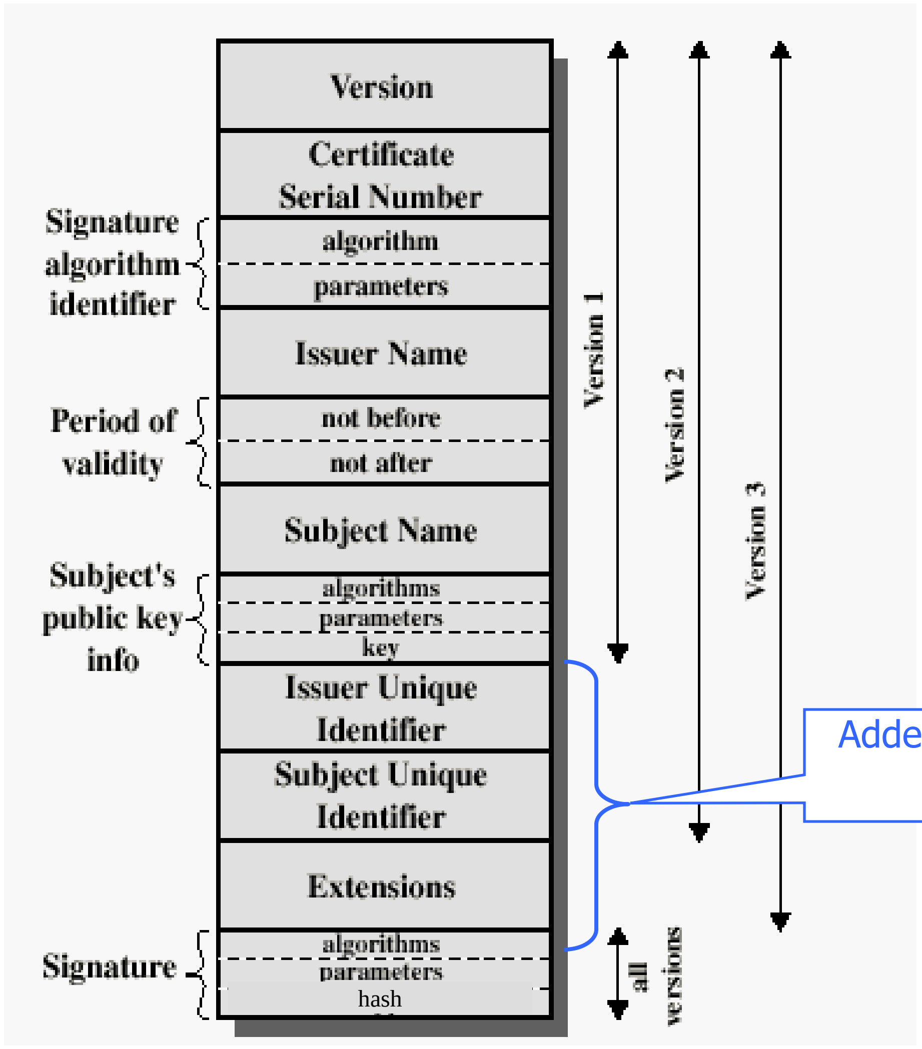
Questions about EV Certificates

- 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



Added in X.509 versions 2 and 3 to address usability and security problems

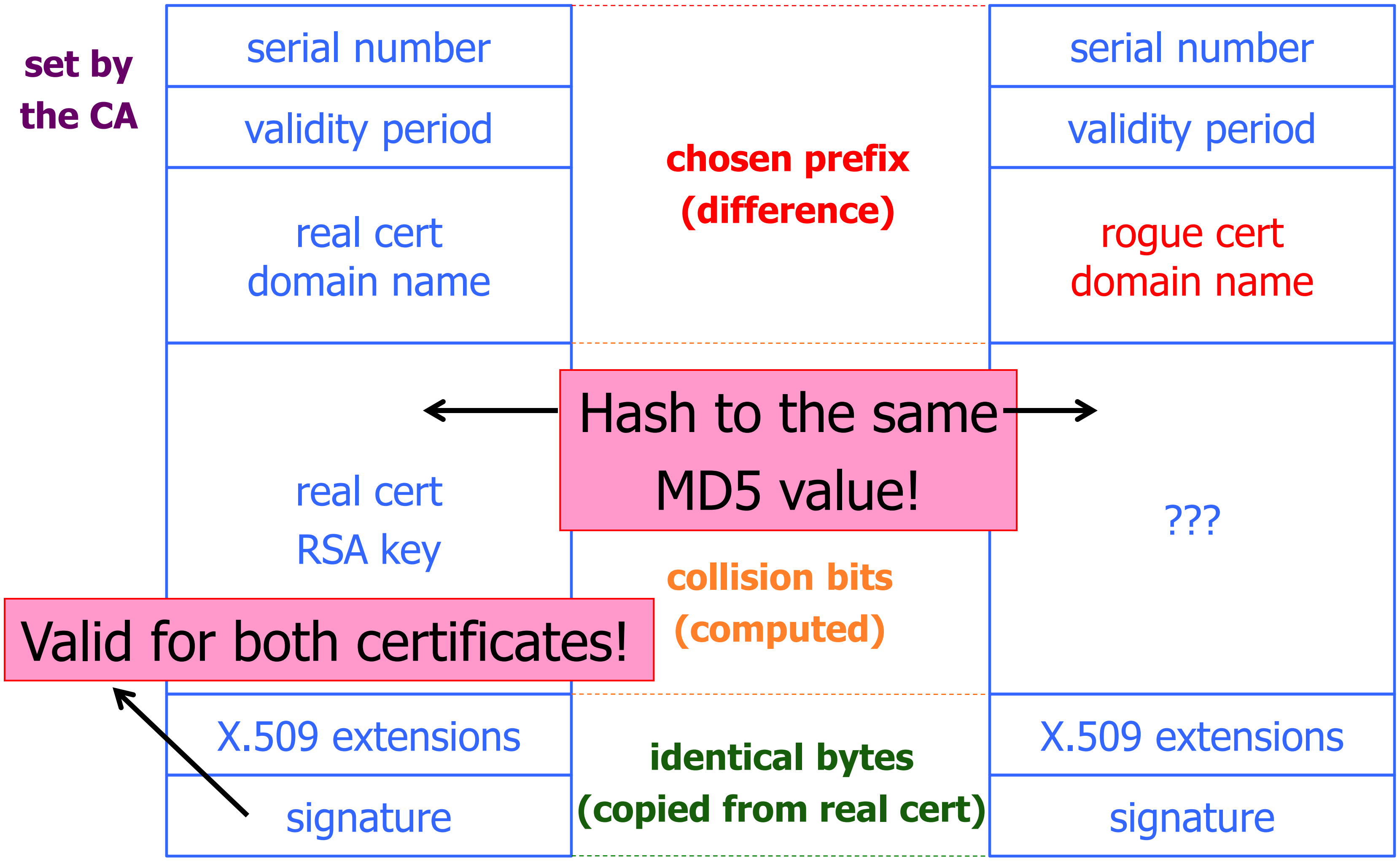
Back in 2008

[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

[Sotirov et al.]

