Applied Cryptography and Network Security
CS 1653

Summer 2023

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(Slides are adapted from Prof. Adam Lee's CS1653 slides.)

Announcements

- Homework 8 due this Friday @ 11:59 pm
- Project Phase 3 Due tonight @ 11:59 pm
- Homework 9 due next Friday @ 11:59 pm
- Project Phase 4 Due on 7/31 @ 11:59 pm
  - Teams must meet with me on or before Thursday 7/27

TLS Protocol summary

At a high level, this protocol proceeds in four phases

- Setup and parameter negotiation
- Key exchange/derivation
- Authentication
- Data transmission

For security reasons, both parties participate in (almost) all phases

- Setup: Client proposes, server chooses
- Key derivation: Randomness contributed by both parties
- Authentication: Usually, just the server is authenticated (Why?)
- Data transmission: Both parties can encrypt and integrity check

The low-level details are not much more complicated than that!

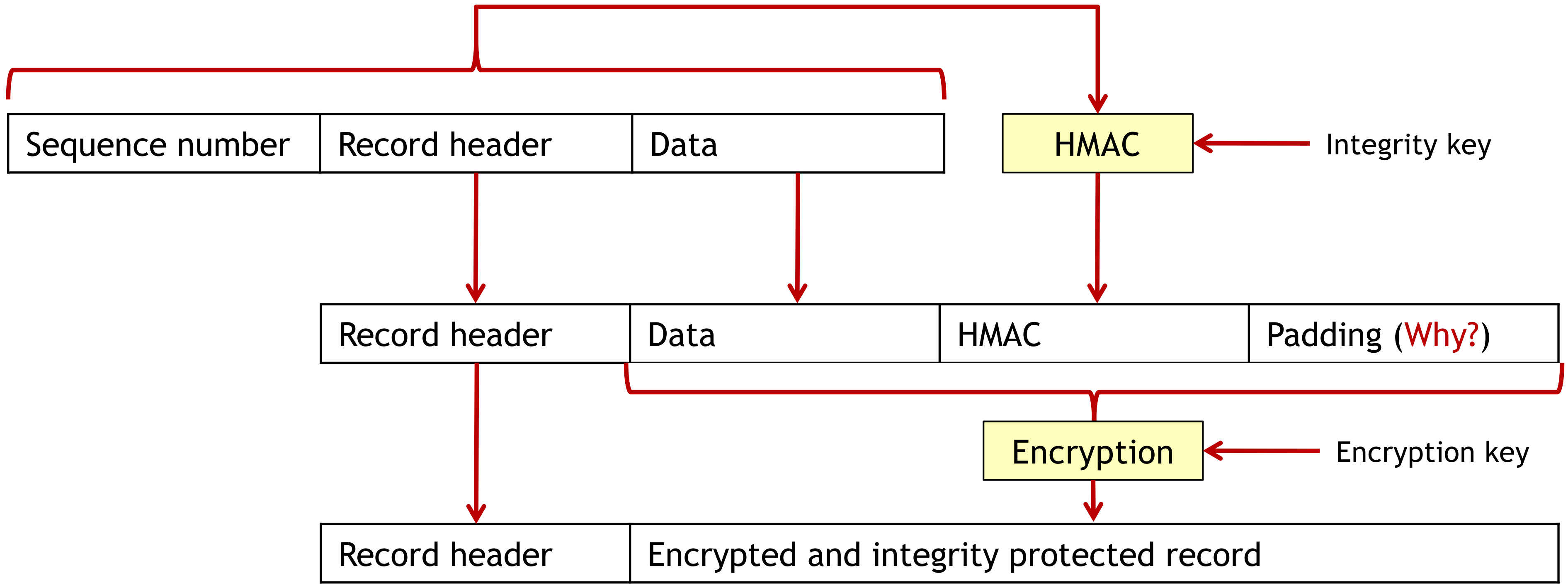
All records sent after ChangeCipherSpec are encrypted and integrity protected

All of this protection is afforded by the algorithms identified in the cipher suite chosen by the server

Example: `TLS_RSA_WITH_AES_128_CBC_SHA`

- Encryption provided using 128-bit AES in CBC mode
- Integrity protection provided by HMAC-SHA-1

Note: Data is protected one record at a time



This handshake procedure is fairly heavyweight

Public key cryptography is used by both parties

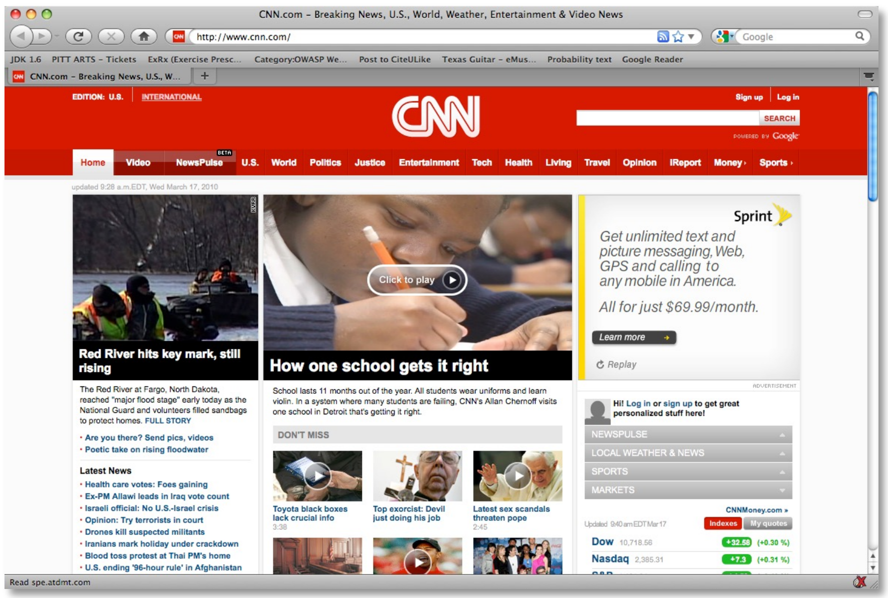
- Alice encrypts her pre-master secret using the server's public key
- The server decrypts this pre-master secret

So what! Aren't connections long lived?

Example: Visiting http://www.cnn.com

Visiting this single web page triggers over 130 separate HTTP connections!

This is less than optimal.
Can we do better?



updated 9:28 a.m.EDT, Wed March 17, 2010

Red River hits key mark, still rising

The Red River at Fargo, North Dakota, reached "major flood stage" early today as the National Guard and volunteers filled sandbags to protect homes. FULL STORY

- Are you there? Send pics, videos
- Poetic take on rising floodwater

Latest News

- Health care votes: Foes gaining
- Ex-PM Allawi leads in Iraq vote count
- Israeli official: No U.S.-Israel crisis
- Opinion: Try terrorists in court
- Drones kill suspected militants
- Iranians mark holiday under crackdown
- Blood toss protest at Thai PM's home
- U.S. ending '96-hour rule' in Afghanistan

How one school gets it right

School lasts 11 months out of the year. All students wear uniforms and learn violin. In a system where many students are failing, CNN's Allan Chernoff visits one school in Detroit that's getting it right.

DON'T MISS

Toyota black boxes lack crucial info 3:38

Top exorcist: Devil just doing his job

Latest sex scandals threaten pope 2:45

Sprint

Get unlimited text and picture messaging, Web, GPS and calling to any mobile in America.

All for just $69.99/month.

Hi! Log in or sign up to get great personalized stuff here!

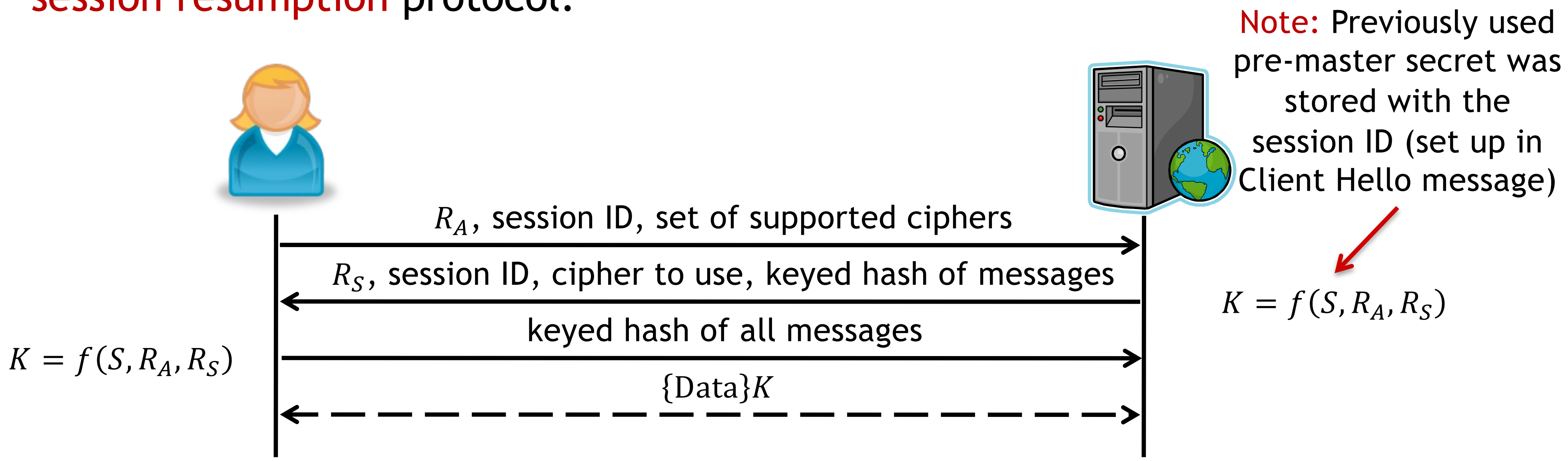
Updated 9:40 am EDT Mar 17

Dow	10,718.56	+32.58	(+0.30 %)
Nasdaq	2,385.31	+7.3	(+0.31 %)

