


Cryptography Best Practices


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Outline

- 1. Cryptology: concepts and algorithms
 - symmetric algorithms for confidentiality
 - symmetric algorithms for data authentication
 - public-key cryptology
- 2. Cryptology: protocols
 - identification/entity authentication
 - key establishment
- 3. Public-Key Infrastructure principles
- 4. Networking protocols
 - email, web, IPsec, SSL/TLS
- 5. New developments in cryptology
- 6. **Cryptography best practices**



Outline

- Architecture
- Network protocols
- Security APIs
- Key establishment: protocols, generation, storage
- Implementing digital signature schemes

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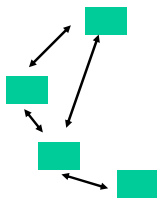
Symmetric vs. Asymmetric Algorithms

• hardware costs: 3K–100K gates	• hardware costs: 100K–1M gates
• performance: 100 Mbit/s – 70 Gbit/s	• performance: 100 Kbit/s – 10 Mbit/s
• keys: 64-256 bits	• keys: 128-4096 bits
• blocks: 64-128 bits	• blocks: 128-4096 bits
• power consumption: 20-30 μ J/bit	• power consumption: 1000-2000 μ J/bit

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Architectures (1a)

• Point to point	• Number of keys: 1 or n^2
• Local	• Manual keying
• Small scale	

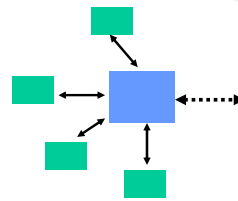


Example: ad hoc PAN or WLAN

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Architectures (2a)

• Centralized	• Number of keys: n
• Small or large scale	• ! Central database: risk + big brother
• Manual keying	• Non-repudiation of origin? (physical assumptions)

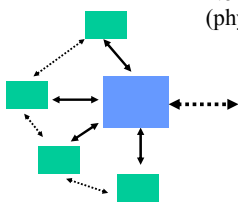


Example: WLAN, e-banking, GSM

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Architectures (3a)

- Centralized
- Small or large scale
- Manual keying
- Number of keys: $n + 1/\text{session}$
- ! Central database: risk + big brother
- Non-repudiation of origin? (physical assumptions)

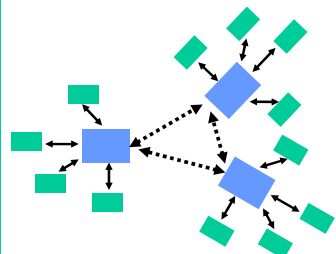


Example: LAN (Kerberos)

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Architectures (4a)

- Decentralized
- Large scale
- Number of keys: $n + N^2$
- Risks?
- Trust
- Hard to manage

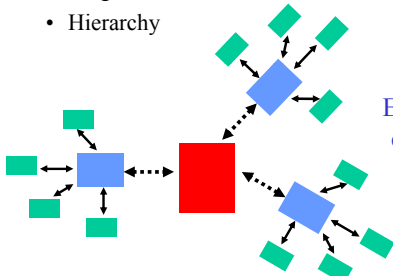


Example: network of LANs, GSM

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Architectures (5a)

- Centralized
- Large scale
- Hierarchy
- Number of keys: $n + N$

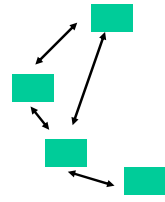


Example: credit card and ATM

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Architectures (1b)

- Point to point
- Worldwide
- Small networks
- No CA (e.g. PGP)

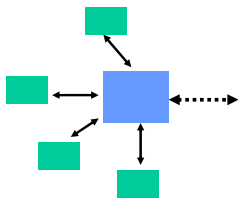


Example: P2P, international organizations

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Architectures (2b)

