Formal Methods for Payment Protocols

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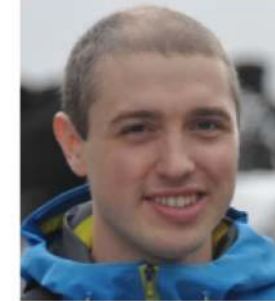# Research on Tamarin & EMV — Collaborators

Tamarin Team

Simon Meier

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. . .

EMV

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EMV Standard

EMV is the global standard for smartcard payments: 9+ billion cards used!

Founded by Europay, Mastercard, and Visa.   Others have joined too

The standard claims to offer the highest security

EMV: Security and Convenience

Low-value purchases do not need a PIN

CHF 5.—

1234 5678 9012 3456

High-value purchases should be protected by a PIN

CHF 400.—

Enter PIN: ****

1234 5678 9012 3456

But they are not!

Take Home Messages

1. **Developed *first* comprehensive model of EMV**
   Paper specification runs over 2,000 pages
   ⤳ **directly formalized in Tamarin**

2. **Found both known and new security issues**
   The PINs for your credit cards are useless!

3. **We proposed and machine-checked fixes (disclosed to relevant vendors)**
   Fixes do not affect cards in circulation

4. **Experience supports general hypothesis:**
   Don't trust, verify!

Details described on the web at emvrace.github.io
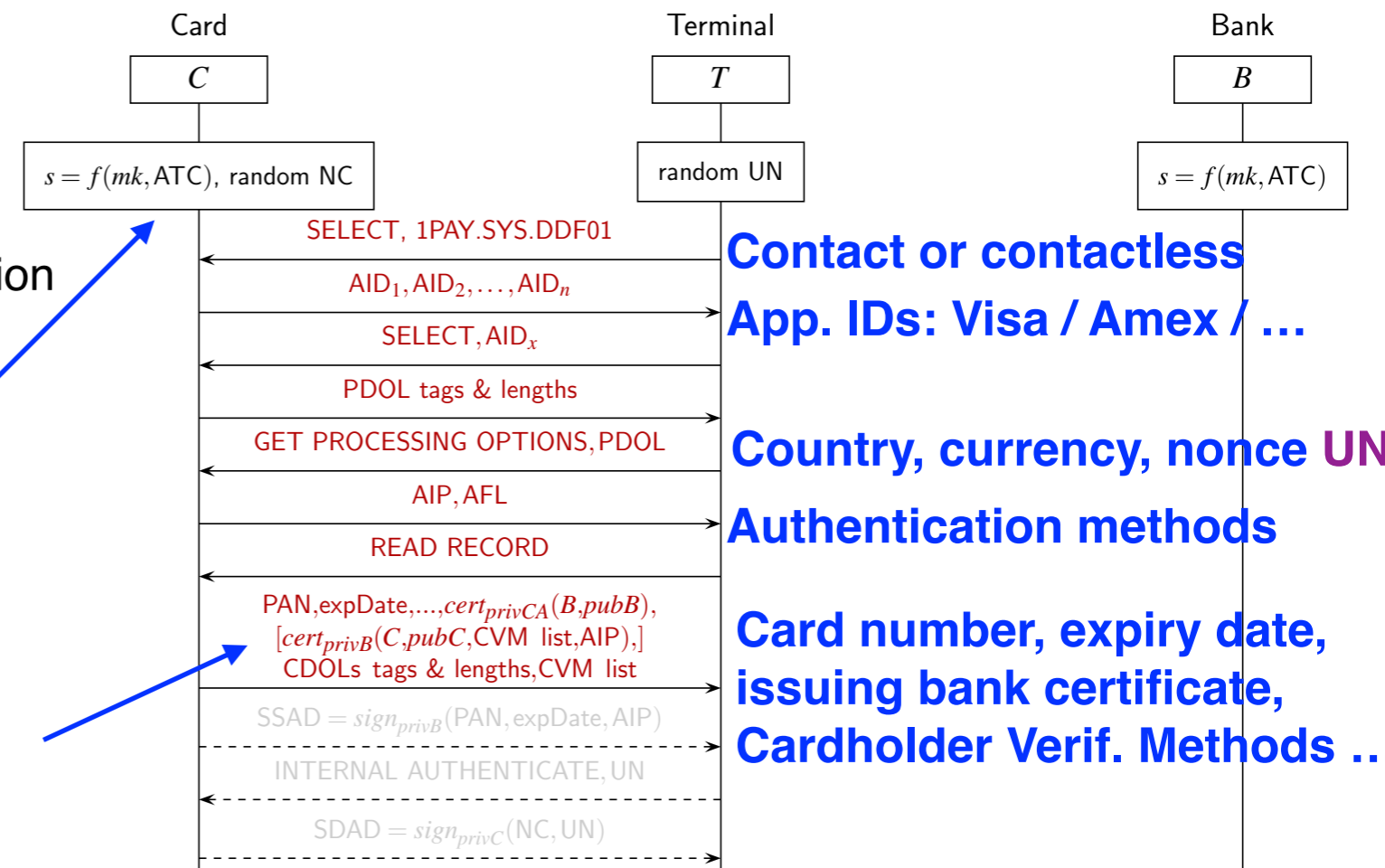
EMV Protocol