Sessions vs. Connections

In TLS, sessions are assumed to be long-lived entities that may involve many smaller connections

Connections can be spawned from an existing session using a streamlined session resumption protocol:

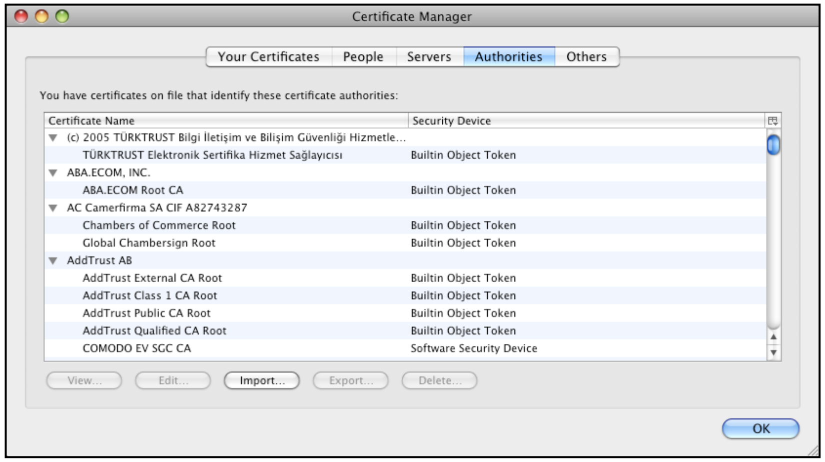

Note: Previously used pre-master secret was stored with the session ID (set up in Client Hello message)
R_A, session ID, set of supported ciphers
R_S, session ID, cipher to use, keyed hash of messages
keyed hash of all messages
$\{\text{Data}\}K$
$K = f(S, R_A, R_S)$
$K = f(S, R_A, R_S)$

In this model, a single session could be set up with CNN and connections can be spawned as needed to retrieve content

Using HTTP/2, this concept can be taken even farther: server can respond with data for queries before they're even requested

Servers authenticate themselves using certificates. How do we authenticate the certificates?

Most TLS deployments use an oligarchy PKI model



You have certificates on file that identify these certificate authorities:

Certificate Name	Security Device
▼ (c) 2005 TÜRKTRUST Bilgi İletişim ve Bilişim Güvenliği Hizmetle...	
TÜRKTRUST Elektronik Sertifika Hizmet Sağlayıcısı	Builtin Object Token
▼ ABA.ECOM, INC.	
ABA.ECOM Root CA	Builtin Object Token
▼ AC Camerfirma SA CIF A82743287	
Chambers of Commerce Root	Builtin Object Token
Global Chambersign Root	Builtin Object Token
▼ AddTrust AB	
AddTrust External CA Root	Builtin Object Token
AddTrust Class 1 CA Root	Builtin Object Token
AddTrust Public CA Root	Builtin Object Token
AddTrust Qualified CA Root	Builtin Object Token
COMODO EV SGC CA	Software Security Device

That is, as long as the server presents a certificate chain that uses one of our trusted roots, we're happy

What about naming?

- Servers are usually known by their DNS names
- X.509 is not set up for DNS naming
- Usually the CN field of the X.509 certificate contains the DNS name

Example: C = US, ST = Washington, L = Seattle, O = Amazon.com Inc., CN = www.amazon.com ← Why is this safe?

Summary of TLS

Although TCP provides a reliable data transfer protocol, it is not secure

- TCP can recover from bit-flips and dropped packets
- But malicious adversaries can alter data undetected

TLS provides cryptographic confidentiality and integrity protection for data sent over TCP

The security afforded by TLS is defined by using cipher suites

- Developers to easily incorporate new algorithms
- Security professionals can tune the level of security offered
- Breaking a cipher does not break the protocol

Breaking Crypto!

- Breaking PKI by breaking collision resistance

- Brute force attacks without using brute force
    - SSL key generation
    - Kerberos v4

- Brute force attacks against symmetric key ciphers
    - massively parallel attack
    - Deep Crack

- Subverting public key cryptography protocols

- Attacking real world implementations
    - Timing analysis of RSA
    - Power analysis of DES
    - Keyjacking cryptographic APIs

What is a hash function?

Recall: A hash function is a function that maps a variable-length input to a fixed-length code

Hash functions should possess the following 3 properties:

- Preimage resistance: Given a hash output value z, it should be infeasible to calculate a message x such that $H(x) = z$
- Second preimage resistance: Given a message x, it is infeasible to calculate a second message y such that $H(x) = H(y)$
- Collision resistance: It is infeasible to find two messages x and y such that $H(x) = H(y)$

Question: Why are cryptographic hash functions important to PKIs?

Digital signature operations are expensive to compute! Instead of signing a certificate c, we actually sign $H(c)$.

What happens if we don’t have these properties?

Attack 1: No preimage resistance

- One attack is being able to recover a password from $H(\text{password})$
- Not critical to the security of PKIs, but would cause issues in general

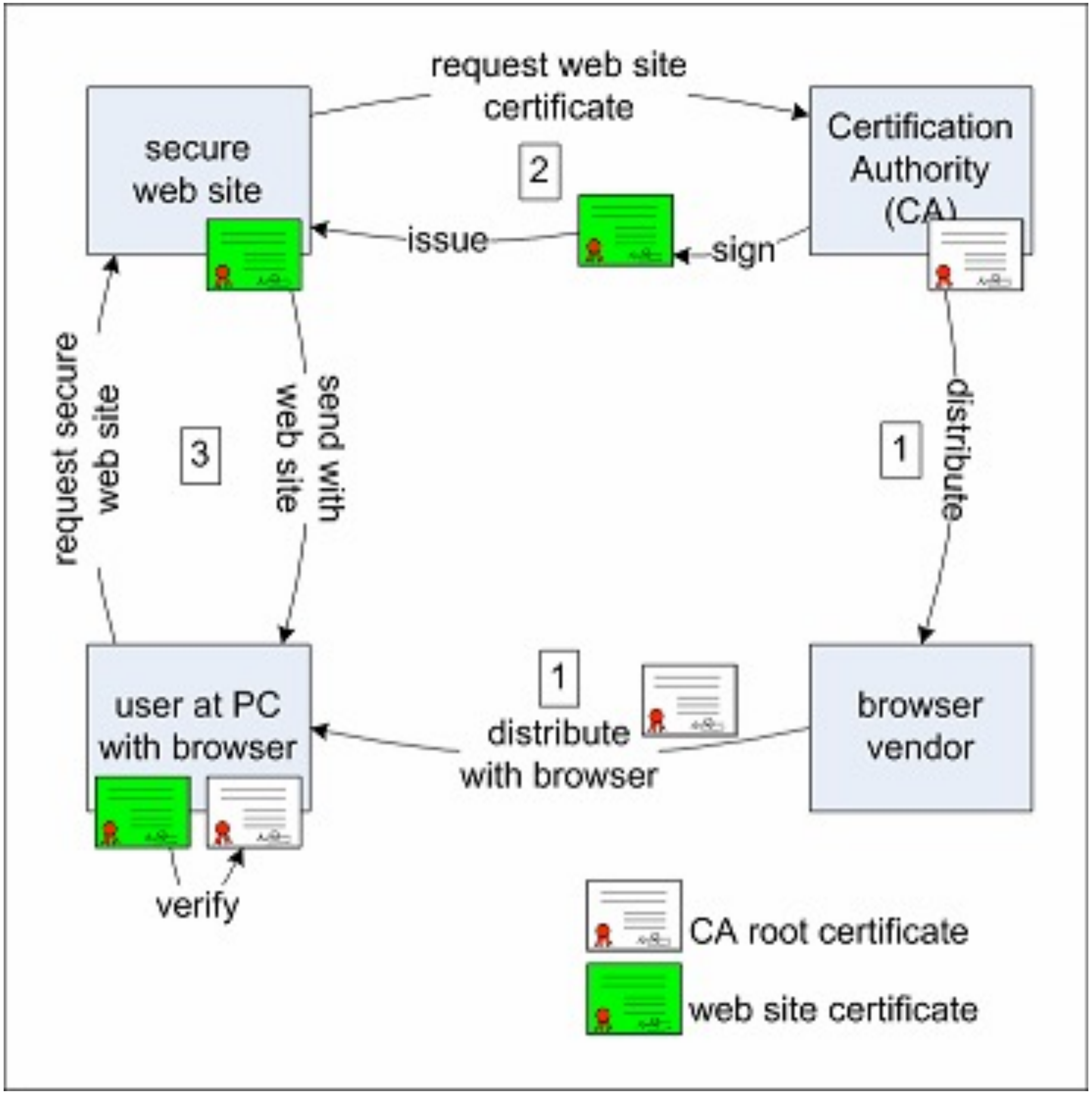
Attack 2: No second preimage resistance

- Assume that we have a message m_1 with a signature computed over $H(m_1)$
- If we don’t have second preimage resistance, we can find a message m_2 such that $H(m_1) = H(m_2)$
- The result: It looks like the signer signed m_2!

