Cryptography Best Practices

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February 2011

Outline

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- Architecture

- Network protocols

- Security APIs

- Key establishment: protocols, generation, storage

Symmetric vs. Asymmetric Algorithms

- hardware costs: 3K– 100K gates

- performance: 100 Mbit/s – 70 Gbit/s

- keys: 64-256 bits

- blocks: 64-128 bits

- power consumption: 20-30 μJ/bit

- hardware costs: 100K-1M gates

- performance: 100 Kbit/s – 10 Mbit/s

- keys: 128-4096 bits

- blocks: 128-4096 bits

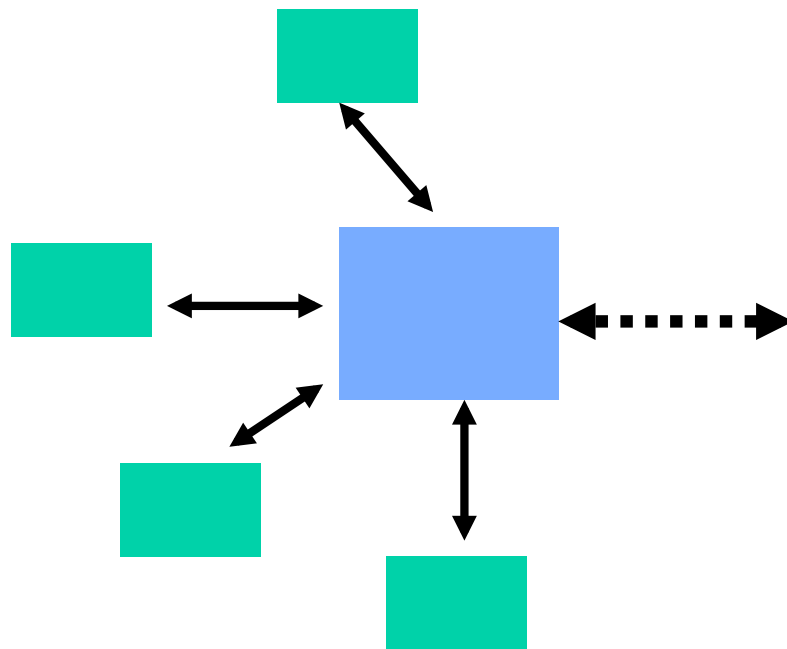- power consumption: 1000-2000 μJ/bit

Architectures (1a)

- Point to point
- Local
- Small scale

- Number of keys: 1 or n^2
- Manual keying
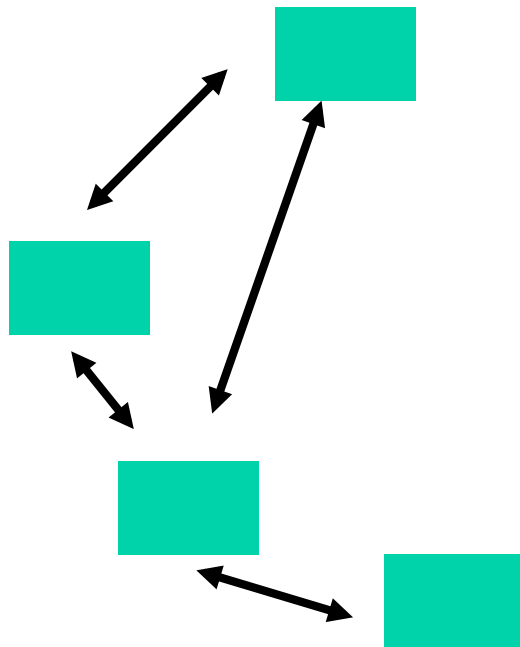
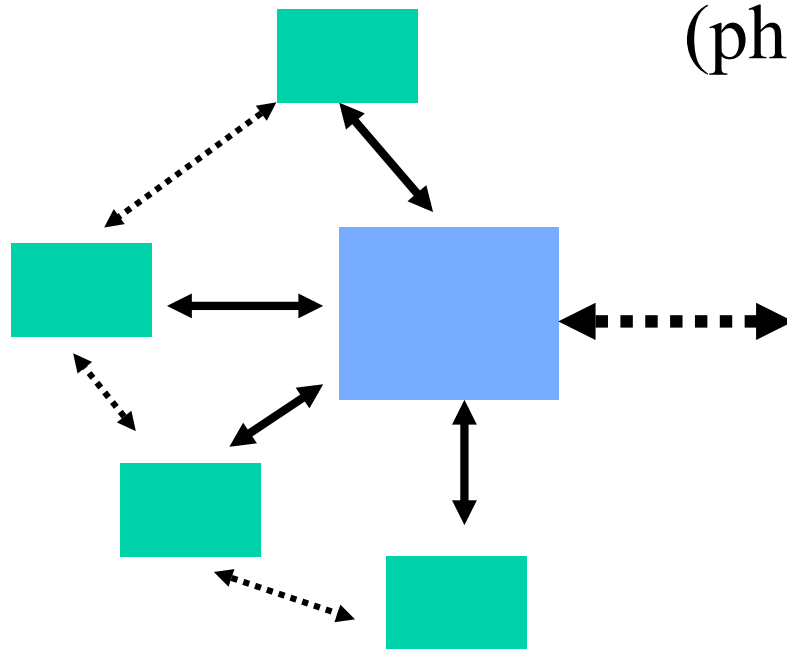Example:
ad hoc PAN or WLAN

Architectures (2a)

- Centralized
- Small or large scale
- Manual keying

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

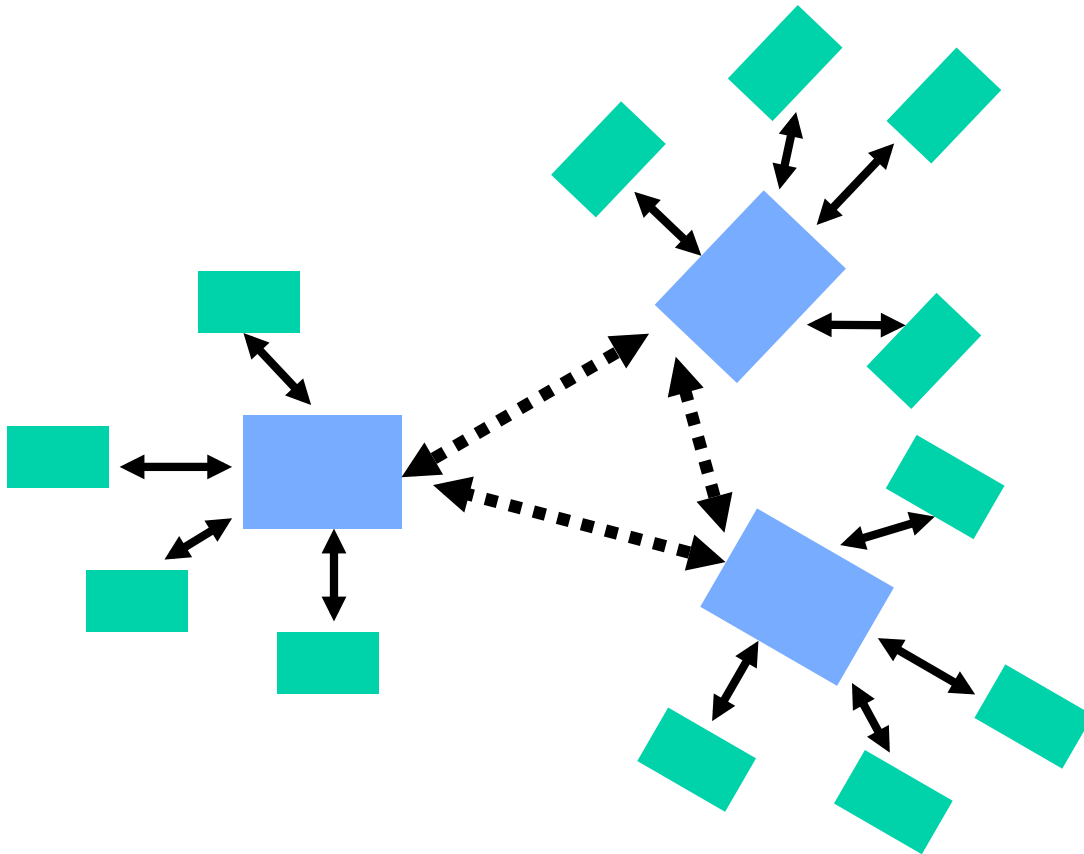Example: WLAN, e-banking, GSM

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)

Architectures (4a)

- Decentralized
- Large scale

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

Example:
network of LANs,
GSM

Architectures (5a)