1. Initialization: card & terminal agree on application used for transaction & exchange static data.

mk: symmetric master key shared between card and bank
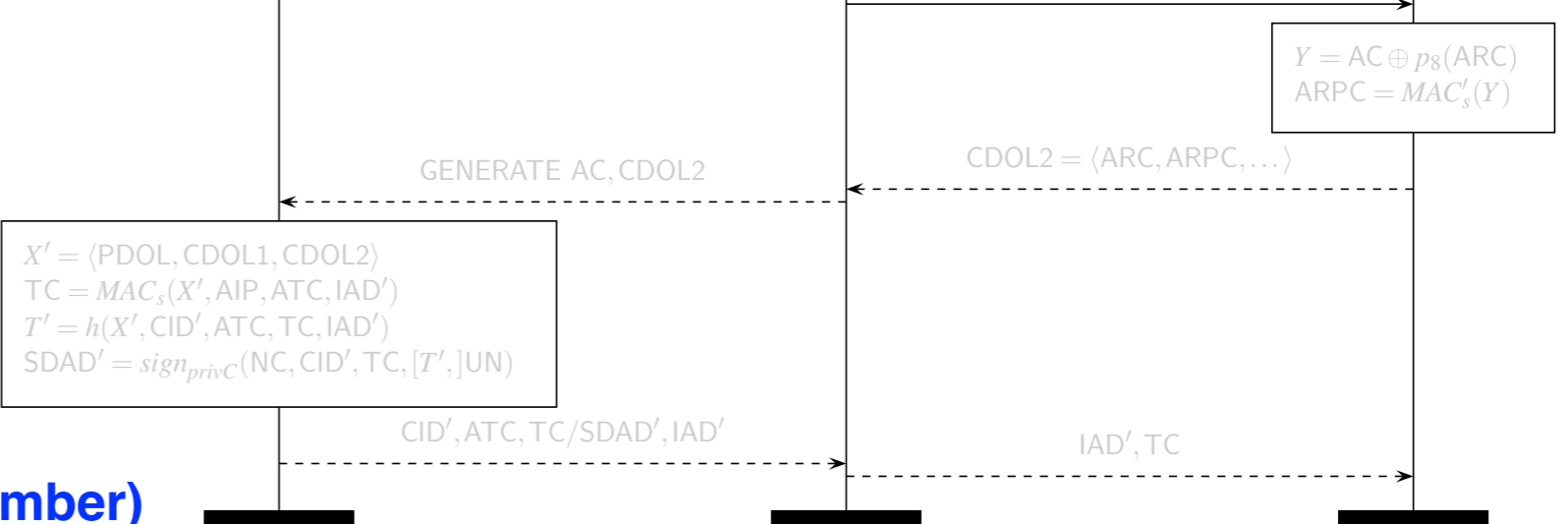**ATC: transaction counter**
result s used for MACs

Uses PKI with certificates for CAs, Banks & Cards (but not Terminals)

