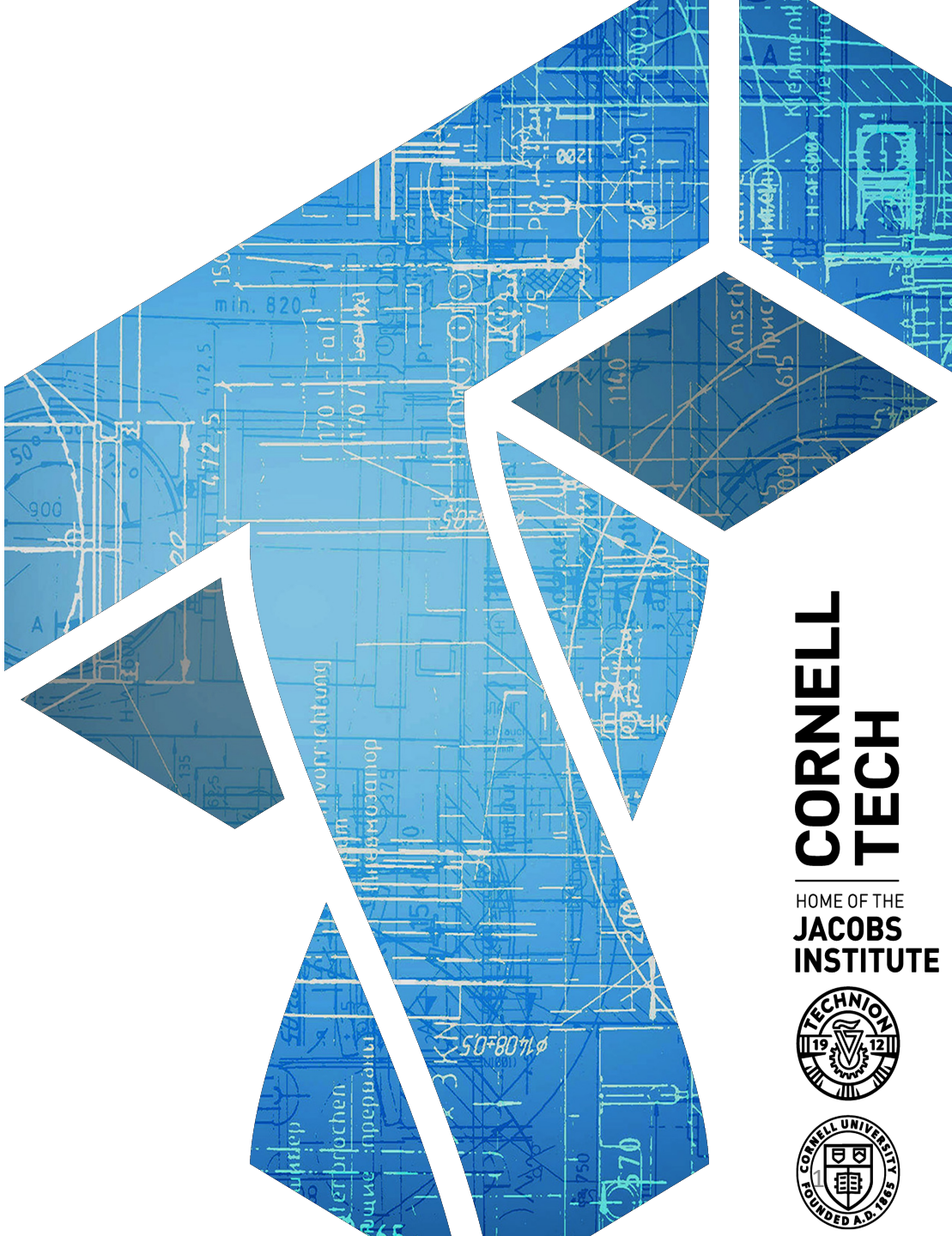
CS 5830
Cryptography



CORNELL TECH

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TLS handshake for Diffie-Hellman Key Exchange

Client

Server

Pick random Nc

ClientHello, MaxVer, Nc, Ciphers/CompMethods →

Check CERT using CA public verification key
Check σ

← ServerHello, Ver, Ns, SessionID, Cipher/CompMethod

Pick random Ns

Pick random x
$X = g^x$

← CERT = (pk_s , signature over it)

← p , g , X , σ = Sign(sk_s, Nc||Ns||p||g||X)

Pick random y
$Y = g^y$

Y →

$PMS = g^{xy}$

$PMS = g^{xy}$

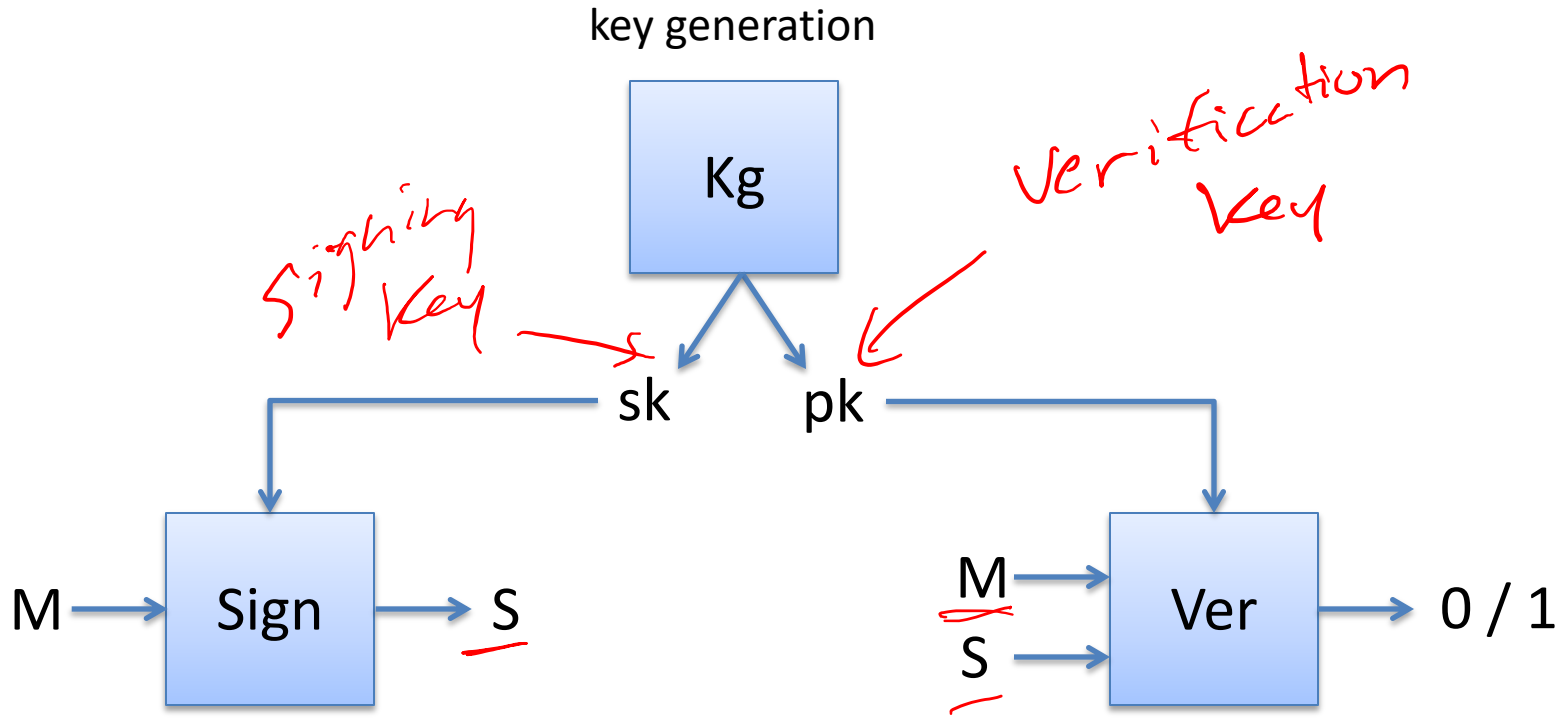
ChangeCipherSpec,
{ Finished, PRF(MS, "Client finished" || H(transcript)) } →