- Centralized
- Large scale
- Hierarchy

- Number of keys: n + N
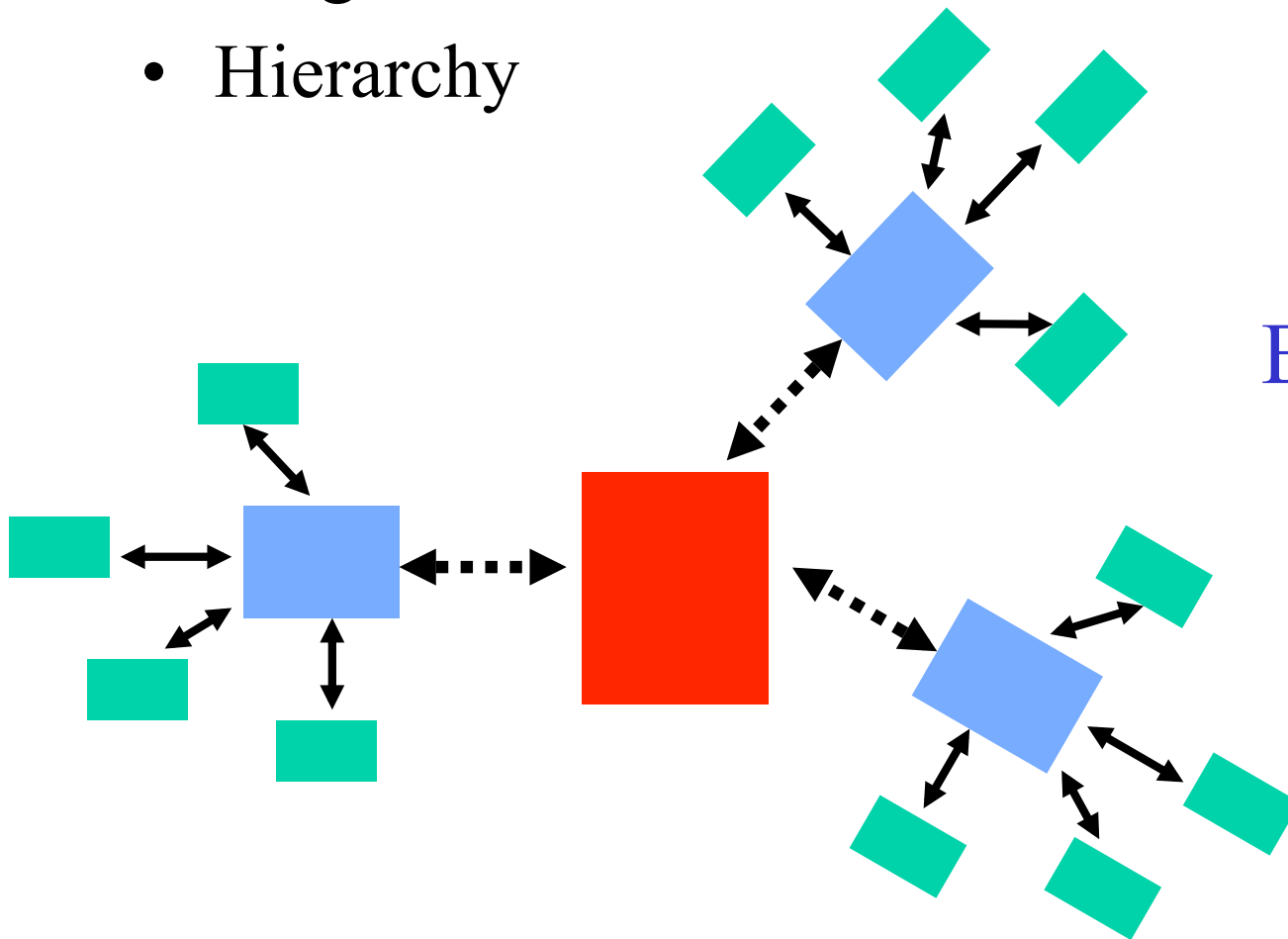
Example: credit card and ATM

Architectures (1b)

- Point to point
- Worldwide
- Small networks

- No CA (e.g. PGP)
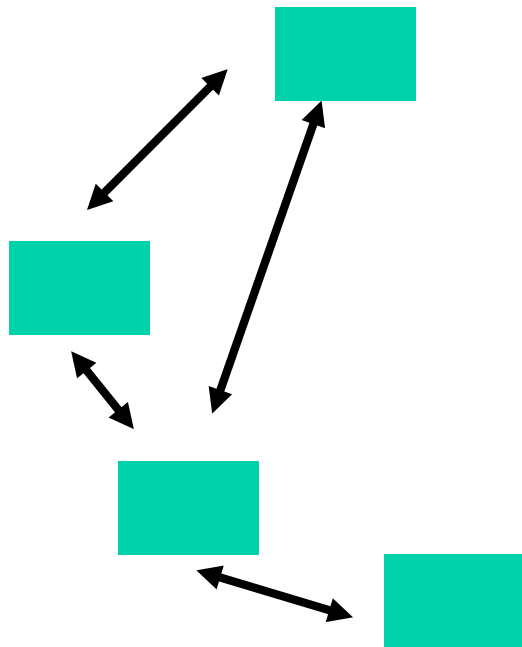
Example:
P2P, international
organizations

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Architectures (2b)

- Centralized
- Large or small scale

- Reduced risk
- Non-repudiation of origin
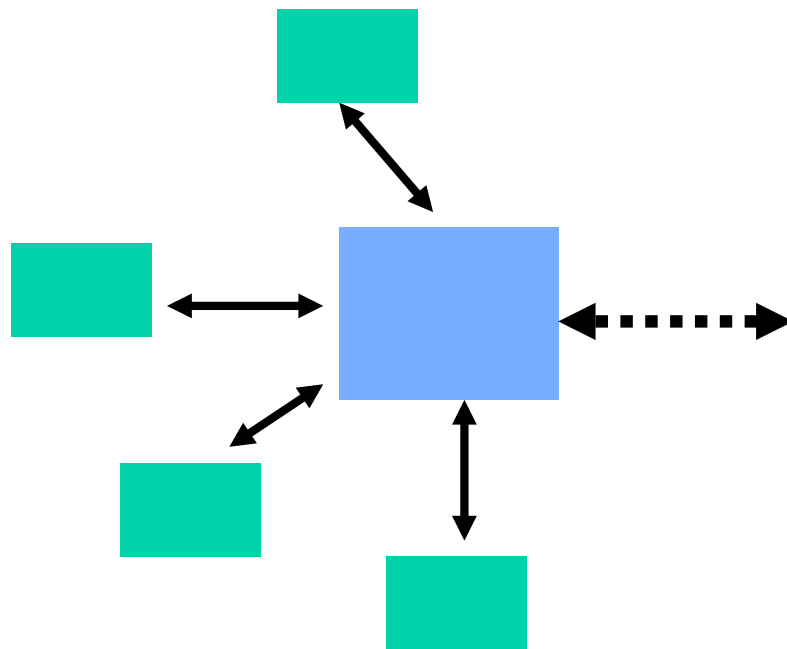
Example: B2C
e-banking

Architectures (3b)

- Centralized
- Small or large scale

- Reduced risk
- Non-repudiation of origin
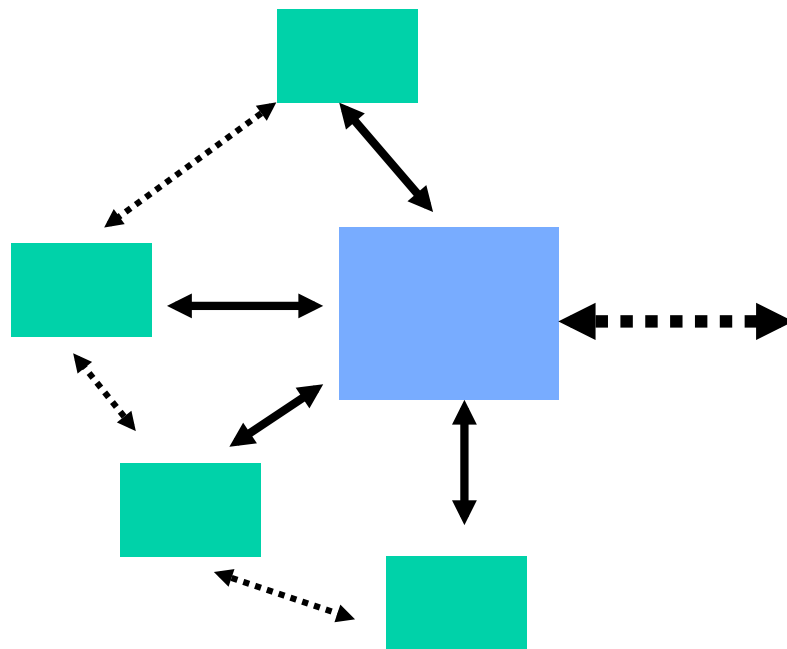
Example: B2B and
e-ID

Architectures (4b)

- Decentralized
- Large scale
- (Open)