2,000+ pages

Acronym Zoo:
PDOL/CDOL: Data Object Lists
AID: Application Identifiers
PAN: Primary Account Number (Card number)
CVM: Cardholder Verification Methods
…

Card — C
Terminal — T
Bank — B

$s = f(mk, \text{ATC}), \text{ random NC}$
random UN
$s = f(mk, \text{ATC})$

SELECT, 1PAY.SYS.DDF01
$AID_1, AID_2, \ldots, AID_n$
SELECT, AID_x
PDOL tags & lengths
GET PROCESSING OPTIONS, PDOL
AIP, AFL
READ RECORD
PAN, expDate, ..., $cert_{privCA}(B, pubB)$,
$[cert_{privB}(C, pubC, \text{CVM list}, \text{AIP}),]$
CDOLs tags & lengths, CVM list
$\text{SSAD} = sign_{privB}(\text{PAN}, \text{expDate}, \text{AIP})$
INTERNAL AUTHENTICATE, UN
$\text{SDAD} = sign_{privC}(\text{NC}, \text{UN})$

Contact or contactless
App. IDs: Visa / Amex / …

Country, currency, nonce UN

Authentication methods

Card number, expiry date, issuing bank certificate, Cardholder Verif. Methods …

Substantially simplified account! Also with variants for different EMV kernels

AC $[, aenc_{pubB}(\text{PIN})]$

$Y = \text{AC} \oplus p_8(\text{ARC})$
$\text{ARPC} = MAC'_s(Y)$

GENERATE AC, CDOL2
$\text{CDOL2} = \langle \text{ARC}, \text{ARPC}, \ldots \rangle$

$X' = \langle \text{PDOL}, \text{CDOL1}, \text{CDOL2} \rangle$
$\text{TC} = MAC_s(X', \text{AIP}, \text{ATC}, \text{IAD}')$
$T' = h(X', \text{CID}', \text{ATC}, \text{TC}, \text{IAD}')$
$\text{SDAD}' = sign_{privC}(\text{NC}, \text{CID}', \text{TC}, [T',]\text{UN})$

$\text{CID}', \text{ATC}, \text{TC}/\text{SDAD}', \text{IAD}'$
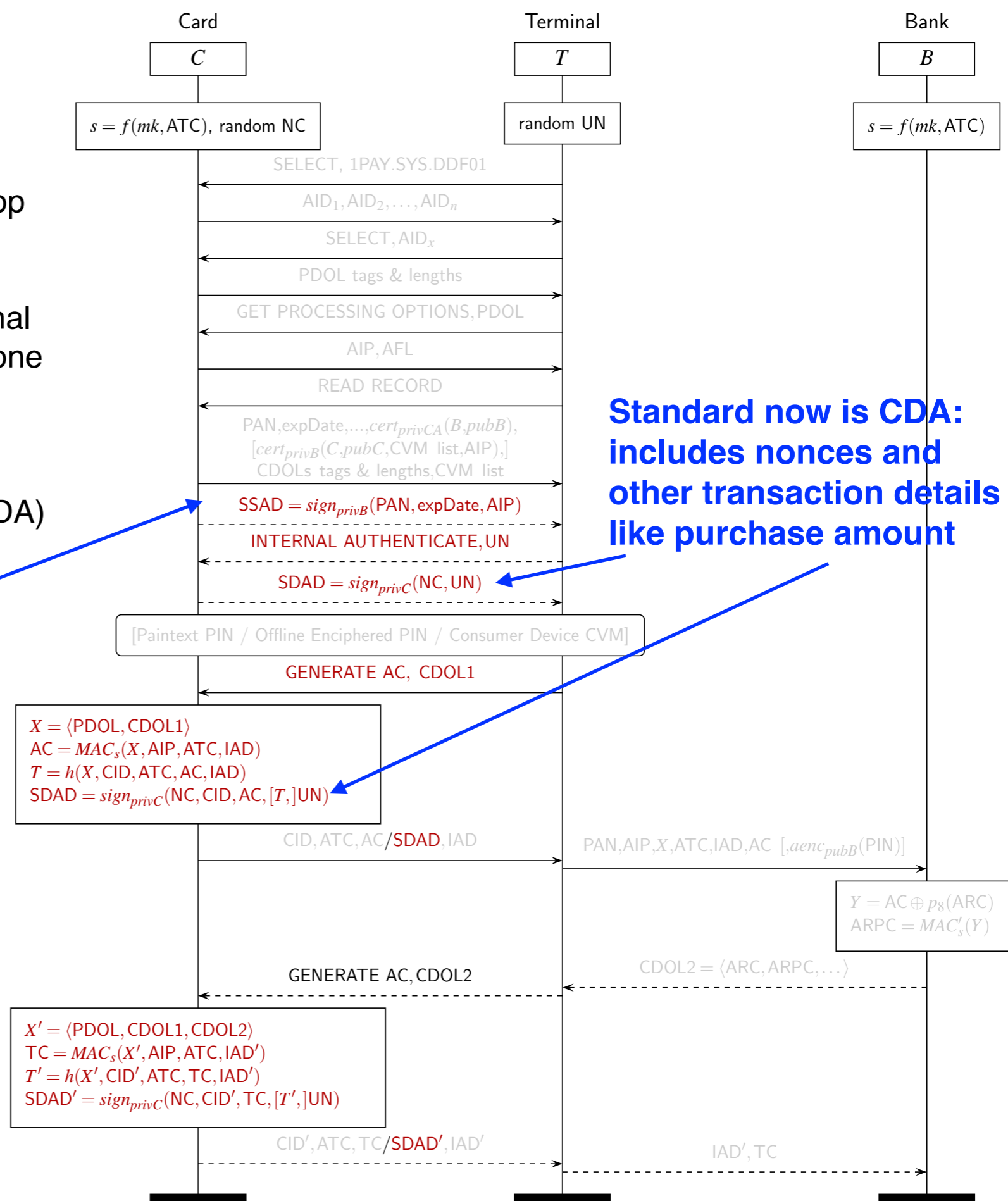IAD', TC