- Centralized
- Large or small scale
- Reduced risk
- Non-repudiation of origin

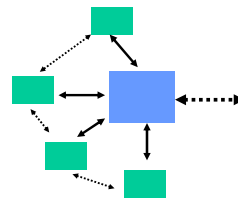


Example: B2C e-banking

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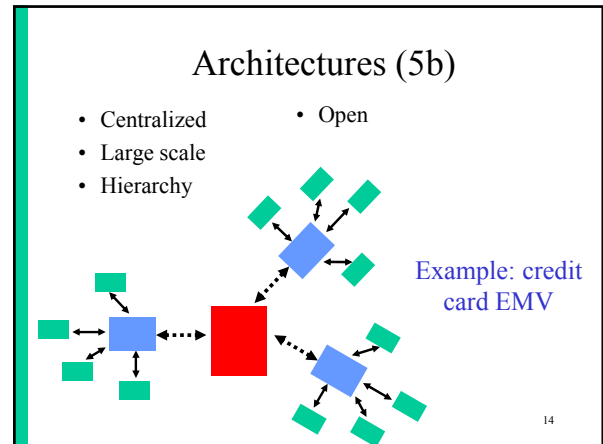
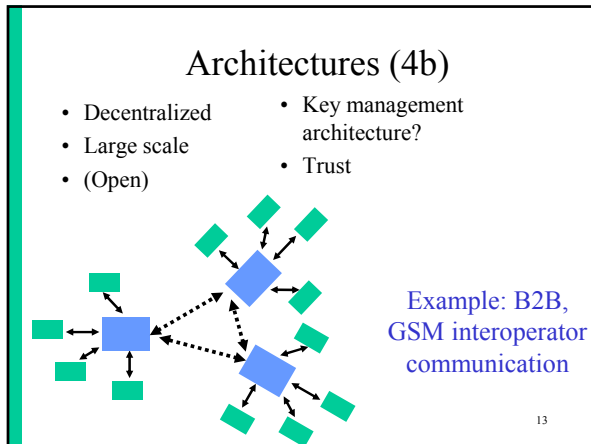
Architectures (3b)

- Centralized
- Small or large scale
- Reduced risk
- Non-repudiation of origin



Example: B2B and e-ID

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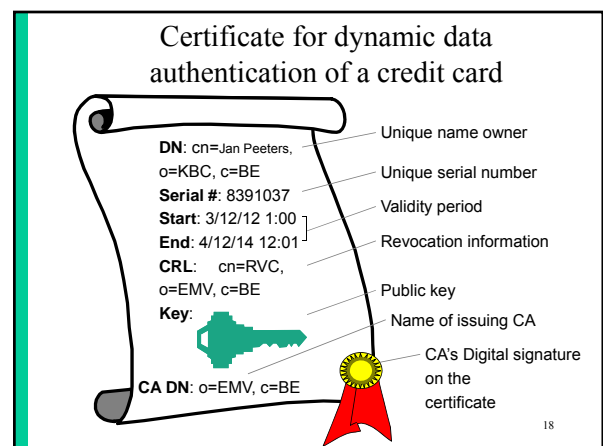
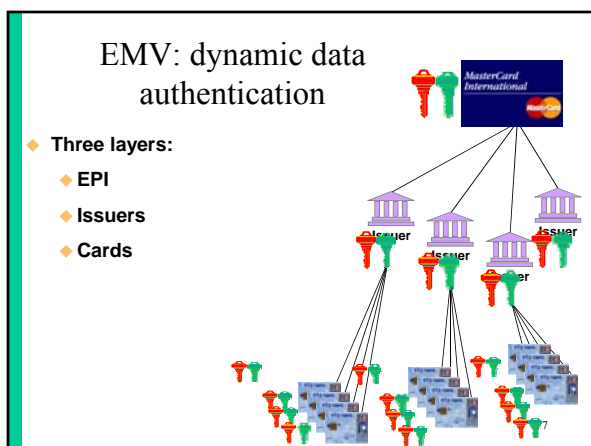
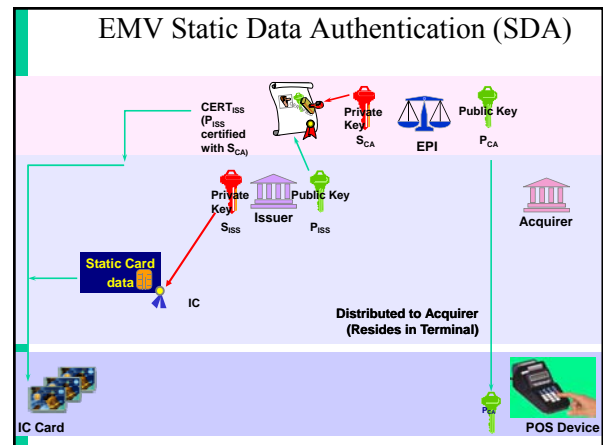