- Key management architecture?
- Trust
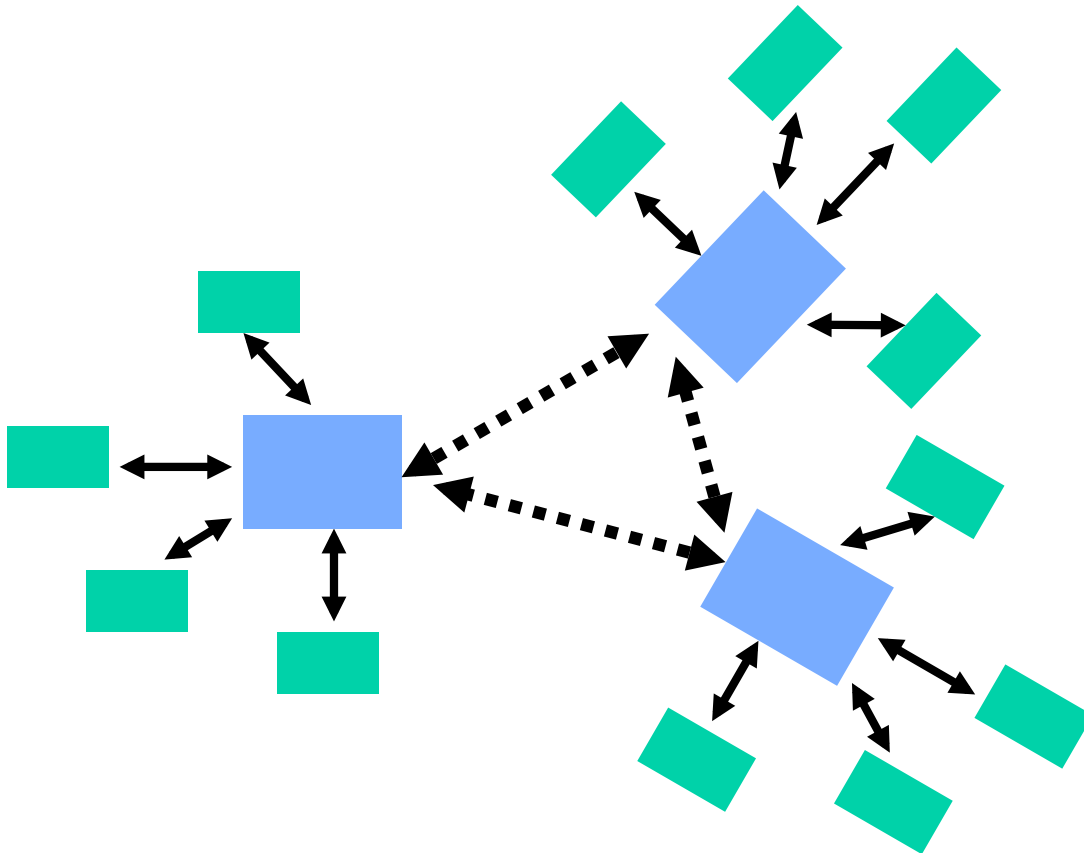
Example: B2B, GSM interoperator communication

Architectures (5b)

- Centralized
- Large scale
- Hierarchy

- Open
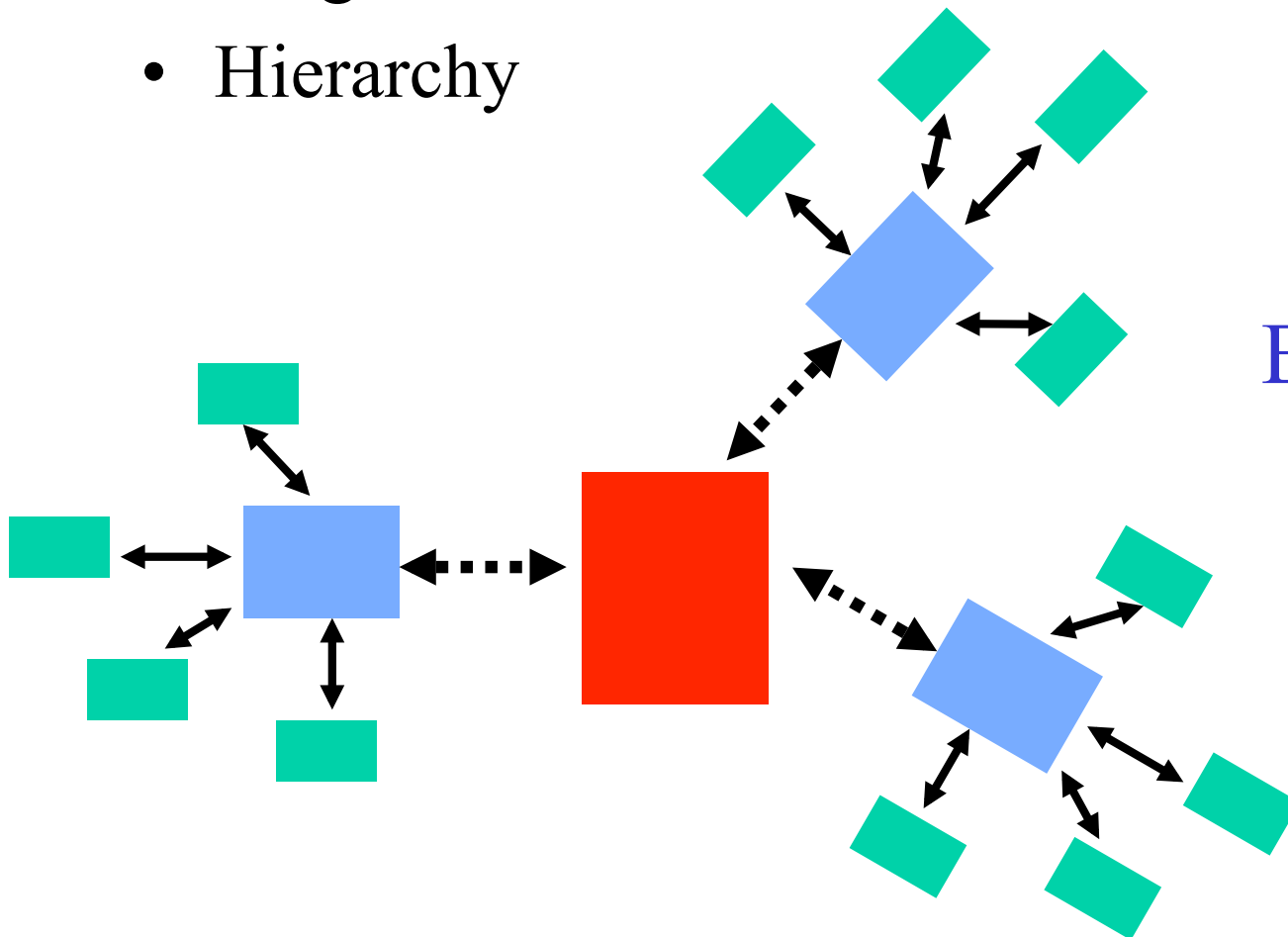
Example: credit card EMV

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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)

CERT$_{ISS}$
(P$_{ISS}$ certified with S$_{CA}$)

Private Key S$_{CA}$

EPI

Public Key P$_{CA}$

Private Key S$_{ISS}$

Issuer

Public Key P$_{ISS}$

Acquirer

Static Card data

IC

Distributed to Acquirer (Resides in Terminal)

IC Card

P$_{CA}$

POS Device
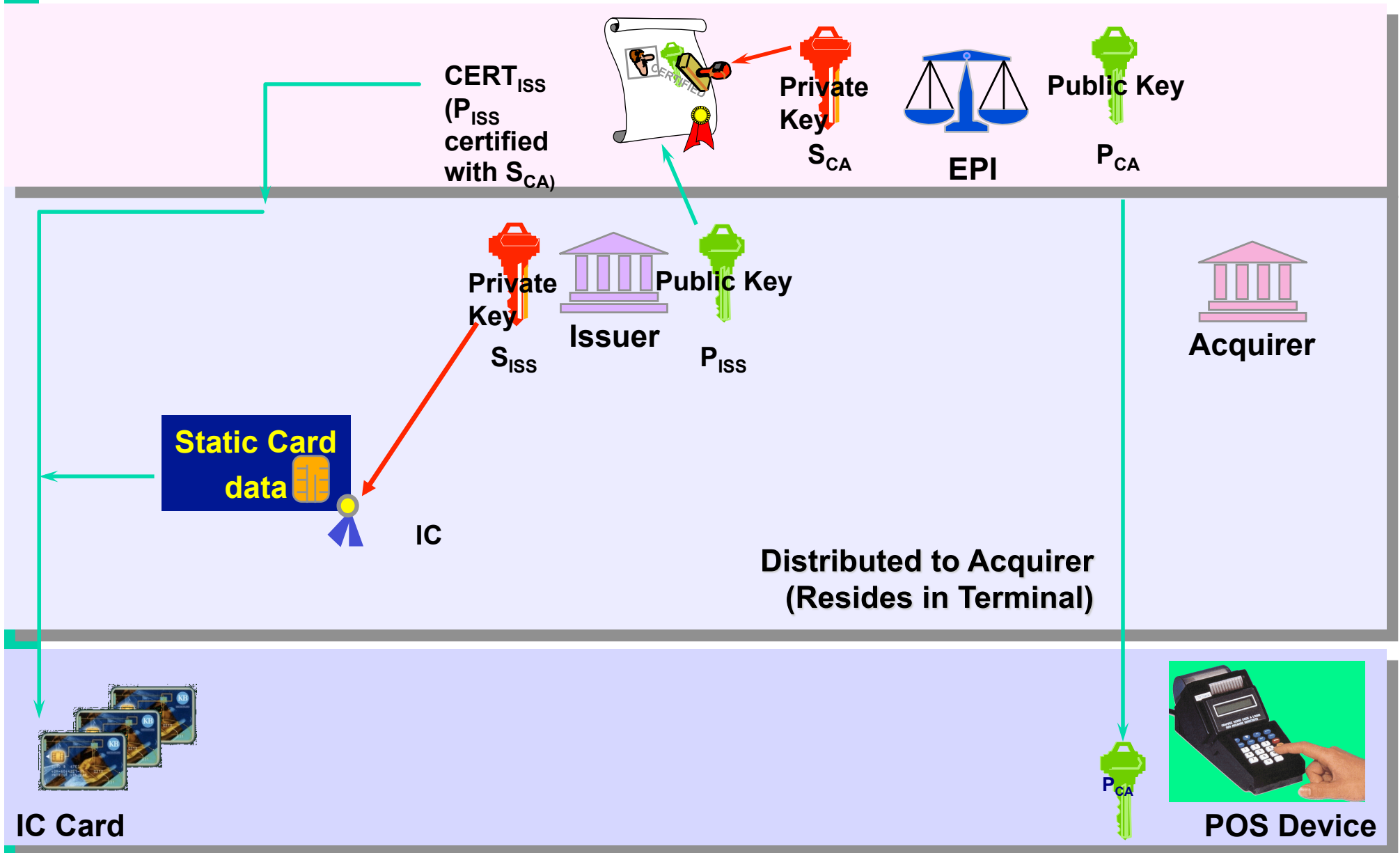
EMV: dynamic data authentication