Attack 3: No collision resistance

- This means that we can find two messages that have the same hash
- The authors use a clever variant of this type of attack to **construct two certificates that have the same MD5 hash**
- This is bad news…

How TLS should work…

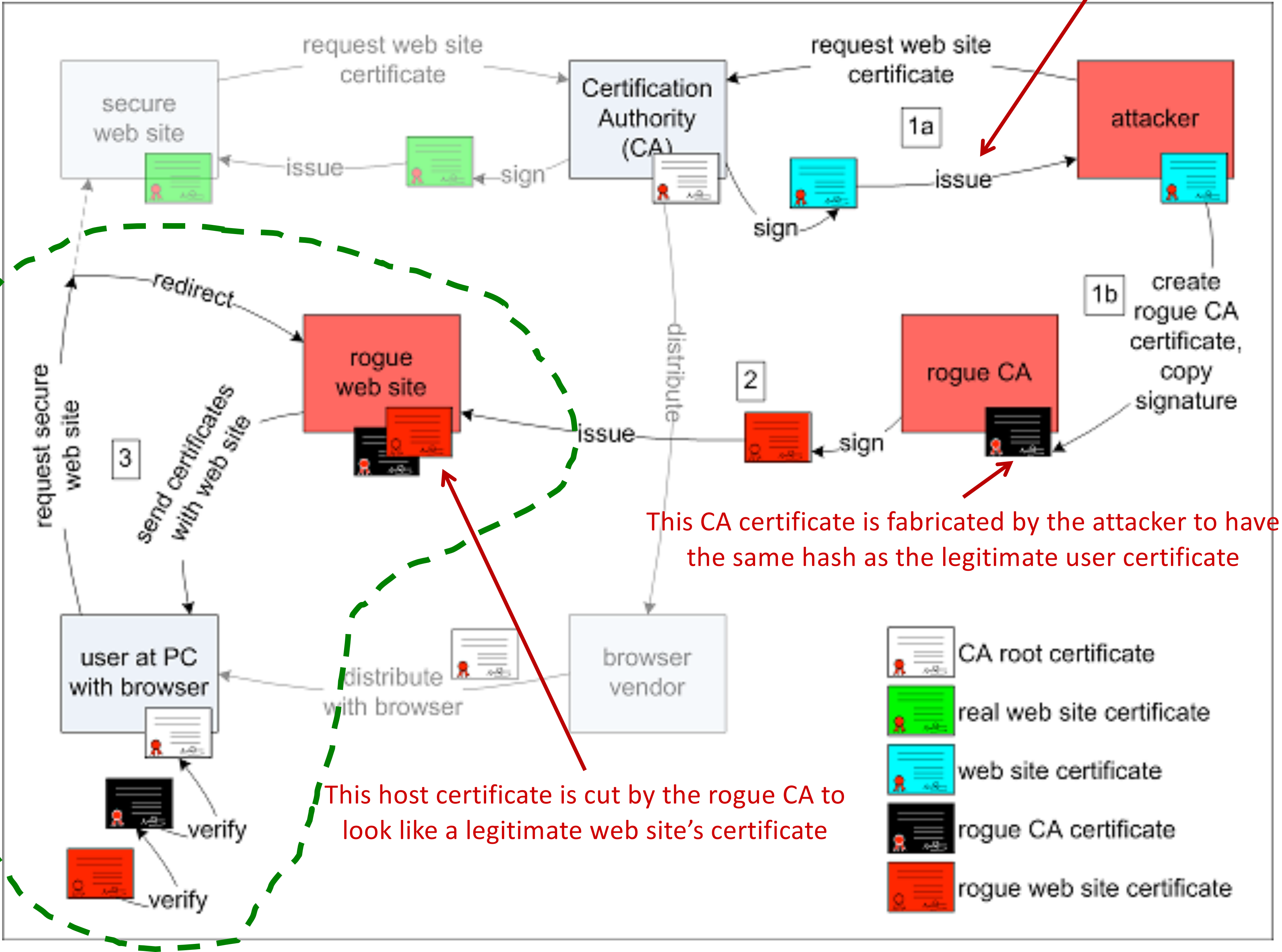


What’s the big deal?

Question: Can you describe a scenario in which having two certificates with the same hash would be problematic?

Attack Overview

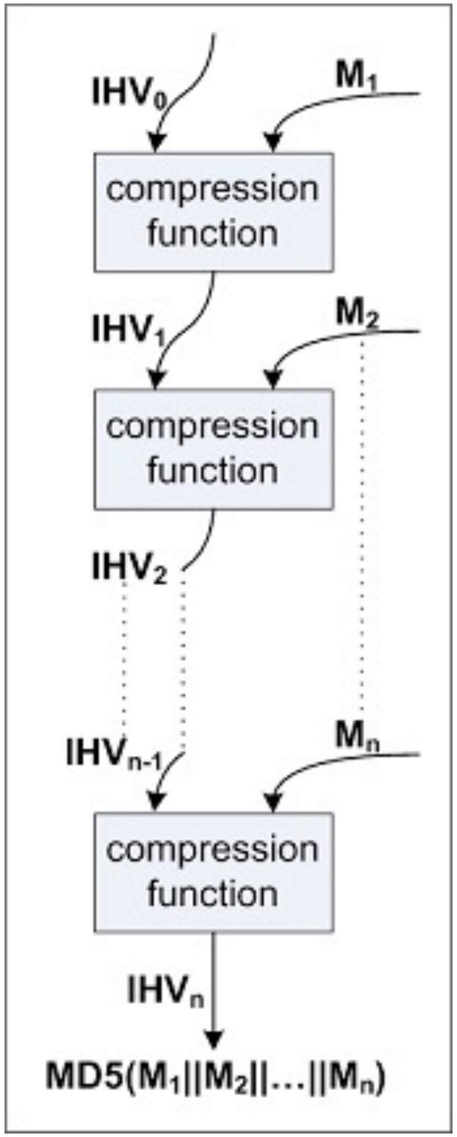
This is a legitimate host certificate obtained through standard channels



This CA certificate is fabricated by the attacker to have the same hash as the legitimate user certificate

This host certificate is cut by the rogue CA to look like a legitimate web site's certificate

How does MD5 work?



Given a variable length input string, MD5 produces a 128-bit hash value

MD5 uses a Merkle-Damgård iterative construction

- 128-bit intermediate hash value (IHV) and a 512-bit message chunk are fed into a compression function that generates a 128-bit output
- This output is compressed with the next 512-bit message chunk and the process is repeated
- The final IHV is the hash value for the message

Note that:

- The initial message must be padded out to a multiple of 512 bits
- IHV_0 is a publicly-known fixed value (0x67452301 0xEFCDAB89 0x98BADCFE 0x10325476)

Early attacks against MD5

Early partial attacks on MD5 were suggestive of larger troubles

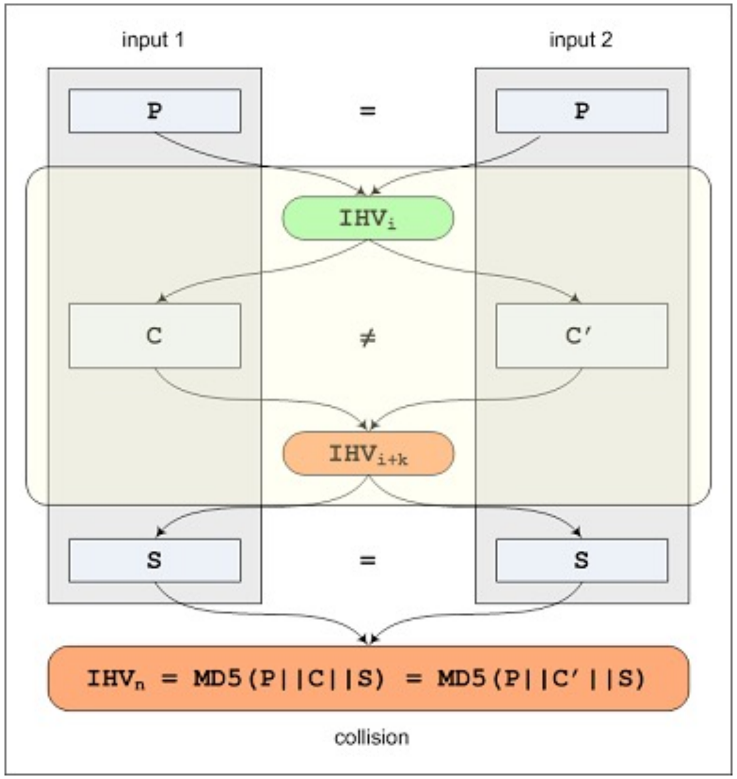
- [1993] Den Boer and Bosselaers found a partial collision of the MD5 compression function (two different IHVs lead to the same output value)
- [1996] Dobbertin found a full collision of the MD5 compression function

The first real attack on MD5 was found by Wang and Yu in 2004

Given any IHV, they showed how to compute two pairs $\{M_1, M_2\}$ and $\{M_1', M_2'\}$ such that:

- $IHV_1 = CF(IHV, M_1) \neq IHV_1' = CF(IHV, M_1')$
- $IHV_2 = CF(IHV_1, M_2) = CF(IHV_1', M_2')$

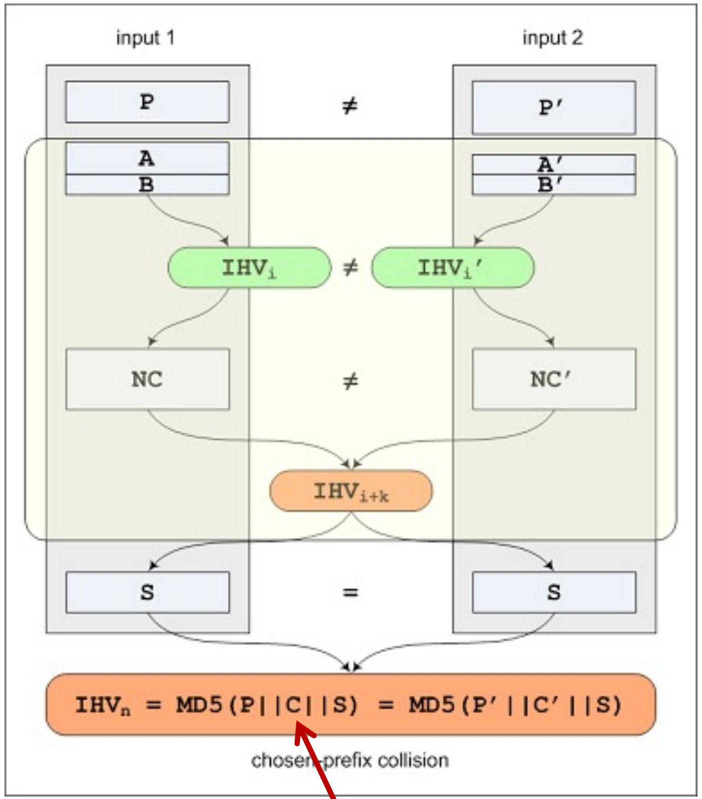
This yields a fairly scary generalization



In 2007 Stevens refined the Wang and Yu attack to allow differing message prefixes

How does this process work?