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EMV Protocol

1. **Initialization:** card and terminal agree on app used for transaction & exchange static data.

2. **Offline Data Authentication (ODA):** terminal performs PKI-based **card validation** using one of three methods:
   • Static Data Authentication (SDA)
   • Dynamic Data Authentication (DDA)
   • Combined Dynamic Data Authentication (CDA)

Static data like card number and exp. date signed earlier by bank and stored on card.   Legacy status.

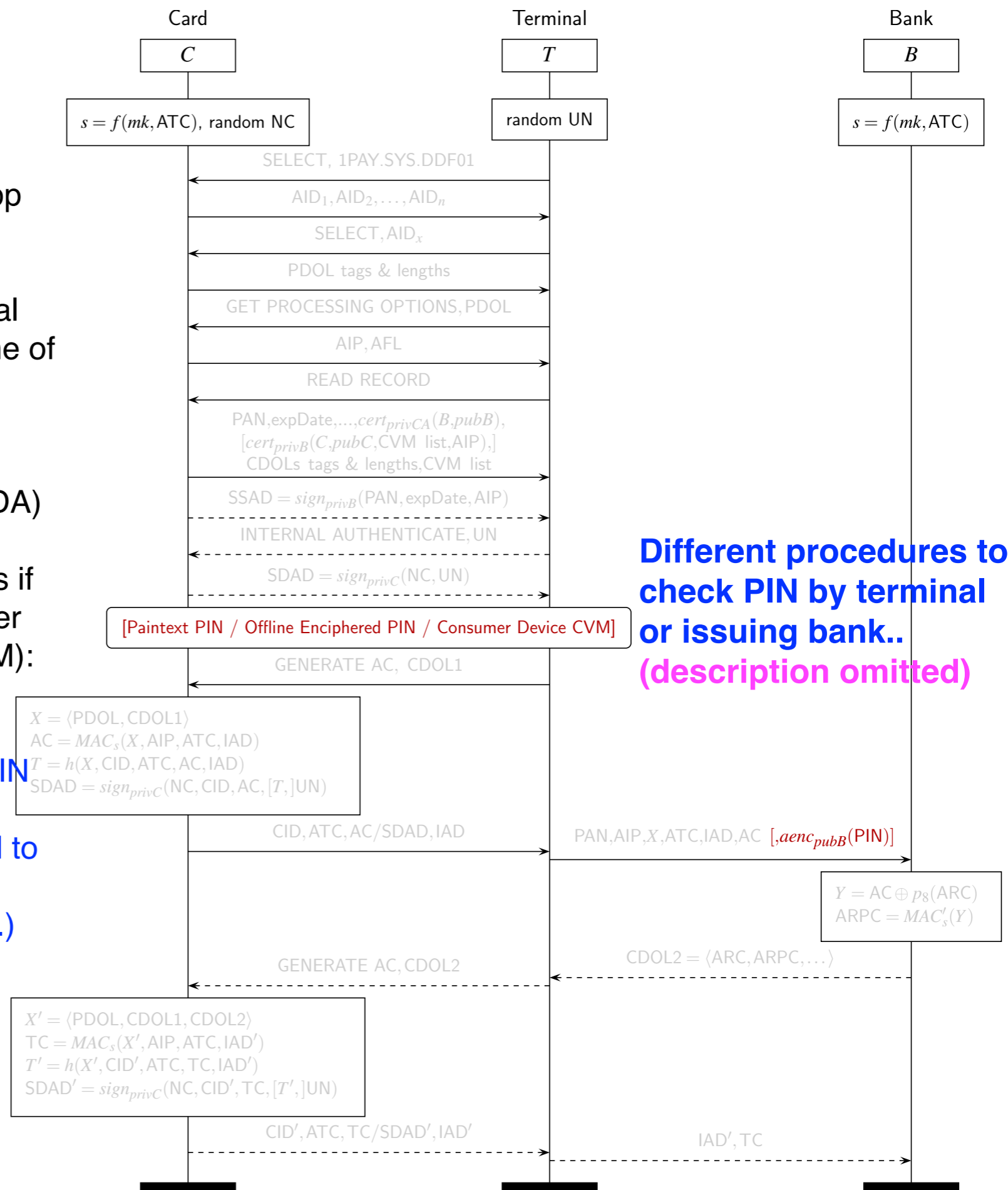**Standard now is CDA: includes nonces and other transaction details like purchase amount**

Card
C

Terminal
T

Bank
B

$s = f(mk, \text{ATC}), \text{random NC}$

random UN

$s = f(mk, \text{ATC})$

SELECT, 1PAY.SYS.DDF01

$AID_1, AID_2, \ldots, AID_n$

SELECT, AID_x

PDOL tags & lengths

GET PROCESSING OPTIONS, PDOL

AIP, AFL

READ RECORD

PAN, expDate, ..., $cert_{privCA}(B, pubB)$,