ChangeCipherSpec,
{ Finished, PRF(MS, "Server finished" || H(transcript')) } ←

Bracket notation means contents encrypted

MS <- PRF(PMS, "master secret" || Nc || Ns)

Digital signatures



Signing can be deterministic or randomized

Anyone with public key can verify a signature

Only holder of secret key should be able to generate a signature

Digital signatures

Three algorithms:

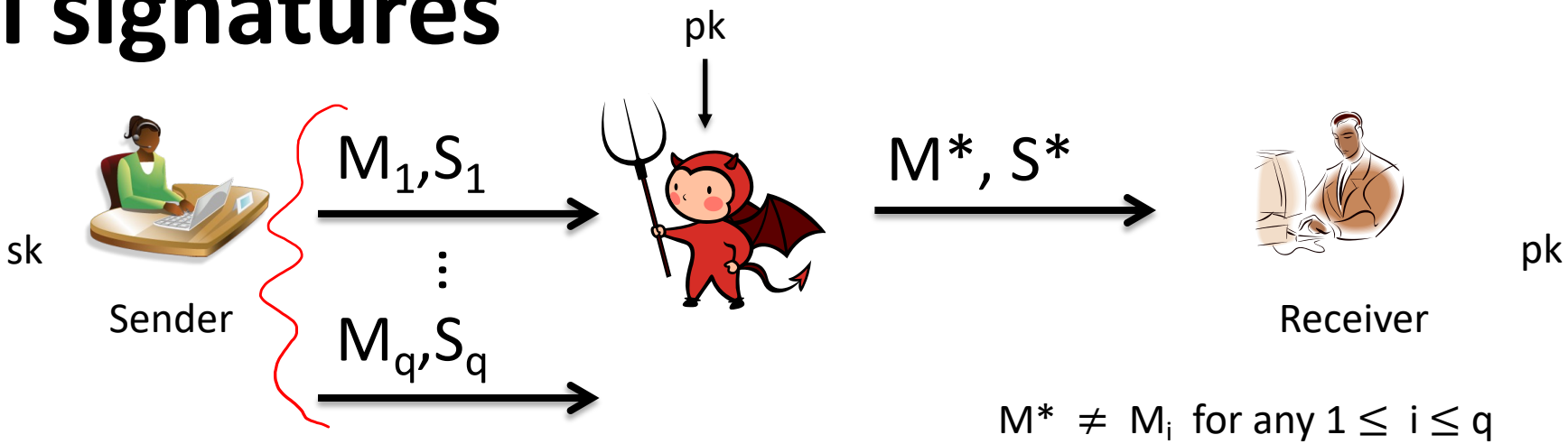
(1) Key generation outputs (pk,sk)

(2) Sign(sk,M) outputs a signature S (may be randomized)

(3) Ver(pk,M,S) outputs 0/1 (invalid / valid)

Correctness: Ver(pk,M,Sign(sk,M)) = 1 always

Digital signatures



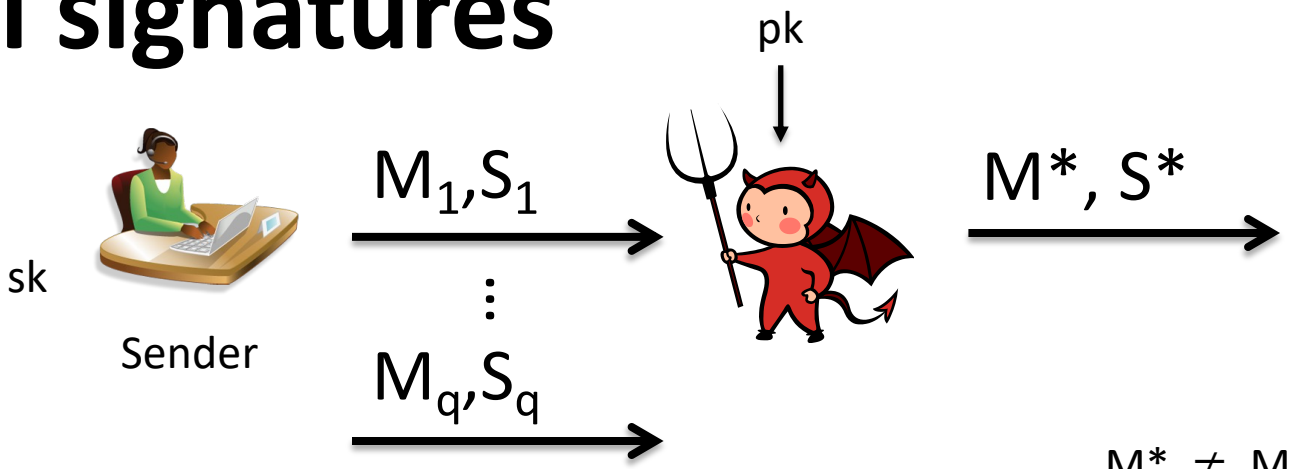
Unforgeability under chosen message attack (UF-CMA)

No computationally efficient attacker can forge valid signature for a new message even when attacker gets

$$(M_1 , S_1) , (M_2 , S_2), \dots , (M_q , S_q)$$

for messages of his choosing and reasonably large q.

