UNIVERSITY OF CAMBRIDGE
Computer Laboratory

Security APIs:
The last word on ATM security?
The first word on TC?

Mike Bond
Computer Security Group

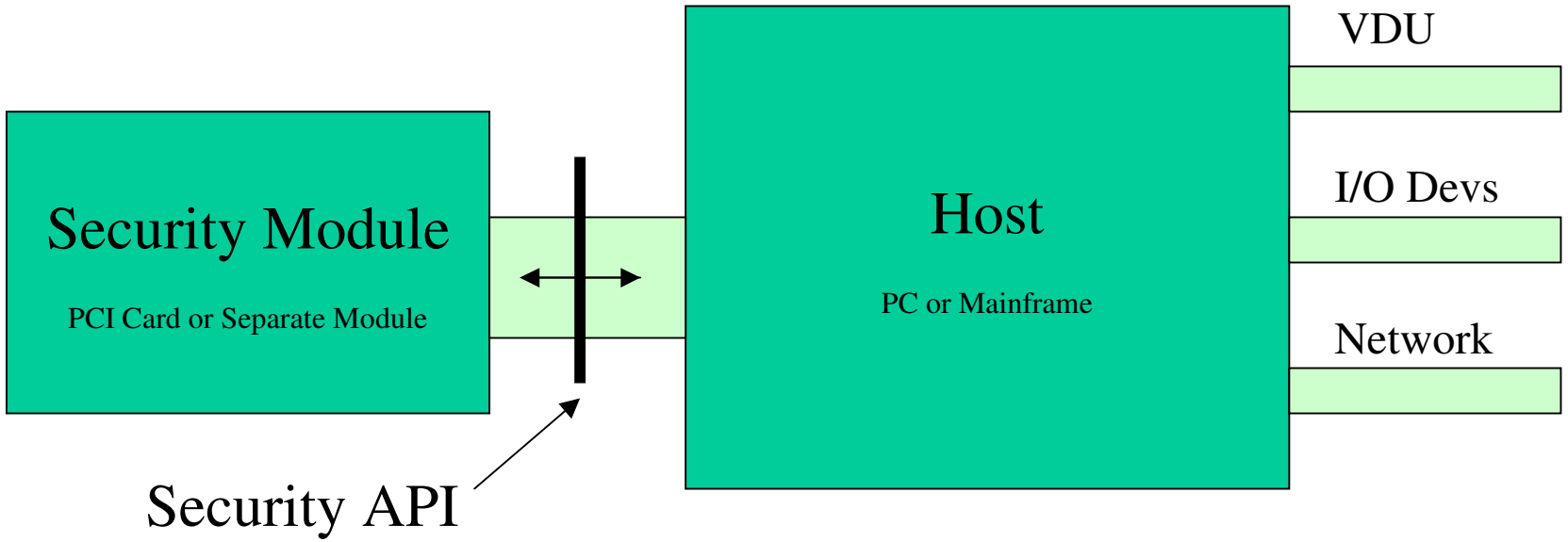
Royal Holloway Information Security Group **11th May '04**

Talk Structure

- Introducing Security APIs
- Discovering Security APIs: ATM security
  - ATM Security Basics
  - Early attacks on Financial HSMs
  - Finding Faults in Type Systems
  - Problems with DES
  - Information Leakage Attacks
- The Future of Security APIs : Trusted Computing
  - “Digital Battlefields”
  - Getting formal
- Conclusions

What is a Security API ?

- An API that allows users to work with sensitive data and keys, and uses cryptography to enforce a policy on the usage of data



Who Needs Security APIs ?

- Those who need to enforce access policies to sensitive information

  Example: Granting signing permission at a Certification Authority
- Those who need to protect mission critical sensitive data

  Example: Protecting PIN generation keys at banks
- Those who need to protect data in hostile environments

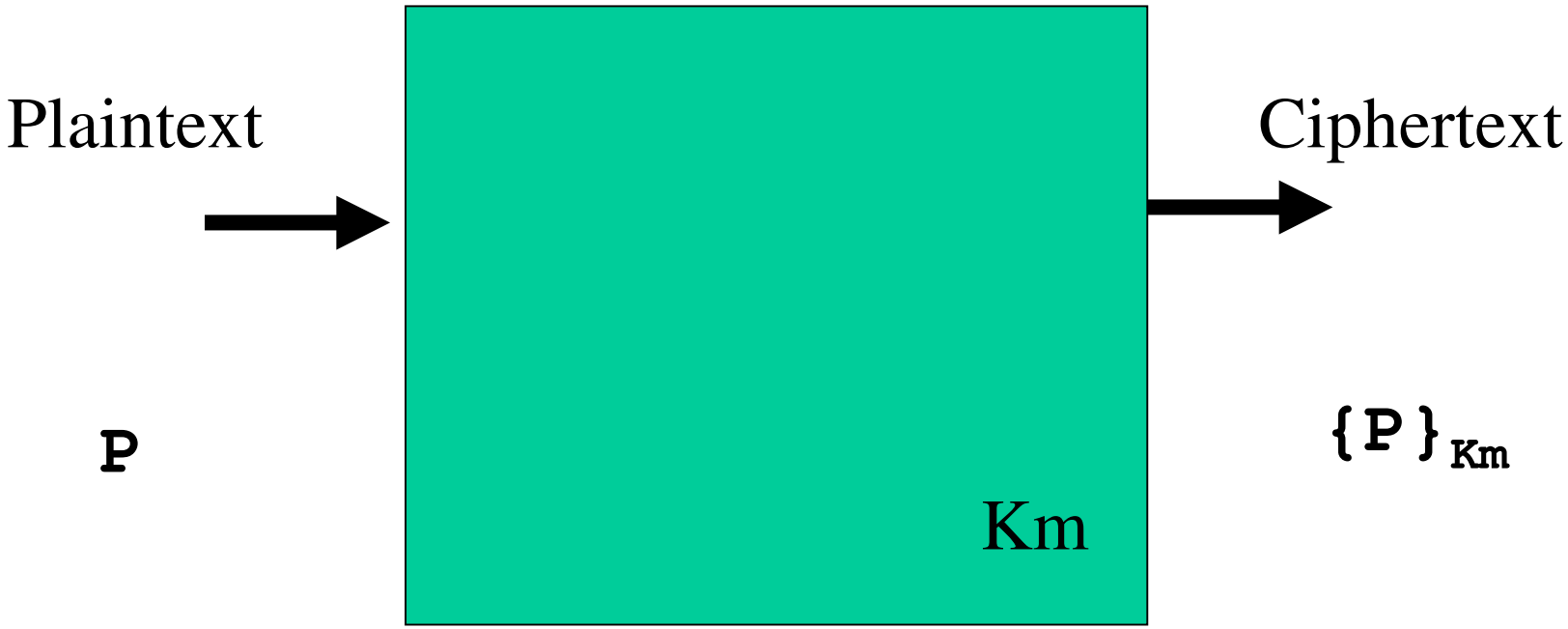
  Example: Protecting Token Vending Machines (Electricity, National Lottery etc…)
- Those with high crypto throughput requirements

  Example: SSL acceleration for webservers

Research into Security APIs

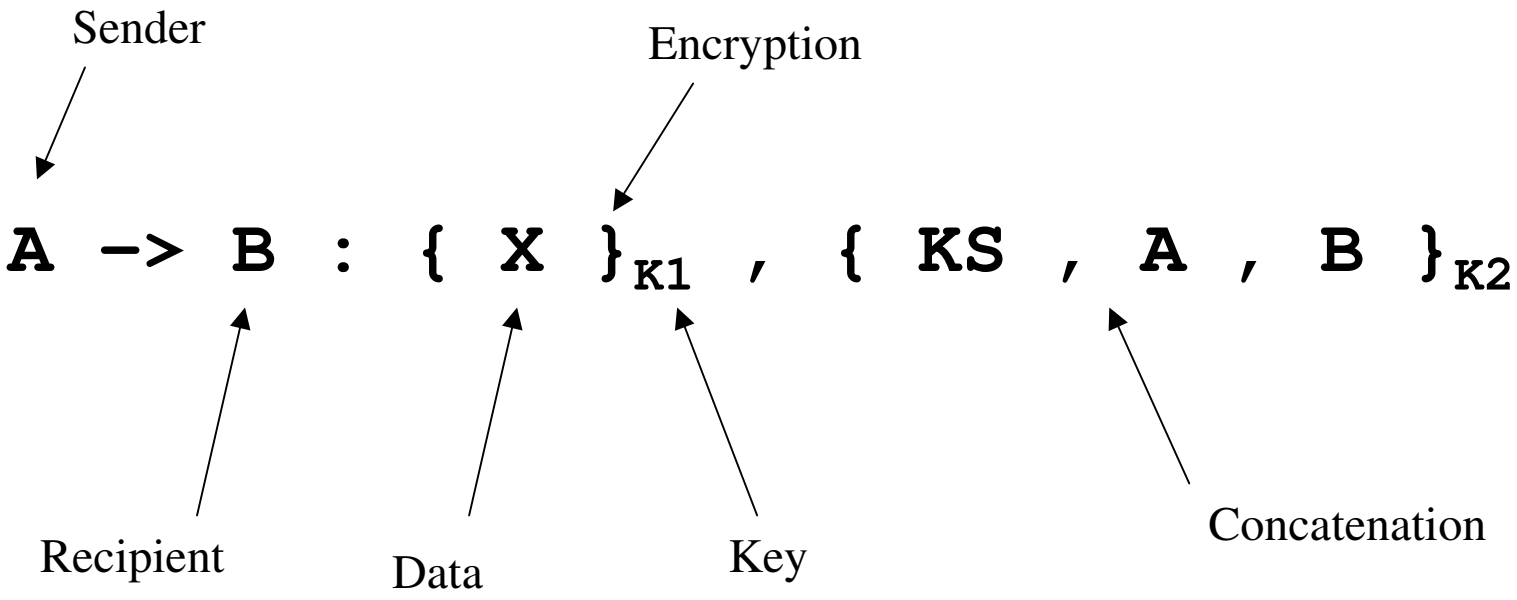
- Some work in early 90s using prolog style search to find attacks, but few documented attacks
- Work started in 2000 at University of Cambridge with analysis of Hardware Security Modules used in banks to protect PINs for ATMs
- New work found many more attacks, and produced first significant catalogue of API failures
- Scope has been broadened to include security modules used by certification authorities and also general purpose crypto libraries (e.g. PKCS#11, Chrysalis-ITS Luna CA3, nCipher nCore and payShield APIs)
- Latest work revisiting financial APIs examining PIN generation and verification procedures

The Simplest Security API



Protocol Notation

- Informal notation, common in textbooks



Example Security API Commands

U->C : $\{ A \}_{KM}$, $\{ B \}_{KM}$

C->U : $\{ A+B \}_{KM}$

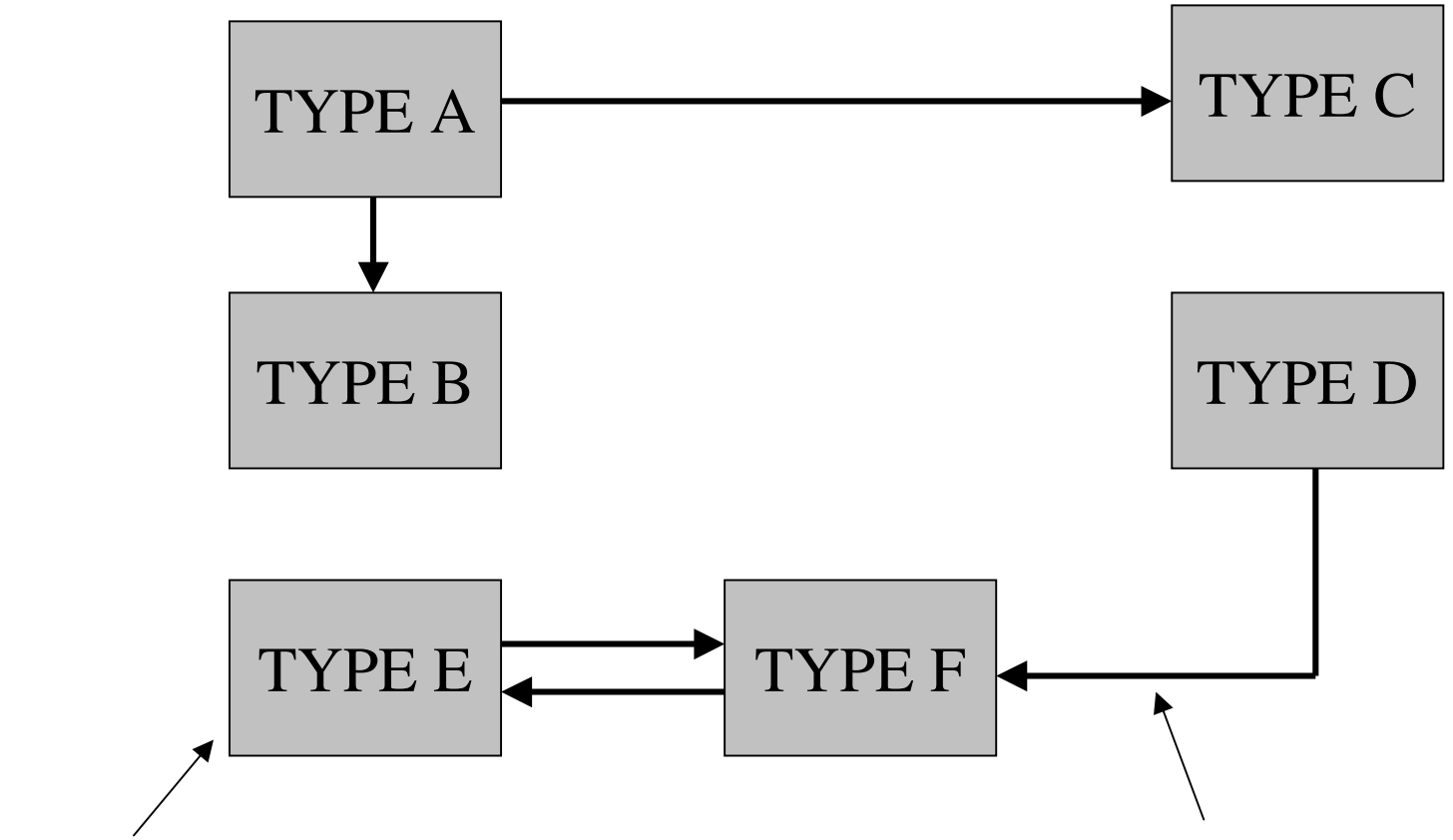
U->C : GUESS , $\{ ANS \}_{KM}$

C->U : YES (if GUESS=ANS else NO)

U->C : $\{ X \}_{K1}$, $\{ K1 \}_{KM}$, $\{ K2 \}_{KM}$

C->U : $\{ X \}_{K2}$

Example Type Diagram



Hardware Security Modules

- An instantiation of a security API
- Often physically tamper-resistant
  (epoxy potting, temperature & xray sensors)
- May have hardware crypto acceleration
  (not so important with speed of modern PC)
- May have special ‘trusted’ peripherals
  (key switches, smartcard readers, key pads)

(referred to as **HSMs** subsequently)

Hardware Security Modules

Why ATM Network Security?