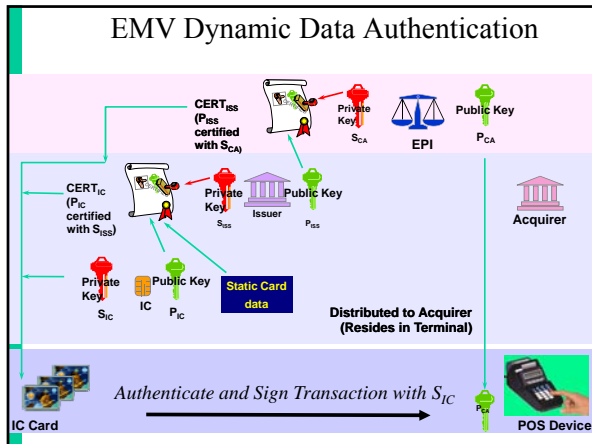
When asymmetric cryptography?

- if manual secret key installation not feasible (also in point-to-point)
- open networks (no prior customer relation or contract)
- get rid of risk of central key store
- mutually distrustful parties
 - strong non-repudiation of origin is needed
- fancy properties: e-voting

Important lesson: on-line trust relationships should reflect real-world trust relationships

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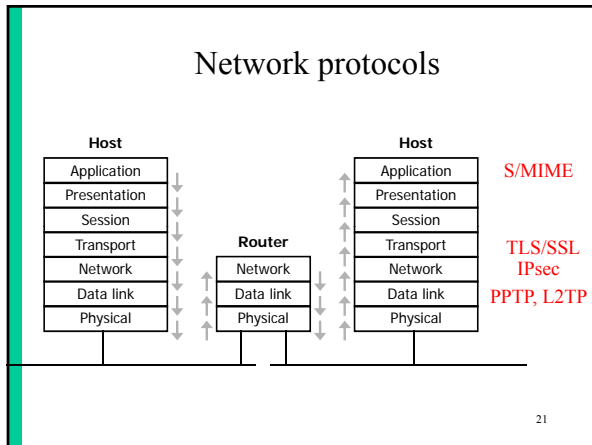


Warning about EMV

<http://www.cl.cam.ac.uk/research/security/banking/nopin/oakland10chipbroken.pdf>

- Pin checking and authentication are not coupled
- **EMV PIN verification “wedge” vulnerability**
S.J. Murdoch, S. Drimer, R. Anderson, M. Bond, IEEE Security & Privacy 2010

The diagram compares Normal PIN check and Fraudulent PIN check. In Normal PIN check, the user enters a PIN, and the terminal checks it. In Fraudulent PIN check, the user enters a PIN, and the terminal checks it, but the PIN is not correct. The user then enters a new PIN, and the terminal checks it. The fraudulent PIN check is shown as a sequence of steps: 1. enter PIN, 2. PIN correct?, 3. yes, 4. yes, 5. yes. The normal PIN check is shown as a sequence of steps: 1. enter PIN, 2. PIN correct?, 3. no, 4. yes.



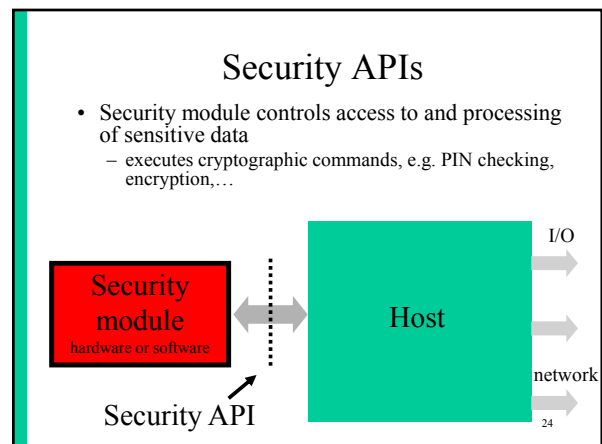
Where to put security?