Digital signatures



$M^* \neq M_i$ for any $1 \leq i \leq q$

"Raw" RSA as a signature scheme:

Key generation gives (N,e) , (N,d)

Sign((N,d),M) = $M^d \bmod N$

Verify((N,e),M,S) checks if $S^e \bmod N = M$

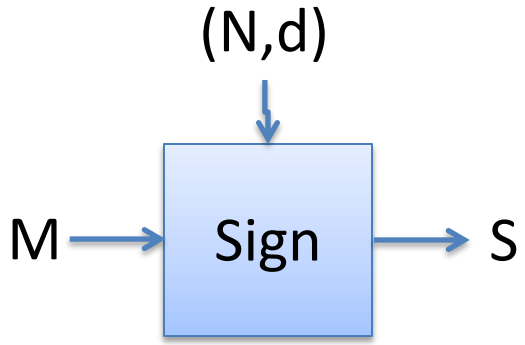
Secure? No!

PKCS #1 v1.5 RSA signing

Kg outputs (N,e),(N,d) where $|N|_8 = n$

Want to sign using hash with output length m bytes

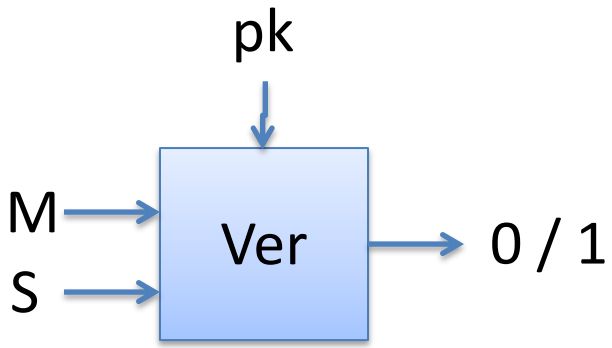
Let p = n – m - 3



Sign((N,d), M)

Y = 00 || 01 || FF^p || 00 || H(M)

Return Y^d mod N



Verify((N,e), M, S)

Y = S^e mod N ; aa||bb||cc||dd||h = Y

If (aa ≠ 00) or (bb ≠ 01) or (cc ≠ FF^p)

or (dd ≠ 00)

Return error

Return H(M) = h

PKCS#1 v1.5 digital signature security

Padding oracle attacks that work against RSA PKCS#1 v1.5 decryption can be used to forge a signature

- Treat Y = 00 || 01 || FF^p || 00 || H(M) as ciphertext in Bleichanbacher attack, allows computing S = Y^d mod N
  - See [Bock et al. 2018] paper (https://www.usenix.org/system/files/conference/usenixsecurity18/sec18-bock.pdf)

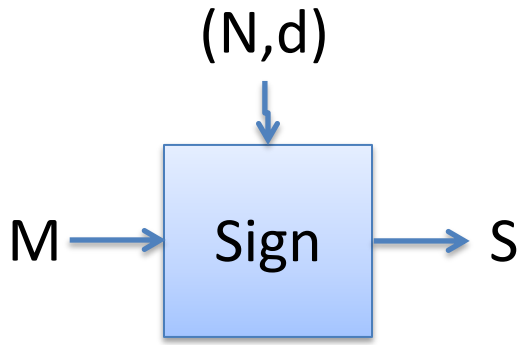
- If same RSA key pair used for signatures, then this is problem

- Don’t use same keys for signing and encryption

Full Domain Hash RSA

Kg outputs pk = (N,e) , sk = (N,d) where $|N|_8 = n$

H is hash with m-byte output k = ceil((n – 1)/m)

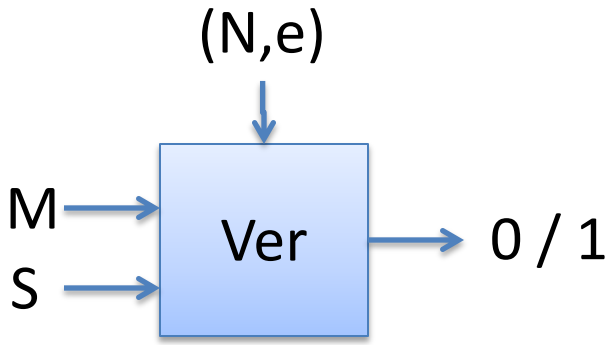


Sign((N,d), M)

X = ~~00 ||~~ H(1||M) || … || H(k||M)

S = X^d mod N

Return S



Ver((N,e), M, S)

X = S^e mod N

X' = ~~00 ||~~ H(1||M) || … || H(k||M)

If X = X' then Return 1

Return 0

Probabilistic Signature Scheme (PSS) provides stronger security bounds and also deployed now, see PKCS#1 v2

Groups for Schnorr and DSA Signatures

Let p be a large prime number

Let q be a prime such that q divides p-1

Example: $p = 2q + 1$ (so-called safe prime p)

Fix the group $G = \mathbf{Z}_p^* = \{1,2,3,\ldots, p-1\}$

Let g be generator of sub-group of order q:

$$\{ g^0, g^1, g^2, \ldots, g^{q-1} \} \text{ subset of } G$$

How to pick g?

$g = h^{(p-1)/q} \bmod p$ for some h and check $g \neq 1 \bmod p$

If so, try again with another h. Usually start with h = 2

(Variant of) Schnorr signatures

p,q,g specified

sk = x chosen randomly from $\mathbf{Z}_q$ pk = $X = g^x$

Sign(x, M)

~~$r \leftarrow \$ \mathbf{Z}_q$~~ ; $r \leftarrow H(x \| M \| \ldots)$

$R = g^r$; $c = H(M \| R)$; $z = r + cx \mod q$

Return (R,z)

Ver(X, M, (R,z))

$c = H(M \| R)$

If $g^z = RX^c$ then Return 1

Return 0

Correctness? $g^z = g^{r + cx} = g^r g^{xc} = RX^c$

Security intuition

Assume an adversary that can output forgery (M,(R,z))
Then to be valid:

$$g^z = RX^c \quad \text{implies} \quad z = r + cx$$

for $c = H(M \,||\, R)$.
Assume c is random (H is random oracle)

Imagine we can run adversary twice but force forgery to be on same R, different c .
In second execution, getting (M',(R,z'))

Then success second time around gives:

$$g^{z'} = RX^{c'} \quad \text{implies} \quad z' = r + c'x$$

But now can compute $(z - z') / (c - c') = x$ the secret key

Fragility of signatures

Repeat randomness failure:

Sign two messages M ≠ M' and reuse randomness

Sign(x,M) -> (R,z) = (R, r + cx mod q)

Sign(x,M') -> (R,z') = (R, r + c'x mod q)

Then: $x = (z - z') / (H(M||R) - H(M'||R))$

If r is predictable/leaked, can recover secret from (R,z)

