# Cryptography Best Practices

Prof. Bart Preneel
COSIC
Bart.Preneel(at)esatDOTkuleuven.be
http://homes.esat.kuleuven.be/~preneel
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iMinds
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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. Post-Snowden cryptography
- **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: 2 K– 100K gates
- performance: 100 Mbit/s – 100 Gbit/s
- keys: 64-256 bits
- blocks: 64-128 bits
- power consumption: 20-30 μJ/bit

- hardware costs: 20 K- 1M gates
- performance: 100 Kbit/s – 50 Mbit/s
- keys: 128-4096 bits
- blocks: 128-4096 bits
- power consumption: 1000-2000 μJ/bit

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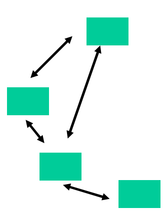
## Architectures (1a)

- Point to point
- Local
- Small scale

- Number of keys: 1 or $n^2$
- Manual keying



Example:
ad hoc PAN or WLAN

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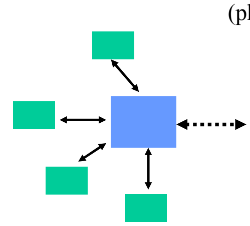
## Architectures (2a)

- Centralized
- Small or large scale
- Manual keying

- Number of keys: n
- ! Central database: risk + big brother
- Non-repudiation of origin? (physical assumptions)



Example: WLAN, e-banking, GSM

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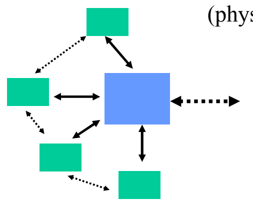
## Architectures (3a)

- Centralized
- Small or large scale
- Manual keying

- Number of keys: n + 1/session
- ! Central database: risk + big brother
- Non-repudiation of origin? (physical assumptions)



Example: LAN (Kerberos)

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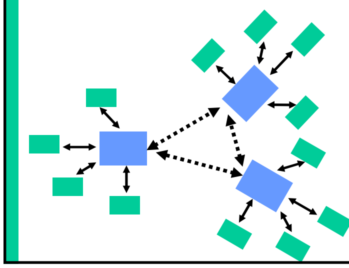
## Architectures (4a)

- Decentralized
- Large scale

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



Example: network of LANs, GSM

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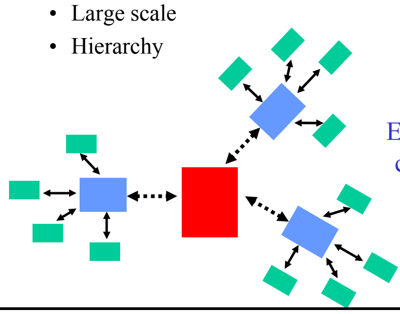
## Architectures (5a)

- Centralized
- Large scale
- Hierarchy

- Number of keys: n + N



Example: credit card and ATM

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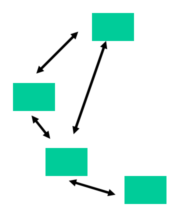
## Architectures (1b)

- Point to point
- Worldwide
- Small networks

- No CA (e.g. PGP)



Example: P2P, international organizations

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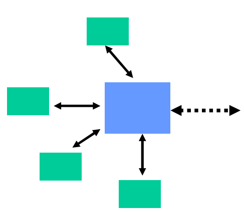
## Architectures (2b)

- Centralized
- Large or small scale

- Reduced risk
- Non-repudiation of origin



Example: B2C e-banking

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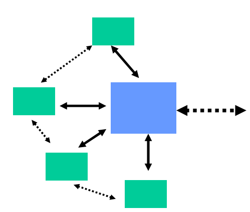
## Architectures (3b)

- Centralized
- Small or large scale

- Reduced risk
- Non-repudiation of origin



Example: B2B and e-ID

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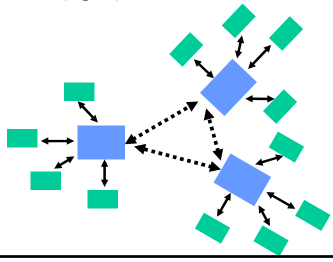
## Architectures (4b)

- Decentralized
- Large scale
- (Open)
- Key management architecture?
- Trust



Example: B2B, GSM interoperator communication

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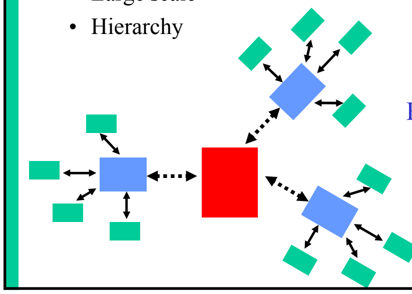
## Architectures (5b)

- Centralized
- Large scale
- Hierarchy
- Open



Example: credit card EMV

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## When asymmetric cryptology?