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

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

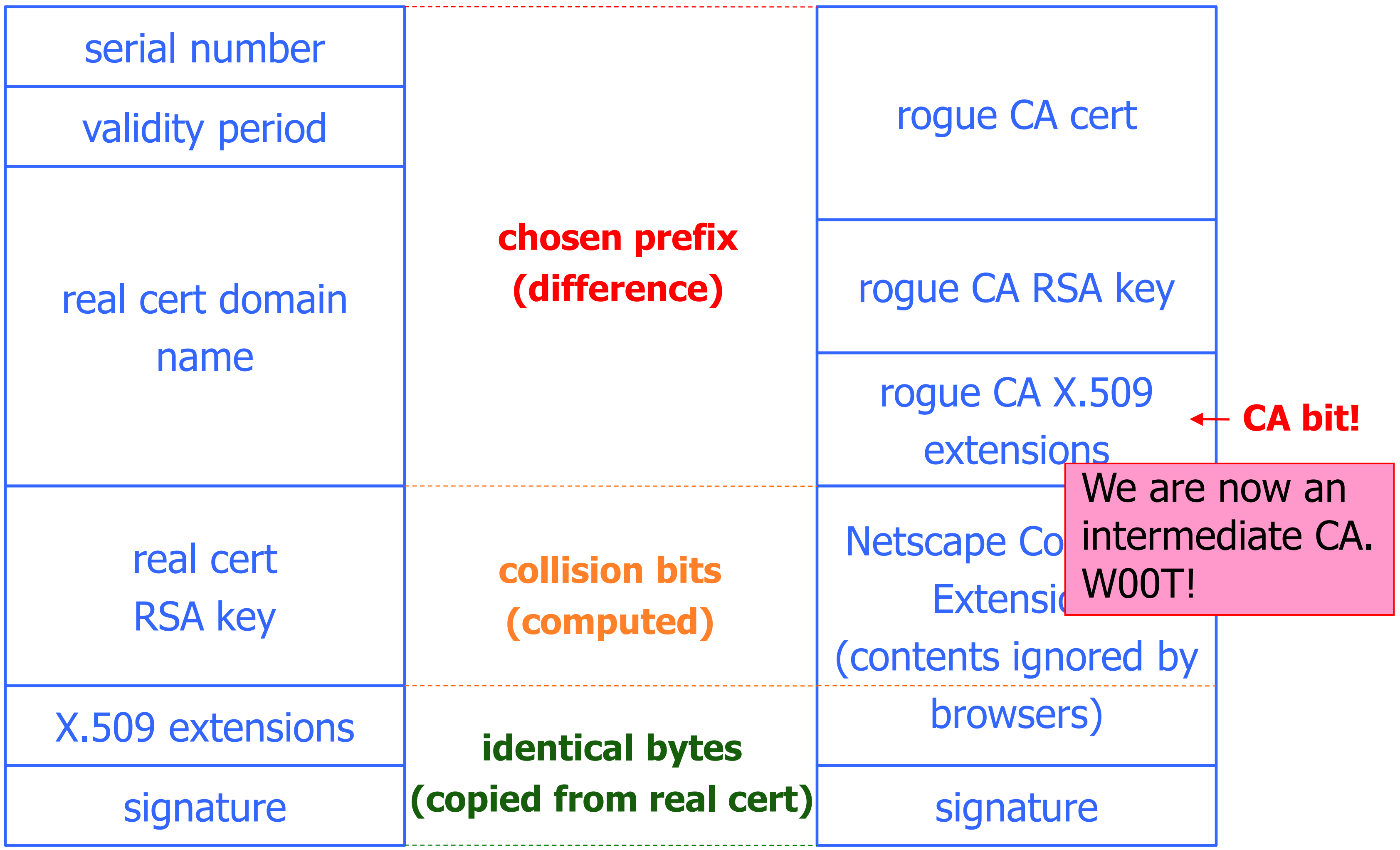
Generating Colliding Certificates

[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

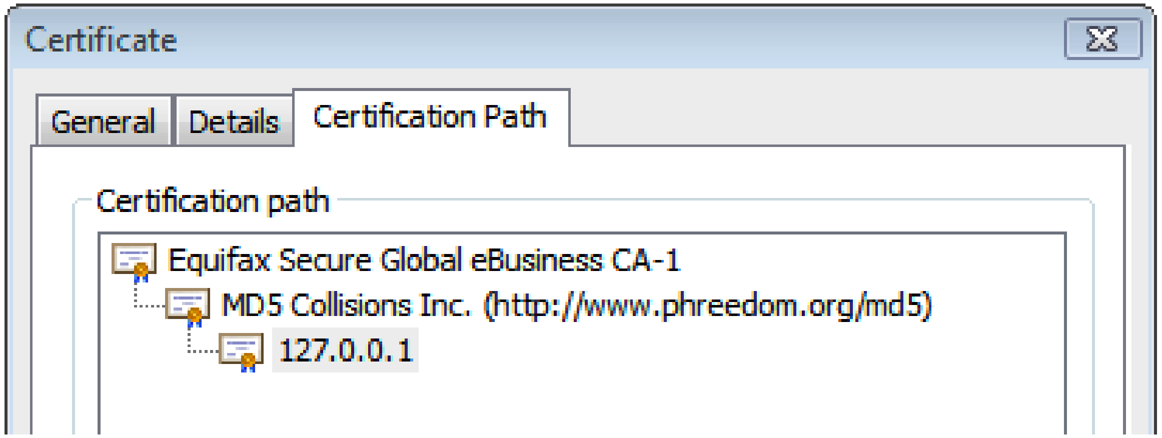
Creating a Fake Intermediate CA

[Sotirov et al.]


serial number
validity period
real cert domain name
real cert RSA key
X.509 extensions
signature
chosen prefix (difference)
collision bits (computed)
identical bytes (copied from real cert)
rogue CA cert
rogue CA RSA key
rogue CA X.509 extensions
CA bit!
Netscape Comment Extension (contents ignored by browsers)
signature
We are now an intermediate CA. W00T!