Actual Schnorr signatures

p,q,g specified

sk = x chosen randomly from $\mathbf{Z}_q$ pk = $X = g^x$

Sign(x, M)

r <-$ $\mathbf{Z}_q$

$R = g^r$; $c = H(M \,||\, R)$; $z = r + cx \mod q$

Return (c,z)

Ver(X, M, (c,z))

$R' = g^z X^{-c}$

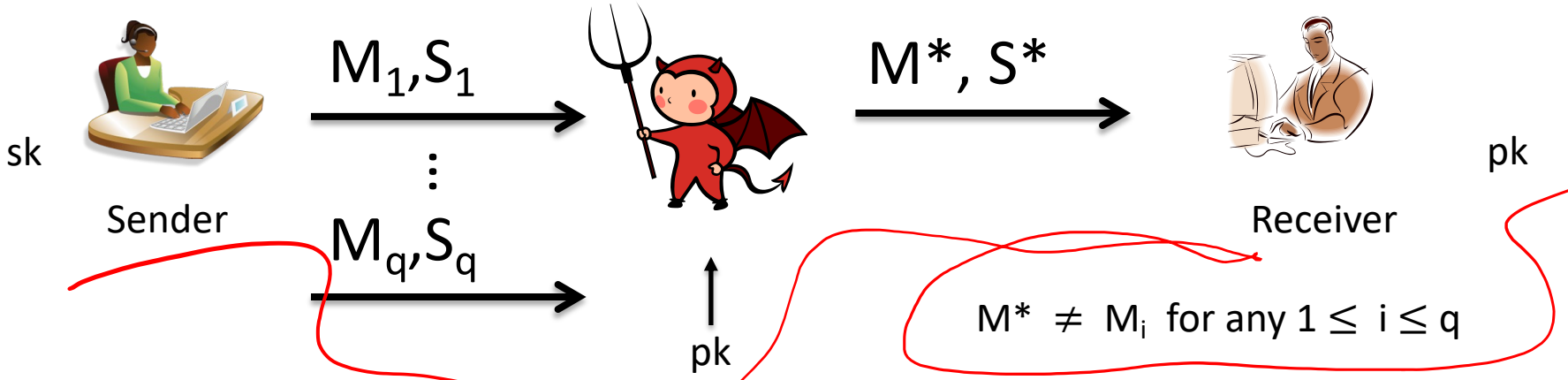
$c' = H(M \,||\, R')$

If c' = c then Return 1

Return 0

Correctness? $R' = g^z X^{-c} = g^{r + cx} g^{x(-H(M||R))} = g^r$

Formalizing unforgeability



UF-CMA for digital signatures

UF-CMA($\mathcal{MS}$, $\mathcal{A}$):
(pk,sk) <-$ Kg
(M*,S*) <-$ $\mathcal{A}^{Sign}$(pk)
If M* ∈ MsgSet then
  Return 0
Return Verify(pk,M*,S*)

Sign(M)
MsgSet <- MsgSet U {M}
Return Sign(sk,M)

UF-CMA: Symmetric vs asymmetric settings

UF-CMA(MA, $\mathcal{A}$):
K <-$ Kg
(M*,T*) <-$ $\mathcal{A}^{\text{Tag}}$
If M* ∈ MsgSet then
  Return 0
Return Verify(K,M*,T*)

Tag(M)
MsgSet <- MsgSet U {M}
Return Tag(K,M)

Unforgeability under chosen message attack for message authentication schemes

UF-CMA(DS, $\mathcal{A}$):
(pk,sk) <-$ Kg
(M*,S*) <-$ $\mathcal{A}^{\text{Sign}}$(pk)
If M* ∈ MsgSet then
  Return 0
Return Verify(pk,M*,S*)

Sign(M)
MsgSet <- MsgSet U {M}
Return Sign(sk,M)

Unforgeability under chosen message attack for digital signature schemes

Schnorr formal security analysis

- UF-CMA for digital signatures
- Requires modeling H as a ***random oracle***
  - Public random function all parties have access to
  - Very successful modeling approach
- Fiat-Shamir analysis : security if DL is hard
  - Fiat-Shamir transform converts any of a class of zero-knowledge protocols to a digital signature
  - Security of protocol shown to imply UF-CMA in random oracle model
- Time allowing we will do a lecture on zero-knowledge proofs

UF-CMA(MA,$\mathcal{A}$):
(pk,sk) <-$ Kg
(M*,S*) <-$ $\mathcal{A}^{Sign}$(pk)
If M* ∈ MsgSet then
  Return 0
Return Verify(pk,M*,S*)

Sign(M)
MsgSet <- MsgSet U {M}
Return Sign(sk,M)

H(x) : return p(x)

p is a random function

Formal security analysis

UF-CMA(MA,$\mathcal{A}$):
(pk,sk) <-$ Kg
(M*,S*) <-$ $\mathcal{A}^{\text{Sign}}$(pk)
If M* ∈ MsgSet then
  Return 0
Return Verify(pk,M*,S*)

Sign(M)
MsgSet <- MsgSet U {M}
Return Sign(sk,M)

- Schnorr formally shown to be UF-CMA assuming discrete log problem is hard
- Schnorr signatures highly vulnerable if per-message randomness known or repeated
- Why are these not contradictory?
- "Hedged" cryptography (e.g., [Ristenpart, Yilek NDSS 2010])
  - Formal models that capture randomness failures
  - New schemes that "hedge" against bad randomness: r = H(x || M || randomness)
  - Full deterministic versions: https://tools.ietf.org/id/draft-pornin-deterministic-dsa-00.xml

DSA (digital signature algorithm)

Don't patent crypto!

p,q,g specified

sk = x chosen randomly from $\mathbf{Z}_q$ pk = X = g^x

Sign(x, M)

r <-$ $\mathbf{Z}_q$; R = $(g^r \bmod p) \bmod q$

z = r^{-1} (H(M) + x R) mod q

Return (R,z)

Ver(X, M, (R,z))

w = z^{-1} mod q

u1 = H(m) * w mod q

u2 = R*w mod q

If R = $(g^{u1} X^{u2} \bmod p) \bmod q$

then Return 1

Else Return 0

Correctness?

$$g^{u1} X^{u2} = g^{H(M)\, w}\, g^{x R w} = g^{(H(M)+xR)\, w}$$

$$= g^{(H(M)+xR)\,(H(M)+xR)^{-1} r} = g^r$$

Fragility of DSA

Repeat randomness failure:

Sign two messages M ≠ M' and reuse random value r

Sign(x,M) -> (R,z) = (R, r^{-1} (H(M) + x R) mod q)

Sign(x,M') -> (R,z') = (R, r^{-1} (H(M') + x R) mod q)

Then: Solve for r^{-1}, solve for x

If r is predictable/leaked, can recover secret from (R,z)