- ATM security was the “killer-app” that brought cryptography into the commercial mainstream – so long history of financial API development
- Concrete and simple security policy for APIs:

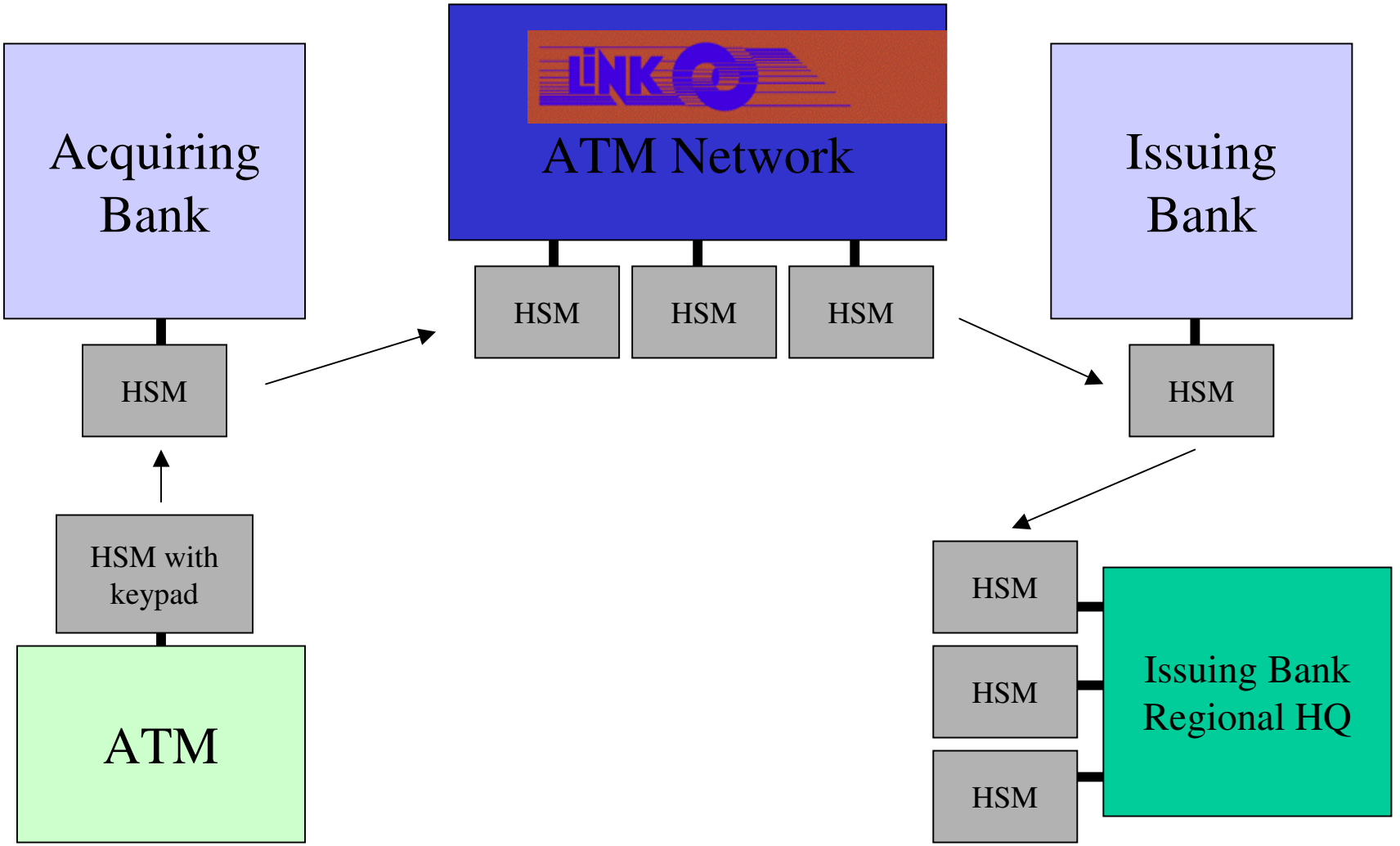
  “Only the customer should know her PIN.”

  “Keys protecting PINs may only be manipulated when authorised by two different employees.”
- IBM made CCA manual publicly available
  - Excellent detailed description of API
  - Good explanation of background to PIN processing APIs
  - Unfortunately: lots of uncatalogued weaknesses.

ATM Security Basics

- The crucial secret is the customer PIN. The customer should be the only person that knows the value of this PIN
- PINs need to be protected from malicious insiders and outsiders
- PINs must be protected when generated, in storage, when issued to customers, when travelling via the international ATM network, and when being verified
- To this end, banks use **Hardware Security Modules** (HSMs) to perform cryptography and implement a policy which prevents both insiders and outsiders from gaining unauthorised access to PINs.

Security Modules in Banks

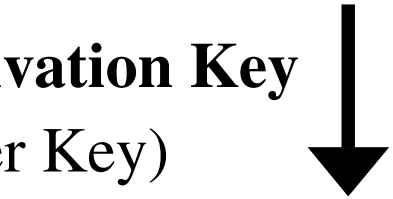


How are PINs Generated ?

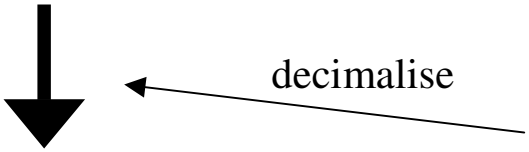
Start with your bank account number (PAN)

5641 8203 3428 2218

Encrypt with **PIN Derivation Key**
(aka **PMK** – Pin Master Key)



22BD 4677 F1FF 34AC



Chop off the End

2213

(B->1)
(D->3)

What's a Decimalisation Table ?

- Remember encrypted result was in hexadecimal?
- Encryption produces output that looks uniformly distributed, so `0-F` are all equally likely
- Decimalisation Table used to map `0-F` back to `0-9`

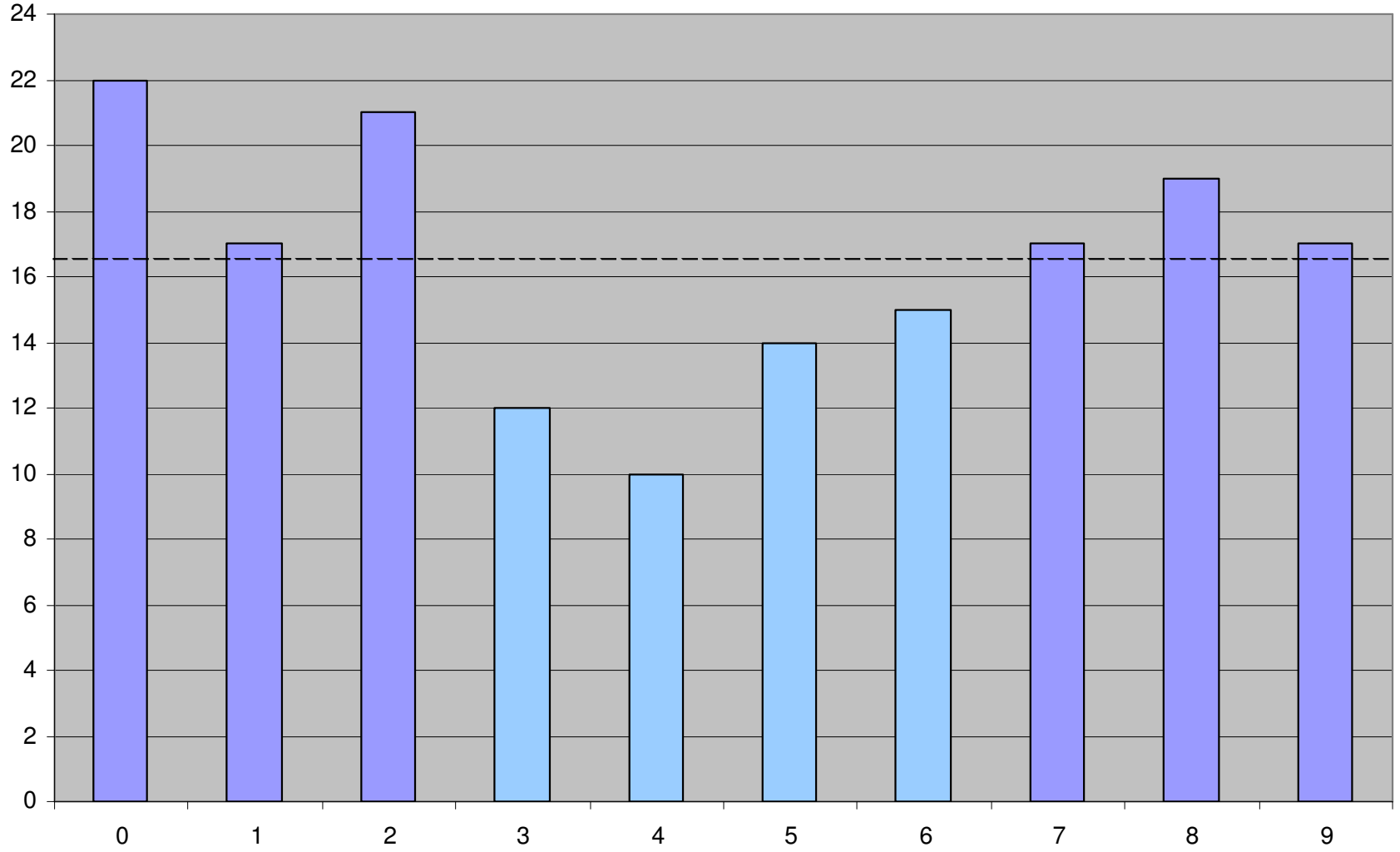
```
digit in   0123456789ABCDEF
digit out  0123456789012345
```

`e.g. 22BD -> 2213`

- Because some numbers have several hexadecimal digits mapped to them, they are more likely to occur in issued PINs than others

Collecting Frequency Distributions

Example Distribution : HSBC



Sample size: 45 people (just large enough to prove non-uniform hypothesis with 1% conf)

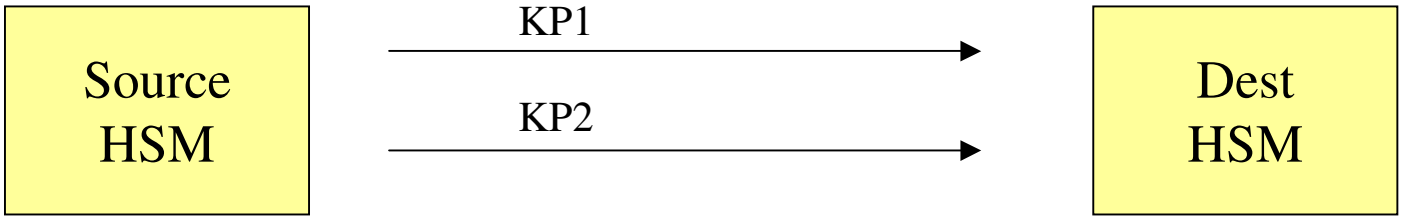
How do I change my PIN?

- Most store an offset between the original derived PIN and your chosen PIN
- Example bank record…
  - PAN 5641 8233 6453 2229
  - Name Mr M K Bond
  - Balance $1234
  - PIN Offset 0000
- If I change PIN from 4426 to 1979, offset stored is 7553 (each digit is independent modulo 10)
- Some systems do work completely differently. You choose your PIN at the outset in these.

Early Attacks on Financial HSMs

XOR To Null Key Attack

- Top-level crypto keys exchanged between banks in several parts carried by separate couriers, which are recombined using the exclusive-OR function



Repeat twice…

User->HSM : Generate Key Component
HSM->Printer : KP1
HSM->User : { KP1 }$_{ZCMK}$

Combine components…

User->HSM : { KP1 }$_{ZCMK}$, { KP2 }$_{ZCMK}$

HSM->User : { KP1 xor KP2 }$_{ZCMK}$

Repeat twice…

User->HSM : KP1

HSM->User : { KP1 }$_{ZCMK}$

Combine components…

User->HSM : { KP1 }$_{ZCMK}$, { KP2 }$_{ZCMK}$

HSM->User : { KP1 xor KP2 }$_{ZCMK}$

XOR To Null Key Attack

- A single operator could feed in the same part twice, which cancels out to produce an ‘all zeroes’ test key. PINs could be extracted in the clear using this key

Combine components…

User->HSM : $\{ KP1 \}_{ZCMK}$, $\{ KP1 \}_{ZCMK}$

HSM->User : $\{ KP1 \text{ xor } KP1 \}_{ZCMK}$

KP1 xor KP1 = 0

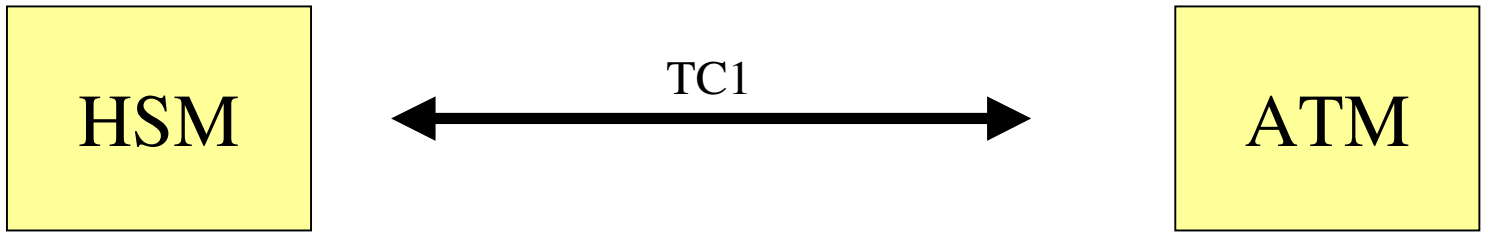
Offset Calculation Attack

- Bank adds a new command to the API to calculate the offset between a new generated PIN and the customer's chosen PIN
- Possessing a bank account gives knowledge of one generated PIN. Any customer PIN could be revealed by calculating the offset between it and the known PIN

```
U->C : Old PAN, Old offset, New PAN
C->U : New offset
```

Type System Attack

- ATMs are simpler than HSMs and have only one master key. ATMs need to be sent Terminal Communications keys (session keys) for link cryptography.