Result: Perfect Man-in-the-Middle

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



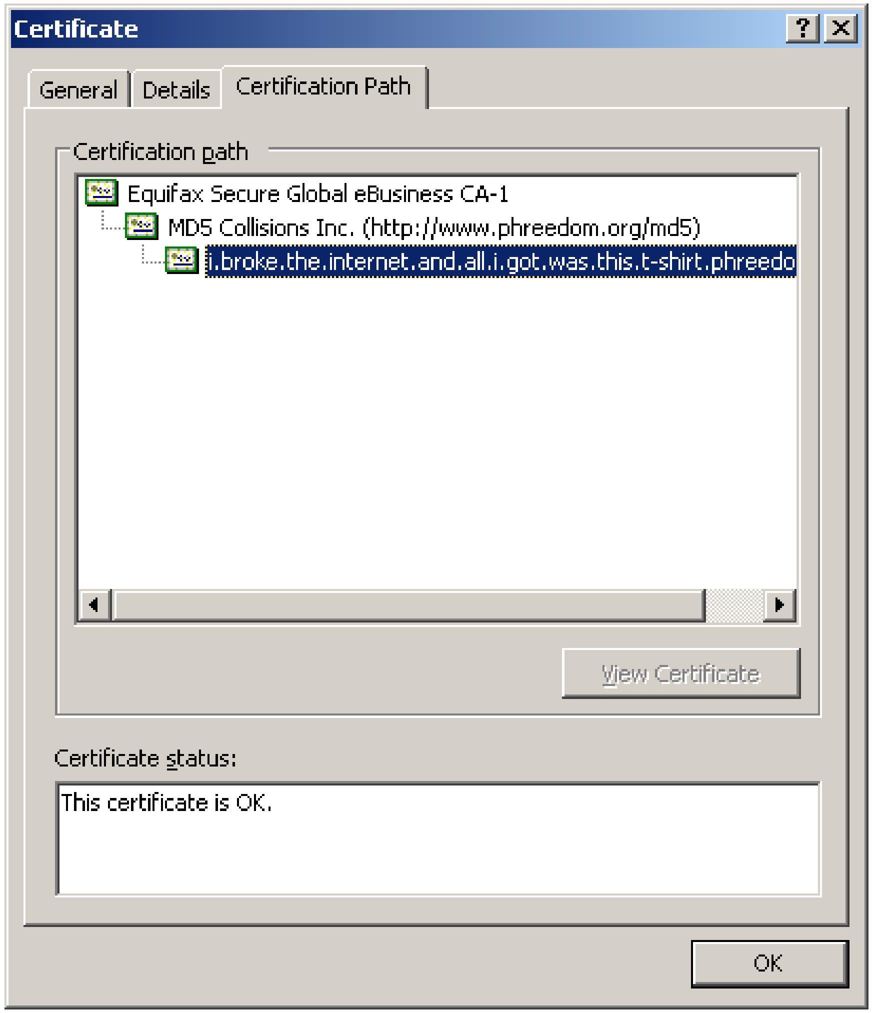
Certificate

Certification path

```
Equifax Secure Global eBusiness CA-1
  MD5 Collisions Inc. (http://www.phreedom.org/md5)
    127.0.0.1
```

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

A Rogue Certificate



Certificate

General | Details | Certification Path

Certification path

Equifax Secure Global eBusiness CA-1
MD5 Collisions Inc. (http://www.phreedom.org/md5)
i.broke.the.internet.and.all.i.got.was.this.t-shirt.phreedo

View Certificate

Certificate status:

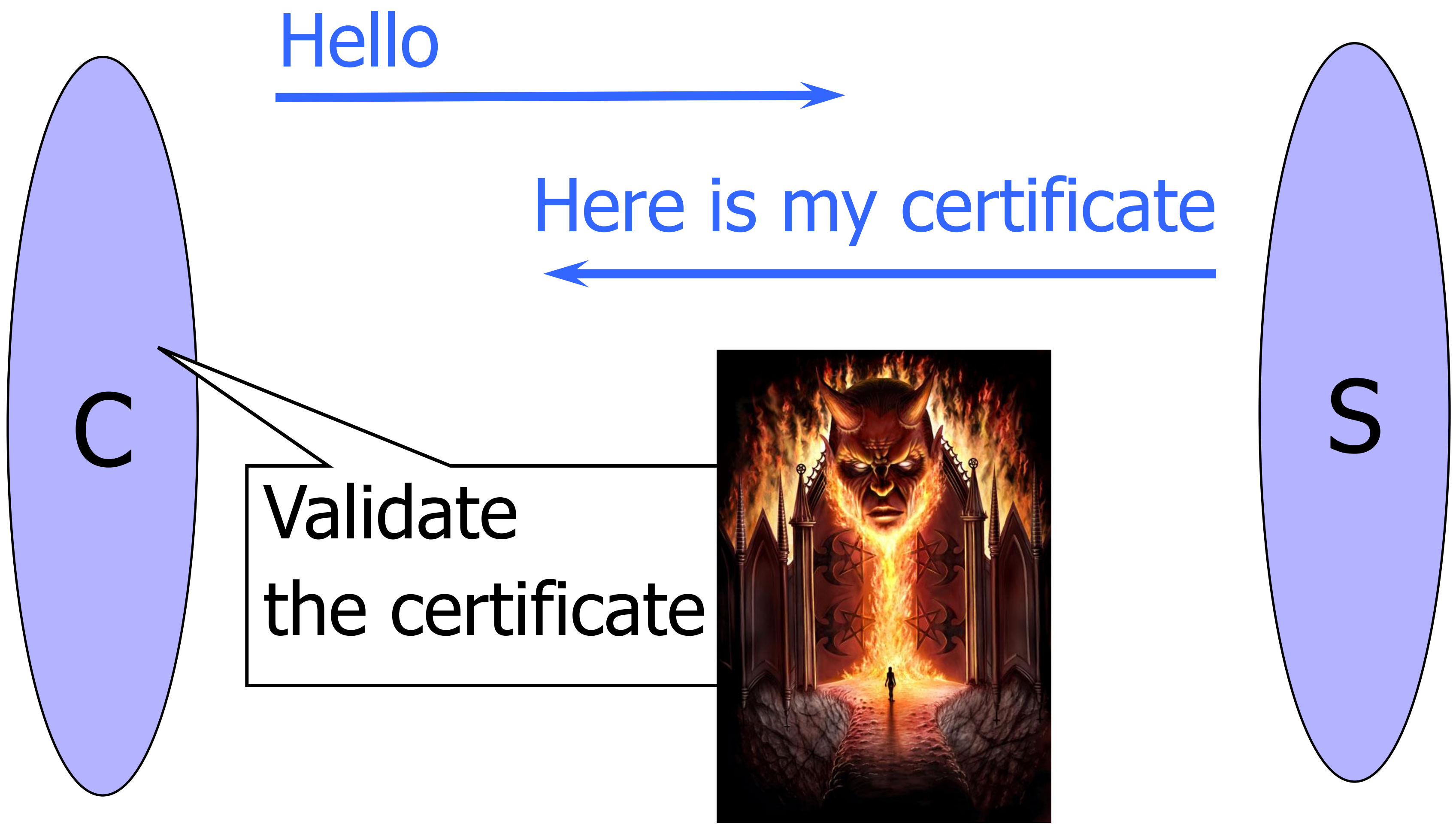
This certificate is OK.