Again, can improve security by "hedging":

choose r = H(x || M || randomness)

Hackers Describe PS3 Security As Epic Fail, Gain Unrestricted Access

BY MIKE BENDEL DECEMBER 29, 2010 @ 11:19 AM

http://psx-scene.com/forums/content/sony-s-ps3-security-epic-fail-videos-within-581/

Digital signature schemes

	Problems?	Proofs?	Uses
RSA PKCS#1 v1.5	Bleichanbacher attacks	[Jager et al. 2018]	TLS, Certificates, XML
RSA PSS (PKCS#1 v2)		Security reduces to hardness of inverting RSA	
Schnorr	Randomness fragility	Security reduces to discrete log problem	
DSA	Randomness fragility	No formal security reduction	Bitcoin (ECC version), TLS, SSH, elsewhere

TLS handshake for Diffie-Hellman Key Exchange

Client

Server

Pick random Nc

ClientHello, MaxVer, Nc, Ciphers/CompMethods →

Check CERT using CA public verification key
Check σ

← ServerHello, Ver, Ns, SessionID, Cipher/CompMethod

Pick random Ns

Pick random x
$X = g^x$

← CERT = (pk_s , signature over it)

← p , g, X , σ = Sign(sk_s,Nc||Ns||p||g||X)

Pick random y
$Y = g^y$

Y →

$PMS = g^{xy}$

$PMS = g^{xy}$

ChangeCipherSpec,
{ Finished, PRF(MS, “Client finished” || H(transcript)) } →

ChangeCipherSpec,
{ Finished, PRF(MS, “Server finished” || H(transcript’)) } ←

Bracket notation means contents encrypted

MS <- PRF(PMS, “master secret” || Nc || Ns)

Apple iOS <7.0.16 signature verification code

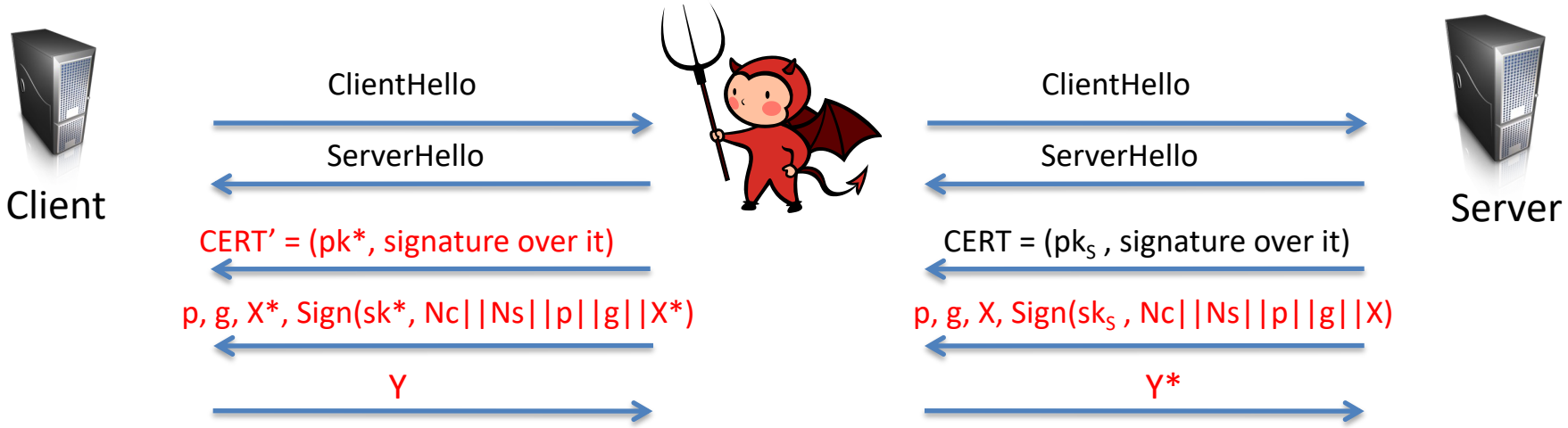
```
    if ((err = ReadyHash(&SSLHashSHA1, &hashCtx)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &signedParams))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

        err = sslRawVerify(ctx,
                           ctx->peerPubKey,
                           dataToSign,                          /* plaintext */
                           dataToSignLen,                  /* plaintext length */
                           signature,
                           signatureLen);
        if(err) {
                sslErrorLog("SSLDecodeSignedServerKeyExchange: sslRawVerify "
                    "returned %d\n", (int)err);
                goto fail;
        }

fail:
    SSLFreeBuffer(&signedHashes);
    SSLFreeBuffer(&hashCtx);
    return err;
```