Master Keys
TC – terminal communications
TMK – terminal master keys & PIN derivation keys
ZCMK – zone control master keys (between HSMs)
WK – working keys (session keys)
LP – local PIN storage key

Master Key
TMK-ATM - used for everything

$\{ \text{TC1} \}_{\text{TC}}$ ----------*but how?*----------> $\{ \text{TC1} \}_{\text{TMK-ATM}}$

Type System Attack (2)

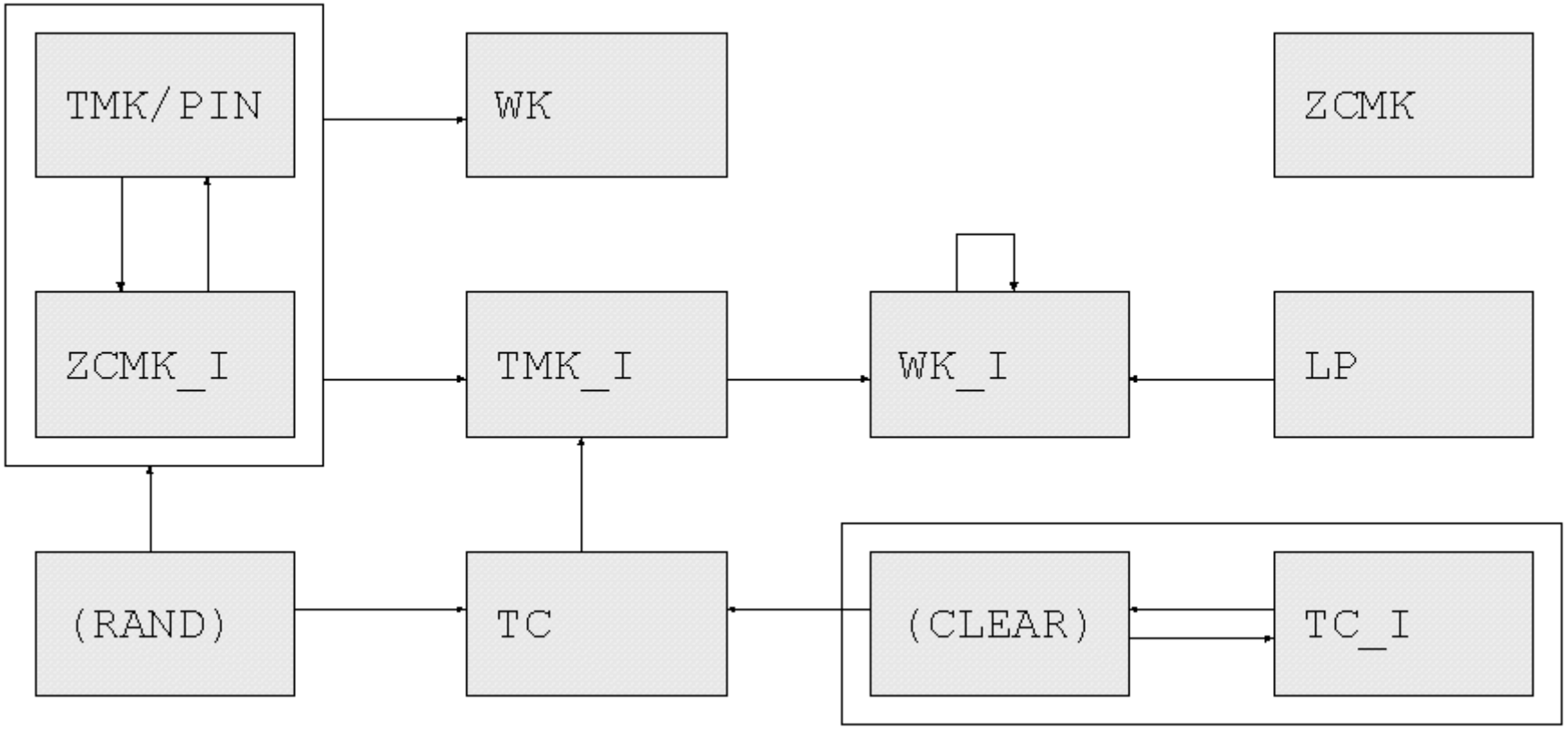
- PIN derivation keys (PDKs) share the same type as Terminal Master Keys (TMKs), and encrypting communication keys for transfer to an ATMs uses exactly the same process as calculating a customer PIN – encryption with single DES.

$$\begin{aligned}
&\text{User}\rightarrow\text{HSM} &&: TC1\\
&\text{HSM}\rightarrow\text{User} &&: \{ TC1 \}_{TC}\\
&\text{User}\rightarrow\text{HSM} &&: \{ TC1 \}_{TC} , \{ TMK\text{-}ATM \}_{TMK}\\
&\text{HSM}\rightarrow\text{User} &&: \{ TC1 \}_{TMK\text{-}ATM}
\end{aligned}$$

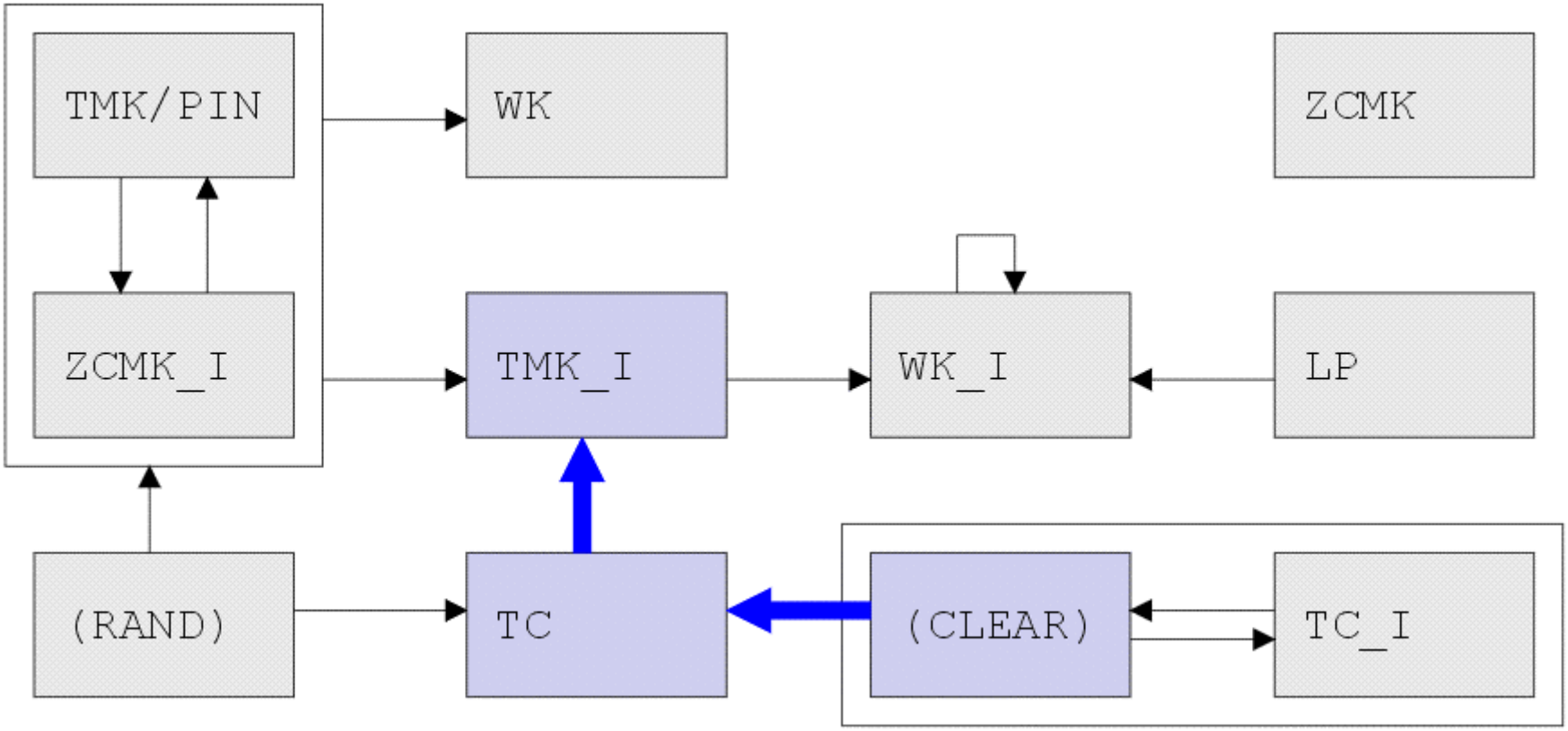
The attack…

$$\begin{aligned}
&\text{User}\rightarrow\text{HSM} &&: PAN\\
&\text{HSM}\rightarrow\text{User} &&: \{ PAN \}_{TC}\\
&\text{User}\rightarrow\text{HSM} &&: \{ PAN \}_{TC} , \{ PDK1 \}_{TMK}\\
&\text{HSM}\rightarrow\text{User} &&: \{ PAN \}_{PDK1}
\end{aligned}$$

VSM Type Diagram



Type System Attack (Graphical)

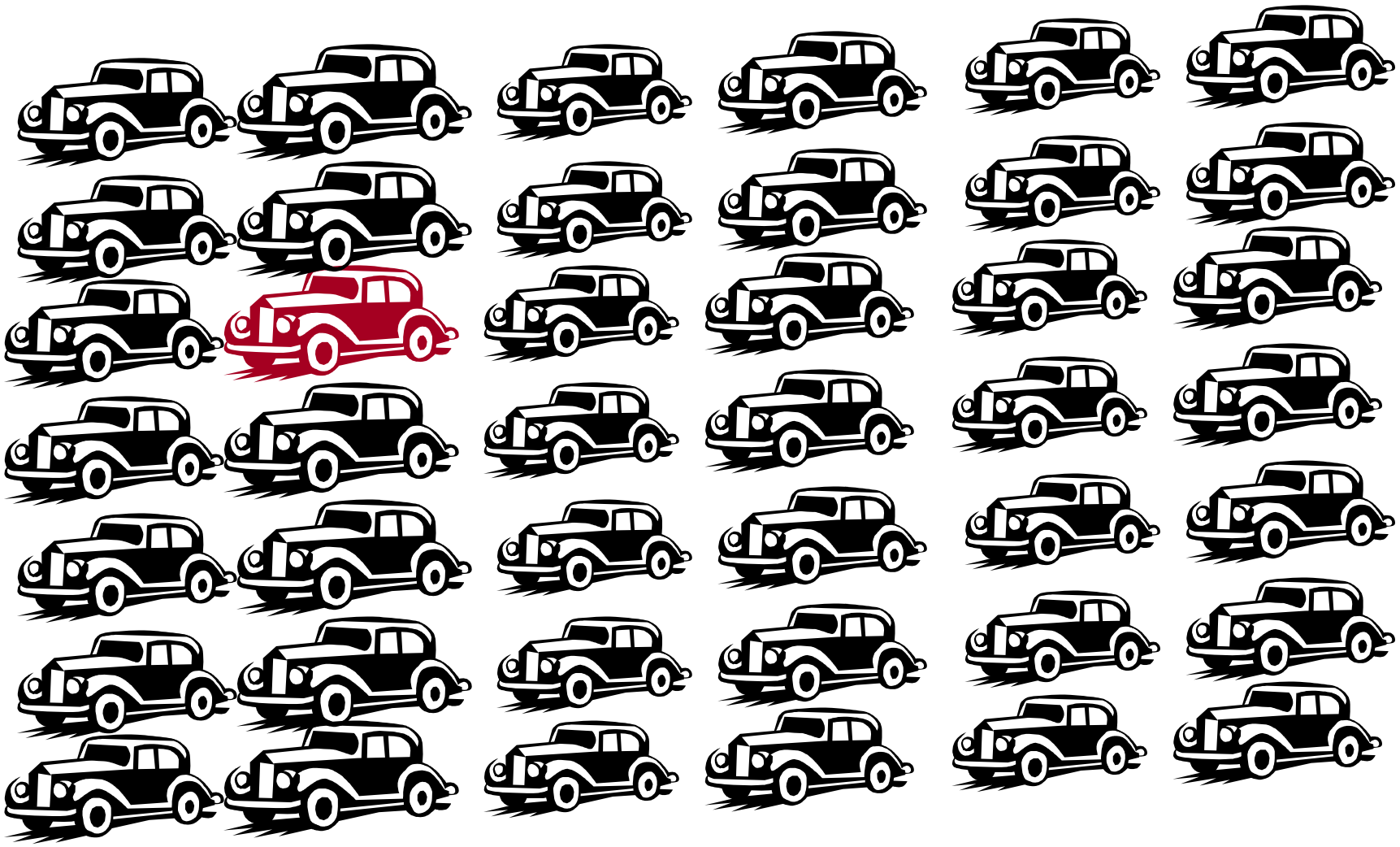


Problems With DES

- A thief walks into a car park and tries to steal a car...

- How many keys must he try?

Car Park Analogy 1900



Car Park Analogy 2000

The Meet in the Middle Attack

- Common sense statistics
- Attack multiple keys in parallel
- Need the same plaintext under each key
- Encrypt this plaintext to get a ‘test vector’
- Typical case: A 2^{56} search for one key becomes a 2^{40} search for 2^{16} keys
- Poor implementations of 3DES key storage allow 3DES key halves to be attacked individually

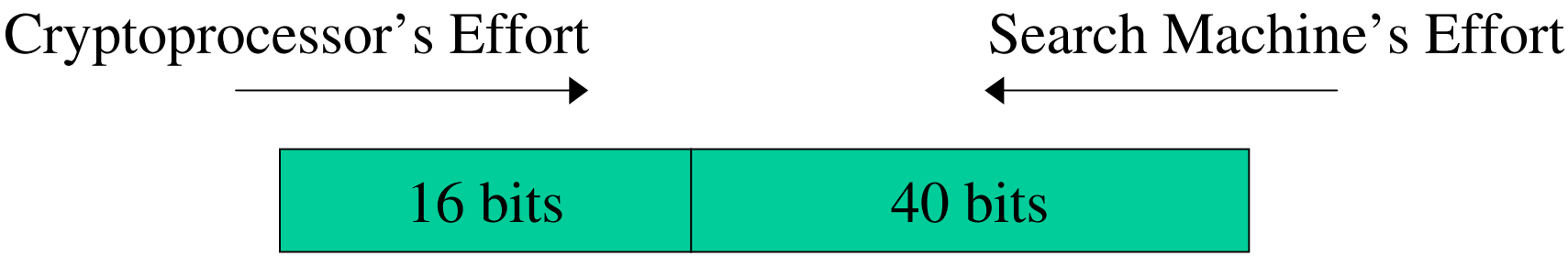
MIM Attack on DES Security Modules

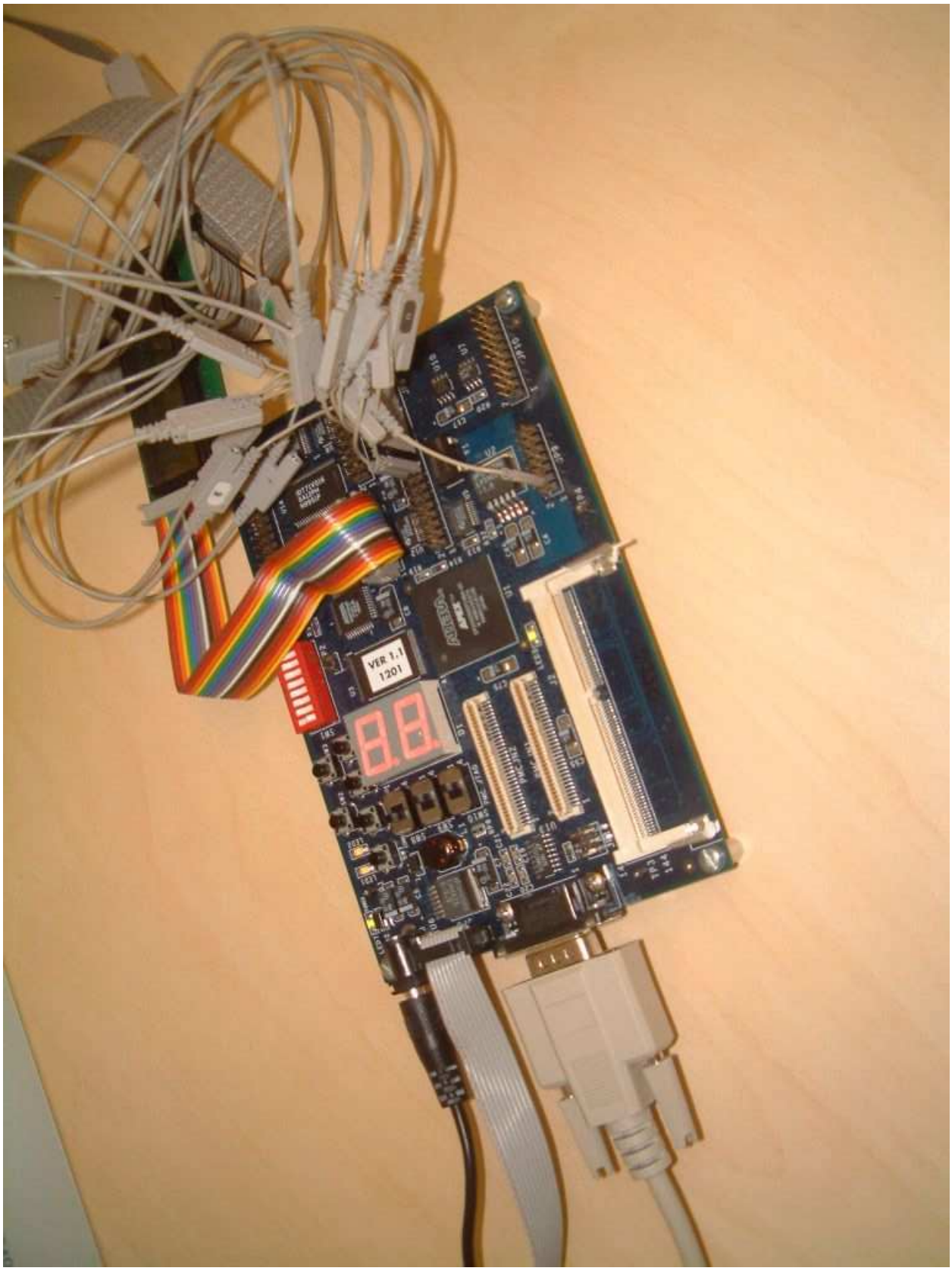
- Generate 2^{16} keys
- Encrypt test vectors