- **Three layers:**
  - **EPI**
  - **Issuers**
  - **Cards**
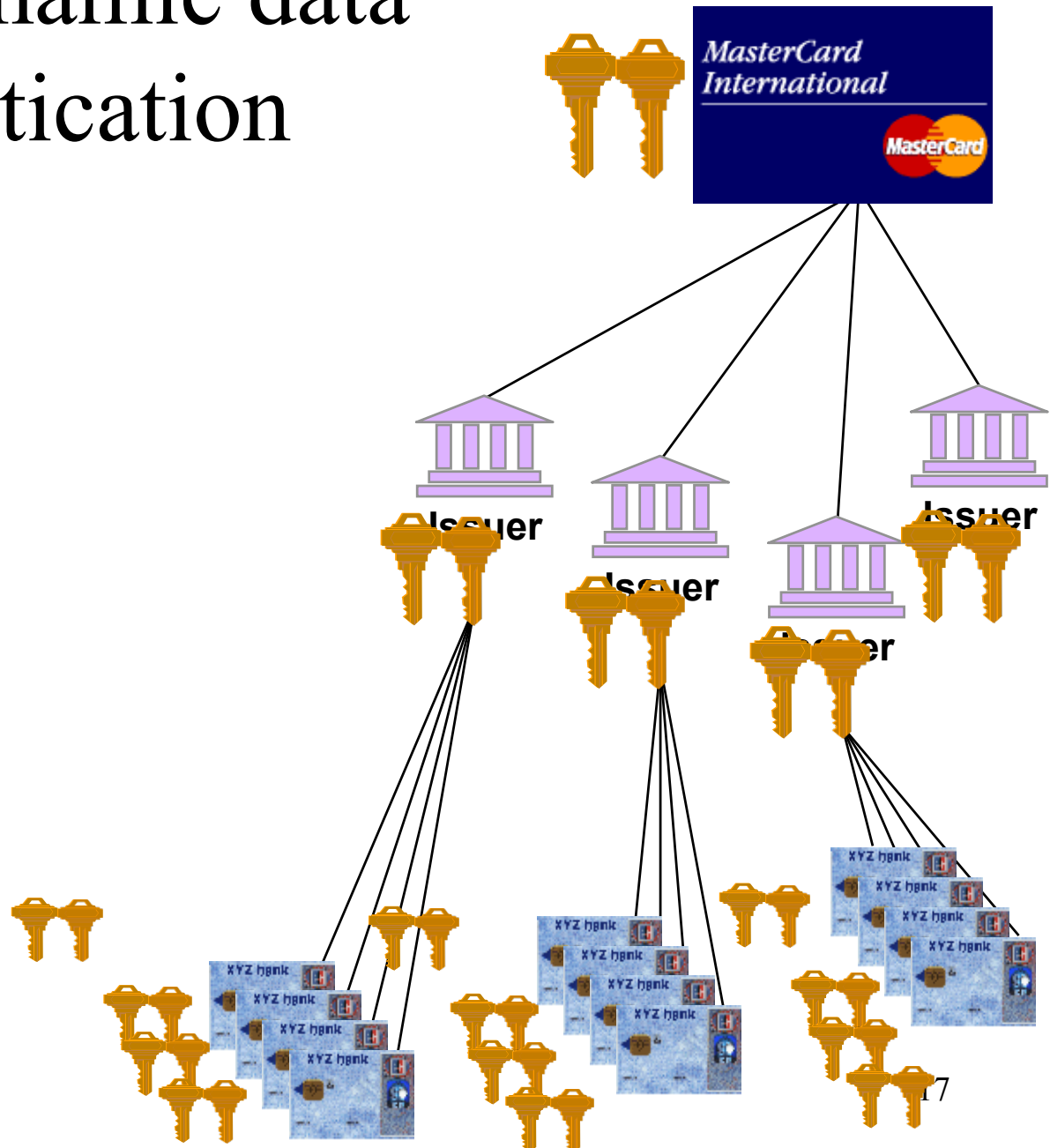
Certificate for dynamic data authentication of a credit card

DN: cn=Jan Peeters, o=KBC, c=BE

Serial #: 8391037

Start: 3/12/11 1:00

End: 4/12/13 12:01

CRL: cn=RVC, o=EMV, c=BE

Key:

CA DN: o=EMV, c=BE

Unique name owner

Unique serial number

Validity period

Revocation information

Public key

Name of issuing CA

CA's Digital signature on the certificate
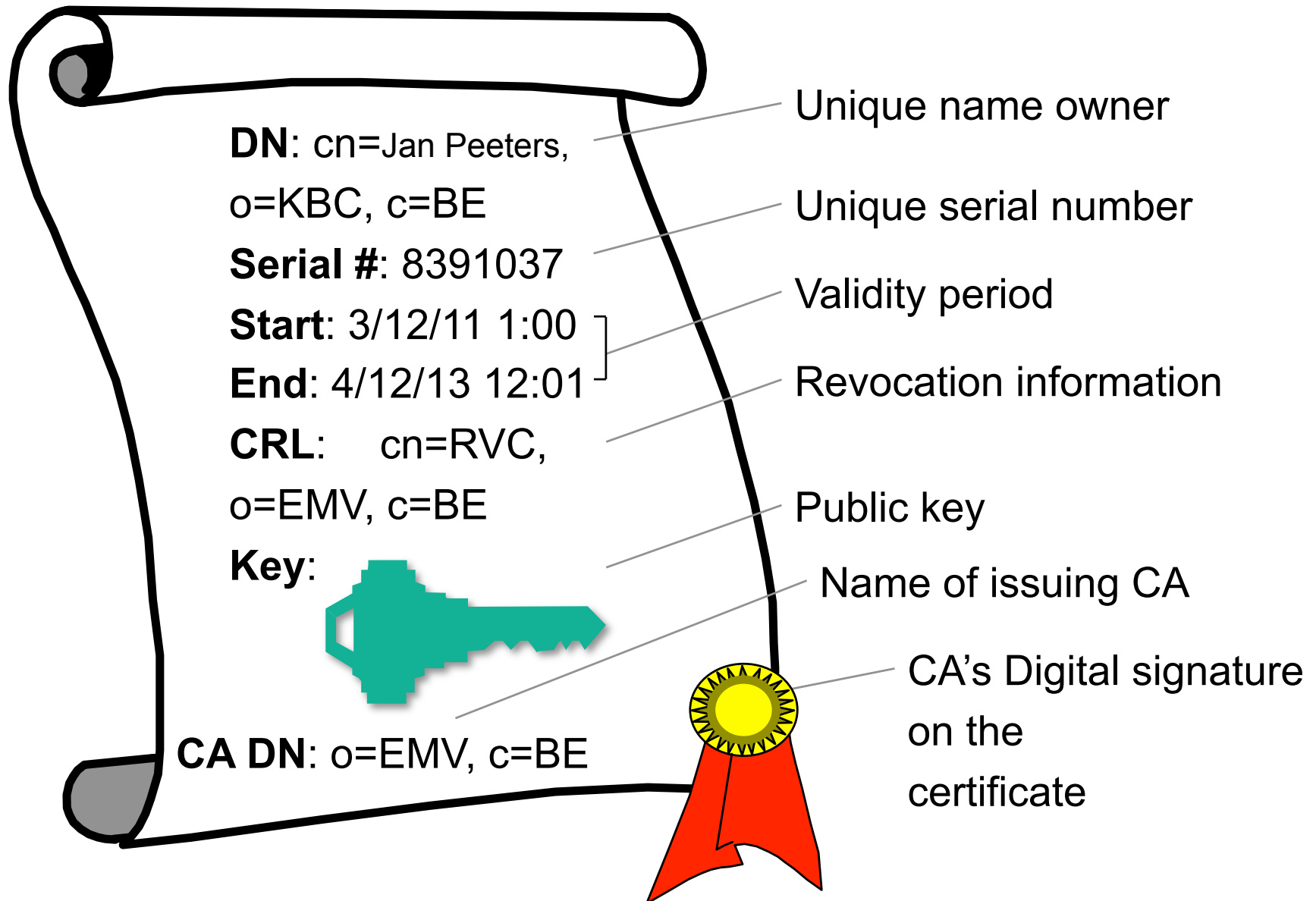
EMV Dynamic Data Authentication
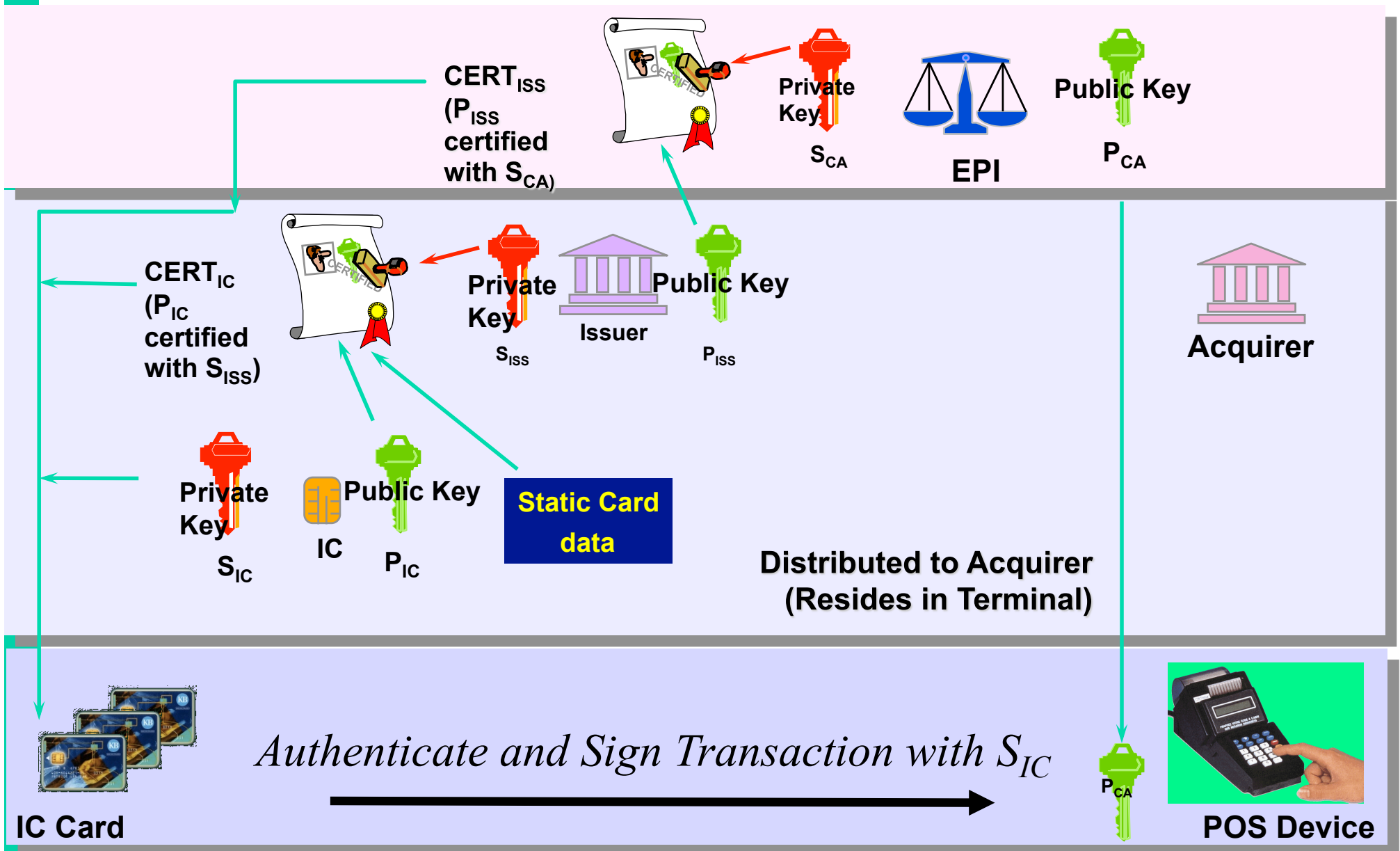
Warning about EMV

- 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

Normal PIN check

1. enter PIN

2. PIN correct?

3. check

4. yes/no

smart card

terminal

Fraudulent PIN check

1. enter **any** PIN

2. is PIN correct?

Man-in-the-middle

3. **yes** (for any PIN)

stolen smart card

terminal

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Network protocols

Host

Application
Presentation
Session
Transport
Network
Data link
Physical

Router

Network
Data link
Physical

Host

Application
Presentation
Session
Transport
Network
Data link
Physical

S/MIME

TLS/SSL
IPsec

PPTP, L2TP

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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?

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

Security APIs

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

Security module

hardware or software

Host

I/O

network

Security API

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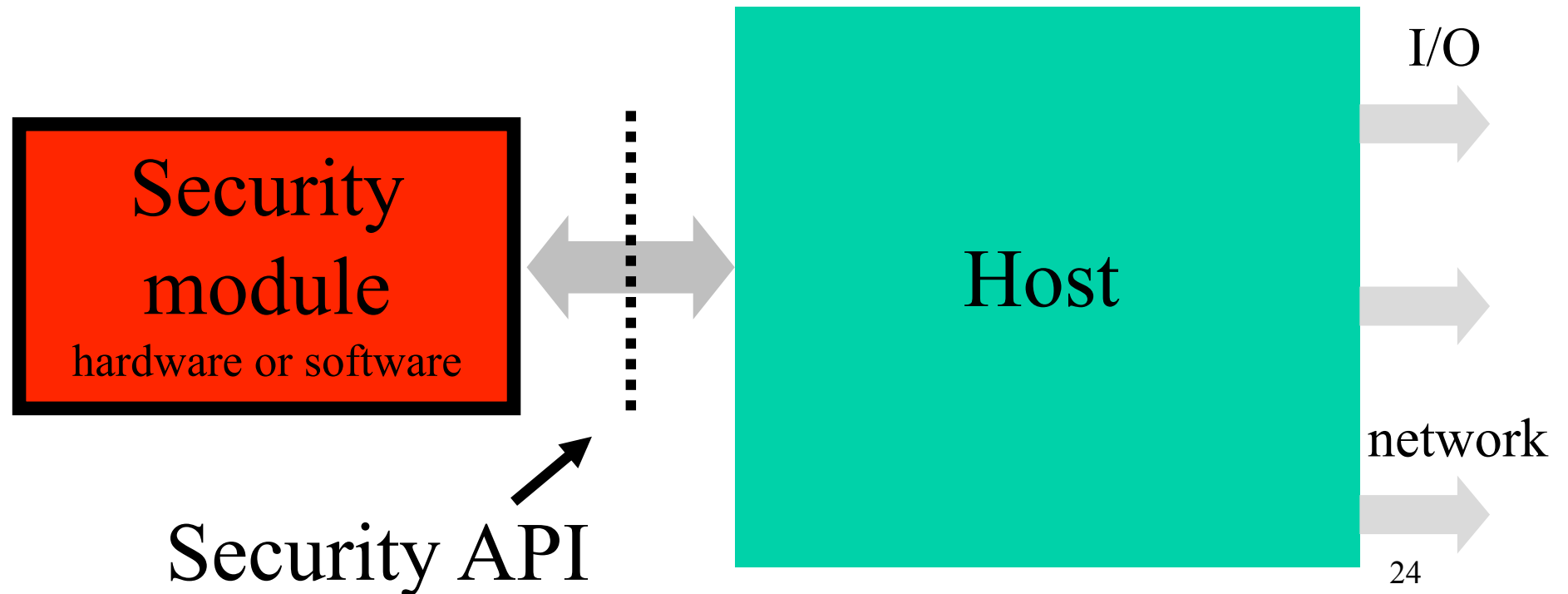
Master key/data key