1. Choose P and P’ at will
2. Choose A and A’ s.t. (P || A) and (P’ || A’) are of the same bit length
3. In a “birthday step”, choose B and B’ such that (P || A || B) and (P’ || A’ || B’) are a multiple of 512 bits and the output IHVs have a special structure
4. This special structure allows the attacker to find two near collision blocks NC and NC’ such that the resulting MD5 function collides!



Note: C = A || B || NC

One use of this attack is generating different documents (plus some hidden content) that end up with the same hash value/signature!

This also opens the door to forged certificates…

How can we launch this attack against X.509?

An X.509 certificate contains quite a bit of information

- Version
- Serial number: Must be unique amongst all certificates issued by the same CA
- Signature algorithm ID: What algorithm was used to sign this certificate?
- Issuer’s distinguished name (DN): Who signed this certificate?
- Validity interval: Start and end of certificate validity
- Subject’s DN: Who is this certificate for?
- Subject’s public key information: The public key of the subject
- Issuer’s unique ID: Used to disambiguate issuers with the same DN
- Subjects unique ID: Used to disambiguate subjects with the same DN
- Extensions: Typically used for key and policy information
- Signature: A digital signature of (a hash of) all other fields

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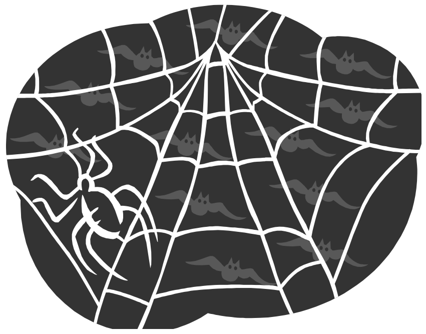
Insight 1: Stevens’ chosen prefix attack means that it might be possible to generate two certificates with different subjects, but the same signature!

Insight 2: Collision blocks can potentially be hidden as (part) of the public key block and/or in extension fields!

Successfully launching this attack means finding a CA that will grant a certificate using an MD5 hash



To find such a server, the authors wrote a web crawler

- Crawler ran for about a week
- Found 100,000 SSL certificates
- 30,000 certificates signed by "trusted" CAs
- Of these, 6 issued certificates with MD5-based signatures signed in 2008

Of the certificates found with signatures over MD5 hashes, 97% were issued by RapidSSL (http://www.rapidssl.com/)

RapidSSL issues certificates in an online manner, so they actually made an ideal target for launching this attack

- Predictable timing
- Not human-based, so multiple requests would not seem strange

Question: Why attack a production server instead of a test server?

Unfortunately, we have no control over the certificate serial number or validity fields!

Question: Why might this pose a problem?

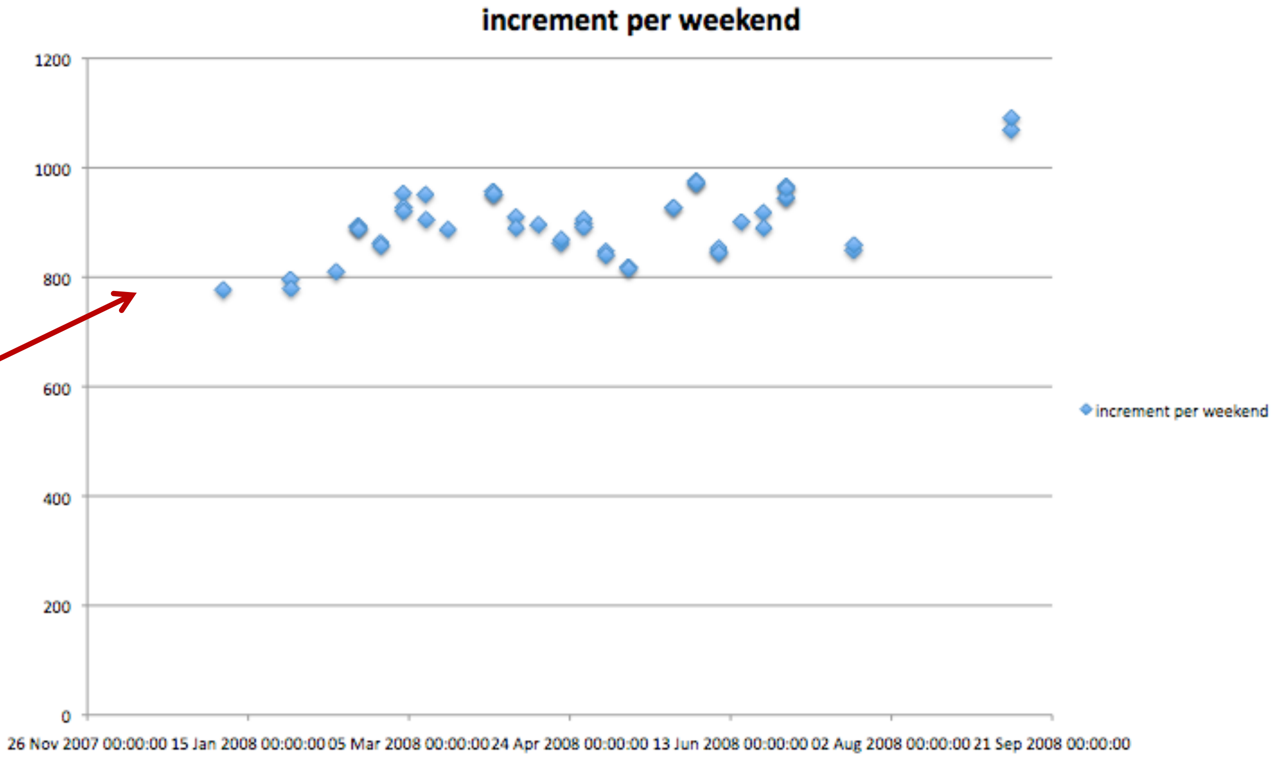
- Because these fields occur in the “chosen” prefix of the certificate and thus must be known before the collision blocks can be computed!

Predicting the validity period turned out to be trivial

- Certificate always issued 6 seconds after it was requested
- Valid for exactly one year

Furthermore, it turns out that RapidSSL uses a counter to populate the serial number field!