U->C : { KEY1 }$_{KM}$

C->U : { 0000000000000000 }$_{KEY1}$

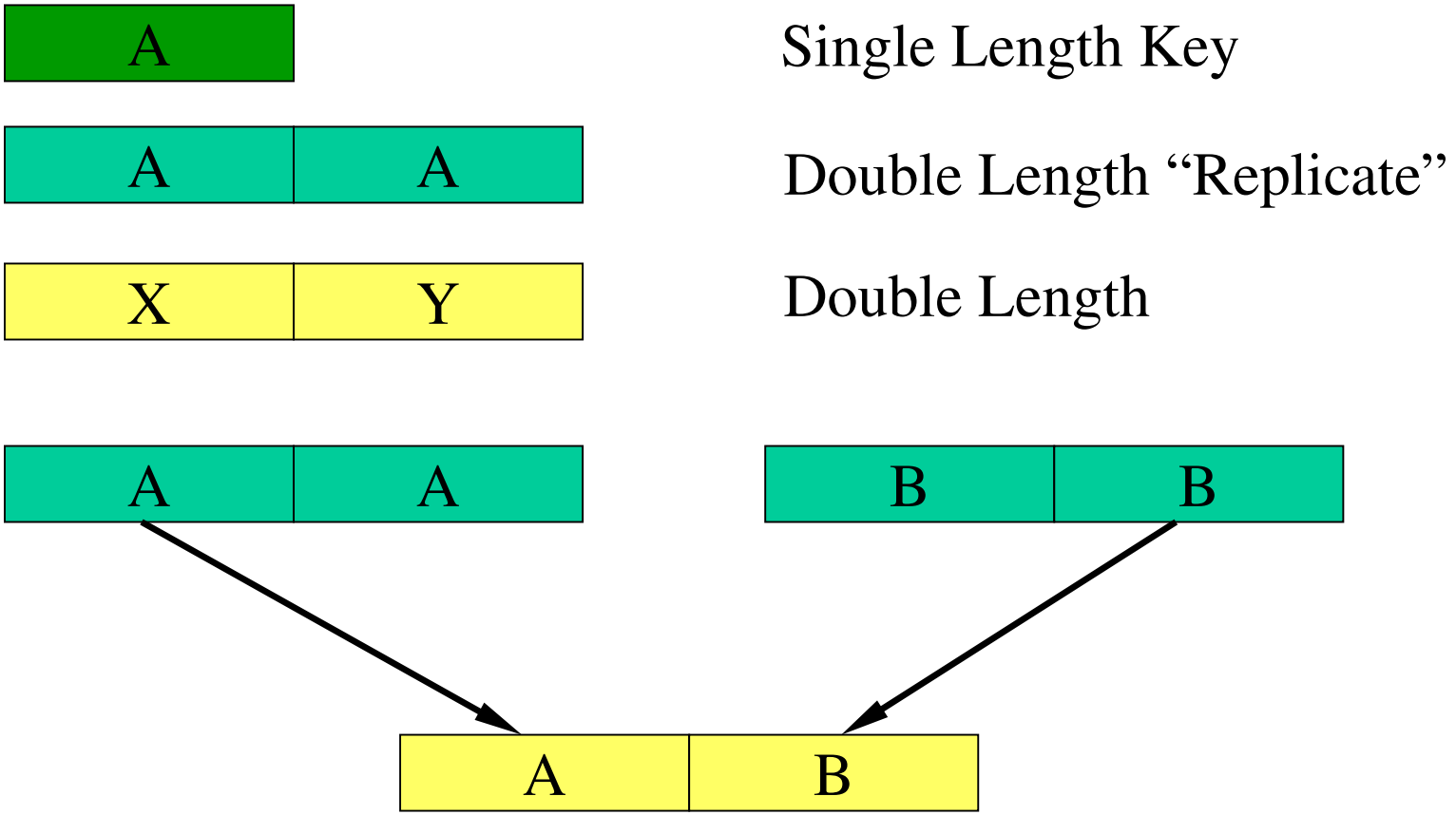
- Do 2^{40} search




VER 1.1
1201

MIM Attack on Triple-DES HSMs

$$E_K(D_K(E_K(\ KEY\ )) = E_K(KEY)$$



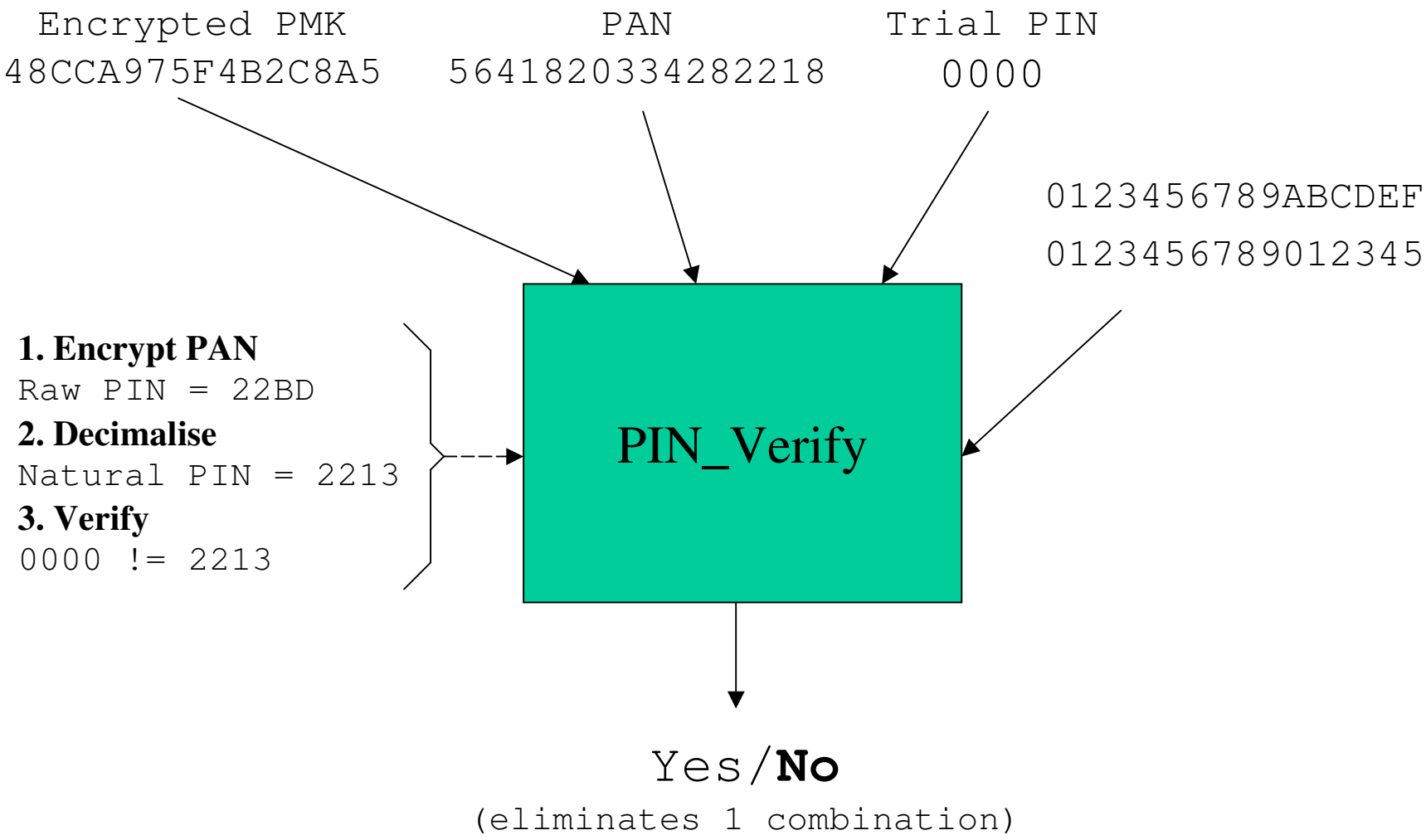
Information Leakage Attacks

- Remember PINs derived from account numbers
- Hexadecimal raw PIN is converted to decimal using decimalisation table
- Most APIs allow the decimalisation table to be specified with each PIN verification command
- A normal verification command eliminates one of 10,000 combinations of PIN for the attacker.
- If the table is altered, whether or not the alteration affects correct verification leaks much more information about the PIN

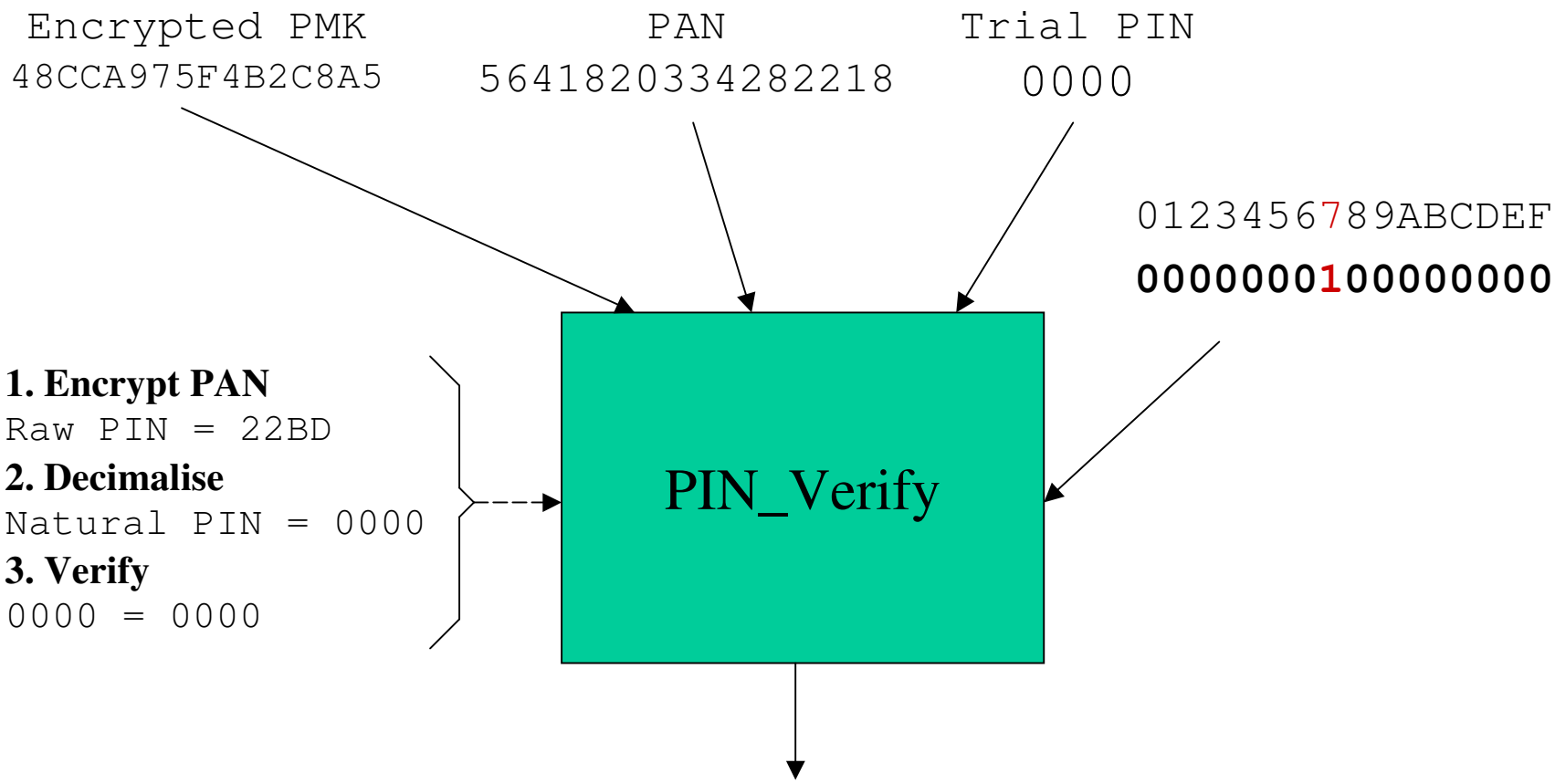
examples…

(Bond/Clulow 2002)

Decimalisation Table Attack (1)