- 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 distrusting parties
  - strong non-repudiation of origin is needed
- fancy properties: e-voting

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

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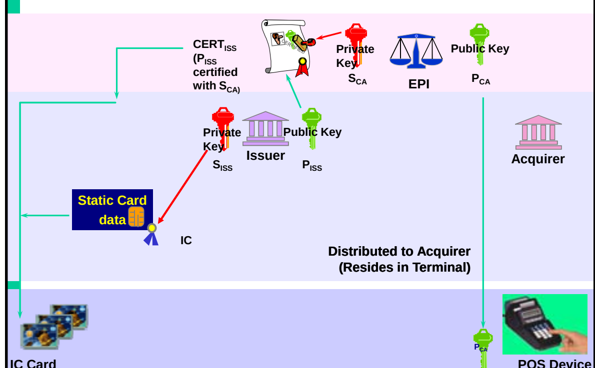
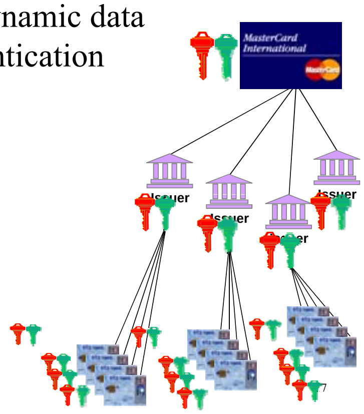
## EMV Static Data Authentication (SDA)

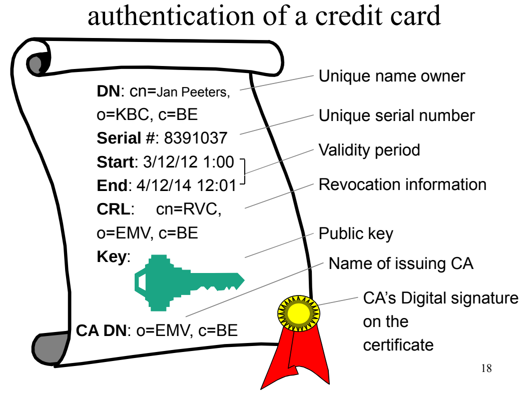



## EMV: dynamic data authentication

- Three layers:
  - EPI
  - Issuers
  - Cards




## Certificate for dynamic data authentication of a credit card

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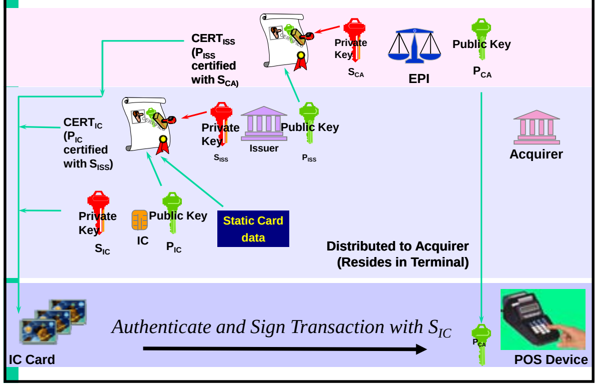
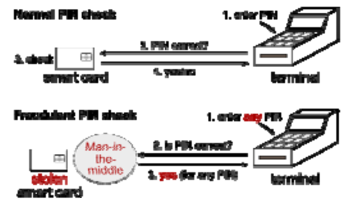
## EMV Dynamic Data Authentication




## 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

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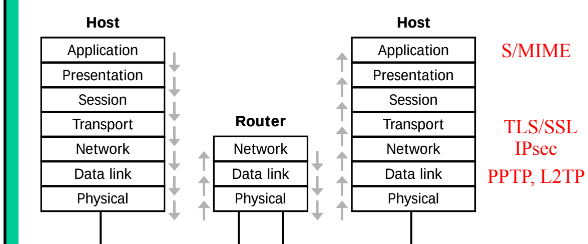
## Network protocols

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## 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?

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## Where to put security? (2)

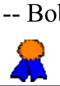
From: Bob@crypto.com

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



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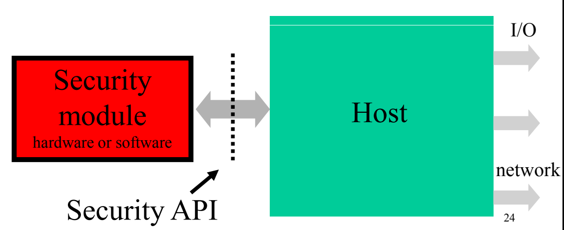
## Security APIs

- Security module controls access to and processing of sensitive data
  - executes cryptographic commands, e.g. PIN checking, encryption,…