800-1000 certificates issued per weekend



Setting up a legitimate certificate request

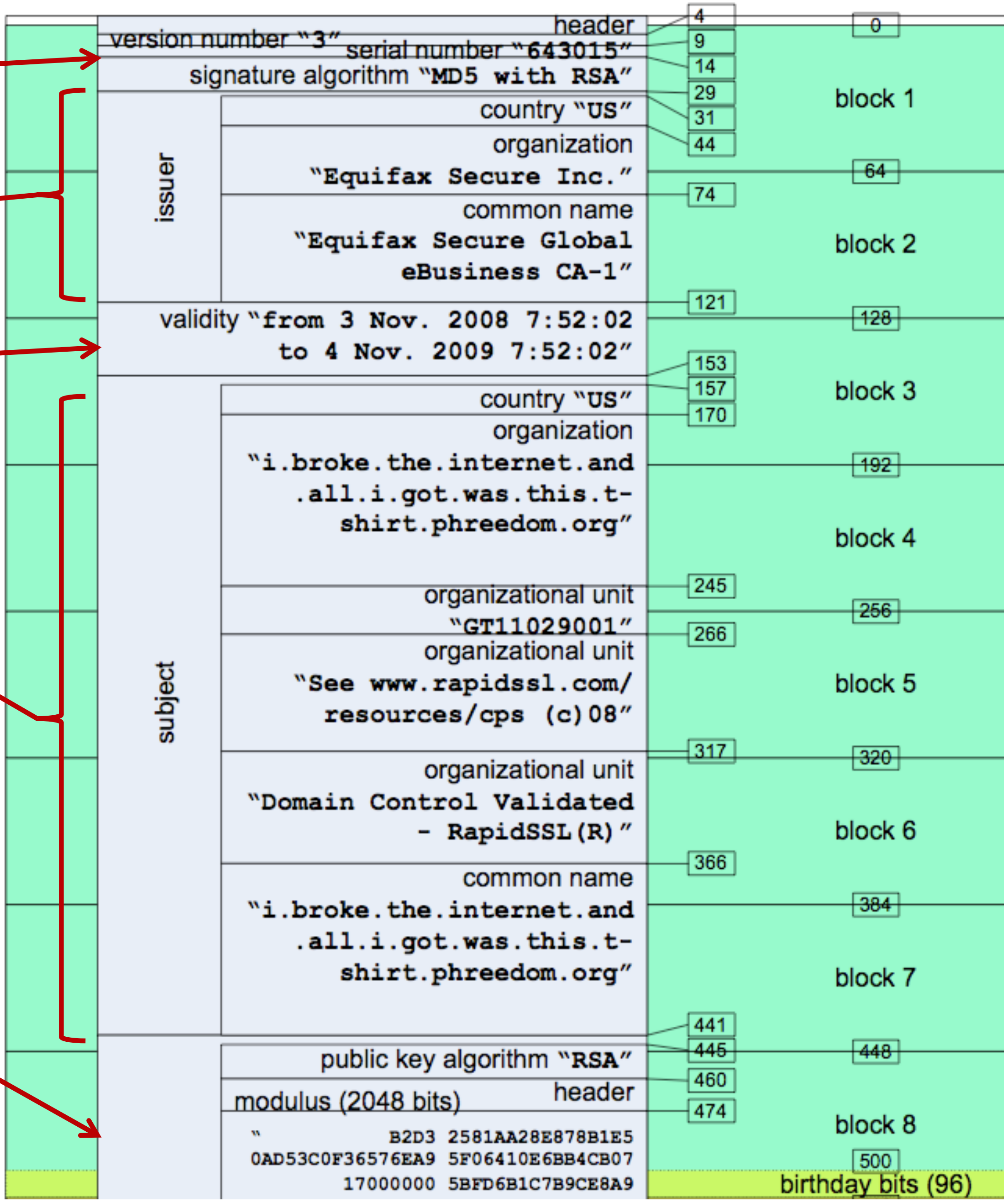
Predicted serial number

Info pulled from CA certificate

Derived validity period

Subject information completely chosen by the attacker

Question: How do you choose a public key (2048-bit modulus and an exponent) when part of it is the collision blocks needed to make the attack work?!?!


header
version number "3"
serial number "643015"
signature algorithm "MD5 with RSA"
issuer
country "US"
organization "Equifax Secure Inc."
common name "Equifax Secure Global eBusiness CA-1"
validity "from 3 Nov. 2008 7:52:02 to 4 Nov. 2009 7:52:02"
subject
country "US"
organization "i.broke.the.internet.and.all.i.got.was.this.t-shirt.phreedom.org"
organizational unit "GT11029001"
organizational unit "See www.rapidssl.com/resources/cps (c)08"
organizational unit "Domain Control Validated - RapidSSL(R)"
common name "i.broke.the.internet.and.all.i.got.was.this.t-shirt.phreedom.org"
public key algorithm "RSA"
modulus (2048 bits)
header
" B2D3 2581AA28E878B1E5
0AD53C0F36576EA9 5F06410E6BB4CB07
17000000 5BFD6B1C7B9CE8A9
4
9
14
29
31
44
74
121
153
157
170
245
266
317
366
441
445
460
474
0
64
128
192
256
320
384
448
500
block 1
block 2
block 3
block 4
block 5
block 6
block 7
block 8
birthday bits (96)

Answer: By being extremely clever

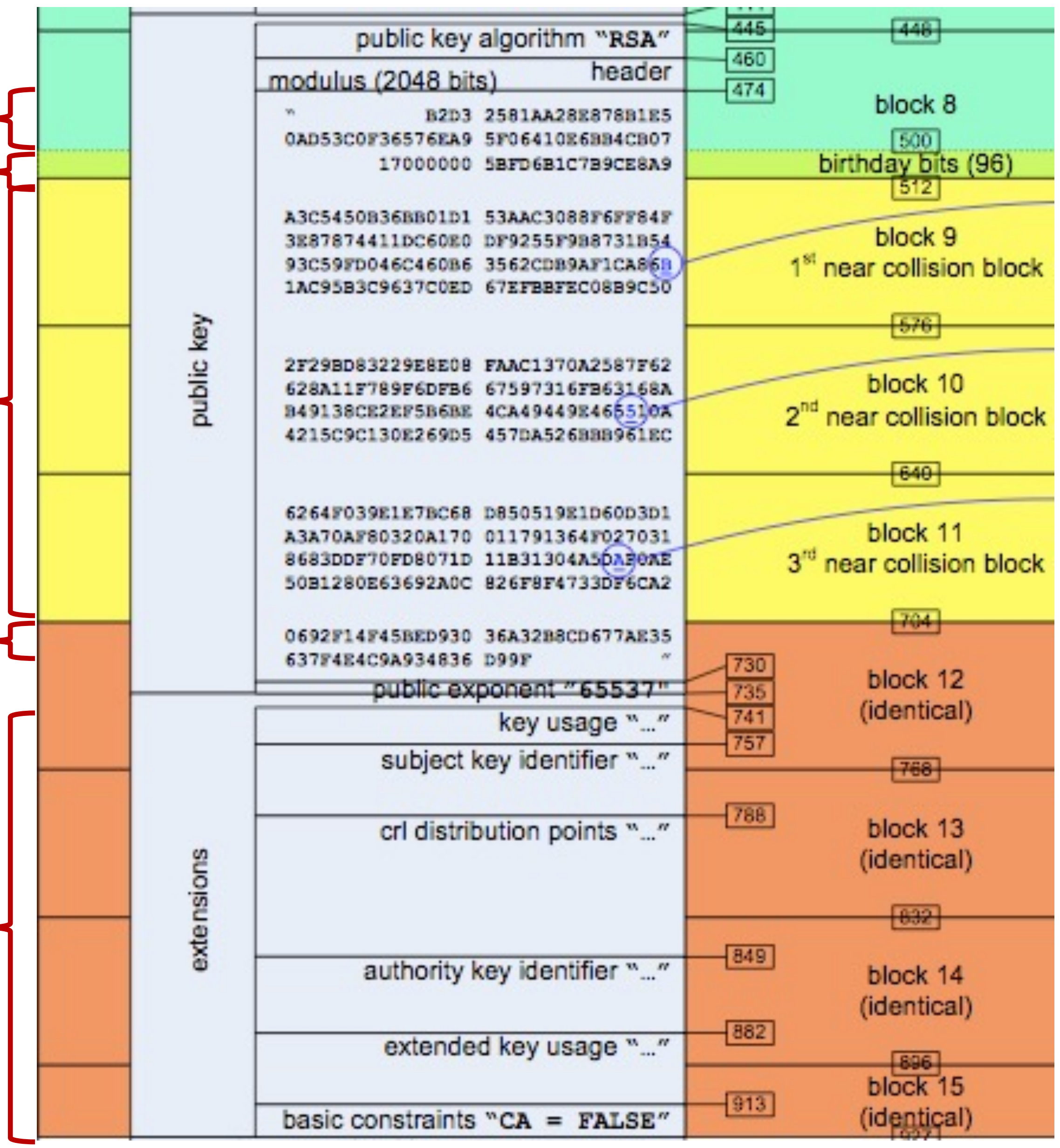
(a) chosen uniformly at random

(b) chosen to set up relationship between this certificate and the rogue CA cert to be generated next

(c) output of the authors' collision-finding algorithm

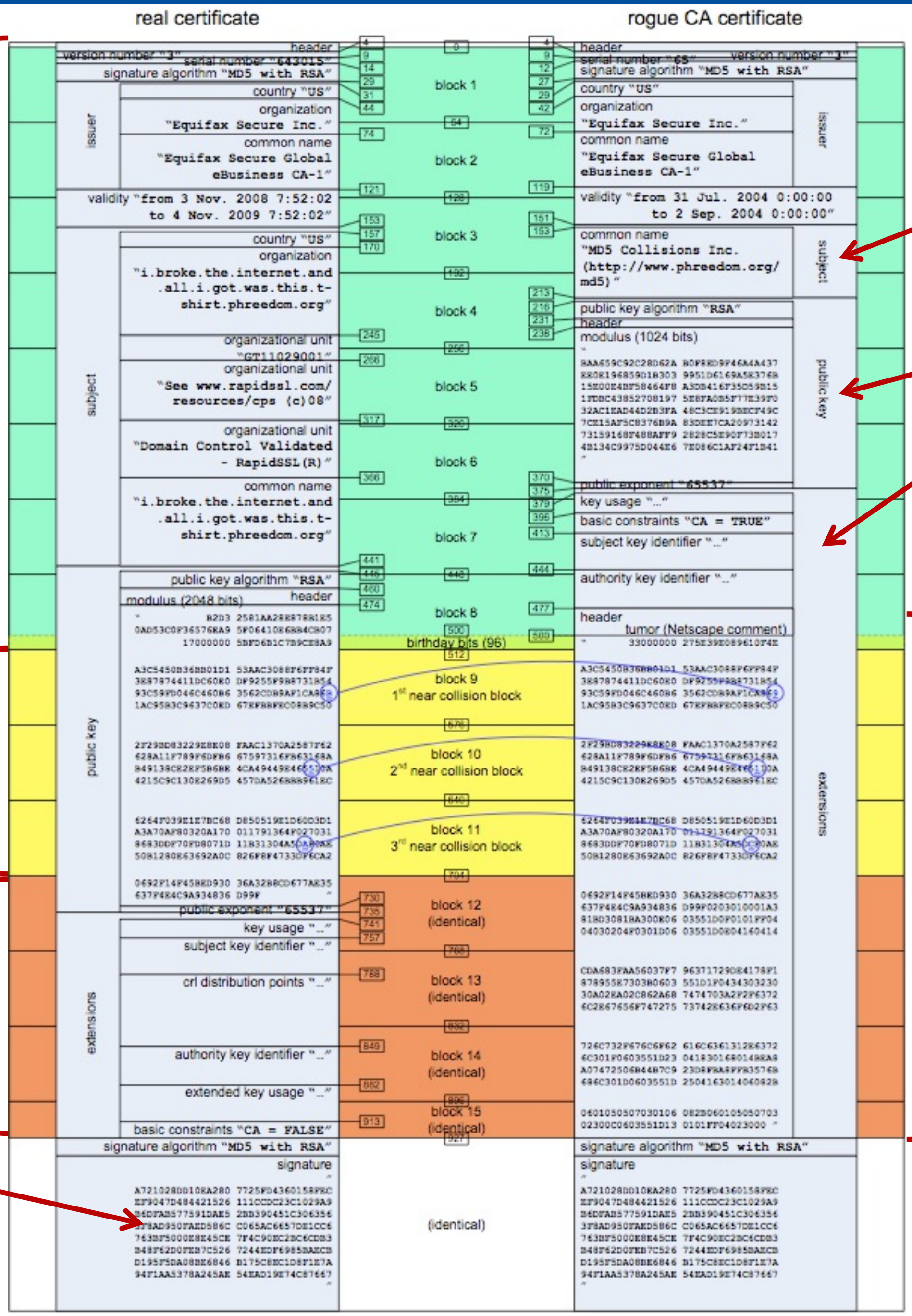
(d) chosen by the attacker such that when the bits comprising parts (a)-(d) are interpreted as an integer, the result is a number "n" such that n = pq

