What’s the worst that could happen?

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DIMACS Workshop on Cryptography: Theory Meets Practice

Overview

- Cryptography alone doesn't do much
  - Real systems combine primitives into *protocols*
- Protocols treat primitives as black boxes
  - With certain idealized properties
    - Indistinguishability, collision-freeness, preimage resistance...
  - The primitives only approximate those properties
    - Sometimes more than others...
- What happens when the primitives fail?
  - Let's look at some plausible scenarios

Major cryptographic algorithms

- Key establishment
  - **RSA**, DH
- Signature
  - **RSA**, DSS
- Encryption
  - **DES, 3DES, AES, RC4,** Blowfish
- Message digests
  - **MD5**, **SHA-1,** MD2

Current status of key est. algorithms

- RSA
  - Basically sound but some active attacks
    - Million message attack
    - Timing analysis
  - There are crypto countermeasures
    - OAEP, KEM, etc.
  - In reality Countermeasures are implementation only
    - Both these attacks caused SSL implementation upgrades
- DH
  - Basically sound but some active attacks
    - Small subgroup
    - Timing analysis
  - Again, implementation countermeasures
    - Most implementations use a fresh key for each transaction

Current status of signature algorithms

- RSA
  - Basically sound
  - Provable variants exist but aren't used
- DSS
  - Believed to be basically sound
  - Limited by key length but NSA is extending

Current status of encryption algorithms (I)

- DES
  - Best analytic attacks require 2^{43} known plaintexts
    - In practice this has had no effect
  - 56-bit key is known to be too weak
    - DES keys can be cracked in < 1 day for order $100k fixed cost
- 3DES
  - No good analytic attacks
  - Effective key strength ~112 bits
    - (3-key version)

Current status of encryption algorithms (II)

- AES
  - So far basically sound
- RC4
  - Some serious flaws
    - First 256-768 or so bytes are somewhat predictable [Mironov 02]
    - Related key vulnerabilities [Fluhrer and Shamir 01]
      - Structured keys are a real problem
  - Still widely used

Current status of digest algorithms

- MD5
  - Collisions are easy to find [Wang et al. 04]
    - … however, they don't appear to be controllable
      - Relationship between M and M' is fixed
  - Preimages are still difficult
  - Still believed safe in HMAC
- SHA-1
  - So far appears sound
  - Some disturbing results [Biham 04]
    - But only real progress is on reduced round versions
- SHA-XXX
  - Unknown, but some scary results [Hawkes et al. 04]

Attack 1: Controllable MD5 collisions

- Current MD5 collisions are tightly constrained
  - Only positions 4,11,41 are not fixed
    - And it's not clear they can be set to chosen values
  - But it seems reasonable to believe this attack can be extended
- Attack description:
  - Given any prefix P and desired values V and V'
  - Create two suffixes *S* and *S'* where
    - H(P||V||S) = H(P||V'||S')
- For example
  - S||V = "Pay $10 <plus garbage>"
  - S'||V' = "Pay $50 <plus other garbage>"

Practical implications of MD5 collisions

- No real effect on most protocols
  - SSL, IPsec, SSH, etc. use MD5 in three ways
    - Key expansion
    - MACs
    - Signatures
  - Not affected by collisions
- Two important cases
  - Signed S/MIME messages
  - Certificates

MD5 Collisions and S/MIME messages

- Classic collision attack
  - Attacker generates two variants
    - M1 = "I will pay Eric $1.00/hr" *(a bargain)*
    - M2 = "I will pay Eric $1000/hr" *(a rip-off)*
  - Attacker gets victim to sign M1
  - Then claims victim signed M2
    - And he has evidence to prove it
  - This makes the most sense with contracts
- Small problems
  - Remember that random garbage?
    - Real contracts don't have that
  - Victim has both variants
- Big problem
  - This isn't how contracts actually work

Victim has both variants

- Victim originally had "good" variant
- The attacker wants to enforce "bad" variant
- Question
  - Which one generated the good/bad pair?
  - Each party points the finger
- But in a lot of situations it's obvious
  - "Unsolicited" messages *must* have been generated by sender
    - Because finding pre-images is still hard
  - Otherwise, sender must claim that receiver sent him a message he signed verbatim
- Why were you using MD5 anyway?