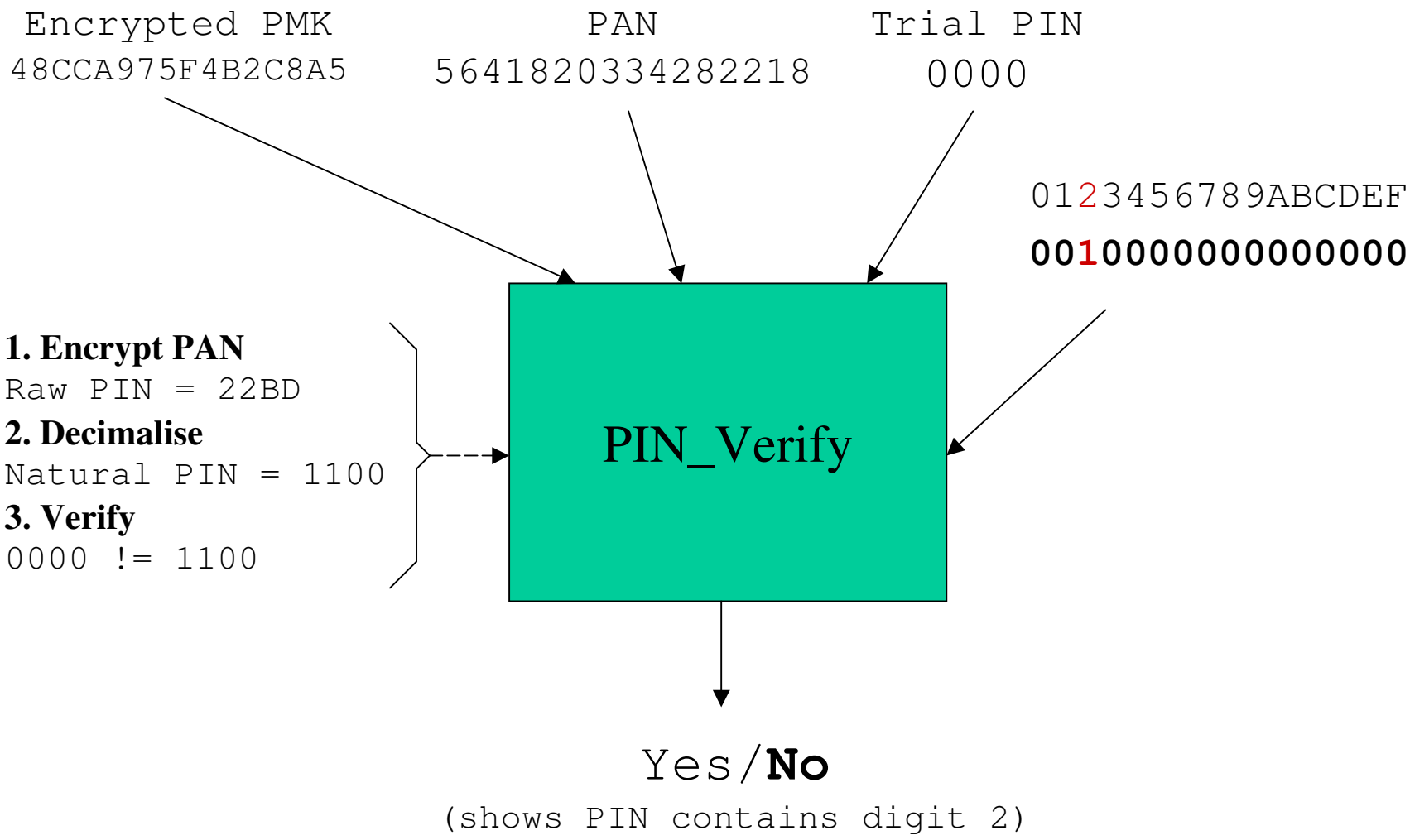


Decimalisation Table Attack (2)

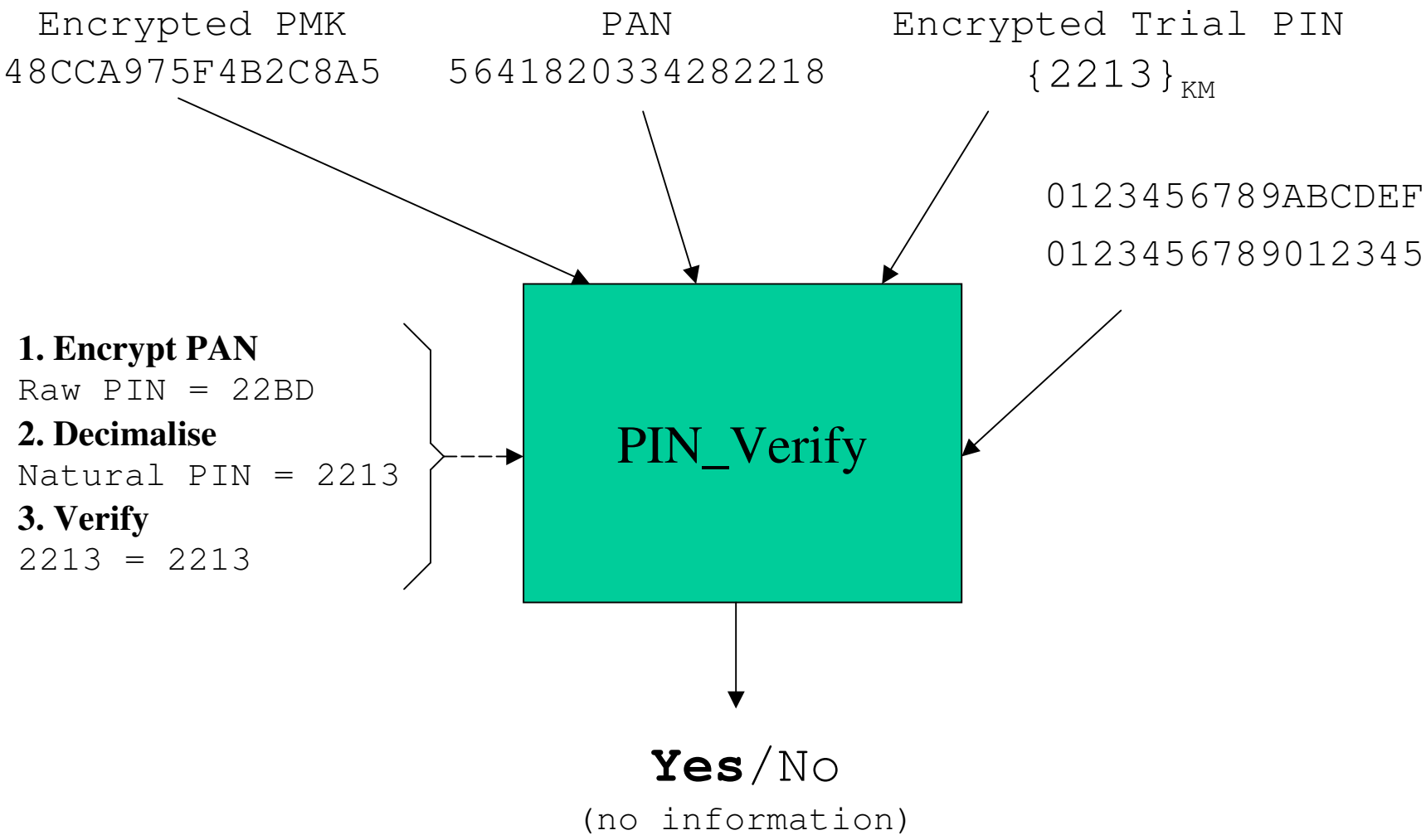


(eliminates all PINs containing digit 7)

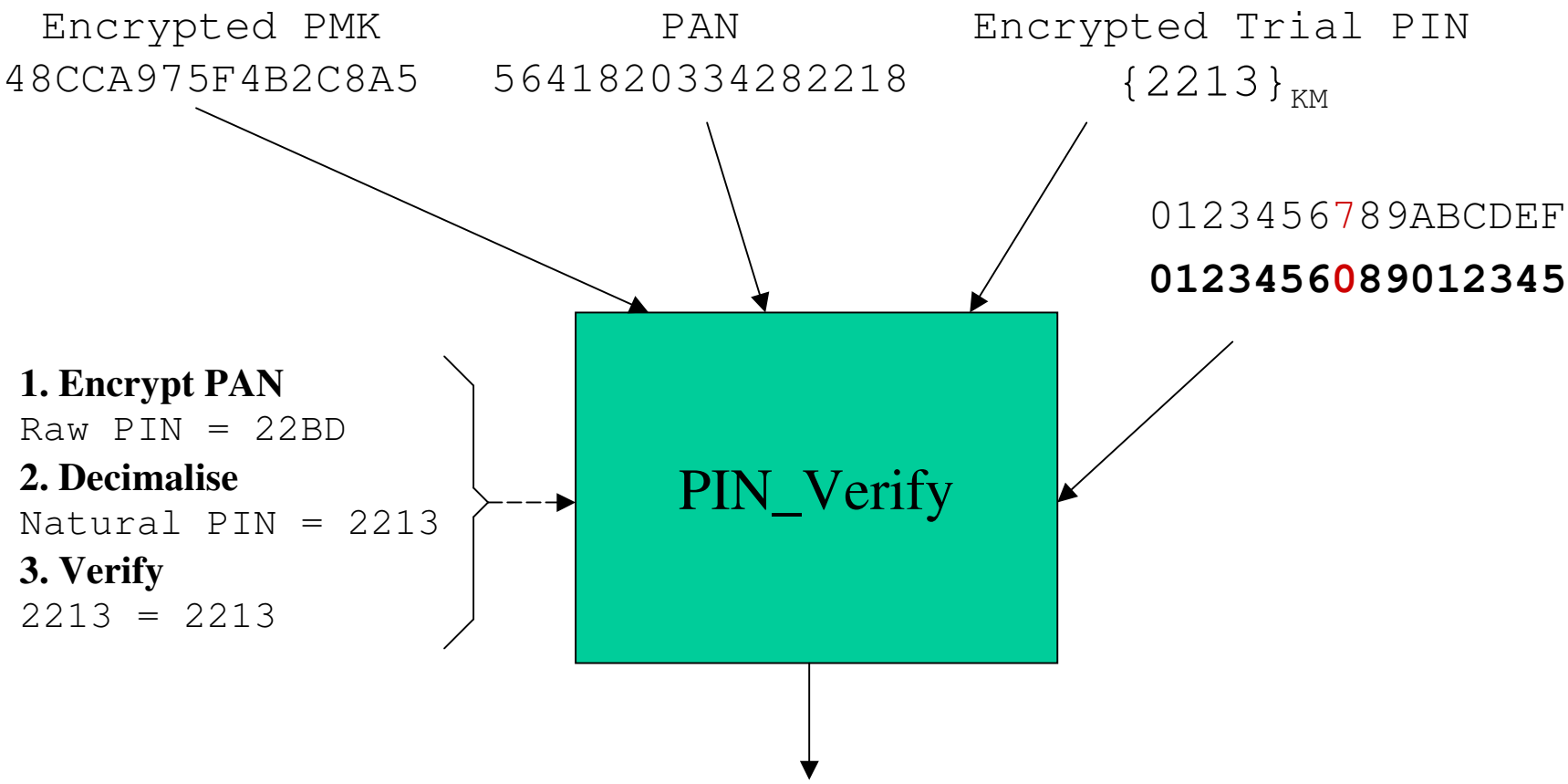
Decimalisation Table Attack (3)



Decimalisation Table Attack (4)



Decimalisation Table Attack (5)



(eliminates PINs containing digit 7)

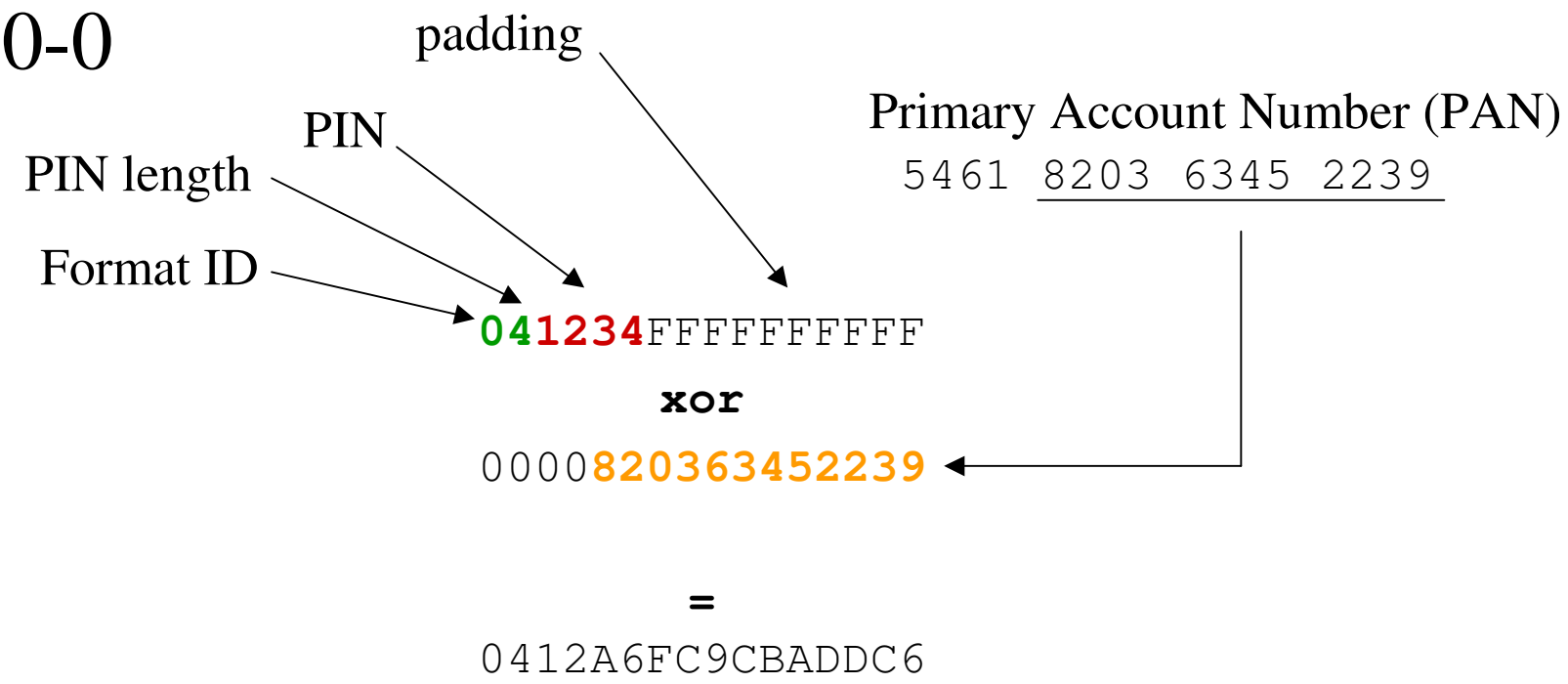
PAN Modification Attack (1)

- Encrypted PINs transferred from ATM to issuing bank via ATM network using point to point encryption
- At each node PIN block must be decrypted with incoming key, and re-encrypted with outgoing key
- Common ISO standard “binds” PIN to particular customer by exclusive-ORing PAN with PIN before encryption
- Attack: specifying incorrect PAN may make deduced PIN contain hexadecimal digit ‘A’-’F’, which causes formatting error. Conditions under which formatting error arises leaks information about PIN.