This is just standard PKI junk…



```
"                 B2D3 2581AA28E878B1E5
0AD53C0F36576EA9 5F06410E6BB4CB07
         17000000 5BFD6B1C7B9CE8A9

A3C5450B36BB01D1 53AAC3088F6FF84F
3E87874411DC60E0 DF9255F9B8731B54
93C59FD046C460B6 3562CDB9AF1CA86B
1AC95B3C9637C0ED 67EFBBFEC08B9C50

2F29BD83229E8E08 FAAC1370A2587F62
628A11F789F6DFB6 67597316FB63168A
B49138CE2EF5B6BE 4CA49449E465510A
4215C9C130E269D5 457DA526BBB961EC

6264F039E1E7BC68 D850519E1D60D3D1
A3A70AF80320A170 011791364F027031
8683DDF70FD8071D 11B31304A5DAF0AE
50B1280E63692A0C 826F8F4733DF6CA2

0692F14F45BED930 36A32B8CD677AE35
637F4E4C9A934836 D99F             "
```

Creating the rogue CA certificate



real certificate
rogue CA certificate
header
version number "3"
serial number "643015"
serial number "65"
signature algorithm "MD5 with RSA"
issuer
country "US"
organization "Equifax Secure Inc."
common name "Equifax Secure Global eBusiness CA-1"
validity "from 3 Nov. 2008 7:52:02 to 4 Nov. 2009 7:52:02"
validity "from 31 Jul. 2004 0:00:00 to 2 Sep. 2004 0:00:00"
subject
organization "i.broke.the.internet.and.all.i.got.was.this.t-shirt.phreedom.org"
organizational unit "GT11029001"
organizational unit "See www.rapidssl.com/resources/cps (c)08"
organizational unit "Domain Control Validated - RapidSSL(R)"
common name "i.broke.the.internet.and.all.i.got.was.this.t-shirt.phreedom.org"
common name "MD5 Collisions Inc. (http://www.phreedom.org/md5)"
public key
public key algorithm "RSA"
modulus (2048 bits)
modulus (1024 bits)
public exponent "65537"
extensions
key usage "..."
subject key identifier "..."
crl distribution points "..."
authority key identifier "..."
extended usage "..."
basic constraints "CA = FALSE"
basic constraints "CA = TRUE"
tumor (Netscape comment)
signature algorithm "MD5 with RSA"
signature
block 1
block 2
block 3
block 4
block 5
block 6
block 7
block 8
birthday bits (96)
block 9 1st near collision block
block 10 2nd near collision block
block 11 3rd near collision block
block 12 (identical)
block 13 (identical)
block 14 (identical)
block 15 (identical)
(identical)

Chosen prefix

Collision blocks (different but related)

Identical trailers

Signature of CA

Shorter subject info

Small public key

Standard public key stuff (Note that this cert is for a CA!)

(Typically ignored) certificate extension to hold collision blocks and trailer from original certificate

Some specifics…

The attack used by the authors had two stages:

1. Finding the 96 “birthday bits”
2. Finding the three near collision blocks

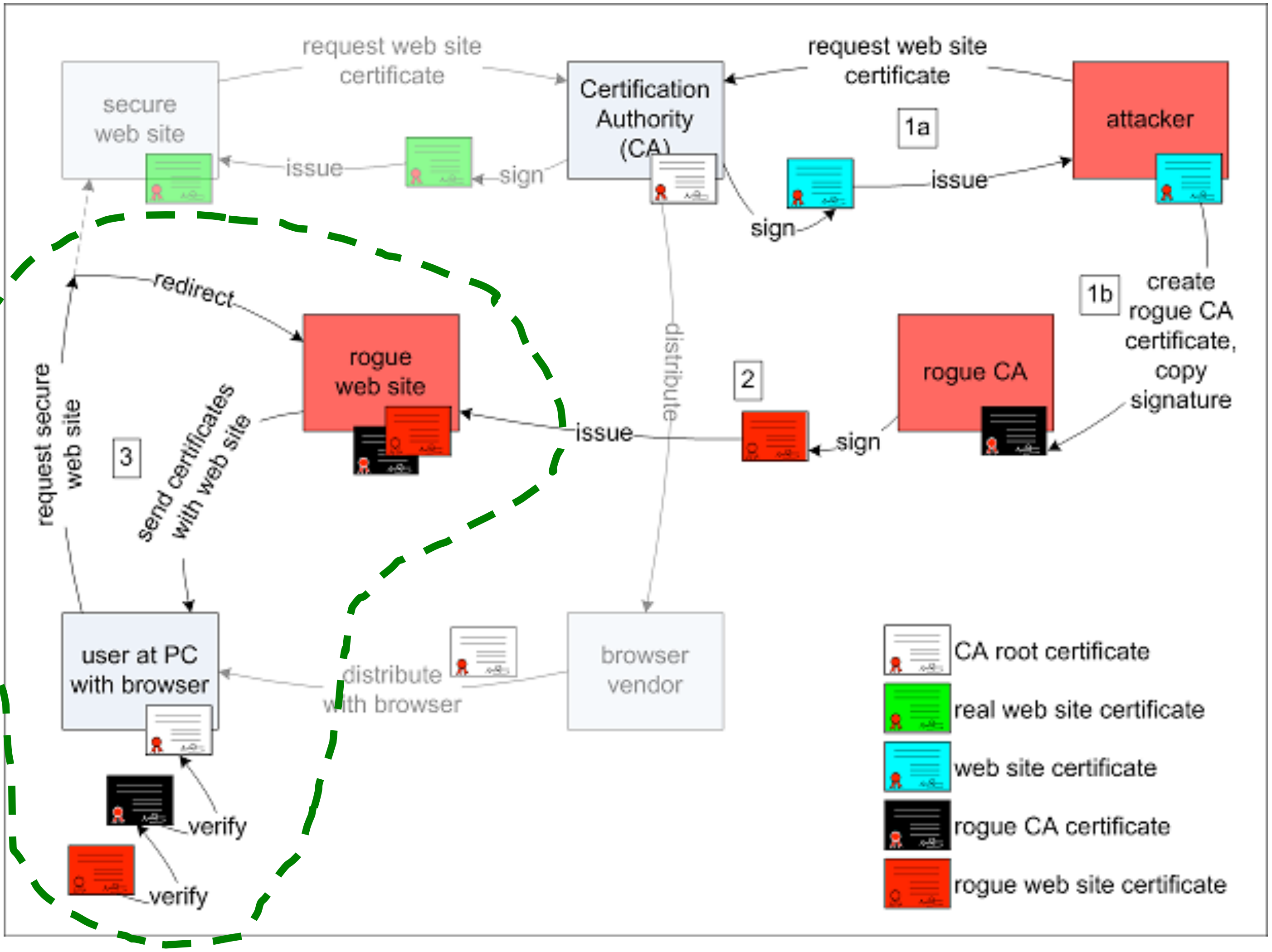
Stage 1 is computationally expensive, but well-suited for execution on the processors used by PlayStation3 game consoles. This took about 18 hours on a cluster of 200 PS3s.

Stage 2 is not terribly expensive, and is better suited to run on commodity PCs. This takes 3-10 hours on a single quad-core PC.

Attacking only on weekends (due to reduced CA load) the authors were able to carry out their attack in 4 weeks for a cost of $657.

This attack has very real implications…

In short, it is possible for a malicious principal to get a cheap X.509 host certificate, and leverage this to create a trusted CA certificate!



The Bottom Line: Consider MD5 broken!

Broken? What do you mean by broken?

Since MD5 does not have all three properties required of cryptographic hash functions, it is not considered to be “cryptographically strong”

While you could still use MD5 for non-cryptographic applications (such as?), it is better to avoid it altogether

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SHA-1 is the cryptographic hash function that is now most often used

Attacks against SHA-1 have been announced, but still require a large amount of computing effort to mount

- e.g., Collision finding in 2^{63} steps, rather than 2^{80}

NIST recently ran a competition to design SHA-3, a new hash family to complement the SHA-{1,2} family of hash functions

- Welcome, Keccak

How did vendors react to the MD5 break?