Contracts in the real world

- You and I negotiate a contract
  - Your lawyer sends me the final copy
  - I sign the last page
  - I fax it over to you
  - You fax it back
- No attempt is made to bind contents to signature
  - At most, I might initial each page
  - But sometimes, just last page is exchanged!
- Signature is unverified
  - How does relying party know, anyway?
  - An "X" can be binding!
- It's the intention that counts

Collisions and certificates

- Attacker generates two names
  - Good: www.attacker.com
  - Bad: www.a-victim.com
- Sends a CSR with good name to CA
  - CA signs cert
  - Attacker now has cert with victim's name
- Two problems
  - Can you predict the prefix?
  - What about the random padding?

The structure of certificates

```
TBSCertificate ::= SEQUENCE {
        version                 Integer value=2
        serialNumber            Integer (chosen by CA)
        signature               algorithm identifier
        issuer                  CA’s name
        validity                date range
        subject                 subject’s name
        subjectPublicKeyInfo    public key
        extensions              arbitrary stuff
}
```

- The signature is over H(TBSCertificate)

Prefix prediction

- Knowing which values to use depends on the prefix
  - But the prefix isn’t totally fixed
  - This is a total design accident!
- All but serial number and validity are fixed
  - Sequential serial numbers are easy to predict
    - At least to within a few
    - Verisign uses H(time_us) which is hard to predict
  - How quantum is the validity?
    - Verisign seems to use a fixed “not before” but a “not after” based on the current time
      - So predictable to within a few hundred seconds?
- Attacker is likely to need to try the attack a number of times
- Randomizing serial number is a simple countermeasure

A vulnerable certificate structure

```
TBSCertificate ::= SEQUENCE {
        version                 Integer value=3
        signature               algorithm identifier
        issuer                  CA’s name
        subject                 subject’s name
        subjectPublicKeyInfo    public key
        serialNumber            Integer (chosen by CA)
        validity                date range
        extensions              arbitrary stuff
}
```

Dealing with the random pads

- Remember, we want a specific target name
  - E.g. www.amazon.com
  - Though we have flexibility in the name we send the CA
- Random padding can be concealed in pubkey
  - Remember, modulus doesn't have to be p*q
    - As long as we can factor it
    - ... which is likely for a random modulus [Back 04]

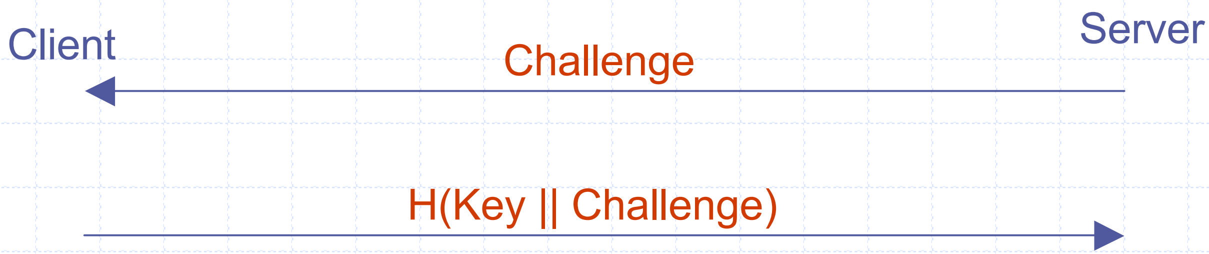
Attack 2: 1st preimages

- Preimages hard to find for "standard" hashes
- Attack description:
  - Given some hash value X
  - Find a message M st H(M) = X
  - Assumption:
    - M is effectively random
    - … not controllable by attacker
- For example
  - S/Key responses are iterated hashes H(H(H(H(H(seed)))))
    - Used in reverse order
  - If I see one response I can predict the next one
- Most scenarios involve 2nd preimages