OK

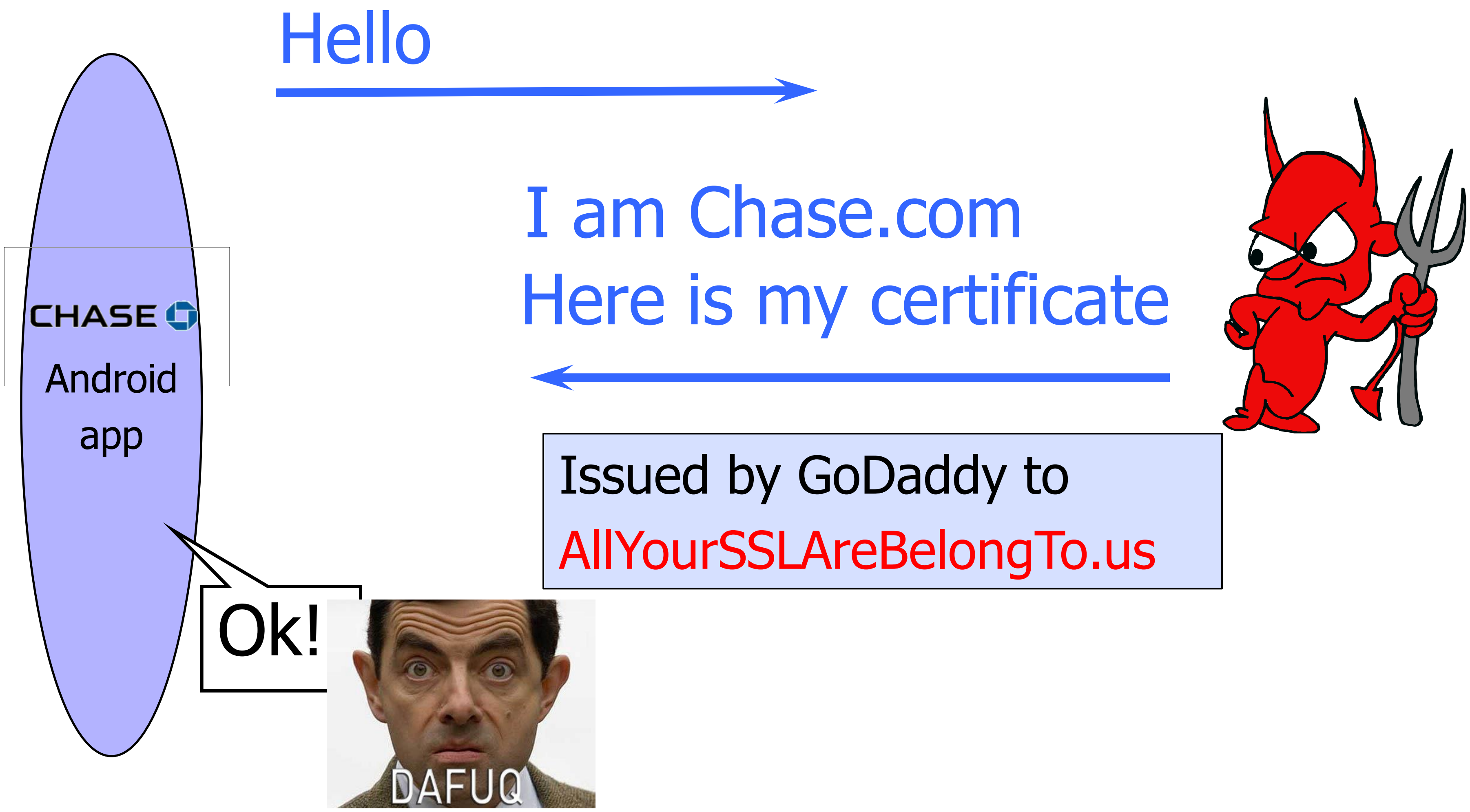
Flame

- Cyber-espionage virus (2010-2012)
- Signed with a fake intermediate CA certificate that appears to be issued by Microsoft and thus 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



Failing to Check Hostname

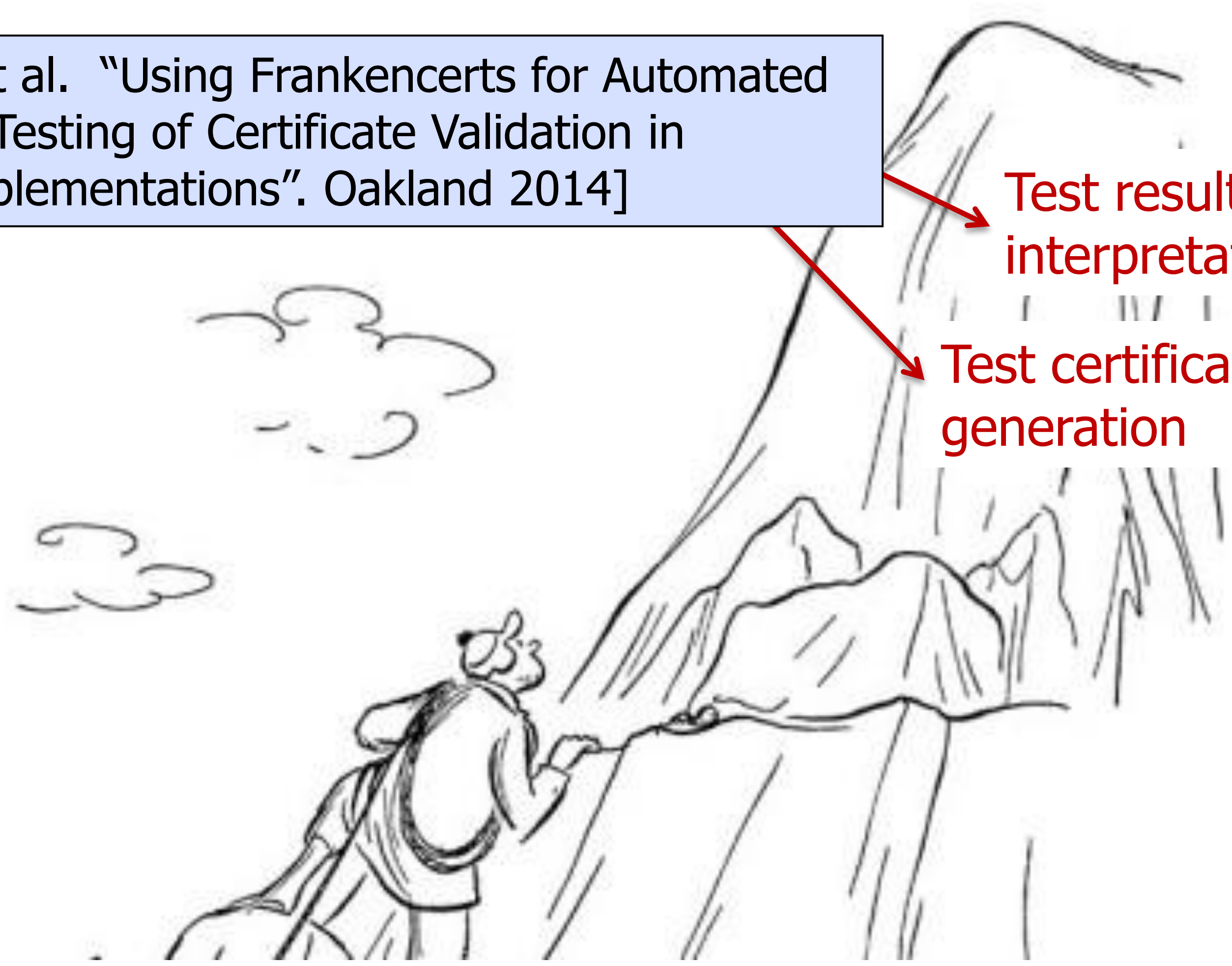
"Researchers at the University of Texas at Austin and Stanford University have discovered that poorly designed APIs used in SSL implementations are to blame for vulnerabilities in many critical non-browser software packages. Serious security vulnerabilities were found in programs such as Amazon's EC2 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.

Testing Certificate Validation Code

[Brubaker et al. "Using Frankencerts for Automated Adversarial Testing of Certificate Validation in SSL/TLS Implementations". Oakland 2014]



Test result interpretation

Test certificate generation

Generating Test Certificates

- Requirements
  - Must generate “semantically bad” certificates
  - Should be syntactically correct, otherwise will fail during parsing and won’t exercise most of the certificate validation code
  - Must scale to millions of certificates
- Idea
  - X.509 certificates contain structured data, can we exploit this?

X.509 Certificate Structure

- Multilayered structured data
- Syntactic constraints for each piece
  - Ex: Version must be an integer
- Semantic constraints for individual piece or across multiple pieces
  - Ex: Version must be 0, 1, or 2
  - Ex: if version!=2, extensions must be NULL

Version

Serial Number

Signature Algorithm Identifier

Issuer Name

Validity Period

Subject Name

Public Key Information

Issuer Unique ID

Subject Unique ID

Extensions

X.509 Standards… Ugh!