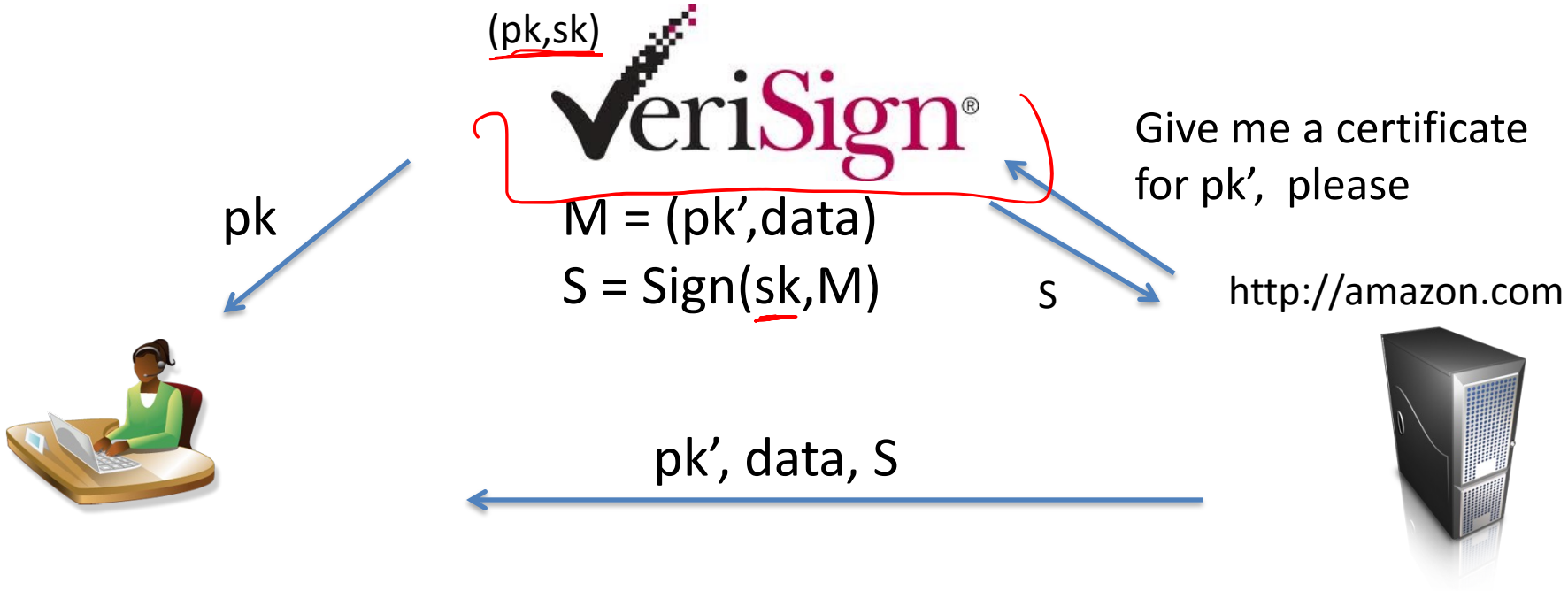
Meddler-in-the-middle attacks

Suppose authentication vulnerability:
CERT can be forged, Client doesn't check CERT, etc.



Attacker can choose X*, Y*, so it knows discrete logs
Completes handshake on both sides
Client thinks its talking to Server
All communications decrypted by adversary, re-encrypted and forwarded to server

Certificate Authorities and Public-key Infrastructure (PKI)

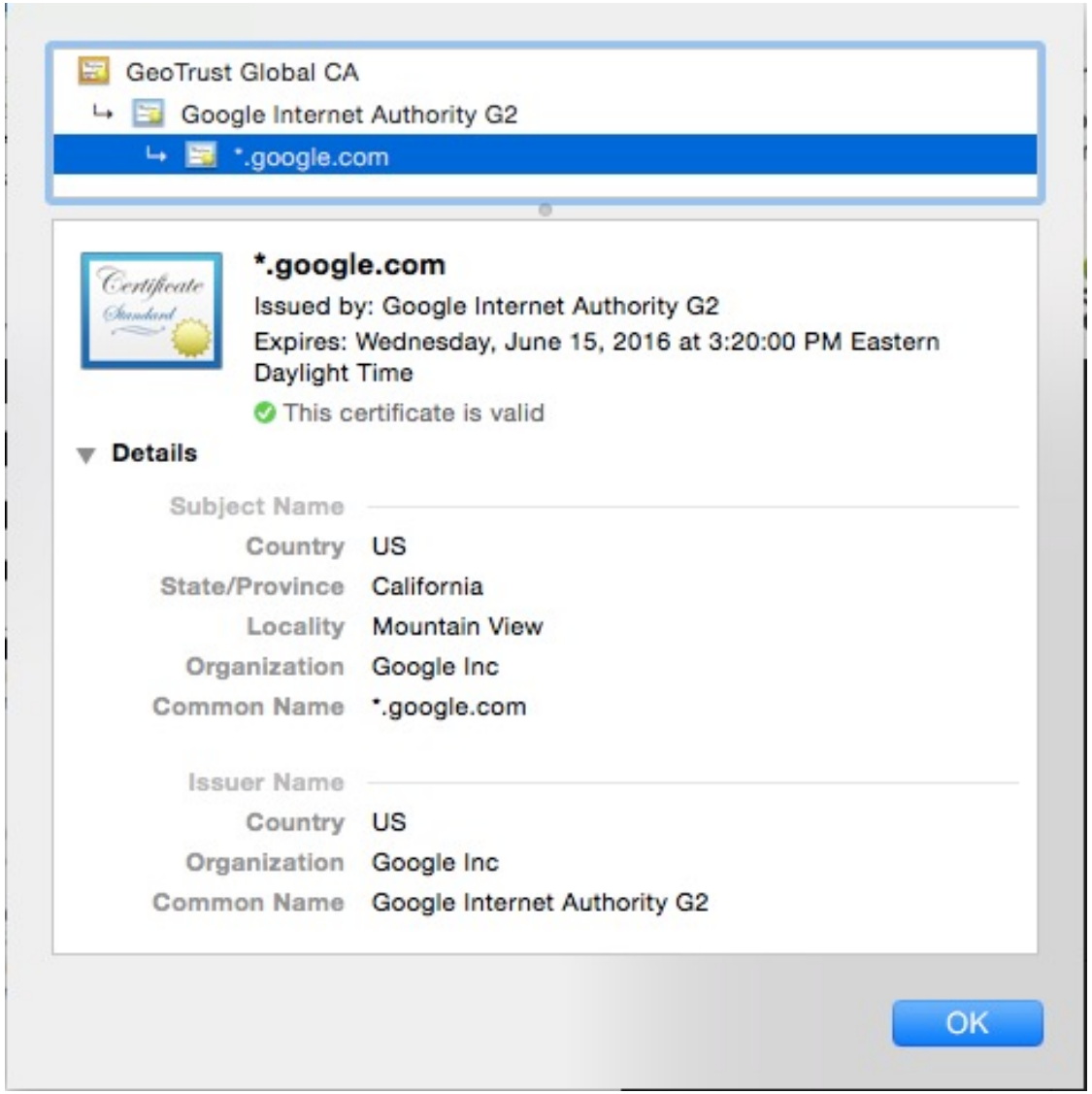


M = (pk',data)
If Ver(pk,M,S) then
trust pk'

This prevents meddler-in-the-middle (MitM) attacks

```
Certificate:
    Data:
        Version: 1 (0x0)
        Serial Number: 7829 (0x1e95)
        Signature Algorithm: md5WithRSAEncryption
        Issuer: C=ZA, ST=Western Cape, L=Cape Town, O=Thawte Consulting cc,
                OU=Certification Services Division,
                CN=Thawte Server CA/emailAddress=server-certs@thawte.com
        Validity
            Not Before: Jul  9 16:04:02 1998 GMT
            Not After : Jul  9 16:04:02 1999 GMT
        Subject: C=US, ST=Maryland, L=Pasadena, O=Brent Baccala,
                 OU=FreeSoft, CN=www.freesoft.org/emailAddress=baccala@freesoft.org
        Subject Public Key Info:
            Public Key Algorithm: rsaEncryption
            RSA Public Key: (1024 bit)
                Modulus (1024 bit):
                    00:b4:31:98:0a:c4:bc:62:c1:88:aa:dc:b0:c8:bb:
                    33:35:19:d5:0c:64:b9:3d:41:b2:96:fc:f3:31:e1:
                    66:36:d0:8e:56:12:44:ba:75:eb:e8:1c:9c:5b:66:
                    70:33:52:14:c9:ec:4f:91:51:70:39:de:53:85:17:
                    16:94:6e:ee:f4:d5:6f:d5:ca:b3:47:5e:1b:0c:7b:
                    c5:cc:2b:6b:c1:90:c3:16:31:0d:bf:7a:c7:47:77:
                    8f:a0:21:c7:4c:d0:16:65:00:c1:0f:d7:b8:80:e3:
                    d2:75:6b:c1:ea:9e:5c:5c:ea:7d:c1:a1:10:bc:b8:
                    e8:35:1c:9e:27:52:7e:41:8f
                Exponent: 65537 (0x10001)
    Signature Algorithm: md5WithRSAEncryption
        93:5f:8f:5f:c5:af:bf:0a:ab:a5:6d:fb:24:5f:b6:59:5d:9d:
        92:2e:4a:1b:8b:ac:7d:99:17:5d:cd:19:f6:ad:ef:63:2f:92:
        ab:2f:4b:cf:0a:13:90:ee:2c:0e:43:03:be:f6:ea:8e:9c:67:
        d0:a2:40:03:f7:ef:6a:15:09:79:a9:46:ed:b7:16:1b:41:72:
        0d:19:aa:ad:dd:9a:df:ab:97:50:65:f5:5e:85:a6:ef:19:d1:
        5a:de:9d:ea:63:cd:cb:cc:6d:5d:01:85:b5:6d:c8:f3:d9:f7:
        8f:0e:fc:ba:1f:34:e9:96:6e:6c:cf:f2:ef:9b:bf:de:b5:22:
        68:9f
```