(Clulow 2002)

PIN Block Formats

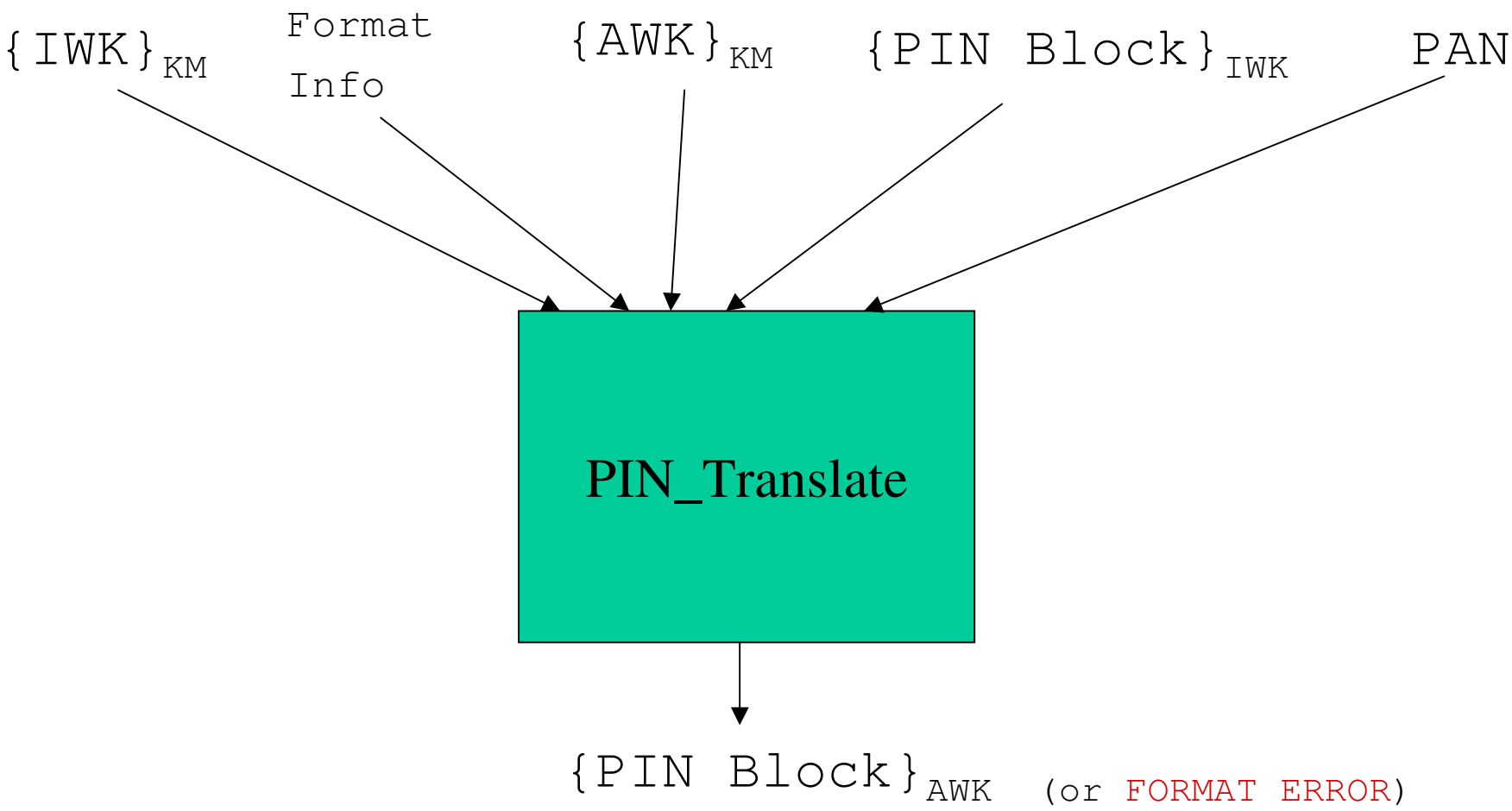
IS0-0



IS0-2

241234FFFFFFFFFF

PAN Modification Attack (2)



PAN Modification Attack (3)

041234FFFFFFFFFF
xor
0000820363452239
=
0412B6FC9CBADDC6

construction of PIN block

0412B6FC9CBADDC6
xor
0000820363452239
=
041234FFFFFFFFFF

correct PAN removed

0412B6FC9CBADDC6
xor
0000**7**20363452239
=
0412C4FFFFFFFFFF

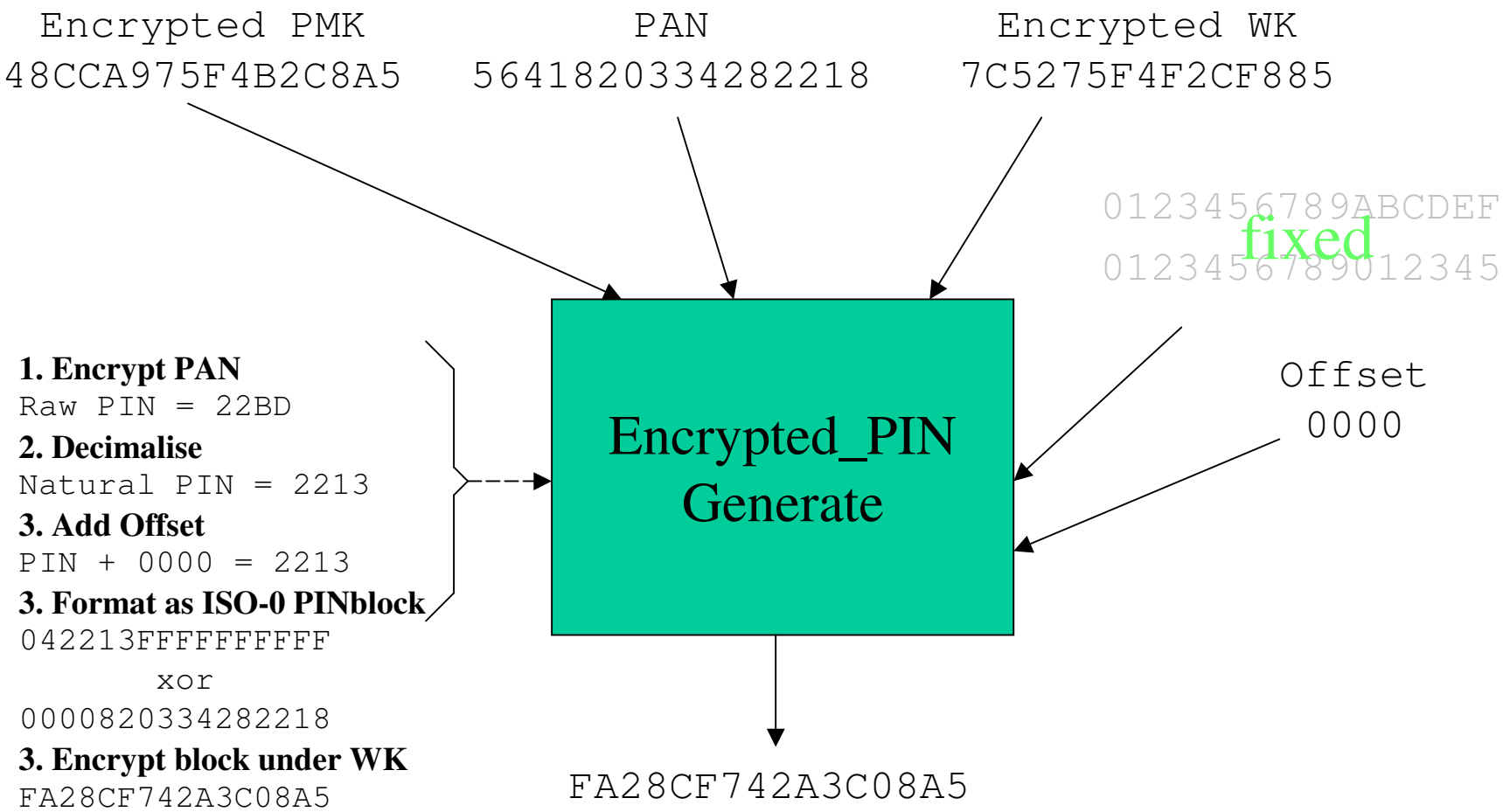
modified PAN Removed – PIN contains 'C' – **error**

PAN

PIN

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0	1	2	3	4	5	6	7	8	9
1	1	0	3	2	5	4	7	6	9	8
2	2	3	0	1	6	7	4	5	**A**	**B**
3	3	2	1	0	7	6	5	4	**B**	**A**
4	4	5	6	7	0	1	2	3	**C**	**D**
5	5	4	7	6	1	0	3	2	**D**	**C**
6	6	7	4	5	2	3	0	1	**E**	**F**
7	7	6	5	4	3	2	1	0	**F**	**E**
8	8	9	**A**	**B**	**C**	**D**	**E**	**F**	0	1
9	9	8	**B**	**A**	**D**	**C**	**F**	**E**	1	0
A	**A**	**B**	8	9	**E**	**F**	**C**	**D**	2	3
B	**B**	**A**	9	8	**F**	**E**	**D**	**C**	3	2
C	**C**	**D**	**E**	**F**	8	9	**A**	**B**	4	5
D	**D**	**C**	**F**	**E**	9	8	**B**	**A**	5	4
E	**E**	**F**	**C**	**D**	**A**	**B**	8	9	6	7
F	**F**	**E**	**D**	**C**	**B**	**A**	9	8	7	6

Encrypted PIN Generate

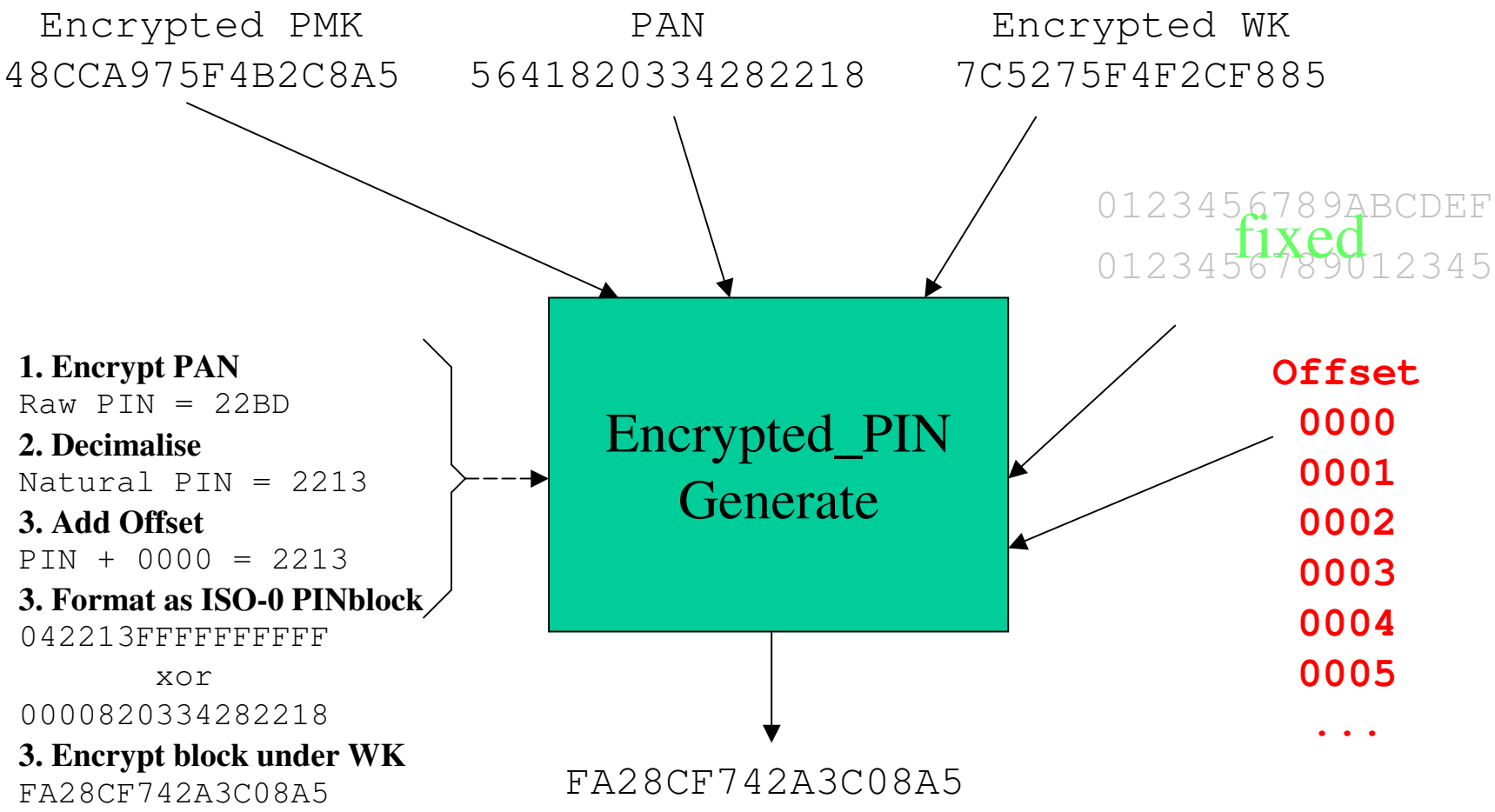


Collecting Frequency Distributions

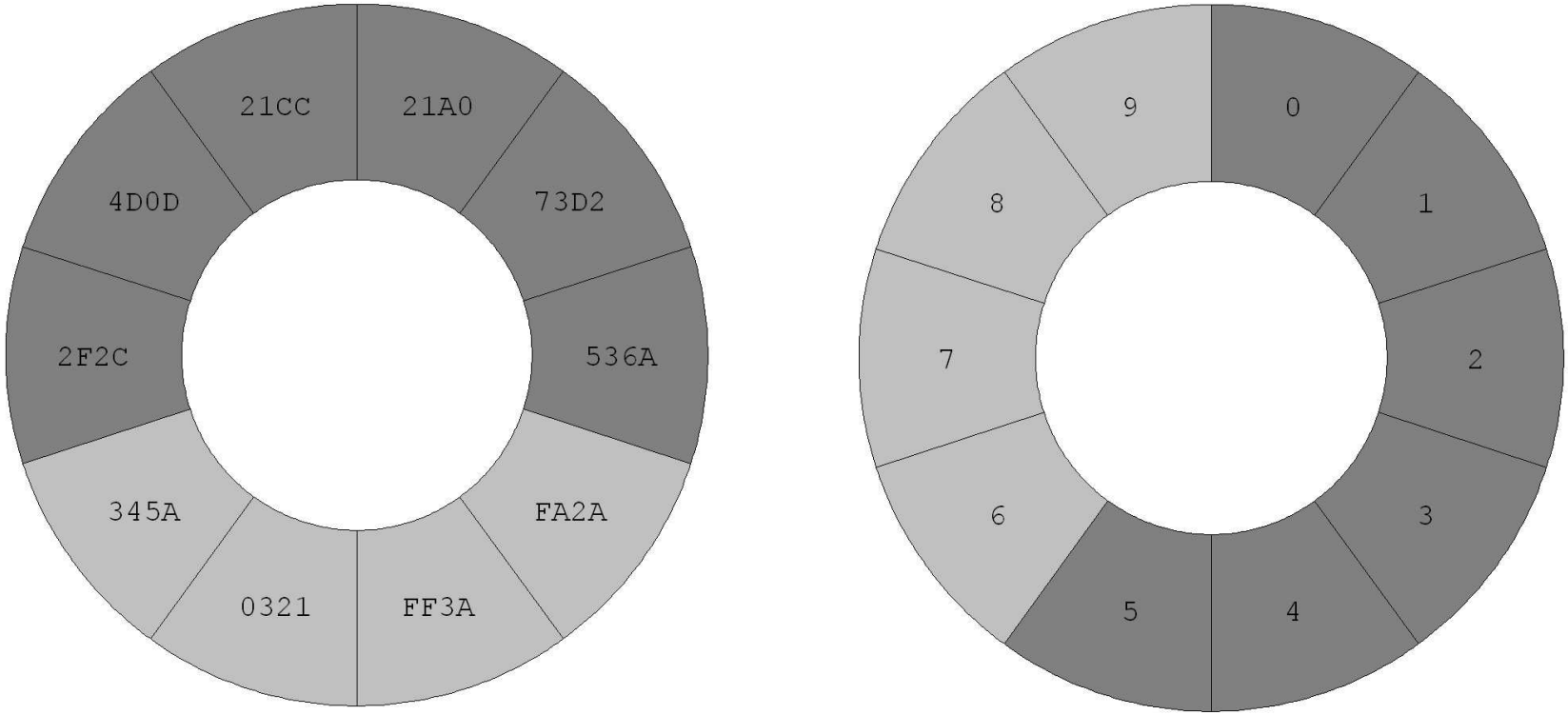
PMK	PIN Block	Output	Frequency
0D7604EBA10AC7F3	04**3328**FFFFFFFFFF xor 0000820362342219	FD29DA10029726DC	
23AD73218F2C0AB1	04**9106**FFFFFFFFFF xor 0000820362342219	EA4118F2C0AB3AC6	
9E760AF7F34EFA10	04**1522**FFFFFFFFFF xor 0000820362342219	104AE02F763A56DF	
66F7604EB263543C	04**6467**FFFFFFFFFF xor 0000820362342219	2E6892FC328D5212	
14E247F78EA876A0	04**2315**FFFFFFFFFF xor 0000820362342219	5323AB35C00273BB	

Next… assemble distribution in a loop (mod 10)

Encrypted PIN Generate



Aligning Frequency Distributions



(four alignment problems along orthogonal axes…)

The Last Word on ATM Security?