$[cert_{privB}(C, pubC, \text{CVM list}, \text{AIP}),]$
CDOLs tags & lengths, CVM list

$SSAD = sign_{privB}(\text{PAN}, \text{expDate}, \text{AIP})$

INTERNAL AUTHENTICATE, UN

$SDAD = sign_{privC}(\text{NC}, \text{UN})$

[Plaintext PIN / Offline Enciphered PIN / Consumer Device CVM]

GENERATE AC, CDOL1

$X = \langle \text{PDOL}, \text{CDOL1} \rangle$
$AC = MAC_s(X, \text{AIP}, \text{ATC}, \text{IAD})$
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$SDAD = sign_{privC}(\text{NC}, \text{CID}, \text{AC}, [T,] \text{UN})$

CID, ATC, AC/SDAD, IAD

PAN, AIP, X, ATC, IAD, AC $[, aenc_{pubB}(\text{PIN})]$

$Y = AC \oplus p_8(\text{ARC})$
$ARPC = MAC'_s(Y)$

GENERATE AC, CDOL2

$CDOL2 = \langle \text{ARC}, \text{ARPC}, \ldots \rangle$

$X' = \langle \text{PDOL}, \text{CDOL1}, \text{CDOL2} \rangle$
$TC = MAC_s(X', \text{AIP}, \text{ATC}, \text{IAD}')$
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CID', ATC, TC/SDAD', IAD'