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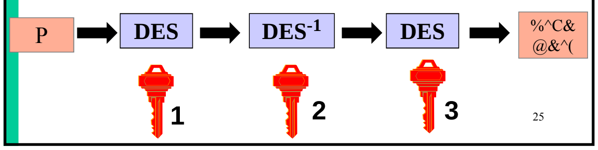
## Master key/data key

- 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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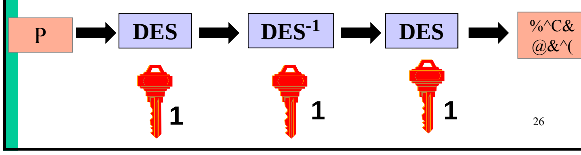
## Master key/data key (2)

- 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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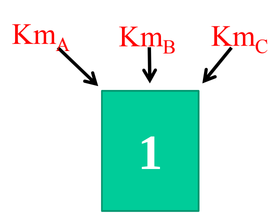
## Master key import




$Km = Km_A + Km_B + Km_C$

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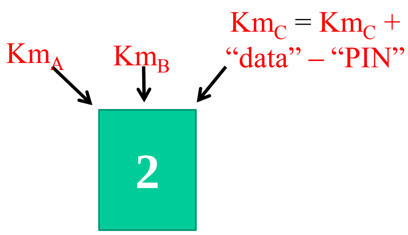
## Fraudulous import




$Km^* = Km_A + Km_B + Km_C^* = Km$ + "data" – "PIN"

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## The attack

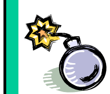
Transport PIN key k from box 1 to box 2

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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## "Efficient padding oracle attacks on cryptographic hardware" (PKCS#11 devices)

[Bardou+ 12] most attacks take less than 100 milliseconds

| Device | PKCS#1v1.5 | | CBC pad | |
|---|---|---|---|---|
| | token | session | token | session |
| Aladdin eTokenPro | X | X | X | X |
| Feitian ePass 2000 | OK | OK | N/A | N/A |
| Feitian ePass 3003 | OK | OK | N/A | N/A |
| Gemalto Cyberflex | X | N/A | N/A | N/A |
| RSA Securid 800 | X | N/A | N/A | N/A |
| Safenet iKey 2032 | X | X | N/A | N/A |
| SATA dKey | OK | OK | OK | OK |
| Siemens CardOS | X | X (89 secs) | N/A | N/A |

## 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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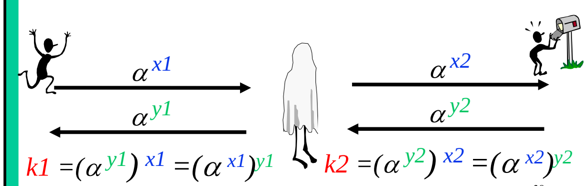
## Meet-in-the middle attack on Diffie-Hellman

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

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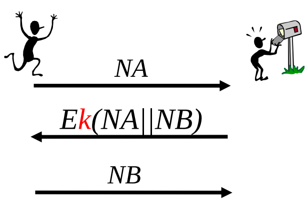
## Entity authentication

- Alice and Bob share a secret k

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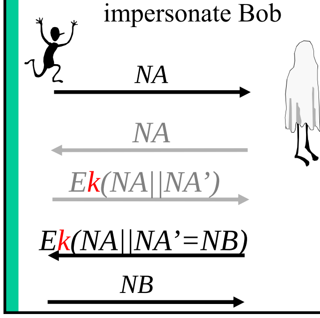
## Entity authentication: reflection attack

- Eve does not know k and wants to impersonate Bob

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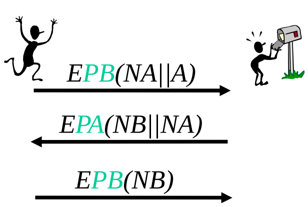
## Needham-Schroeder (1978)

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




Derive a session key k from NA||NB

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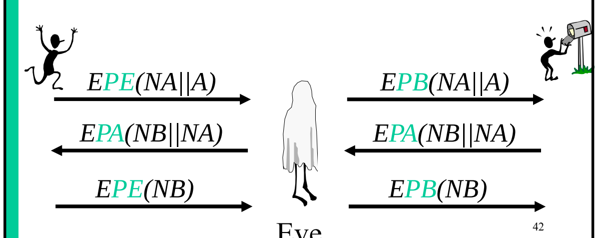
## Lowe's attack on Needham-Schroeder (1995)

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

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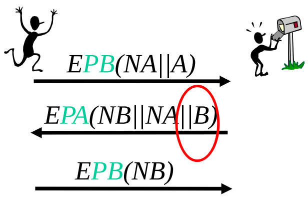
## Lowe's attack on Needham-Schroeder (1995)