2008, December 30th: This work was presented at the Chaos Computing Congress

December 31st

- Verisign issues a statement, stops using MD5
- Microsoft issues Security Advisory (961509): “Research proves feasibility of collision attacks against MD5”
- Mozilla has a short item in the Mozilla Security Blog: “MD5 Weaknesses Could Lead to Certificate Forgery”

January 2nd

- RSA has an entry in the Speaking of Security blog: “A Real New Year’s Hash”
- US-CERT, the US Department of Homeland Security’s Computer Emergency Readiness Team, published Vulnerability Note VU#836068: “MD5 vulnerable to collision attacks”

January 15th

- Cisco published “Cisco Security Response: MD5 Hashes May Allow for Certificate Spoofing”

Discussion

Question 1: People have had evidence that MD5 was weak since the mid 1990s. Why did it take this long to finally convince vendors to stop using MD5? Do you think that this will change the response to future cryptographic vulnerabilities?

Question 2: In the 1980s, Adi Shamir and Eli Biham "discovered" differential cryptanalysis, which is a general means of attacking block ciphers. It was later revealed that NSA and IBM actually discovered this technique first, but kept it a secret. What if this MD5 attack was known before it was discovered in the public domain? What would the implications be?

The aftermath: Flame malware

“[A]rguably, it is the most complex malware ever found”

Developed by NSA and GCHQ for cyber espionage targeting middle eastern countries. Records:

- Screenshots
- Audio
- Network activity
- Keyboard activity
- Nearby devices’ contacts via bluetooth

Used components signed by Microsoft?!

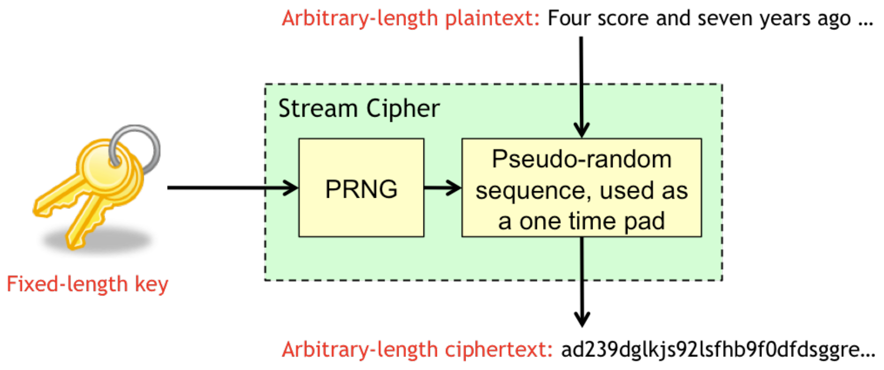
Counterfeit certificate crafted from a terminal service certificate with code-signing enabled, signed using MD5

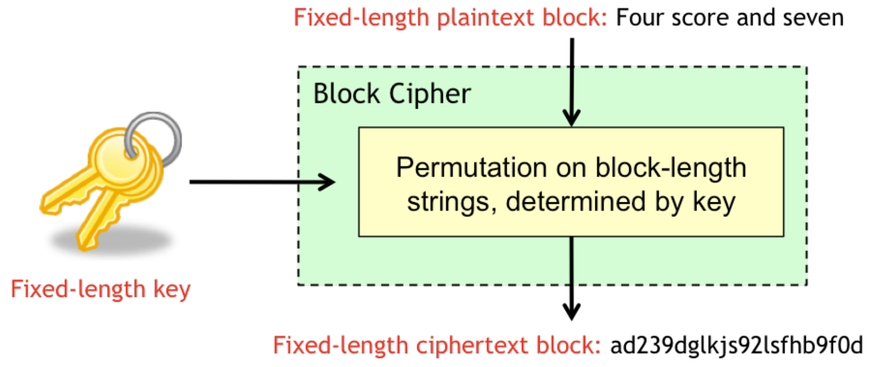
Previously unknown variant of the chosen-prefix collision attack

First detected in 2012…

… but its main component was first seen in 2007

So far, we have treated cryptography largely as a black box


Arbitrary-length plaintext: Four score and seven years ago …
Stream Cipher
PRNG
Pseudo-random sequence, used as a one time pad
Fixed-length key
Arbitrary-length ciphertext: ad239dglkjs92lsfhb9f0dfdsggre…


Fixed-length plaintext block: Four score and seven
Block Cipher
Permutation on block-length strings, determined by key
Fixed-length key
Fixed-length ciphertext block: ad239dglkjs92lsfhb9f0d

This certainly simplifies the engineering process

- Smart people build the boxes, and we can just put them together
- Just worry about I/O, not the (messy) details

Unfortunately, it also abstracts away lots of details…

Today, we'll see how these types of details can cause the downfall of otherwise hardened black boxes

Can we break symmetric key cryptography without brute forcing the keyspace?

In theory, there is no difference between theory and practice. In practice, there is.

-- Not Yogi Berra

In theory, cryptographic keys are chosen randomly.

- For an m-bit keyspace, each of the 2^m keys is equally likely
- As such, figuring the key out requires a brute force search

In practice, things are not really random

- Computers are deterministic machines!
- Keys are picked using a pseudo-random process
- Figuring out this process can yield keys with less than brute-force effort

Question: How many people have used a PRNG? How did you seed it?

Goldberg and Wagner used this insight to break Netscape’s key generation routines

All web browsers that use TLS/SSL need to generate secret keys that are exchanged during the connection setup process

- Typically, this is done using a cryptographically strong PRNG
- The initial seed to the PRNG determines the keys that are generated

After some reverse engineering, PRNG was found to be seeded using

- The current time
- The process ID of the web browser (PID)
- The parent process ID of the web browser (PPID)

The result: 128-bit keys were generated from 47 bits of randomness!

With a user account on the machine, the search could be reduced to about 10^6 = 1,000,000 guesses!

How can we prevent this?

What is one way that we might be able to prevent these types of well-known coding errors?

Case study: Kerberos v4

Kerberos is a popular network authentication protocol

- Initially developed at MIT as part of project Athena
- Used within the department for AFS “tokens”

Note: Kerberos is available as a widely-used and widely-studied open-source software package

The security of Kerberos v4 depends on 56-bit DES or 112-bit TDES keys

In 1997, a group of grad students at Purdue showed that Kerberos v4 used the XOR of several 32-bit quantities to seed its PRNG

- Timing information
- PID and PPID
- Count of keys generated
- Host ID

So what does this tell us?

Observation: The XOR of any number of 32-bit quantities is 32 bits long!

- In 1997, brute forcing this 32-bit seed space only took about 28 hours!

As if that wasn't bad enough, many of these quantities are predictable

- Timing information can be guessed
- Process IDs can be read if the attacker has an account on the system
- The host ID is known
- …

The result of the above is that the actual entropy of the 56- or 112-bit keyspace is reduced to 20 bits!

- This can be brute forced in a few seconds…

The moral of the story: Not even open-source software that has been scrutinized by lots of smart people is totally free of errors

An interesting aside…

This weakness was first discovered nearly a decade earlier (1988)

After this initial discovery, a stronger PRNG was written and checked into the Kerberos source tree, but was never actually used!

- The PRNG was written as a new function (not a replacement)
- Extensive use of `#define` statements in the code obscured which PRNG was actually being used

The result: Good code was available, but bad code was used…

The lesson? Don't get too cute and write incomprehensible code!

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Brute force attacks without using brute force

- SSL key generation
- Kerberos v4

Brute force attacks against symmetric key ciphers

- massively parallel attack
- Deep Crack

Subverting public key cryptography protocols

Attacking real world implementations

- Timing analysis of RSA attacks
- Power analysis of DES
- Keyjacking cryptographic APIs

Surely, breaking *some* systems must require a brute force search of their keyspace, right?

If all else fails, any cryptosystem can be broken by "simply" decrypting a ciphertext with all possible keys

Recall: NSA reduced Lucifer's keyspace when developing DES

- Lucifer was a 64-bit cipher, DES is a 56-bit cipher
- Many cryptographers began to speculate as to why this was done

Certainly, brute forcing a 56-bit space on a single computer would take a very long time, but why use just a single computer?

Quisquater and Desmendt discussed the possibility of a massively parallel attack

- Key-cracking hardware could be built into TVs and radios
- State-run media could farm out searches to these devices
- A back of the envelope example:
  - Keys tested at 1 million/second
  - 1 Billion TVs/radios
  - Break a DES key in about a minute…

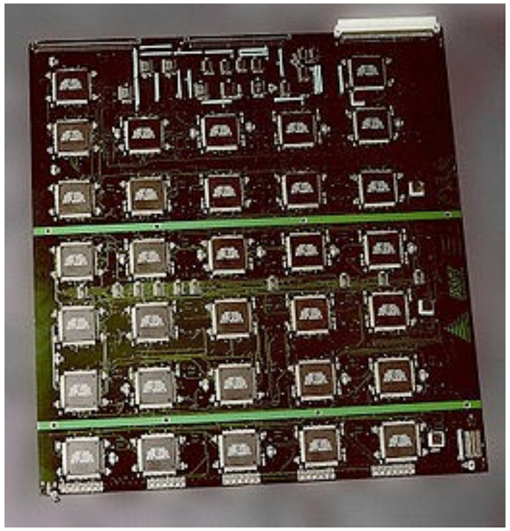
Deep crack is a slightly less “big brother” version of this principle

The Electronic Frontier Foundation (EFF) is a digital rights advocacy group based in the US

To demonstrate that 56-bit keys are not secure enough for widespread use (despite the government’s claims to the contrary), the EFF built a machine called Deep Crack

Deep Crack is an extremely parallel machine (esp. by 1997 standards)

- 29 individual circuit boards
- 64 specially-designed DES-cracking chips per board
- 1,856 chips running in parallel could test about 90 billion keys per second!
- The entire DES key space could be tested in about 9 hours



With a price tag of about $250,000, Deep Crack was well within the budget of many criminal organizations and/or enemy governments

Take-home message

Definitions of words like “big”, “infeasible”, and “difficult” are rooted in hardware, software, or algorithmic assumptions. Make sure to revisit these assumptions often!

e.g., check keylength.com

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Is it possible to subvert public key systems without attacking the mathematics?