- Application layer:
 - closer to user
 - more sophisticated/granular controls
 - end-to-end
 - but what about firewalls?
- Lower layer:
 - application independent
 - hide traffic data
 - but vulnerable in middle points
- Combine?

Where to put security? (2)

From: Bob@crypto.com
To: Alice@digicrime.com
Subject: Re: Can you meet me on Monday at 3pm to resolve the price issue?

This proposal is acceptable for me.
-- Bob



Master key/data key

- Load master 3DES key **KM** (tightly controlled)
- Load data key:
 $3DES_{KM}(K1) || 3DES_{KM}(K2) || 3DES_{KM}(K3)$
- Send plaintext P and ask for encryption
 $DES_{K1}(DES^{-1}_{K2}(DES_{K3}(P)))$

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Master key/data key (2)

- Load master 3DES key **KM** (tightly controlled)
- Load corrupted data key:
 $DES_{KM}(K1) || DES_{KM}(K1) || DES_{KM}(K1)$
- Send plaintext P and ask for encryption
 $DES_{K1}(DES^{-1}_{K1}(DES_{K1}(P))) = DES_{K1}(P)$

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Control vectors in the IBM 4758 (1)

- Potted in epoxy resin
- Protective tamper-sensing membrane, chemically identical to potting compound
- Detectors for temperature & X-Rays
- “Tempest” shielding for RF emission
- Low pass filters on power supply rails
- Multi-stage “latching” boot sequence
- = **STATE OF THE ART PROTECTION!**

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IBM 4758

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Features of the IBM 4758

- Control vector: *type* (e.g., PIN, data, MAC)
store key of type *type* as $E_{Km + \text{“type”}}(k)$
 - Output of encryption with key of type “PIN” is never allowed to leave the box
 - Output of encryption with key of type data, MAC, ... may leave the box
- High security master key import: 3 shares
 - Import Km as $Km_A + Km_B + Km_C$

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Master key import

$Km = Km_A + Km_B + Km_C$

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Fraudulent import

Km_A Km_B $Km_C = Km_C + \text{"data"} - \text{"PIN"}$

2


$Km^* = Km_A + Km_B + Km_C^* = Km + \text{"data"} - \text{"PIN"}$

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The attack

Transport PIN key k from box 1 to box 2

1. Encrypt on box 1, type PIN:
 $x = E_{Km + \text{"PIN"}}(k)$
2. Decrypt on box 2, type data:
 $D_{Km^* + \text{"DATA"}}(x) = D_{Km + \text{"PIN"}}(x) = k$



The system now believes that k is a key to decrypt data, which means that the result will be output (PINs are never output in the clear).

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Lessons learned: security APIs

- Complex – 150 commands
- Need to resist to insider frauds
- Hard to design – can go wrong in many ways
- Need more attention
- Further reading: Mike Bond, Cambridge University
<http://www.cl.cam.ac.uk/users/mkb23/research.html>

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Key management

- Key establishment protocols
- Key generation
- Key storage
- Key separation (cf. Security APIs)

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Key establishment protocols: subtle flaws

- Meet-in-the middle attack
 - Lack of protected identifiers
- Reflection attack
- Triangle attack

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Attack model: Needham and Schroeder [1978]:

We assume that the intruder can interpose a computer in all communication paths, and thus can alter or copy parts of messages, replay messages, or emit false material. While this may seem an extreme view, it is the only safe one when designing authentication protocols.