Idea: Random Re-assembly

Create X.509 certs using randomly picked syntactically valid pieces

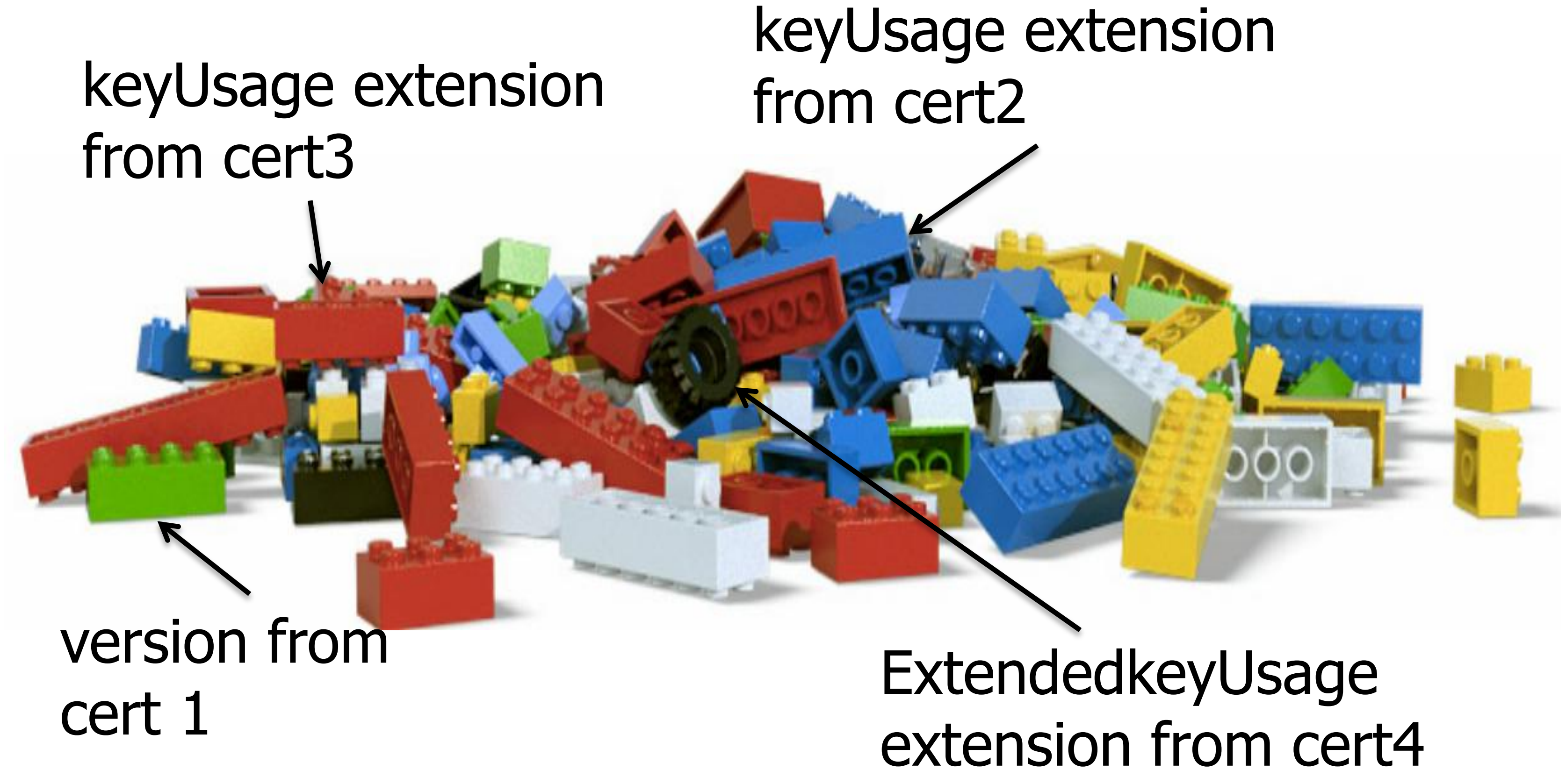
Likely to violate some semantic constraints and will thus generate "bad" test certs just as we wanted

Wait, how can we generate a large set of such syntactically valid pieces without reading X.509 specs?

1. Scan the Internet

Collect 243,246 X.509 server certificates

2. Extract Syntactically Valid Pieces


keyUsage extension from cert3
keyUsage extension from cert2
version from cert 1
ExtendedkeyUsage extension from cert4

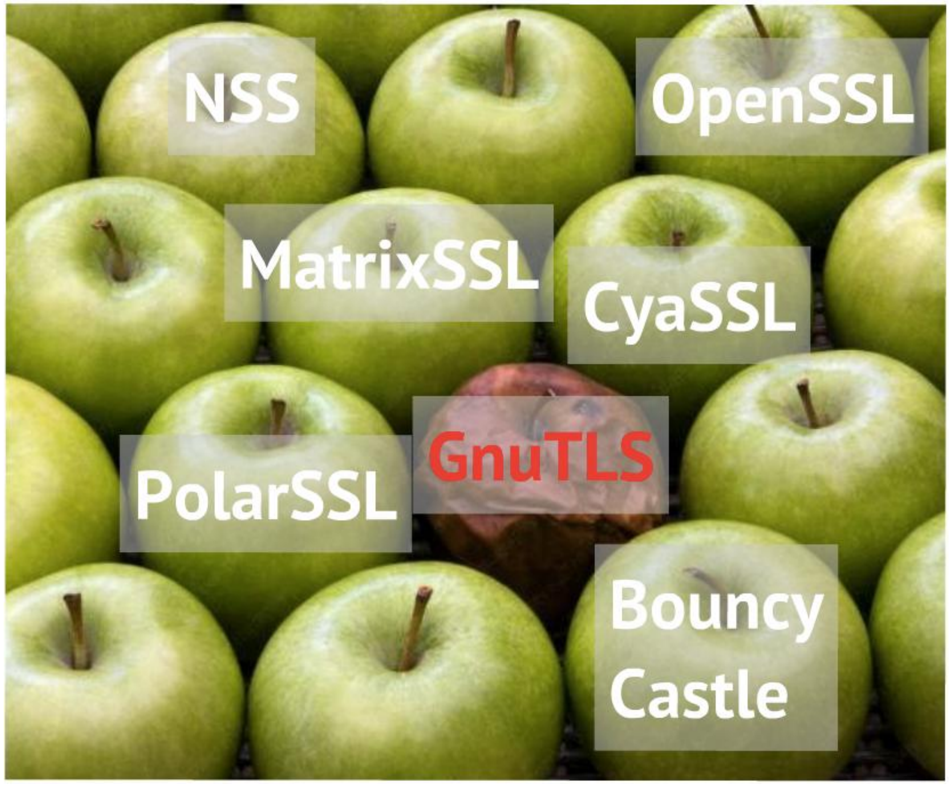
3. Frankencerts

Generate 8 million frankencerts from random combinations of certificate pieces

Differential Testing

- Multiple implementations of SSL/TLS should implement the same certificate validation logic
- If a certificate is accepted by some and rejected by others, what does this mean?