- 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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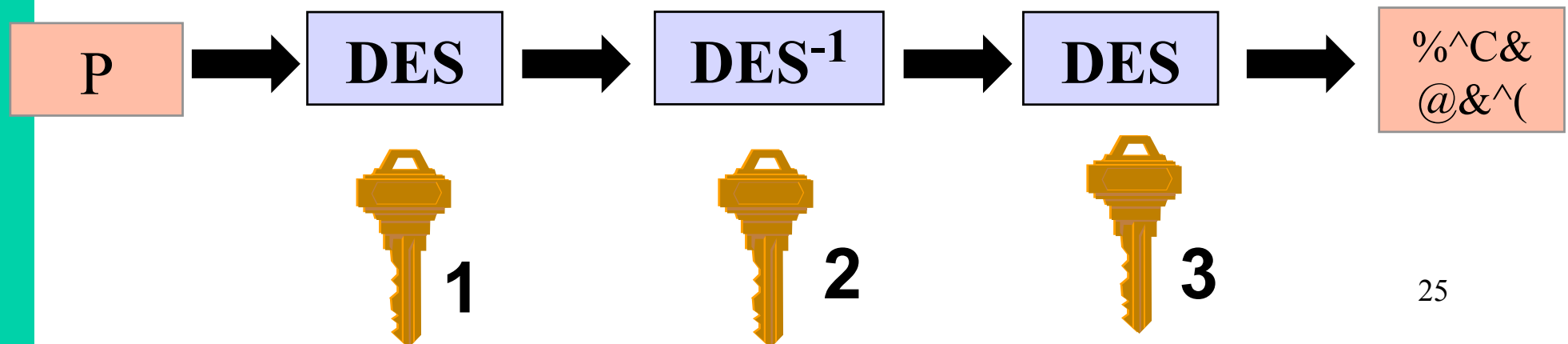
Master key/data key (2)

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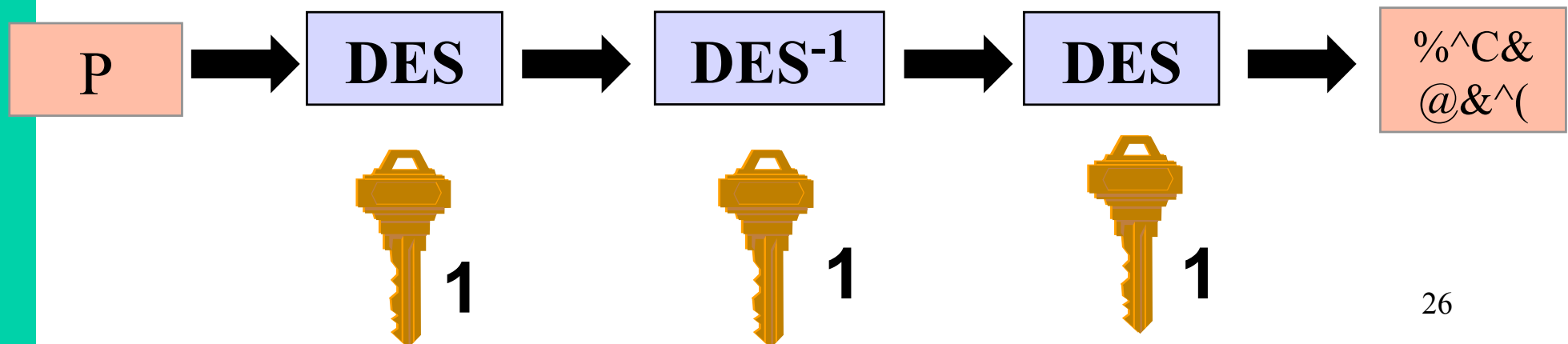- Load corrupted data key:
$$\text{DES}_{\textbf{KM}}(K1) \| \text{DES}_{\textbf{KM}}(K1) \| \text{DES}_{\textbf{KM}}(K1)$$
- Send plaintext P and ask for encryption
$$\text{DES}_{K1}(\text{DES}^{-1}{}_{K1}(\text{DES}_{K1}(P))) = \text{DES}_{K1}(P)$$

| P | → | **DES** | → | **DES^{-1}** | → | **DES** | → | %^C& @&^(|

1   1   1

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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!**

IBM 4758

Control vectors in the IBM 4758 (2)

- Control vector: type (e.g., PIN, data, MAC)
  $E_{Km + type}(k)$, type

- High security: triple control
  - Import Km as $Km_A + Km_B + Km_C$

- User C performs one correct and one fraudulous import by entering the 2nd time $Km_C + \Delta$ with $\Delta = type_{DATA} + type_{PIN}$
- Result: $Km^* = Km + \Delta$

Control vectors in the IBM 4758 (3)

Km: master key

$Km^* = Km + \Delta = Km + type_{DATA} + type_{PIN}$

or $Km^* + type_{DATA} = Km + type_{PIN}$

k = PIN encrypting key

Normally: $D_{Km + typePIN}(E_{Km + typePIN}(k)) = k$

But attack: $D_{Km^* + typeDATA}(E_{Km + typePIN}(k)) = k$

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)

Security APIs

- Complex – 150 commands
- Need to resist to insider frauds
- Hard to design – can go wrong in many ways

- See: Mike Bond, Cambridge University http://www.cl.cam.ac.uk/users/mkb23/research.html

Key management

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

Key establishment protocols: subtle flaws

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

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.

Meet-in-the middle attack on Diffie-Hellman

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

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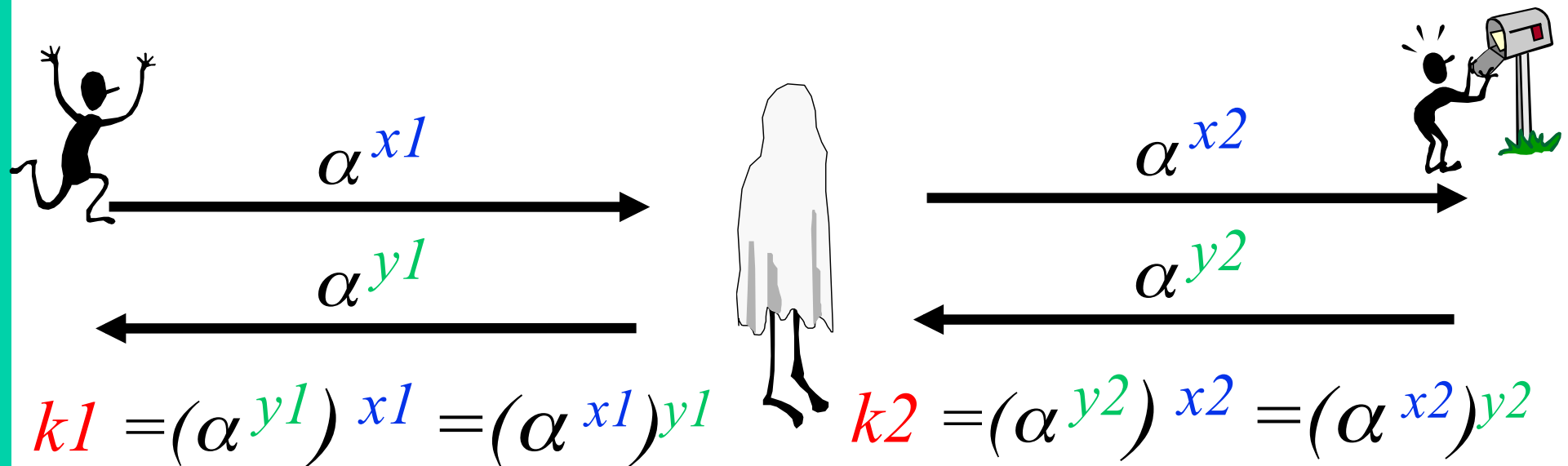
Entity authentication

- Alice and Bob share a secret k

NA

$Ek(NA\|NB)$

NB
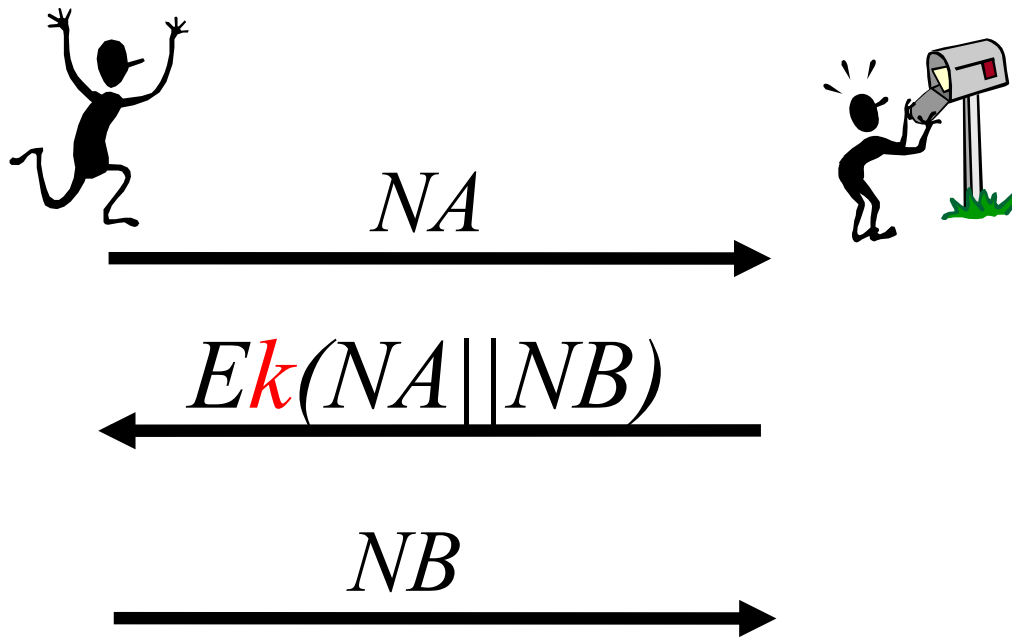
Entity authentication: reflection attack