Attack 2 variant: partial 1st preimage

- Attacker sees:
  - Digest value
  - Some of digest inputs
  - Common situations
    - Challenge/response
    - MACs for protocol data
- Attacker wants to forge future values
  - Using secret data

Trivial challenge/response protocol



- Attacker wants to find Key
  - Can use it to forge future responses
  - If Key and Challenge are in same block, then chances that preimage will be useful are small
  - Assume Key is padded to a block multiple
    - As in HMAC

Attacking partial 1st preimages

- Problem definition:
  - Given M and hash compression function
  - Find state st Compress(State,M) = X
    - For all future values of M,X
- Not the same as a preimage
  - Since we need a specific state
  - … in order to forge future messages
  - This isn't possible in general
    - Is it possible for ordinary hashes?

Preimage != State

- Contrived hash function
  - CBC-MAC variant with a fixed key
  - Zero about half the CBC residue bits
    - $H_0 = 0$
    - $H_{n+1} = E((H_n \& MD5(M_{n+1})) \wedge M_{n+1})$
- Preimages are found by decrypting
- Consider the two block case
  - Decrypting H_2 gives $(H_1 \& MD5(M_2)) \wedge M_2$
  - Attacker can recover $H_1 \& MD5(M_2)$
  - But any other challenge (M_2) will zero different bits
    - So can't forge new responses
    - Though each response leaks different bits...

What if you could forge MACs?

- Does this break protocols?
  - It depends...
- Authenticate then encrypt (SSL/TLS)
  - Block ciphers
    - Can't re-insert the MAC
    - And wouldn't match the data in any case
  - Stream ciphers
    - Can reinsert MAC
    - ... but only if you know the plaintext
- Encrypt than authenticate (IPsec)
  - Easy to do an existential forgery
  - Hard to do a controlled one unless plaintext is known
- SSH is weird
  - Authenticate then encrypt (but not the MAC)
  - Can reinsert MAC
    - But it doesn't match the data

Attack 3: 2nd preimages

- Attack description:
  - Given some message M
  - Find some message M′ st H(M) = H(M′)
- Classic example: message forgery
  - Start with signed "Good" message
  - Transform it into signed "Bad" message

2^{nd} preimages and certificates

- This is really serious
  - Attacker should be able to forge a cert of his choice
  - Validity of all certs with this digest is now questionable
  - No useful countermeasures
- How likely do we think this is with MD5?
  - If so, really bad
  - Lots of valid certificates use MD5!
- SHA-1 comfort level is higher

2nd preimages and other protocols

- Three major uses of hashes
  - MACs
  - Key expansion
  - Signatures
- Only signatures are threatened
- But they're commonly used
  - SSH, SSL, IPsec key agreement
    - Signatures are over nonces
    - Only works if very fast
      - Need to beat timeouts
  - S/MIME authentication
- So, this is bad…

Attack 4: Weakness in initial RC4 bytes

- RC4 initial bytes known to be imperfect
  - Recommendation: discard first 256 bytes
  - But most protocols don't do this
    - SSL/TLS in particular
- Attack description:
  - Extension of Mironov and Fluhrer/Shamir work
  - Recover key information from initial keystream
  - Don't need to recover key
    - Just predict other initial bytes…

Consequences of Attack 4

- Attacker can recover connection plaintext
- Credit cards over HTTPS are particularly weak
  - First 4 plaintext bytes known
  - Next 28-32 (TLS) or 52-56 (SSLv3) plaintext bytes are random
  - Next plaintext bytes are HTTP fetch and header
    - 100-500 bytes
    - Very predictable
  - Followed by a credit card #
    - Predictable structure helps here