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Meet-in-the middle attack on Diffie-Hellman

- Eve shares a key $k1$ with Alice and a key $k2$ with Bob
- Requires *active* attack

$k1 = (\alpha^{y1})^{x1} = (\alpha^{x1})^{y1}$ $k2 = (\alpha^{x2})^{y2} = (\alpha^{y2})^{x2}$

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Entity authentication

- Alice and Bob share a secret k

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Entity authentication: reflection attack

- Eve does not know k and wants to impersonate Bob

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Needham-Schroeder (1978)

- Alice and Bob have each other's public key PA and PB

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Lowe's attack on Needham-Schroeder (1995)

- Alice thinks she is talking to Eve
- Bob thinks he is talking to Alice

Eve

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Lowe's attack on Needham-Schroeder (1995)

- Eve is a legitimate user = insider attack
- Fix the problem by inserting B in message 2

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Lessons from Needham-Schroeder (1995)

- Prudent engineering practice (Abadi & Needham): include names of principals in all messages
- **IKE v2 – plausible deniability**: don't include name of correspondent in signed messages: <http://www.ietf.org/proceedings/02nov/I-D/draft-ietf-ipsec-soi-features-01.txt>

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Rule #1 of protocol design

Don't!

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Why is protocol design so hard?

- Understand the security properties offered by existing protocols
- Understand security requirements of novel applications
- Understanding implicit assumptions about the environment underpinning established properties and established security mechanisms

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And who are Alice and Bob anyway?

- Users?
- Smart cards/USB tokens of the users?
- Computers?
- Programs on a computer?

If Alice and Bob are humans, they are vulnerable to social engineering

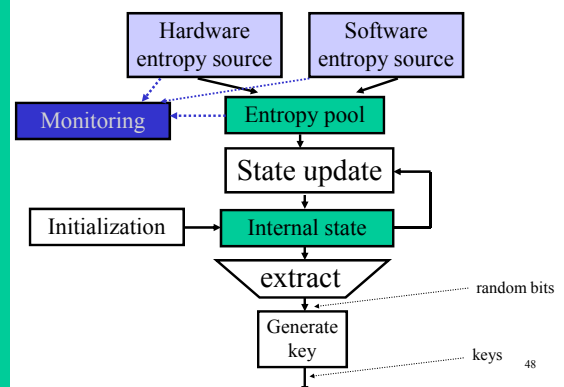
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Random number generation

- “The generation of random numbers is too important to be left to chance”
- John Von Neumann, 1951: “Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin”
- Used for
 - Key generation
 - Encryption and digital signatures (randomization)
 - Protocols (nonce)

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Key generation: overview



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Key generation: hardware entropy sources

- radioactive decay
- reverse biased diode
- free running oscillators
- radio
- audio, video
- hard disk access time (air turbulence)
- manually (dice)
- lava lamps

Risk: physical attacks, failure

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Key generation: software entropy sources

- system clock
- elapsed time between keystrokes or mouse movements
- content of input/output buffers
- user input
- operating system values (system load, network statistics)
- interrupt timings

Risk: monitoring, predictable

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Key generation: monitoring

- Statistical tests (NIST FIPS 140)
- typical tests: frequency test, poker test, run's test
- necessary but not sufficient
- 5 lightweight tests to verify correct operation continuously
- stronger statistical testing necessary during design phase, after production and before installation

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State update

- Keep updating entropy pool and extracting inputs from entropy pool to survive a state compromise
- Combine both entropy pool and existing state with a non-invertible function (e.g., SHA-512, $x^2 \bmod n, \dots$)

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Output function

- One-way function of the state since for some applications the random numbers become public
- A random **string** is not the same as a random **integer** mod p
- A random **integer/string** is not the same as a random **prime**

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What **not** to do

- use `rand()` provided by programming language or O/S
- restore entropy pool (seed file) from a backup and start right away
- use the list of random numbers from the RAND Corporation
- use numbers from <http://www.random.org/>
 - 66198 million random bits served since October 1998
- use digits from π , e , $\pi/e, \dots$
- use linear congruential generators [Knuth]
 - $x_{n+1} = a x_n + b \bmod m$

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RSA moduli

- Generate a 1024-bit RSA key
Use random bit generation to pick random a integer r in the interval $[2^{512}, 2^{513}-1]$
If r is even $r:=r+1$
Do $r:=r+2$ until r is prime; output p
Do $r:=r+2$ until r is prime; output q

What is the problem?