Find the Rotten One

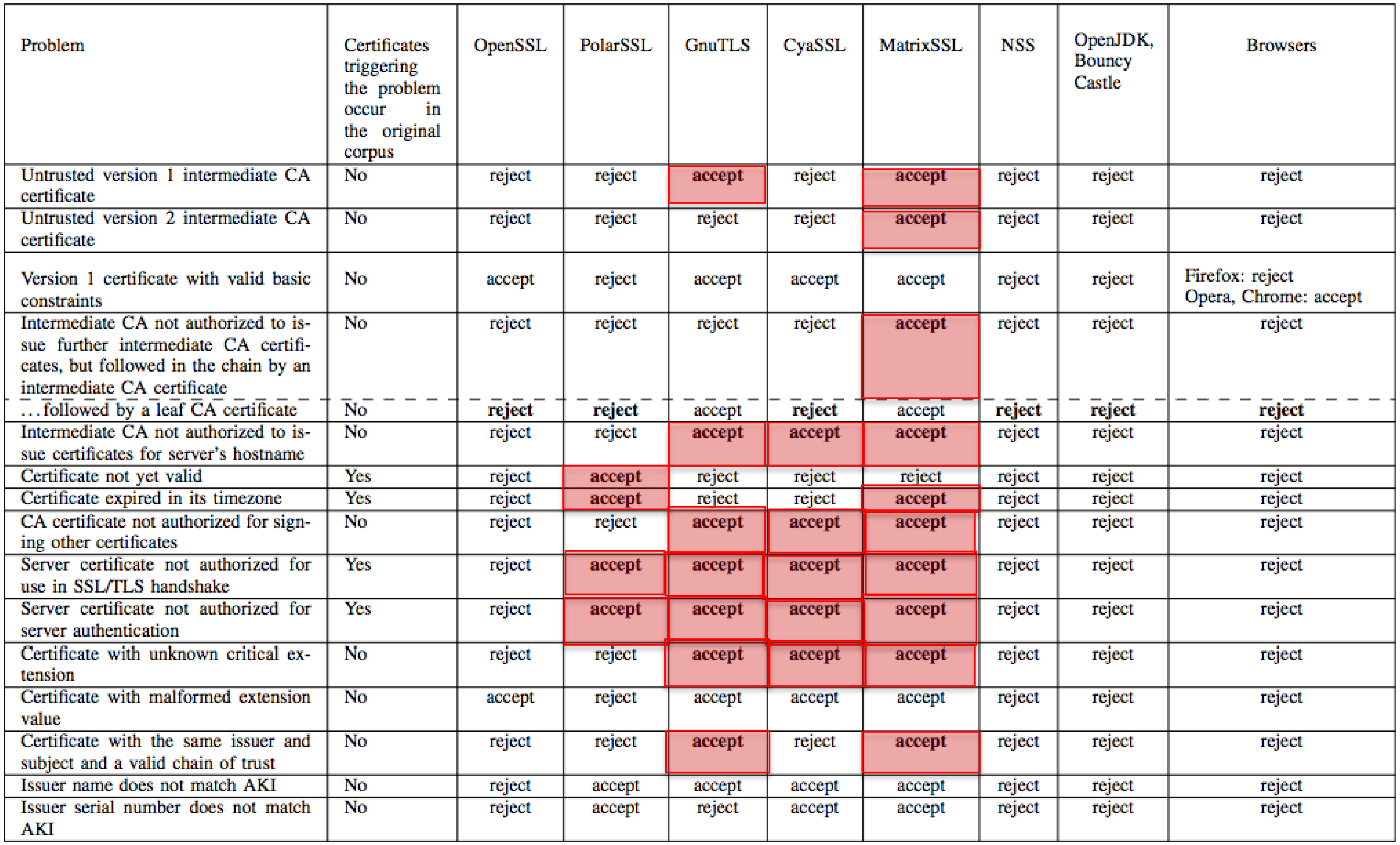


No false positives, although some discrepancies might be due to different interpretations of X.509

Results of Differential Testing

- 14 different SSL/TLS implementations
- 208 discrepancies due to 15 root causes
- Multiple bugs
  - Accepting fake and unauthorized intermediate certificate authorities $\longrightarrow$ attacker can impersonate any website!
  - Accepting certificates not authorized for use in SSL or not valid for server authentication
  - Several other issues

Results Summary



Problem	Certificates triggering the problem occur in the original corpus	OpenSSL	PolarSSL	GnuTLS	CyaSSL	MatrixSSL	NSS	OpenJDK, Bouncy Castle	Browsers
Untrusted version 1 intermediate CA certificate	No	reject	reject	**accept**	reject	**accept**	reject	reject	reject
Untrusted version 2 intermediate CA certificate	No	reject	reject	reject	reject	**accept**	reject	reject	reject
Version 1 certificate with valid basic constraints	No	accept	reject	accept	accept	accept	reject	reject	Firefox: reject Opera, Chrome: accept
Intermediate CA not authorized to issue further intermediate CA certificates, but followed in the chain by an intermediate CA certificate	No	reject	reject	reject	reject	**accept**	reject	reject	reject
…followed by a leaf CA certificate	No	**reject**	**reject**	accept	**reject**	accept	**reject**	**reject**	**reject**
Intermediate CA not authorized to issue certificates for server's hostname	No	reject	reject	**accept**	**accept**	**accept**	reject	reject	reject
Certificate not yet valid	Yes	reject	**accept**	reject	reject	reject	reject	reject	reject
Certificate expired in its timezone	Yes	reject	**accept**	reject	reject	**accept**	reject	reject	reject
CA certificate not authorized for signing other certificates	No	reject	reject	**accept**	**accept**	**accept**	reject	reject	reject
Server certificate not authorized for use in SSL/TLS handshake	Yes	reject	**accept**	**accept**	**accept**	**accept**	reject	reject	reject
Server certificate not authorized for server authentication	Yes	reject	**accept**	**accept**	**accept**	**accept**	reject	reject	reject
Certificate with unknown critical extension	No	reject	reject	**accept**	**accept**	**accept**	reject	reject	reject
Certificate with malformed extension value	No	accept	reject	accept	accept	accept	reject	reject	reject
Certificate with the same issuer and subject and a valid chain of trust	No	reject	reject	**accept**	reject	**accept**	reject	reject	reject
Issuer name does not match AKI	No	reject	accept	accept	accept	accept	reject	reject	reject
Issuer serial number does not match AKI	No	reject	accept	reject	accept	accept	reject	reject	reject

Version 1 CA certificates

If an SSL/TLS implementation encounters a version 1 (v1) CA certificate that cannot be validated out of band, it must reject it

RFC 5280 Section 6.1.4(k)