- Eve does not know k and wants to impersonate Bob

NA

NA

$Ek(NA||NA')$

$Ek(NA||NA'=NB)$

NB
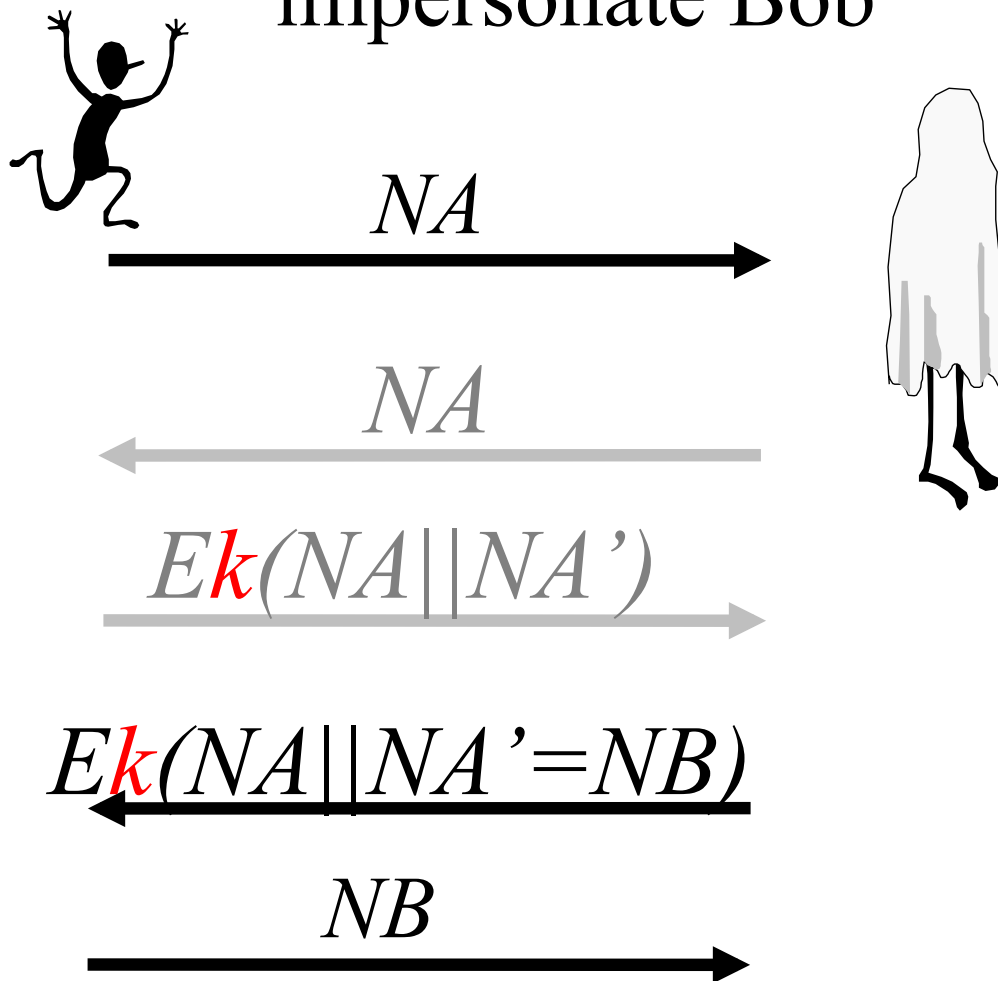
Needham-Schroeder (1978)

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

$EPB(NA||A)$

$EPA(NB||NA)$

$EPB(NB)$
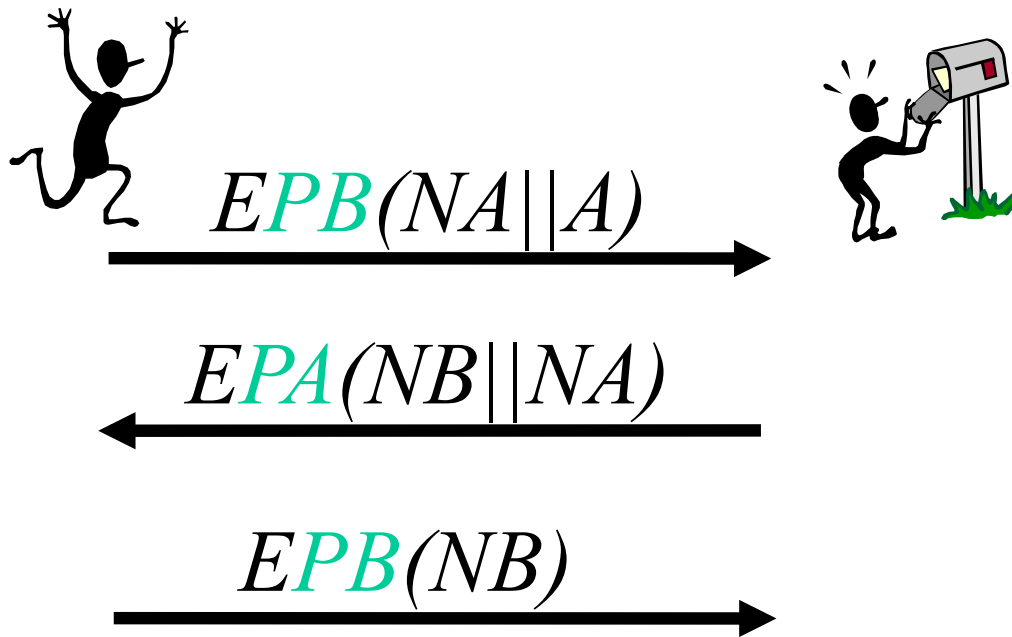
Derive a session key k from NA|| NB

Lowe's attack on Needham-Schroeder (1995)

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

$EPE(NA||A)$ $\longrightarrow$

$EPA(NB||NA)$ $\longleftarrow$

$EPE(NB)$ $\longrightarrow$

$EPB(NA||A)$ $\longrightarrow$

$EPA(NB||NA)$ $\longleftarrow$

$EPB(NB)$ $\longrightarrow$

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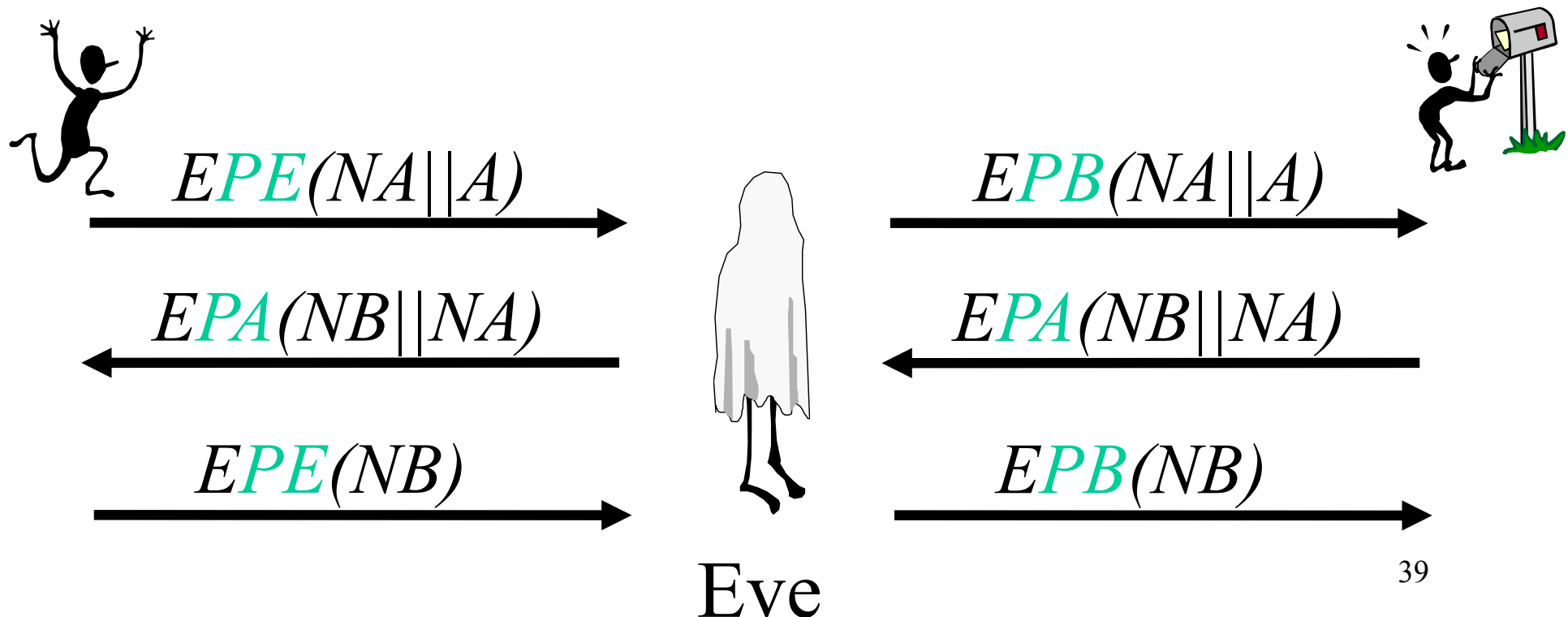
Lowe's attack on Needham-Schroeder (1995)