- We have come along way since the first flaws in PIN processing systems were put in the public domain
- In Europe, this entire architecture may be on the way out, as EMV ("Chip and PIN") is phased in
- Could these be the last published attacks on PIN processing systems?
- Banking security is concerned as much with risk and liability as with cryptographic security – there may be more to learn in fields where cryptographic security is a higher priority
- What next for Security API research?

The First Word on Trusted Computing?

- Trusted Computing proposals put simple hardware security modules in every PC
- TC also encourages compartmentalisation of applications into trusted and untrusted components – just like the evolution of ATM security
- Security API research may be able to help the designers of these interfaces avoid the worst mistakes, or maybe even make the interfaces secure?

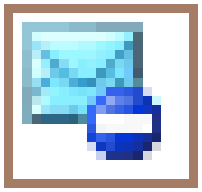
A double-edged sword?

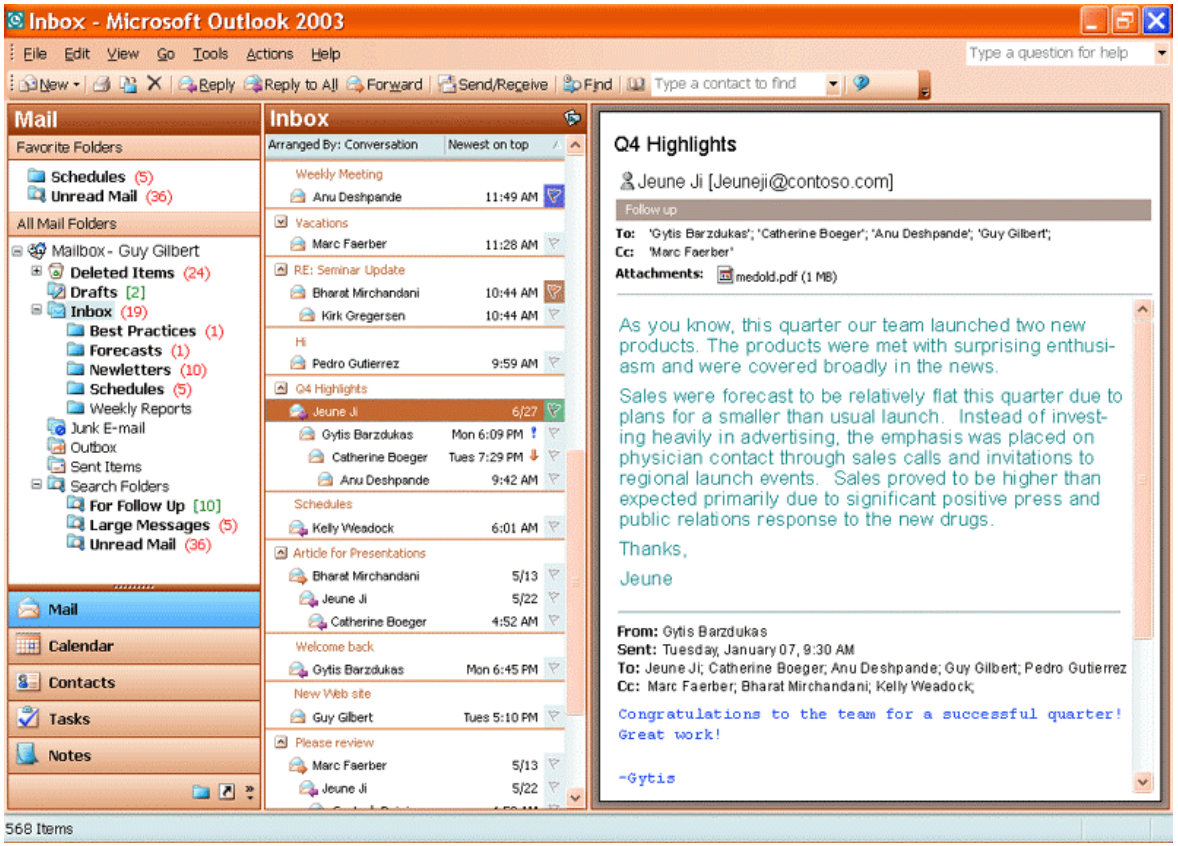
- IRM – Information Rights Management
  - Companies can stop leaks
  - Mafia can keep their records secret
- DRM – Digital Rights Management
- Trusted IO – Enter your ATM PIN at your PC
- Global PKI – All devices potentially indentifiable
- Trusted Anonymity Systems
- Truly Anonymous peer-to-peer systems
- High-availability systems
- Reverse-engineering resistant viruses

Example: Information Rights Management

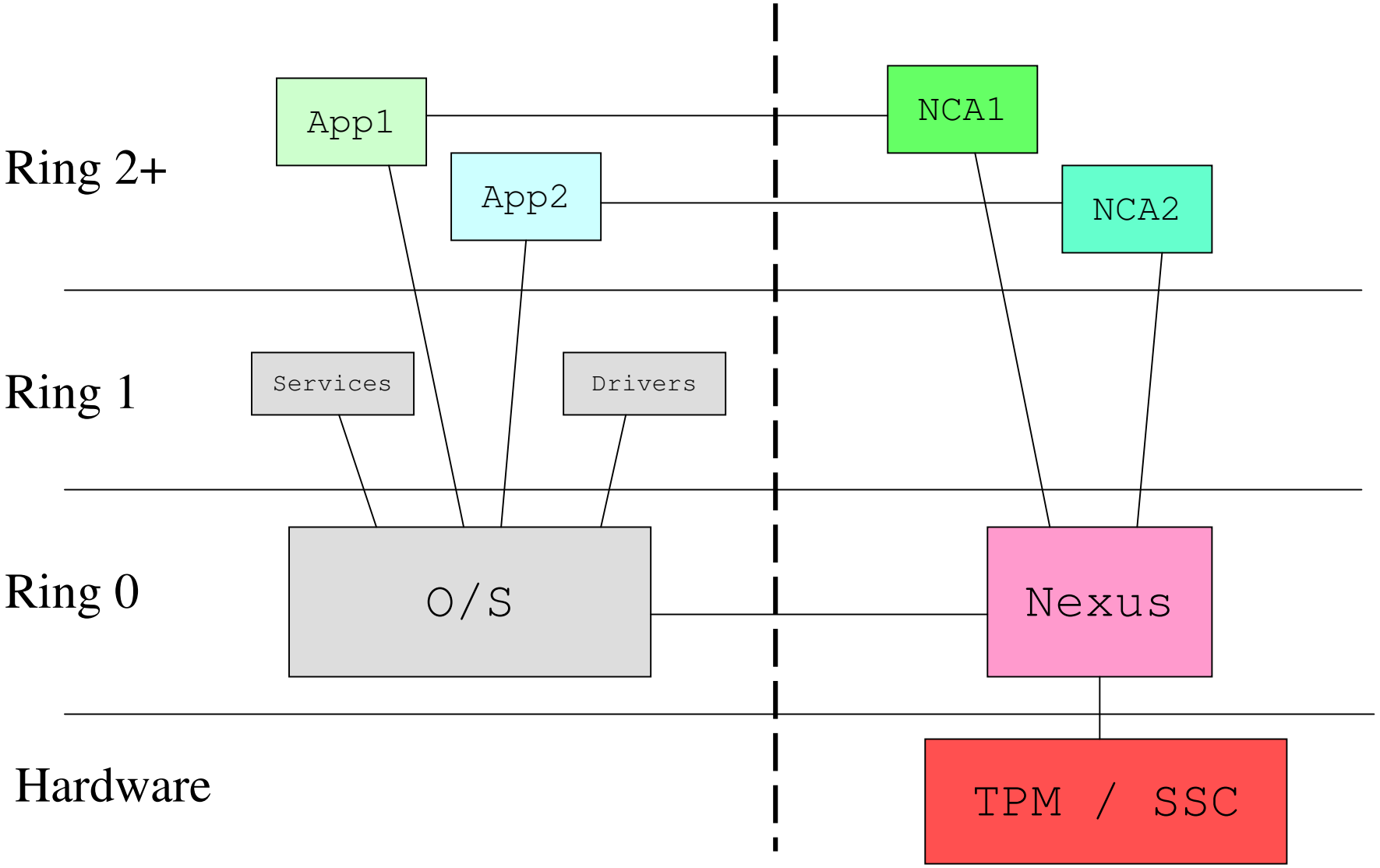
- Microsoft Office 2003 with
  Microsoft Rights Management Server
- Will it be secure when supported by TC?