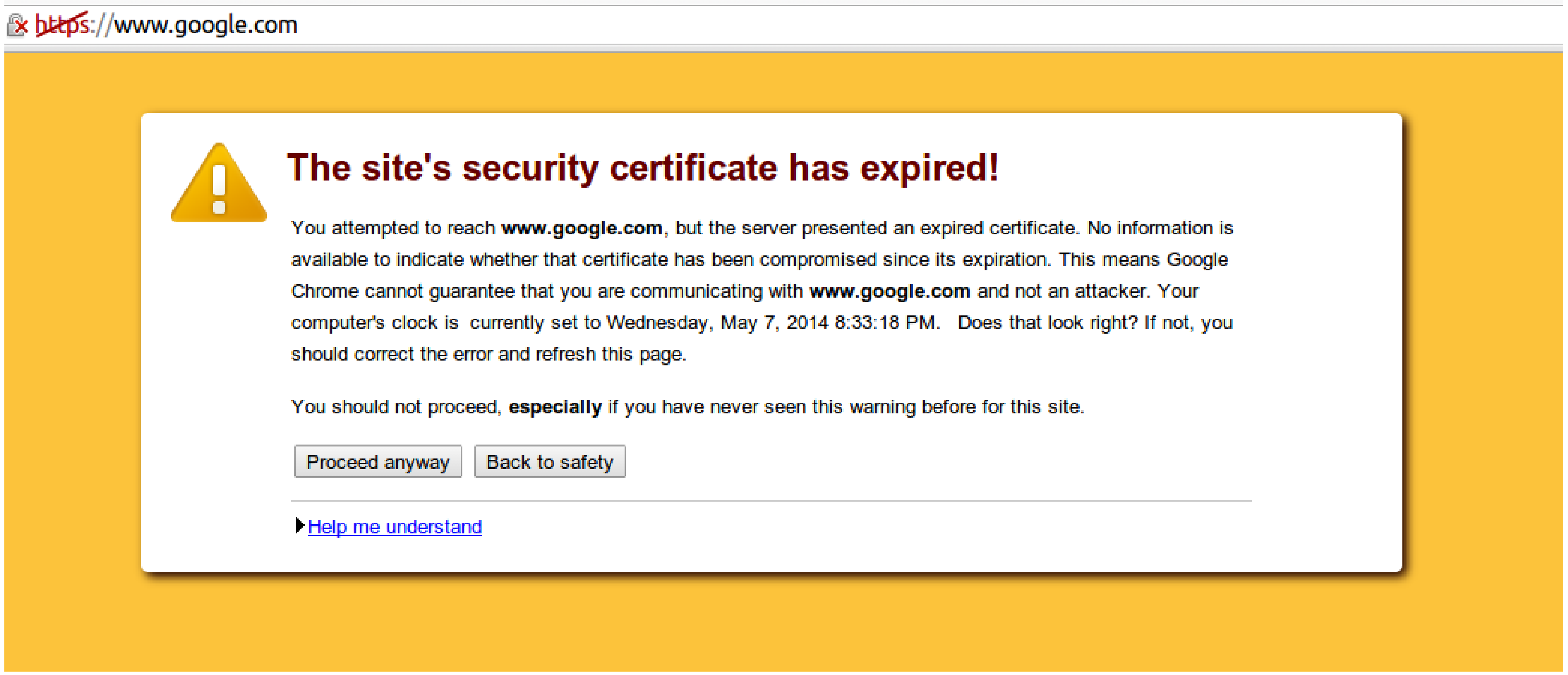
v1 CA certificates do not support the CA bit: anybody with a valid v1 certificate can pretend to be a CA

Exhibit 1: GnuTLS

```
/* Disable V1 CA flag to prevent version 1 certificates in a supplied
chain. */
   flags &= ~(GNUTLS_VERIFY_ALLOW_X509_V1_CA_CRT);
   ret = _gnutls_verify_certificate2 (flags,..))

int _gnutls_verify_certificate2(flags, ..)
{
   if (!(flags & GNUTLS_VERIFY_DISABLE_CA_SIGN) &&
         ((flags & GNUTLS_VERIFY_DO_NOT_ALLOW_X509_V1_CA_CRT)
           || issuer_version != 1))
   {
      /*check the CA bit */
   }
}
```

Exhibit 2: Google Chrome



~~https~~://www.google.com

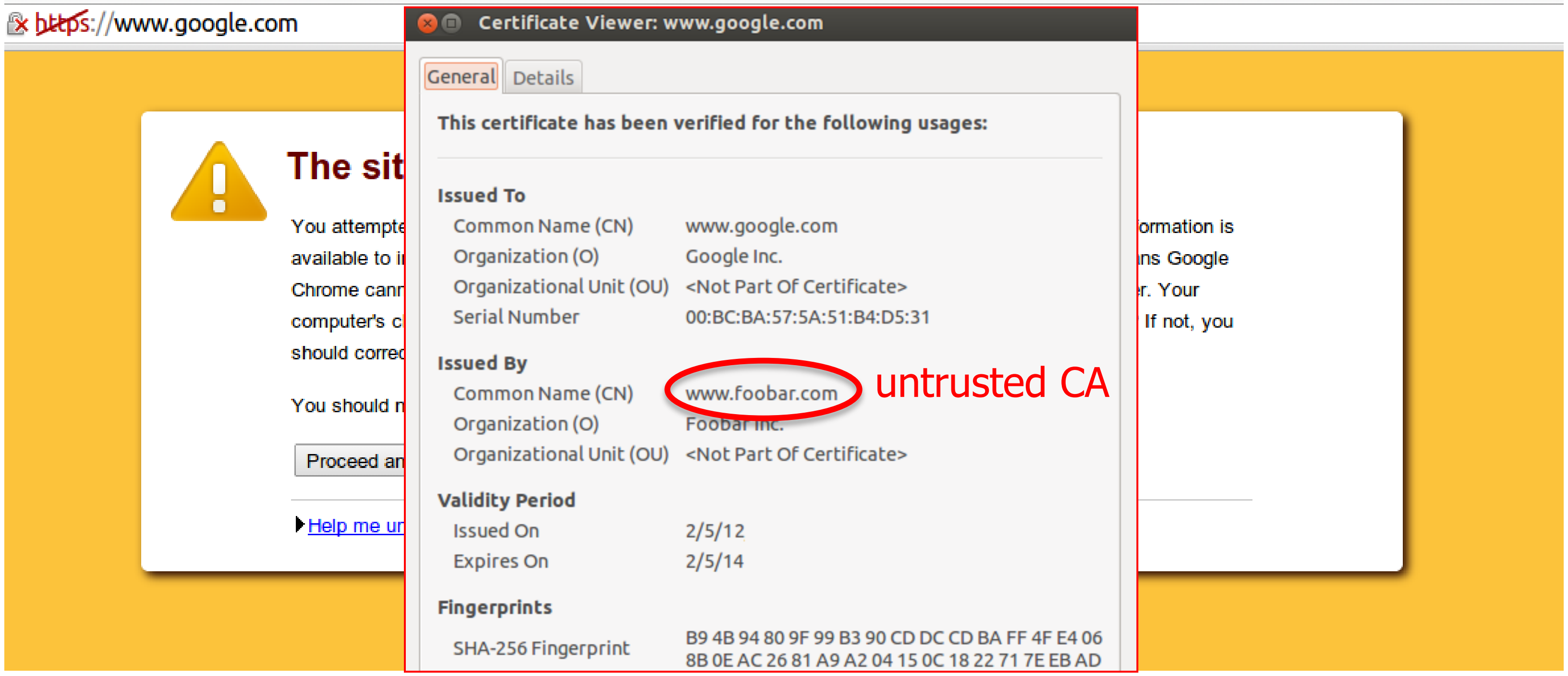
The site's security certificate has expired!

You attempted to reach **www.google.com**, but the server presented an expired certificate. No information is available to indicate whether that certificate has been compromised since its expiration. This means Google Chrome cannot guarantee that you are communicating with **www.google.com** and not an attacker. Your computer's clock is currently set to Wednesday, May 7, 2014 8:33:18 PM. Does that look right? If not, you should correct the error and refresh this page.

You should not proceed, **especially** if you have never seen this warning before for this site.

OK to click through?

Exhibit 2: Google Chrome



~~https~~://www.google.com

The sit

You attempte... available to i... Chrome cann... computer's c... should correc...

...ormation is ...ns Google ...r. Your ... If not, you

You should n...

Proceed an...

Help me u...