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

$EPB(NA||A)$

$EPA(NB||NA||B)$

$EPB(NB)$
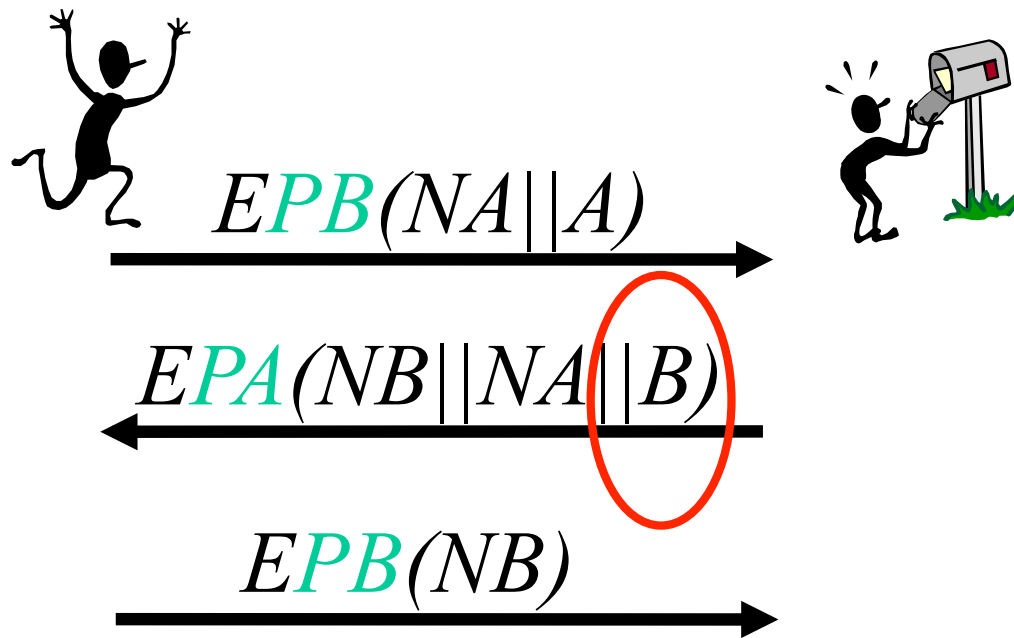
Lessons from Needham-Schroeder (1995)

- 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

Rule #1 of protocol design

Don't!

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

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)

Key generation: overview

Hardware entropy source

Software entropy source

Monitoring

Entropy pool

State update

Initialization

Internal state

extract

random bits

Generate key

keys

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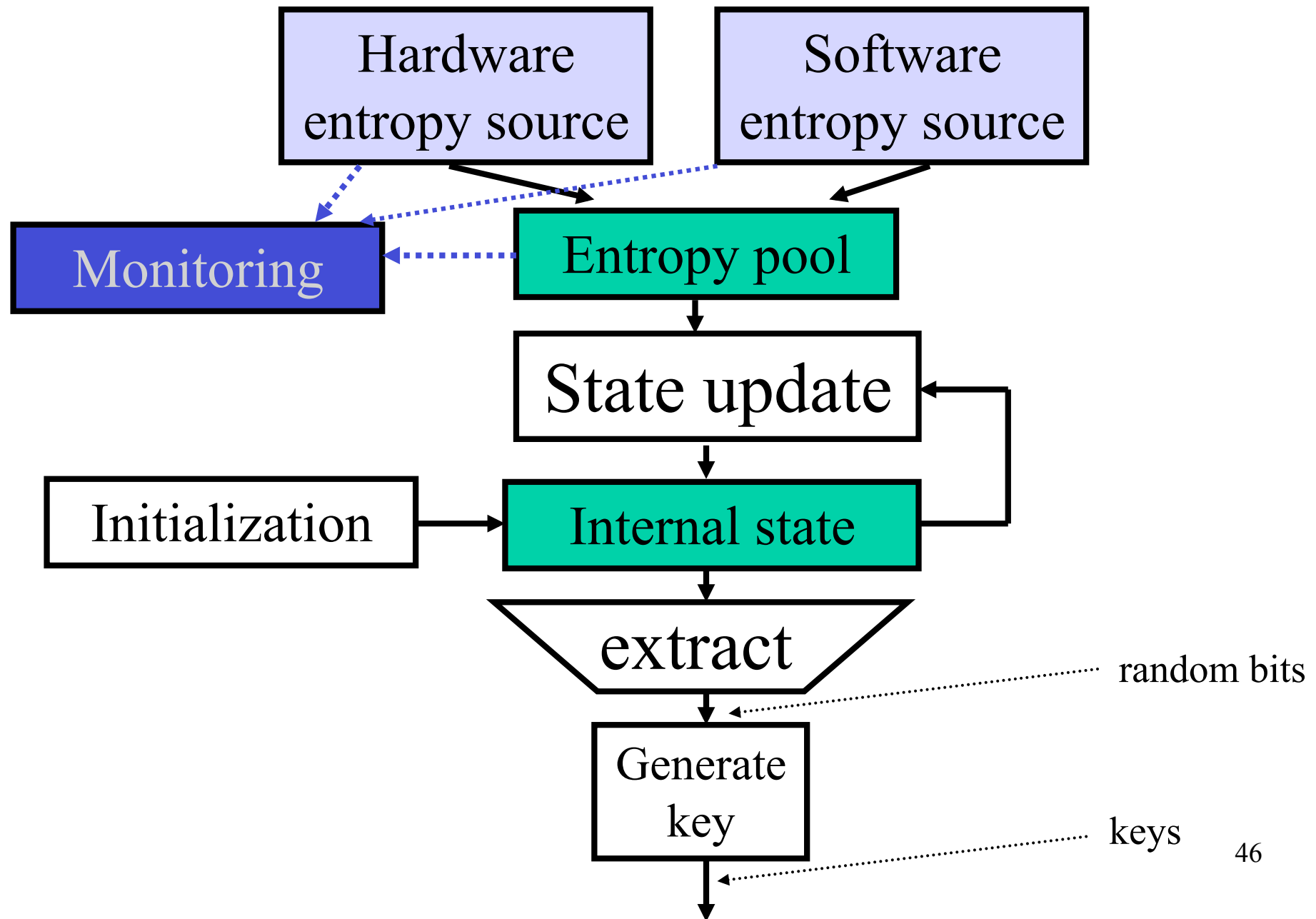
Key generation: hardware entropy sources

- 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

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

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

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, $x^2 \bmod n, \ldots$)

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**

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]
  - $x_{n+1} = a\ x_n + b \bmod m$

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?

The Sony Play Station 3 Problem (1/2)

- ElGamal-type signatures

- 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 $m \equiv y^r\ r^s \bmod p$

The Sony Play Station Problem (2/2)

- $y = g^x$
- 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 Sony's root key x
- can now do code signing
- similar problems in the past with small deviation in randomness of k (e.g. GNU GPG)
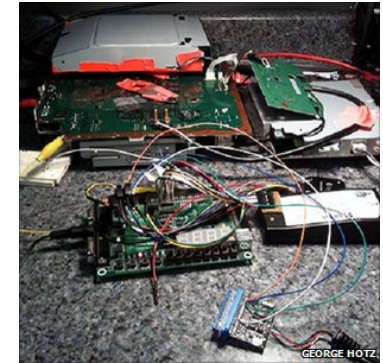
What to consider/look at

- **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

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 reader and keypad
- Hardware security module

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

5 sec 30 sec 60 sec 5 min
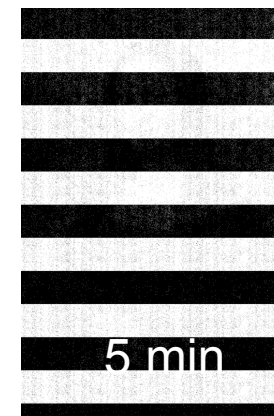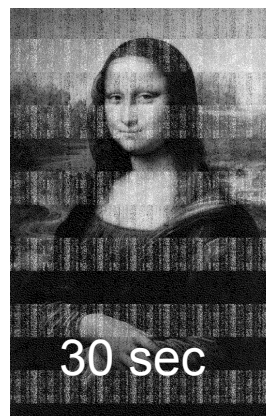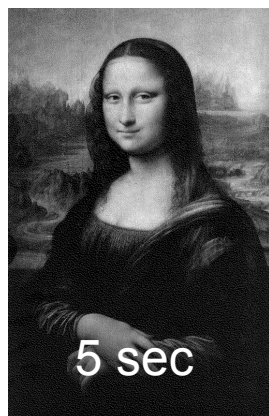
New attack on keys in memory (21/02/08)

- 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

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