Countermeasures for Attack 4

- In principle easy
  - At least for SSL
    - 802.11 already moving to AES
  - Almost all clients and servers support DES, 3DES, etc.
    - It's a negotiable item
    - Server admin can just turn off RC4
- In practice not so easy
  - Admins are concerned about performance
  - Uptake of fixes is very slow [Rescorla 03]
- May not be the easiest attack
  - You only recover 1 credit card number
  - Poorly maintained servers may have other flaws

Attack 5: DES-quality attacks on AES/3DES

- Current AES/3DES attacks are nearly useless
  - What if we had attacks on AES as good as those on DES?
- Attack description:
  - Recover key with 2^{43} known plaintexts and 2^{43} ops
  - This would be a major success
    - 2^{69} improvement for 3DES
    - 2^{85} improvement for AES
- But what does it mean for a real system?

Implications for common protocols

- SSL
  - Each connection uses a separate key
  - Most connections are short (HTTP)
    - 5 minutes is considered long
- SSH
  - Longer but not a lot of data is moved
- S/MIME
  - Each message uses a separate key
  - When would you have part of a message in the clear?
  - 2^{43} blocks = 10^{14} bytes
    - This is longer than any commercial disk
    - So not realistic as a message
- IPsec
  - 2^{43} blocks is 10 days of full-speed 1Gig traffic
    - Not a common situation
  - This attack doesn't apply to 3DES
    - 3DES uses CBC mode
    - You need to change keys every 2^{32} blocks anyway

Attack 5 Variant: Total cipher break

- Complete key recovery
  - Using a few known plaintexts
  - And relatively fast
- Compromises confidentiality
- No effect on authentication
  - Encryption keys decoupled from MAC keys
    - At least in well designed protocols
  - Often encryption keys too short to recover master secret
    - Even if PRFs were broken

Attack 6: Remote key recovery

- E.g.,timing attacks [Kocher], [Boneh and Brumley 03]
  - Not known if can be executed over Internet
  - Easily fixed (blinding)
- Attack description:
  - Repeated remote probes allow recovery of private key

Implications of Attack 6

- SSH, IPsec typically use DH
  - With a fresh key for each exchange
  - Attacks on signature?
    - No control of plaintext
  - Can't attack connection A from connection B
  - ... SSHv1 was weaker...
- SSL/TLS
  - Generally uses static RSA
    - Though DH variants exist
  - These attacks work well here
- S/MIME
  - What about automated mail responders?
    - Timing?
    - Faults?

Attack 7: RSA signature malleability

- Signature forgery is obviously a disaster
  - What about something weaker?
- Attack description:
  - Given a signature over message M
    - actually hash value M
    - modify the last few bits
- Not very plausible with RSA
  - PKCS-1 padding
  - What about DSA?
- But not message integrity
  - Can't go from encryption keys to MAC keys
    - Both are generated from a master key
  - Even broken hashes don't help
    - Master keys are too long

Implications of signature malleability

- Remember: all signatures are over hashes
  - Forged signature is over a random value
    - Effectively an existential forgery
    - Note: many algorithms already have this property
  - Need to find usable preimage
- Use a meet-in-the-middle attack
  - $2^{n/2}$ operations
  - $2^{n/2}$ storage
  - Can't be done in real time….
- Only practical for very high value transactions
  - Unless of course the hash was *also* broken

Take home points

- Protocols are surprisingly resistant failure to primitive
- Randomness really helps
- Timing counts
- Hash early, hash often
- Sometimes it's better to be lucky than good

Major comsec protocols

- SSL/TLS: Application layer generic channel security
  - Web traffic
  - E-mail (SMTP/TLS)
  - SSL VPNs...
  - Mostly short-lived connections between client and server
- SSH: Application layer channel security
  - Remote login
- IPsec: Network-level channel security
  - VPNs
  - Long-term associations between networks
- S/MIME, PGP: Application layer message security
  - E-mail