IAD', TC

Acronym Zoo:
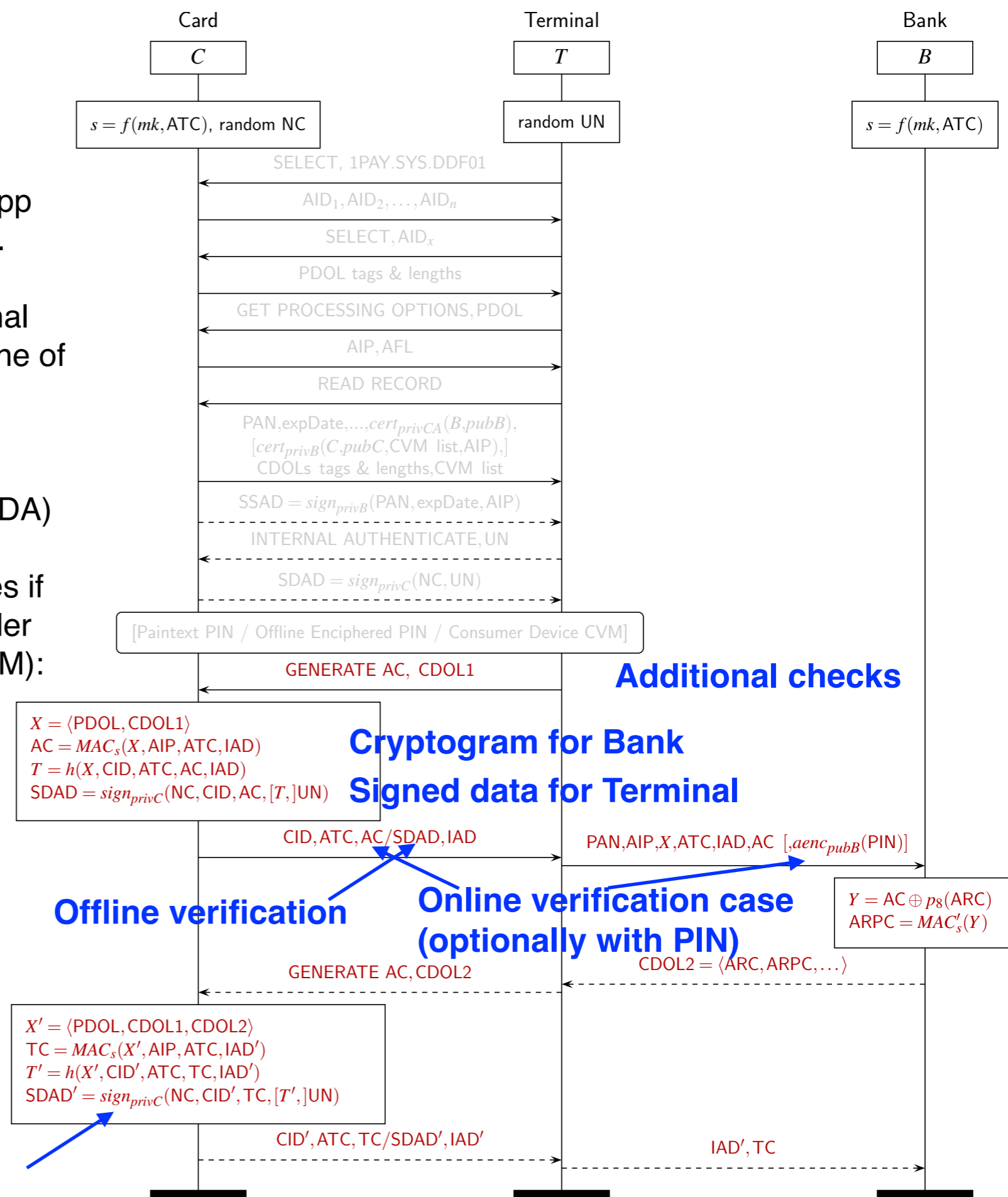**SDAD = Signed Dynamic Authentication Data**

EMV Protocol

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   - Static Data Authentication (SDA)
   - Dynamic Data Authentication (DDA)
   - Combined Dynamic Data Authentication (CDA)

3. **Cardholder Verification:** terminal determines if person presenting card is legitimate cardholder using a Cardholder Verification Methods (CVM):
   - Signature / No PIN / No CVM
   - Plaintext PIN (terminal sends PIN to card)
   - Offline Enciphered PIN (terminal encrypts PIN and sends to card)
   - Online PIN (PIN sent encrypted to issuing bank)
   - Customer Device CVM (mobile phone auth.)