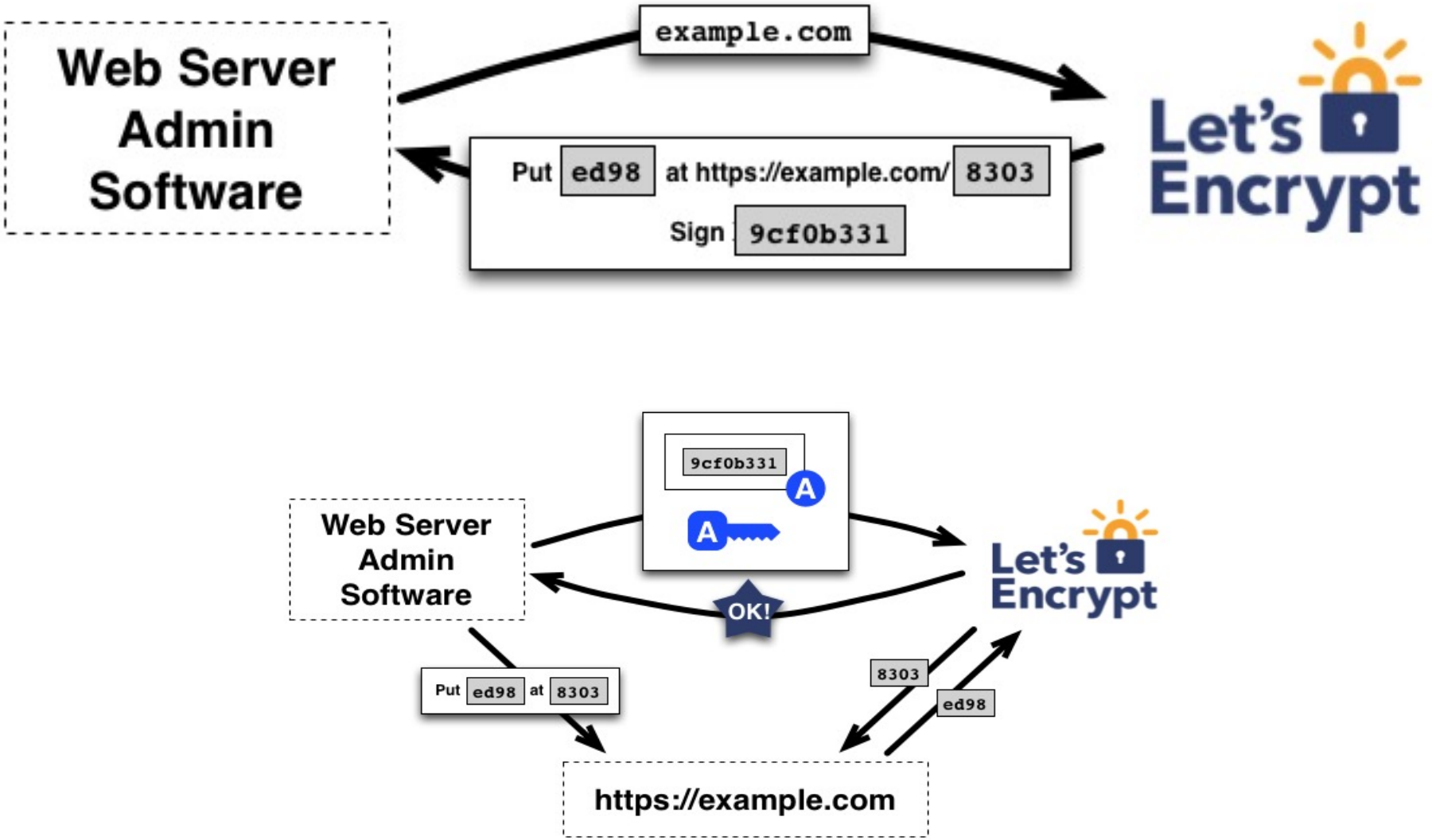
Certificate chains



Identity checks?

- CA's must check that requestor of cert is who they say they are
- Domain validated
  - Prove ownership of domain
- Extended validation
  - Establish legal identity of requestor
  - Physical presence of website owner
  - Confirm ownership of domain
  - Etc.

Free CAs


Web Server Admin Software
example.com
Put ed98 at https://example.com/ 8303
Sign 9cf0b331
Let's Encrypt
9cf0b331
A
A
OK!
Web Server Admin Software
Let's Encrypt
Put ed98 at 8303
8303
ed98
https://example.com

Revocation

- Certificates must often be revoked, big pain point in practice
  - Short expirations
  - CRLs (Certificate revocation lists)
  - OCSP (online certificate status protocol)
    - Client queries CA to check on validity of cert
      - privacy concerns, performance / scalability issues
    - Stapling: server periodically gets fresh, time-stamped OCSP signature from CA. Sends to clients

The Web PKI Ecosystem

- http://conferences.sigcomm.org/imc/2013/papers/imc257-durumericAemb.pdf

- ~1800 CAs that can sign *any* domain controlled by 683 organizations

- DigiNotar compromise, GoDaddy bug, Turktrust incident, …

Buggy Domain Validation Forces GoDaddy To Revoke SSL Certificates (threatpost.com)