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What to consider/look at

- **There are no widely used standardized random number generators**
- Learn from open source examples: ssh, openssl, linux kernel source
- /dev/random (slow)
- Yarrow/Fortuna
- ANSI X9.17 (but parameters are marginal)
- Other references:
 - D. Wagner's web resource: <http://www.cs.berkeley.edu/~daw/md/>
 - P. Gutmann, <http://researchspace.auckland.ac.nz/handle/2292/2310>
 - L. Dorrendorf, Z. Gutterman, Benny Pinkas, Cryptanalysis of the Windows random number generator. ACM CCS 2007, pp. 476-485
 - Z. Gutterman, Benny Pinkas, T. Reinman, Analysis of the Linux random number generator. IEEE Symposium on Security and Privacy 2006, pp. 371-385

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How to store keys

- Disk: only if encrypted under another key
 - But where to store this other key?
- Human memory: passwords limited to 48-64 bits and passphrases limited to 64-80 bits
- Removable storage: Floppy, USB token, iButton, PCMCIA card
- Cryptographic co-processor: smart card USB token
- Cryptographic co-processor with secure display and keypad
- Hardware security module
- PUFs: Physical Unclonable Functions

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Secure key storage with non-initialized SRAM

Due to deep sub-micron process variations ICs are intrinsically unique

Start-up SRAM values establish a unique and robust fingerprint

The electronic fingerprint is turned into a secure secret key, which is the foundation of enhanced security

Enrollment

SRAM PUF → R → Helper Data Algorithm → HD

One-Time Process (during production)

Reconstruction

SRAM PUF → R → Helper Data Algorithm → Key

Helper Data (HD) In the field (many times)

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Side credit: Intrinsic ID

Implementation attacks cold boot attack

- Why break cryptography? Go for the key, stupid!
- Data reminence in DRAMs
 - Lest We Remember: Cold Boot Attacks on Encryption Keys [Halderman-Schoen-Heninger-Clarkson-Paul- Calandrino-Feldman- Appelbaum-Felten'08]
 - Works for AES, RSA,...
 - Products: BitLocker, FileVault, TrueCrypt, dm-crypt, loop-AES

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New attack on keys in memory (21/02/08)

- Key is stored in DRAM when machine is in sleep or hibernation
- Option 1: Reboot from a USB flash drive with O/S and forensic tools (retaining the memory image in DRAM), scan for the encryption keys and extract them.
- Option 2: physically remove the DRAM
 - Cool DRAM using compressed-air canister (-50 C) or liquid nitrogen (-196 C)
- Solution: hardware encryption or 2-factor authentication

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How to back-up keys

- Backup is essential for decryption keys
- Security of backup is crucial
- Secret sharing: divide a secret over n users so that any subset of t users can reconstruct it



Destroying keys securely is harder than you think

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Implementing digital signatures is hard

- ElGamal
- RSA

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The risks of ElGamal (1/3)

- ElGamal-type signatures (including DSA, ECDSA)
- public parameters: prime number p, generator g (modulo p operation omitted below)
- private key x, public key $y = g^x$
- signature (r,s)
 - generate temporary private key k and public key $r = g^k$
 - solve s from $h(m) \equiv x r + k s \pmod{p-1}$
- verification:
 - Signature verification: $1 < r < p$ and $h(m) \equiv y^r r^s \pmod{p}$

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The risks of ElGamal (2/3)

- long term keys: $y = g^x$
- short term keys: $r = g^k$
- the value k has to be protected as strongly as the value x
 - Ex. 1: NIST had to redesign the DSA FIPS standard because of a subtle flaw in the way k was generated [Bleichenbacher'01]
 - Ex 2: attack on ElGamal as implemented in GPG [Nguyen'03]

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The risks of ElGamal (3/3)

- $y = g^x$
- signature:
 - $r = g^k$
 - $h(m) \equiv x r + k s \pmod{p-1}$
- what if k would be the same every time?
 - $h(m_1) \equiv x r + k s \pmod{p-1}$
 - $h(m_2) \equiv x r + k s \pmod{p-1}$
- 2 linear equations in 2 unknowns: easy to solve: yields the signing key x
- one solution: choose $k = h(m || x)$



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Problematic public keys (1/3)

[Lenstra-Hughes+ Crypto 12]

- 11.7 million openly accessible public keys (TLS/PGP)
- 6.4 million distinct RSA moduli
- rest: ElGamal/DSA (50/50) and 1 ECDSA