Certificate Viewer: www.google.com

This certificate has been verified for the following usages:

Issued To

Common Name (CN)	www.google.com
Organization (O)	Google Inc.
Organizational Unit (OU)	<Not Part Of Certificate>
Serial Number	00:BC:BA:57:5A:51:B4:D5:31

Issued By

Common Name (CN)	www.foobar.com
Organization (O)	Foobar Inc.
Organizational Unit (OU)	<Not Part Of Certificate>

untrusted CA

Validity Period

Issued On	2/5/12
Expires On	2/5/14

Fingerprints

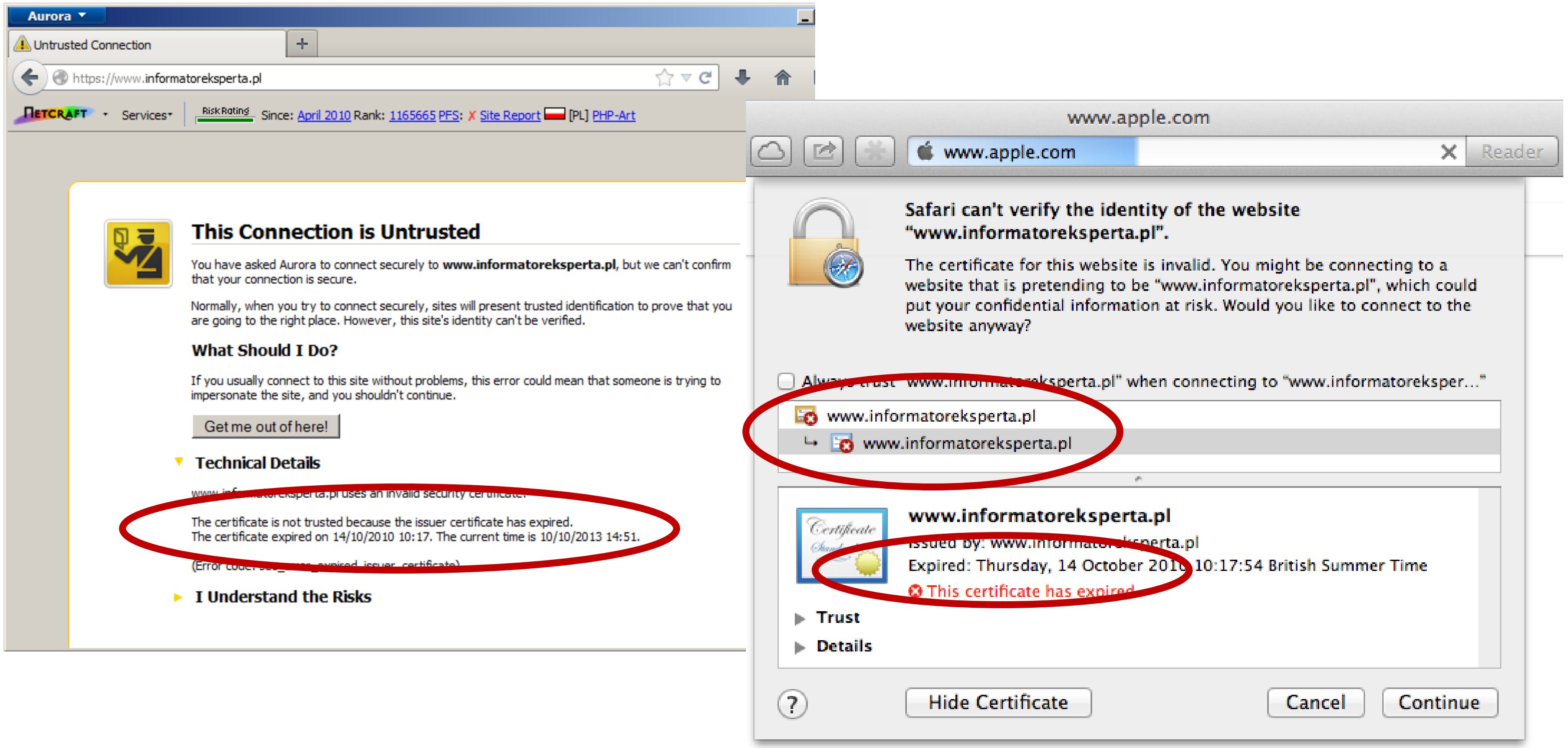
SHA-256 Fingerprint	B9 4B 94 80 9F 99 B3 90 CD DC CD BA FF 4F E4 06 8B 0E AC 26 81 A9 A2 04 15 0C 18 22 71 7E EB AD

Exhibit 2: Root Cause

- Chrome on Linux uses a modified version of NSS
- If a certificate is issued by an untrusted CA and is expired, the NSS certificate validation code returns only the "expired" error
- Firefox uses a glue layer called Personal Security Manager (PSM) over NSS and thus is not affected

Another Bad Warning

[redacted] http://news.netcraft.com/archives/2013/10/16/us-government-aiding-spying-against-itself.html



Aurora
Untrusted Connection
https://www.informatoreksperta.pl
NETCRAFT
Services
Risk Rating
Since: April 2010 Rank: 1165665 PFS: ✗ Site Report [PL] PHP-Art

This Connection is Untrusted

You have asked Aurora to connect securely to **www.informatoreksperta.pl**, but we can't confirm that your connection is secure.

Normally, when you try to connect securely, sites will present trusted identification to prove that you are going to the right place. However, this site's identity can't be verified.

What Should I Do?

If you usually connect to this site without problems, this error could mean that someone is trying to impersonate the site, and you shouldn't continue.

www.informatoreksperta.pl uses an invalid security certificate.

The certificate is not trusted because the issuer certificate has expired.
The certificate expired on 14/10/2010 10:17. The current time is 10/10/2013 14:51.

(Error code: sec_error_expired_issuer_certificate)

Safari can't verify the identity of the website "www.informatoreksperta.pl".

The certificate for this website is invalid. You might be connecting to a website that is pretending to be "www.informatoreksperta.pl", which could put your confidential information at risk. Would you like to connect to the website anyway?

Always trust "www.informatoreksperta.pl" when connecting to "www.informatoreksper…"

www.informatoreksperta.pl
↳ www.informatoreksperta.pl

www.informatoreksperta.pl
Issued by: www.informatoreksperta.pl
Expired: Thursday, 14 October 2010 10:17:54 British Summer Time
This certificate has expired

What Happens After Validation?

Hello

I am PayPal.com

(or whoever you want me to be)

Here is PayPal's certificate for its RSA signing key

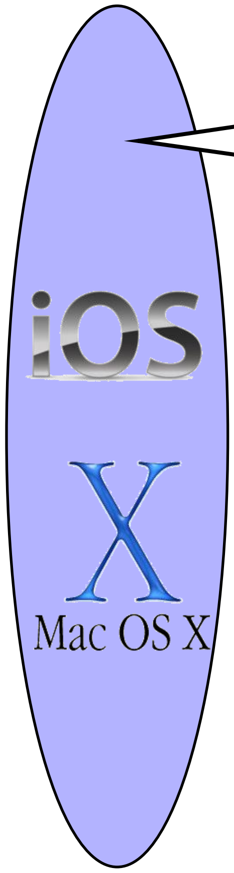
And here is my signed Diffie-Hellman value

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(...);   Signature is verified here
…
fail: … return err …
```

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 <u>no</u> 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 <u>very</u> 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 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!

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?

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