Question: Say that Alice runs a digital notary. We want Alice to sign the message M for us, but do not want her to see M.

Surprisingly, we can trick Alice into doing this!

- Let (n, e) be Alice's public key
- Let d be Alice's private key
- Let X be a random number that we pick
- Let $Y = X^e \bmod n$
- Let $M_D = YM \bmod n$ be a "decoy message"

M_D is a "randomized" version of M

Now, we get Alice to sign M_D, returning $U = M_D^d \bmod n$

Note:
$$\begin{aligned}
UX^{-1} \bmod n &= M_D^d X^{-1} \bmod n && // \ U = M_D^d \\
&= Y^d M^d X^{-1} \bmod n && // \ M_D^d = (YM)^d = Y^d M^d \\
&= X^{ed} M^d X^{-1} \bmod n && // \ Y = X^e \\
&= X M^d X^{-1} \bmod n && // \ X^{ed} = X \\
&= M^d \bmod n && // \ XX^{-1} = 1
\end{aligned}$$

Alice signed M without knowing it!

If Alice also decrypts using her signing key, we can read her private messages!

How? Let:

- $C = M^e \bmod n$ be a message encrypted to Alice
- R be a random number
- $X = R^e \bmod n$
- $Y = XC \bmod n$

Now, we ask Alice to sign Y, which gives us $U = Y^d \bmod n$

Note: $$\begin{aligned} R^{-1}U \bmod n &= R^{-1}Y^d \bmod n && // \; U = Y^d \bmod n \\ &= R^{-1}X^dC^d \bmod n && // \; Y = XC \bmod n \\ &= R^{-1}R^{ed}C^d \bmod n && // \; X = R^e \bmod n \\ &= R^{-1}RC^d \bmod n && // \; R^{ed} \bmod n = R \bmod n \\ &= M^{ed} \bmod n && // \; RR^{-1} = 1, C = M^e \bmod n \\ &= M \bmod n && // \; M^{ed} \bmod n = M \bmod n \end{aligned}$$

This is probably not a good thing…

Why do these attacks work?!

RSA has what is known as a multiplicative homomorphism

- $(X^Z \bmod n)(Y^Z \bmod n) = XY^Z \bmod n$
- i.e., $E(x)E(y) = E(xy)$ if E is the RSA encryption function

The attacks that we just talked about used RSA to operate on raw data

- Data is represented as plain old numbers
- Each number encrypted directly

In real life, RSA is not used this way! Padding functions like OAEP (aka PKCS#1) are used to randomly pad message prior to encryption or signing

- i.e., M becomes $P(M)$
- $P^{-1}\big(P(M)\big) = M$
- $P^{-1}\left(D\left(E\big(P(M)\big)\right)\right) = P^{-1}\big(P(M)\big) = M$

Note: Given $E\big(P(M_1)\big)$ and $E\big(P(M_2)\big)$, we can calculate $E\big(P(M_1)P(M_2)\big)$.

However, $P^{-1}\left(D\left(E\big(P(M_1)P(M_2)\big)\right)\right) = P^{-1}\big(P(M_1)P(M_2)\big) \neq M_1M_2$

Take home message

Breaking public cryptography does not need to involve "breaking" mathematics. More often than not, misusing a protocol or two can be just as effective!

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Successive squaring or Square-and-Multiply

```
// Goal:  Calculate m^d mod n
int pow(m, d, n)
    bitvector b[] = binary representation of d
    int r = 1
    for(int i=0; i <= b.length(); i++)
        r = r*r mod n
        if(b[i] == 1) then r = r * m
    return r
```

MSB in b[0]

Example: Computing pow(2, 5, 64)

Note that $5_{10} = 101_2$

Iteration	r
0	1
1	$1^2 \times 2 = 2$
2	$2^2 = 4$
3	$4^2 \times 2 = 32$

Observation: This algorithm does more work when bits are set to 1

We can leverage this observation to launch an attack on implementations of RSA!

In 1995, Paul Kocher described and demonstrated a timing attack against square-and-multiply implementations of RSA

The gist: If we know C, we don't know d, and we can measure the time that the operation C^d takes, we can eventually learn d by observing many such operations

So, why does this work?

- We can make a guess for the first bit of d
- If our guess is correct, we can predict
  - The intermediate result r
  - How long the algorithm will take
- If our guess is incorrect, we don't learn anything

That only explains one round, how does this work for a large key?

Details, details, details…

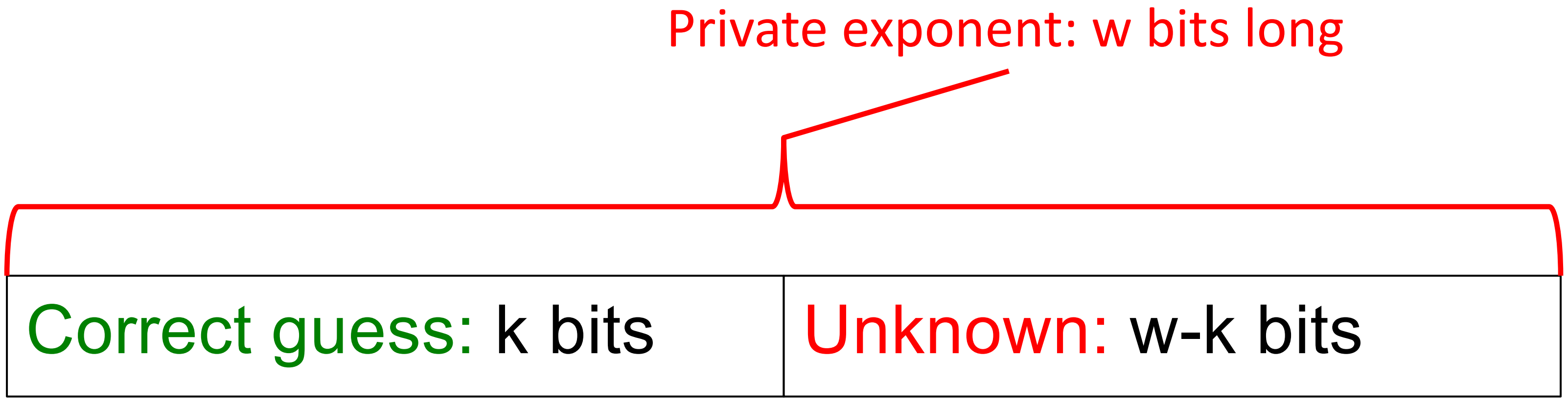
Consider the following observations, assuming a w-bit key:

- The time a decryption operation takes is the sum of the individual times for each of the w bits
- If we can correctly guess the first k bits of the key
  - We can calculate the time required for the first k operations
  - The remaining terms in the sum are essentially random
- Over a large enough sample of C, the difference between how long we calculate C^d to take versus how long C^d actually takes is a distribution whose variance is proportional to w-k

In short, by guessing correctly, we can reduce the variance of this distribution and learn the key k

Furthermore, this method allows us to learn the private key in $O(w)$ time, rather than $O(2^w)$ time

Graphically…



We should be able to predict <u>exactly</u> how long decryption takes for these bits of the private exponent.

Our error in predicting the runtime of the algorithm for these bits is the sum of w-k random variables (one per bit)

This seems really esoteric…

Sure, I'm convinced that this is possible, but how useful is this attack likely to be in practice?

In 2003, Brumley and Boneh showed how to successfully launch timing attacks against OpenSSL-based Apache web server over the Internet!

The lesson? Over time, attacks only get better!

If timing information is useful, what can we do with other sources of information?

Obvious statement: Software runs on hardware, hardware requires power

- Algorithms leak information via the power that they consume
- By monitoring the power consumption of hardware, we may be able to learn something about the inputs to the algorithms running
- Keys are important inputs to cryptographic algorithms!

Kocher et al. demonstrated a viable attack for learning the DES keys used by certain types of smart cards

Their attack was very clever

- Recall that DES keys are 56 bits long
- They observed an odd series of 56 spikes in the power trace
  - ➢ Why? Software checking the parity of the DES key
  - ➢ Spikes were at one of two heights, corresponding to 1 or 0 in the key
- By watching one encryption or decryption, they learned the key!
- This is simple power analysis

Video-based Cryptanalysis of Power LEDs (https://www.nassiben.com/video-based-crypta)

Even a good implementation and solid hardware can be subverted by a bad API…

Most often, cryptographic routines are not built directly into applications, but rather exist as a library that is used by applications

So-called keyjacking attacks work as follows:

1. Run a malicious executable on the victim's machine
2. Use this executable to begin intercepting calls to the victim's crypto API

This allows the attacker to do all kinds of nasty stuff

- Export secret/private keys to other applications
- Decrypt private messages
- Forge signatures
- …

These attacks are very hard to defend against, as once the system is compromised (e.g., via a buffer overflow exploit), there is nothing much that can be done!

Take home message

Cryptographic hardware exists where people can observe it. Cryptographic software may leak information about the inputs that it uses. Our nice little black boxes need to exist in the real world, and are thus subject to scrutiny and attack.

Conclusions

Treating cryptography as a black block simplifies our lives as engineers, but gives us a reason to ignore certain types of threats

Today we saw that

- Sometimes keys can be guessed without a brute force attack
- Sometimes brute force attacks are tractable by thinking outside of the box
- Naive use of public key cryptography can lead to undesirable outcomes
- Engineering decisions when building cryptosystems can be used to break these cryptosystem when they are deployed

As a result, it is important to keep up to date on how to safely use modern cryptography