The “restrict” button

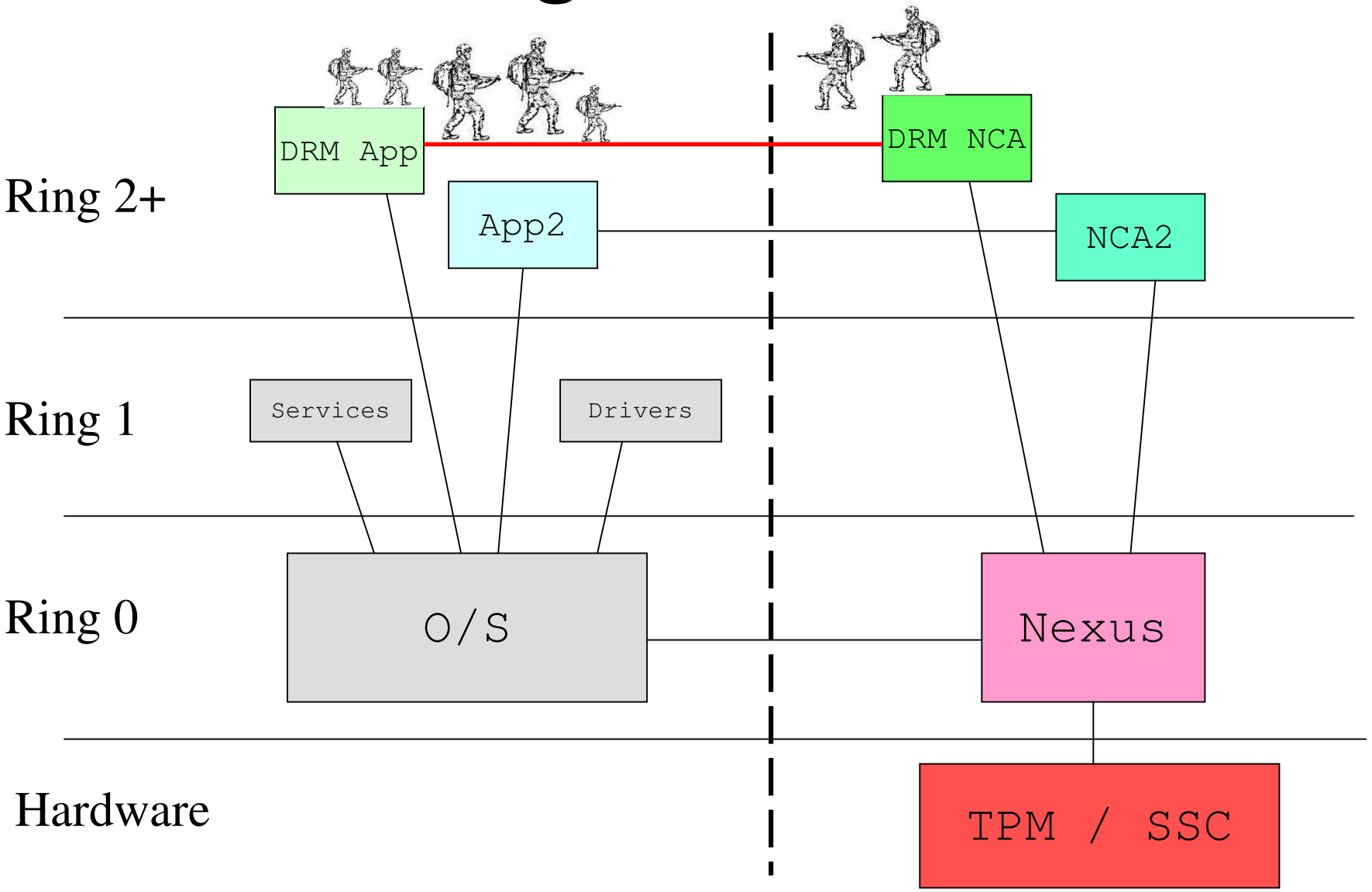




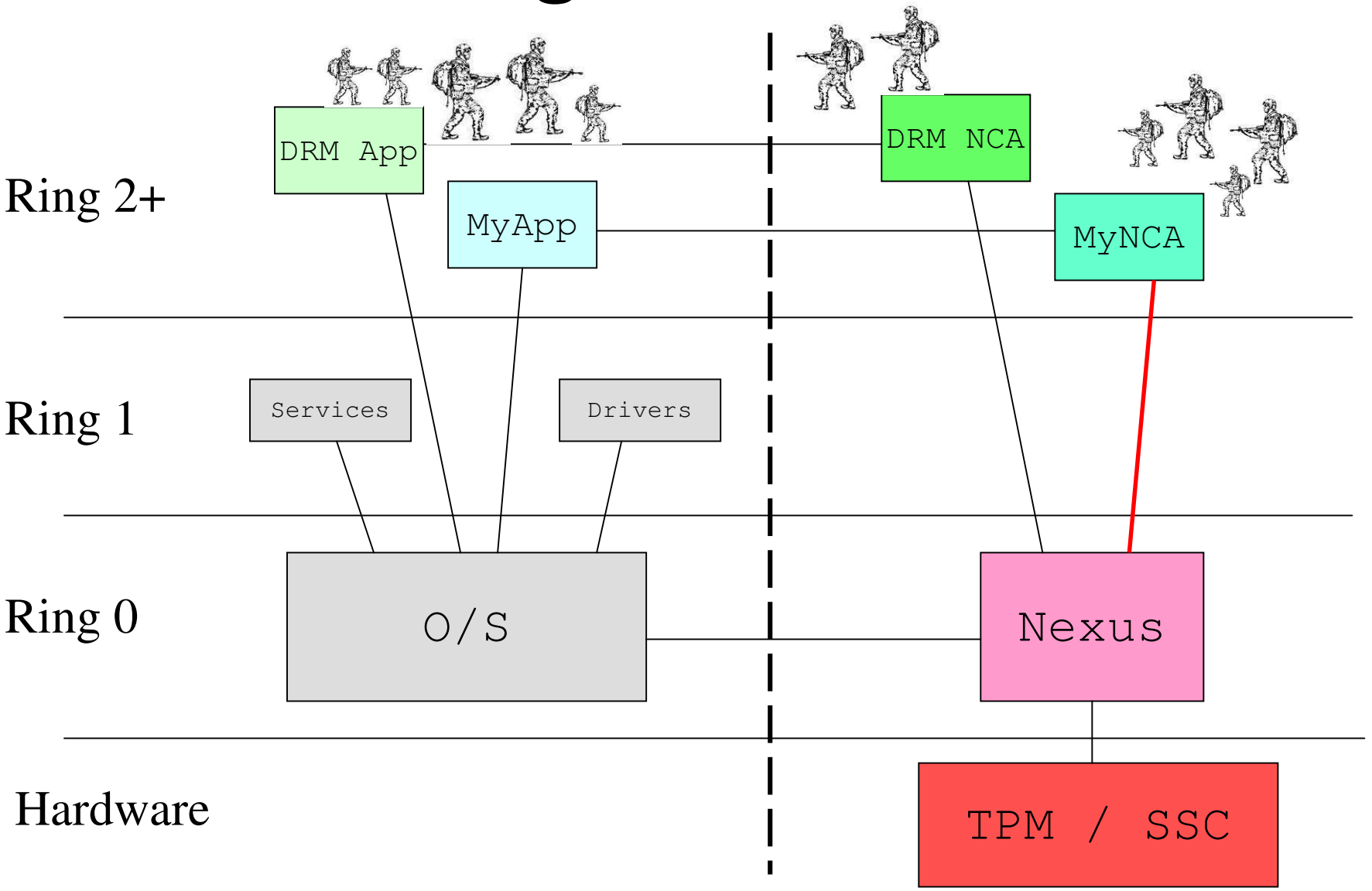
“The Digital Battlefield”



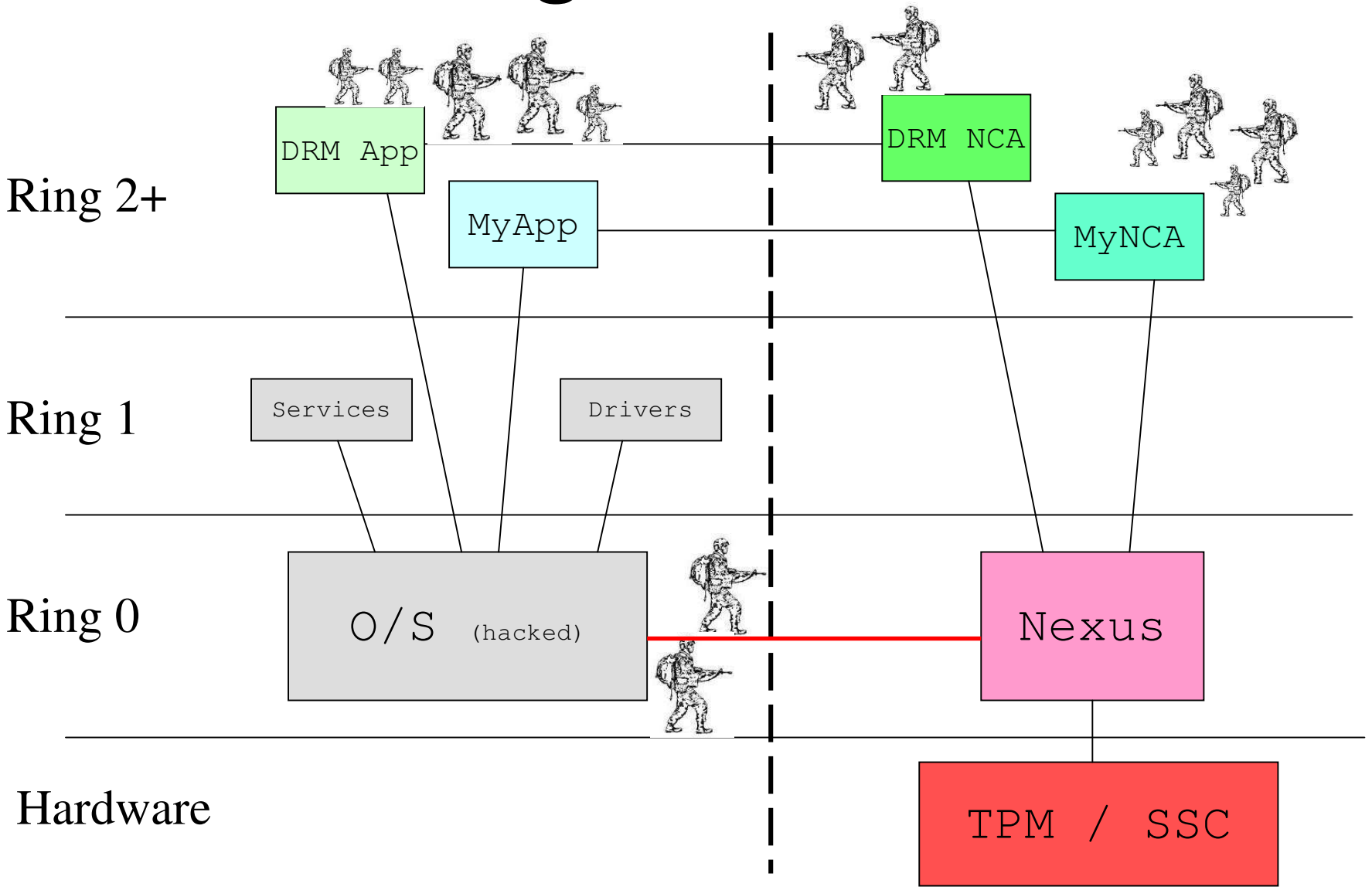
“The Digital Battlefield”



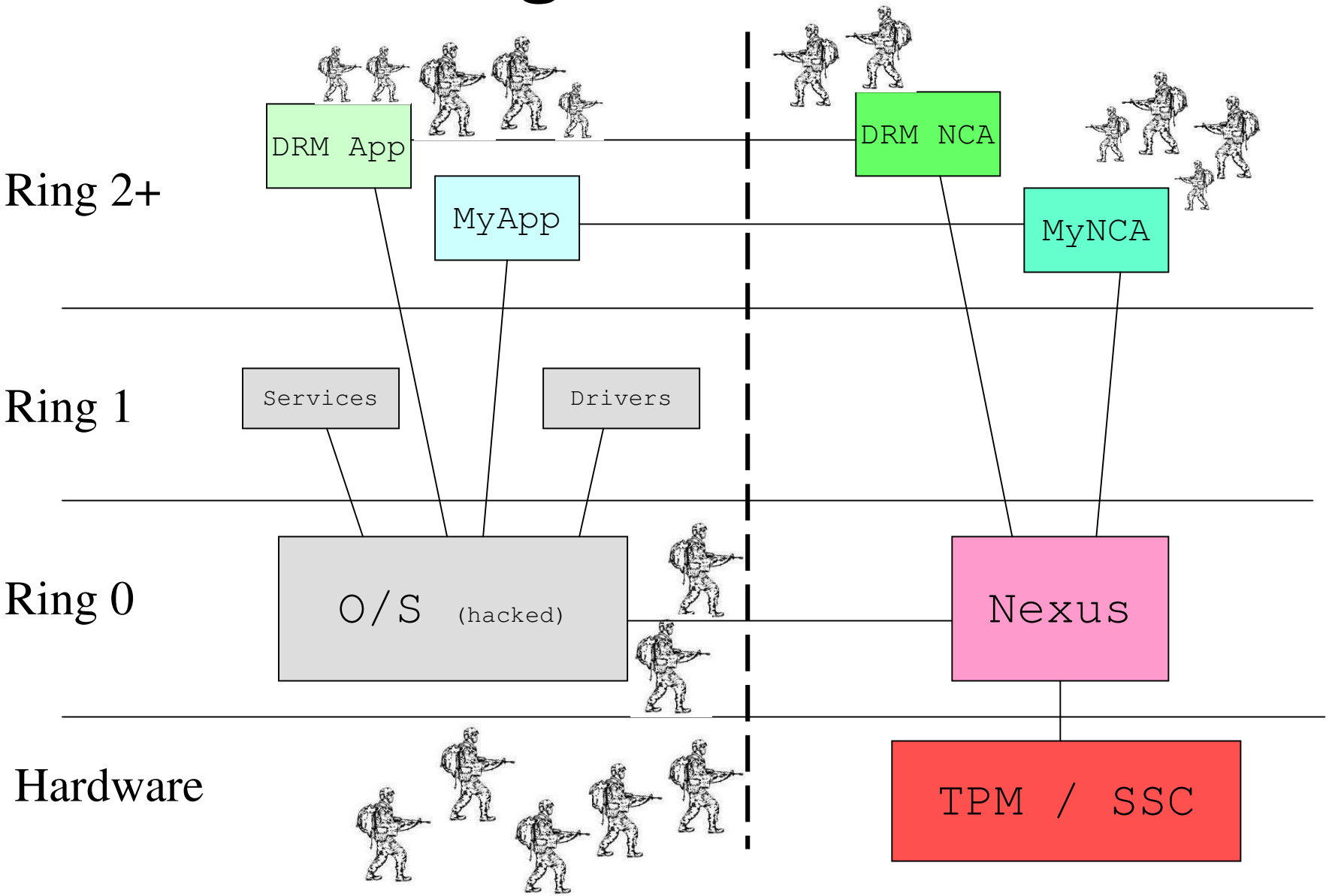
“The Digital Battlefield”



“The Digital Battlefield”



“The Digital Battlefield”



Getting Formal

- How are we going to survive on this ‘battlefield’ if all our technology is for attack, not defence?
- So far we only have heuristics for understanding how to design Security APIs, but there are important properties we would like to gain assurance about (in formal speak: *“prove”*)
- Formalising the specification of Security APIs could help make properties clearer
- Semi-automated analysis of specifications could assist gaining assurance, locating vulnerabilities, and enumerating all instances of vulnerabilities

Example Pages from IBM Manual

Data_Key_Import (CSNBDKM)

Platform/ Product	OS/2	AIX	NT	OS/400
IBM 4758-1	X	X	X	X

The Data_Key_Import verb imports an encrypted, source DES DATA key and creates or updates a target internal key token with the master-key enciphered source key. The verb can import the key into an internal key token in application storage or in key storage. This verb, which is authorized with a different control point than used with the Key_Export verb, allows you to limit the export operations to DATA keys as compared to the capabilities of the more general verb.

Specify the following:

- An external key token containing the source key to be imported. The external key token must indicate that a control vector is present; however, the control vector is usually valued at zero.

  Alternatively, you can provide the encrypted data key at offset 16 in an otherwise all X'00' key token. The verb will process this token format as a DATA key encrypted by the importer key and a null (all zero) control vector.
- An IMPORTER key-encrypting key under which the source key is deciphered.
- An internal or null key token. The internal key token can be located in application data storage or in key storage.

The verb builds the internal key token by the following:

- Creates a default control vector for a DATA key type in the internal key token, if the control vector in the external key token is zero. If the control vector is not zero, the verb copies the control vector into the internal key token from the external key token.
- Multiply-deciphers the key under the keys formed by the exclusive-OR of the key-encrypting key (identified in the *importer_key_identifier*) and the control vector in the external key token, then multiply-enciphers the key under keys formed by the exclusive-OR of the master key and the control vector in the internal key token. The verb places the key in the internal key token.
- Calculates a token-validation value and stores it in the internal key token.

This verb does not adjust the key parity of the source key.

Restrictions

None

Format

CSNBDKM			
return_code	Output	Integer	
reason_code	Output	Integer	
exit_data_length	In/Output	Integer	
exit_data	In/Output	String	*exit_data_length* bytes
source_key_token	Input	String	64 bytes
importer_key_identifier	Input	String	64 bytes
target_key_identifier	In/Output	String	64 bytes

Parameters

For the definitions of the *return_code*, *reason_code*, *exit_data_length*, and *exit_data* parameters, see "Parameters Common to All Verbs" on page 1-10.

source_key_token
The *source_key_token* parameter is a pointer to a 64-byte string variable containing the source key to be imported. The source key must be an external key.

importer_key_identifier
The *importer_key_identifier* parameter is a pointer to a 64-byte string variable containing the (IMPORTER) transport key used to decipher the source key.

target_key_identifier
The *target_key_identifier* parameter is a pointer to a 64-byte string variable containing a null key token, an internal key token, or the key label of an internal key token or null key token record in key storage. The key token receives the imported key.

Required Commands

The Data_Key_Import verb requires the Data Key Import command (offset X'0109') to be enabled in the hardware.

First Steps: Theorem Proving

- Predicate `U(x)` represents adversary knowledge; implications represent adversary gaining knowledge through transactions. Manual pages from previous slide condensed:

```
U(e(x,xor(k,t))) & U(e(k,xor(km,imp)) ->
  U(e(x,xor(km,t)))
```

- We assert that there is an attack, and challenge the tool to prove it

```
U(a_secret).
```

Early Results

- Driving theorem provers is difficult – a whole new world of terminology and expertise to be learned, made more difficult because the tools are highly abstract.
- In the right hands, the tools are powerful: we can model all known “pure” API attacks (not involving properties of crypto)
- It already looks like theorem proving will be useful for enumerating all instances of a general attack method e.g. “type-casting” on the IBM 4758 CCA
- We hope to enumerate all ‘Meet-in-the-Middle’ attacks on a security API next

Conclusions

- We have learnt a lot from analysing ATM security, but there is still much much more to do…
- If and when Trusted Computing arrives on our desktops, Security APIs will not be a specialist backwater of protocol analysis, but an integral part of secure application design
- We are making the first steps to try and bring order and sense to the catalogue of attacks on existing Security APIs, and there is plenty of room for more research, which might have a real impact on the long-term success of Trusted Computing.

More Information

Papers, Links & Resources

http://www.cl.cam.ac.uk/~mkb23/research.html

http://www.cl.cam.ac.uk/~jc407/

Attacks on IBM 4758 CCA & Hardware Cracker

http://www.cl.cam.ac.uk/~rnc1/descrack/

Phantom Withdrawals and Banking Security

http://www.cl.cam.ac.uk/~mkb23/phantom/

I am around for the rest of the afternoon…

Email… `Mike.Bond@cl.cam.ac.uk`