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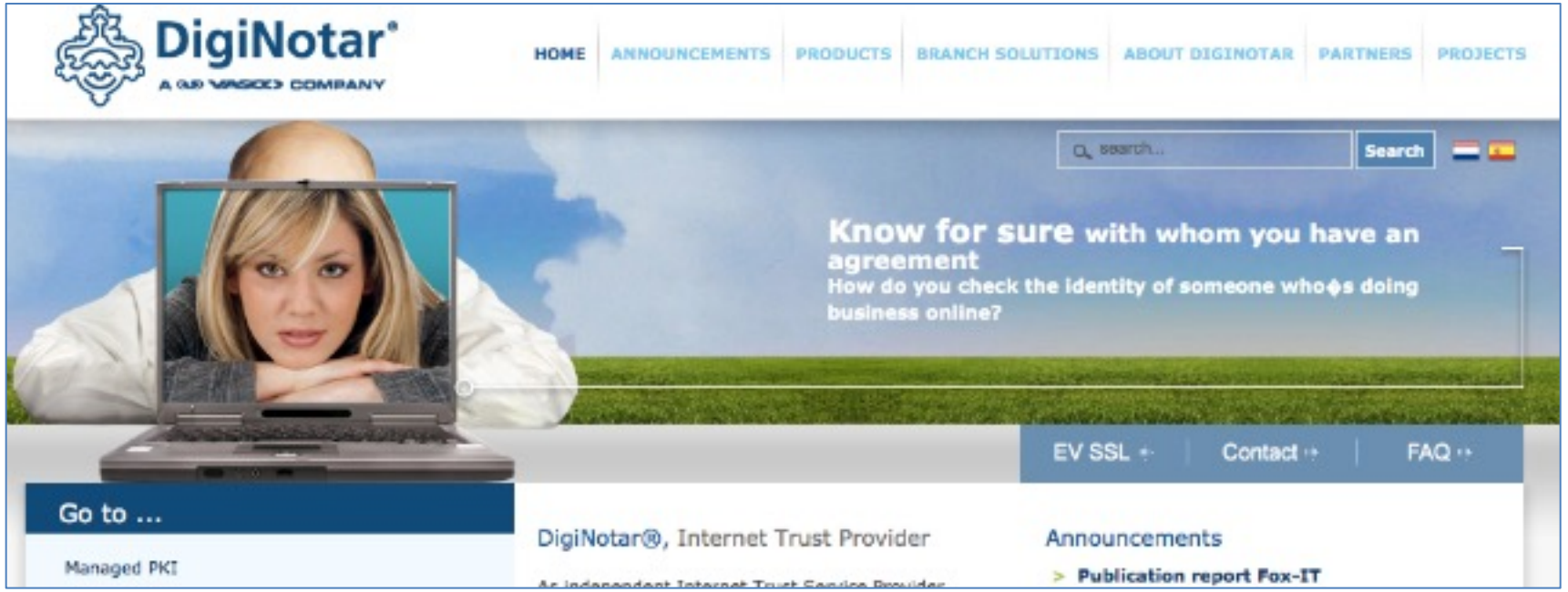
Posted by **BeauHD** on Wednesday January 11, 2017 @09:25PM from the time-to-take-action dept.

msm1267 quotes a report from Threatpost:

> GoDaddy has revoked, and begun the process of re-issuing, new SSL certificates for more than 6,000 customers after a bug was discovered in the registrar's domain validation process. The bug was introduced July 29 and impacted fewer than two percent of the certificates GoDaddy issued from that date through yesterday, said vice president and general manager of security products Wayne Thayer. "GoDaddy inadvertently introduced the bug during a routine code change intended to improve our certificate issuance process," Thayer said in a statement. "The bug caused the domain validation process to fail in certain circumstances." GoDaddy said it was not aware of any compromises related to the bug. The issue did expose sites running SSL certs from GoDaddy to spoofing where a hacker could gain access to certificates and pose as a legitimate site in order to spread malware or steal personal information such as banking credentials. GoDaddy has already submitted new certificate requests for affected customers. Customers will need to take action and log in to their accounts and initiate the certificate process in the SSL Panel, Thayer said.



Today, Microsoft issued a Security Advisory warning that fraudulent digital certificates were issued by the Comodo Certificate Authority. This could allow malicious spoofing of high profile websites, including Google, Yahoo! and Windows Live.

https://nakedsecurity.sophos.com/2011/03/24/fraudulent-certificates-issued-by-comodo-is-it-time-to-rethink-who-we-trust/

https://technet.microsoft.com/library/security/2524375

Measurement studies of TLS ecosystem

- Use internet-wide scanning to measure ecosystem

  Fewer than 2^{32} IP addresses: ~3,706,452,992
  Exclude private addresses (e.g., 192.168.0.0/16), multicast addresses, ...

- Zmap is a state-of-art tool: can scan one port of entire Internet in ~45 minutes
- Extend to perform TLS handshakes with servers that are open on port 443

Some scans

- 2011 scan (Heninger et al.)
  - 12,828,613 certificate chains recovered
  - 5,656,519 distinct RSA public keys
  - 6,241 distinct DSA public keys
  - Found many *factorable* RSA keys, DSA keys signing with repeat randomness
- 2013 scan (Durumeric et al.)
  - Almost all CA's using RSA keys for signing certs
  - ~8 million unique certificates across ~30 million hosts

2013 scan: breakdown by CA

Parent Company	Signed Leaf Certificates	
Symantec	1,184,723	(34.23%)
GoDaddy.com	1,008,226	(29.13%)
Comodo	422,066	(12.19%)
GlobalSign	170, 006	(4.90%)
DigiCert Inc	145,232	(4.19%)
StartCom Ltd.	88,729	(2.56%)
Entrust, Inc.	76,990	(2.22%)
Network Solutions	62,667	(1.81%)
TERENA	42,310	(1.22%)
Verizon Business	32,127	(0.92%)

Certificate/public-key pinning

- Client knows what cert/pk to expect, rejects otherwise
  - Pre-install some keys
  - HPKP (HTTP Public Key Pinning)
    - HTTP header that allows servers to set a hash of public key they will use

```
Public-Key-Pins:
    pin-sha256="d6qzRu9zOECb90Uez27xWltNsj0e1Md7GkYYkVoZWmM=";
    pin-sha256="LPJNul+wow4m6DsqxbninhsWHlwfp0JecwQzYpOLmCQ=";
    max-age=259200
```

https://developers.google.com/web/updates/2015/09/HPKP-reporting-with-chrome-46?hl=en

Certificate transparency

- Force CAs to log the certificates they sign in a public tamper-evident register
  - Experimental IETF standard
- Google has been pushing this
  - Chrome requires it for “extra validation” certs
  - DigiCert has implemented

Summary

- Web PKI relies on various trust assumptions
  - Can be undermined in many ways

- Digital signature schemes power PKI and verifying identities:
  - unforgeability under chosen message attack
  - RSA based schemes PKCS#1 1.5, FDH, PSS