[Heninger+ Usenix Sec. 12]

- 12 million openly accessible public keys (5.8 TLS/6.2 SSH)
- 23 million hosts (12.8/10.2)
- 1%: 512-bit RSA keys

- 1.1% of RSA keys occur in >1 certificate
 - 5.6% of TLS hosts share public keys
 - 5.2% default manufacturer keys
 - 0.34% have by accident the same key
- easy to factor: 0.2% of RSA keys
 - 12,000 keys!
 - 40% have valid certs
- easy to factor: 0.5% of TLS hosts and 0.03% of SSH hosts
- DSA key recovery: 1.6% of DSA hosts

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Problematic public keys (2/3)

- low entropy during key generation
- RSA keys easy to factor, because they form pairs like: $n = p \cdot q$ and $n' = p' \cdot q$ so $\text{gcd}(n, n') = q$
- DSA keys: reuse of randomness during signing or weak key generation
 - why ???
 - embedded systems
 - routers, server management cards, network security devices
 - key generation at first boot

RSA versus DSA
Ron was wrong, What is right or vice versa?

Problematic public keys (3/3)

ethical problem: how to report this?

details:

Lenstra, Hughes, Augier, Bos, Kleinjung, Wachter, "Ron was wrong, What is right" <http://print.iacr.org/2012/064.pdf>, or with as title "Public keys," Crypto 2012.

Heninger, Durumeric, Wustrow, Halderman, "Mining Your Ps and Qs: Detection of Widespread Weak Keys in Network Devices," Usenix Security 2012, <https://www.usenix.org/conference/usenixsecurity12/tech-schedule/technical-sessions>

More problems identified: identity cards in Taiwan

The risks of ElGamal (1/3)

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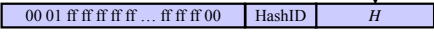
How to sign with RSA?

- public key: (n, e)
- private key: d
- $s = t^d \pmod{n} = t^{1/e} \pmod{n}$
- But
 - message M is often larger than modulus n
 - $\text{RSA}(x * y) = \text{RSA}(x) * \text{RSA}(y)$
 - $\text{RSA}(0) = 0, \text{RSA}(1) = 1, \dots$
- Solution: hash and add redundancy
 - PKCS #1
 - RSA-PSS

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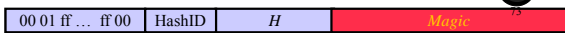
RSA Signatures: PKCS #1 v1.5 [source: RSA Labs]

public key: (n,e)
private key: d

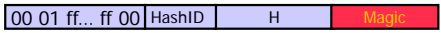

$t =$ 

Generation of RSA signature on M: $s = t^d \text{ mod } n = t^{1/e} \text{ mod } n$

Verification of RSA signature s on M
Compute $t = s^e \text{ mod } n$ and check that t has the required format

Problem: most signature verification software would accept a signature on M of the following form: 

Attack on PKCS #1 v1.5 implementations (1) [Bleichenbacher06]

- consider RSA with public exponent $e = 3$
- for any hash value H, it is easy to compute a string “Magic” such that the above string is a perfect cube of 3072 bits
 - example of a perfect cube $1728 = 12^3$
- consequence:
 - one can sign any message (H) **without knowing the private key**
 - this signature works **for any public key** that is longer than 3072 bits
- vulnerable: OpenSSL, Mozilla NSS, GnuTLS 74

Other ways to fool CAs

- [Moxie Marlinspike’09] Black Hat
 - browsers may accept bogus SSL certs
 - CAs may sign malicious certs
- certificate for www.paypal.com/0.kuleuven.be will be issued if the request comes from a kuleuven.be admin
- response by PayPal: suspend Moxie’s account
 - http://www.theregister.co.uk/2009/10/06/paypal_bani_shes_ssl_hacker/

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Fix of Bleichenbacher’s attack

- Write proper verification code (but the signer cannot know which code the verifier will use)
- Use a public exponent that is at least 32 bits
- Upgrade – finally – to RSA-PSS

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Conclusion

- Implementing cryptography requires a high level of cryptographic expertise
- Application developers should become specialists
 - “A specialist is someone who knows when to call an expert”

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