- 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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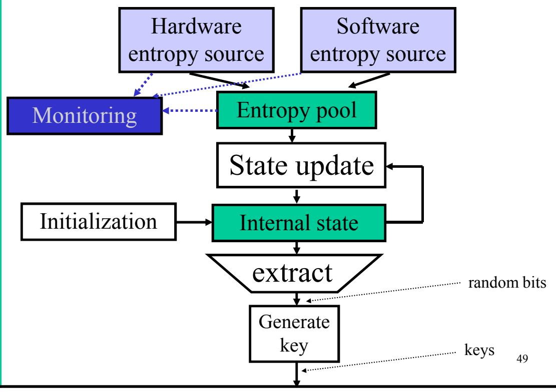
## Key generation: overview

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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, $x^2$ mod n,…)

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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, π/e,…
- 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, openpgp, 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/rnd/
  - 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 Uncloneable Functions

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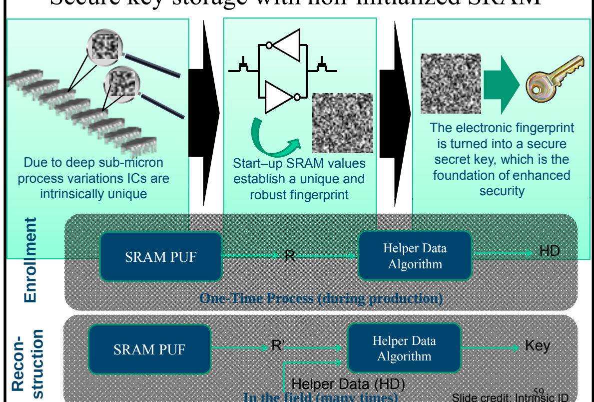
## Secure key storage with non-initialized SRAM




Slide credit: Intrinsic ID

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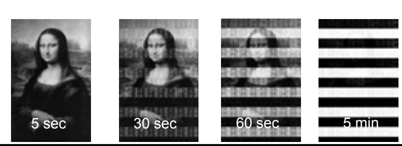
## Implementation attacks cold boot attack

- 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



## 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

$ 11,000

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 $h(m) \equiv x\,r + k\,s \bmod (p-1)$
- verification:
  - Signature verification: $1 < r < p$ and $h(m) \equiv y^r\, r^s \bmod p$

## 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]

## The risks of ElGamal (3/3)

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

## 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

- 1.1% of RSA keys occur in >1 certificate

- easy to factor: 0.2% of RSA keys
  - 12,000 keys!
  - 40% have valid certs

[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

- 5.6% of TLS hosts share public keys
- 5.2% default manufacturer keys
- 0.34% have by accident the same key

- easy to factor: 0.5% of TLS hosts and 0.03% of SSH hosts
- DSA key recovery: 1.6% of DSA hosts

## Problematic public keys (2/3)

- low entropy during key generation
- RSA keys easy to factor, because they form pairs like: n = p.q and n' = p'.q so 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, Whit 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, Whit 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 PRNG flaws

- 1996: Netscape SSL [Goldberg-Wagner]
- 2008: Debian SSL [Bello]
- 15 Aug. 2013: Android Java and OpenSSL PRNG flaw led to theft of bitcoins

16 Sept. 2013 Factoring RSA keys from certified smart cards: Coppersmith in the wild
[Bernstein-Chang-Cheng-Chou-Heninger-Lange-van Someren'13]
IACR Cryptology ePrint Archive 2013: 599

184 keys from Taiwan Citizen Digital Certificate cards
card + OS: EAL 4+; FIPS 140-2 Level 2

## How to sign with RSA?

- public key: (n,e)
- private key: d
- $s = t^d \bmod n = t^{1/e} \bmod n$

- But
  - message M is often larger than modulus n
  - RSA(x*y) = RSA(x)*RSA(y)
  - RSA(0) = 0, RSA(1) = 1,…

- Solution: hash and add redundancy
  - PKCS #1
  - RSA-PSS

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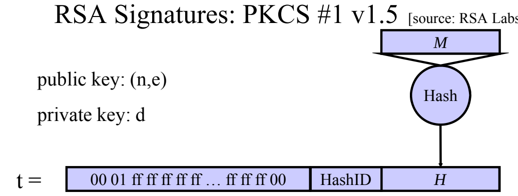
## RSA Signatures: PKCS #1 v1.5 [source: RSA Labs]

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




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

Verification of RSA signature s on M
Compute $t = s^e \bmod n$ *and check that t has the required format*

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

| 00 01 ff … ff 00 | HashID | *H* | *Magic* |
|---|---|---|---|

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## Attack on PKCS #1 v1.5 implementations (1)

[Bleichenbacher06]

| 00 01 ff... ff 00 | HashID | H | Magic |
|---|---|---|---|

- 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

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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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## 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_banishes_ssl_hacker/

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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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