Card

C

$s = f(mk, \mathrm{ATC}),\ \mathrm{random\ NC}$

Terminal

T

random UN

Bank

B

$s = f(mk, \mathrm{ATC})$

SELECT, 1PAY.SYS.DDF01

$\mathrm{AID}_1, \mathrm{AID}_2, \ldots, \mathrm{AID}_n$

SELECT, AID_x

PDOL tags & lengths

GET PROCESSING OPTIONS, PDOL

AIP, AFL

READ RECORD

$\mathrm{PAN}, \mathrm{expDate}, \ldots, \mathrm{cert}_{privCA}(B, pubB),$
$[\mathrm{cert}_{privB}(C, pubC, \mathrm{CVM\ list}, \mathrm{AIP}),]$
$\mathrm{CDOLs\ tags\ \&\ lengths}, \mathrm{CVM\ list}$

$\mathrm{SSAD} = sign_{privB}(\mathrm{PAN}, \mathrm{expDate}, \mathrm{AIP})$

INTERNAL AUTHENTICATE, UN

$\mathrm{SDAD} = sign_{privC}(\mathrm{NC}, \mathrm{UN})$

[Plaintext PIN / Offline Enciphered PIN / Consumer Device CVM]

Different procedures to check PIN by terminal or issuing bank.. (description omitted)

GENERATE AC, CDOL1

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$\mathrm{SDAD} = sign_{privC}(\mathrm{NC}, \mathrm{CID}, \mathrm{AC}, [T,]\mathrm{UN})$

$\mathrm{CID}, \mathrm{ATC}, \mathrm{AC}/\mathrm{SDAD}, \mathrm{IAD}$

$\mathrm{PAN}, \mathrm{AIP}, X, \mathrm{ATC}, \mathrm{IAD}, \mathrm{AC}\ [, aenc_{pubB}(\mathrm{PIN})]$

$Y = \mathrm{AC} \oplus p_8(\mathrm{ARC})$
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GENERATE AC, CDOL2

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$\mathrm{CID}', \mathrm{ATC}, \mathrm{TC}/\mathrm{SDAD}', \mathrm{IAD}'$

$\mathrm{IAD}', \mathrm{TC}$

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   - Plaintext PIN
   - Offline Enciphered PIN
   - Online PIN
   - Customer Device CVM

4. Transaction Authorization (TA): result is:
   - Declined offline
   - Accepted offline (typically low value)
   - Authorized online by issuer bank

This 2nd phase is for contact, where card authenticates bank and updates its state

Card — C

Terminal — T

Bank — B

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random UN

$s = f(mk, \text{ATC})$

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[Plaintext PIN / Offline Enciphered PIN / Consumer Device CVM]

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Additional checks

Cryptogram for Bank

Signed data for Terminal

CID, ATC, AC/SDAD, IAD

PAN, AIP, X, ATC, IAD, AC $[, aenc_{pubB}(\text{PIN})]$

$Y = \text{AC} \oplus p_8(\text{ARC})$
$ARPC = MAC'_s(Y)$

Offline verification

Online verification case (optionally with PIN)

GENERATE AC, CDOL2

$CDOL2 = \langle \text{ARC}, \text{ARPC}, \ldots \rangle$

$X' = \langle \text{PDOL}, \text{CDOL1}, \text{CDOL2} \rangle$
$TC = MAC_s(X', \text{AIP}, \text{ATC}, \text{IAD}')$
$T' = h(X', \text{CID}', \text{ATC}, \text{TC}, \text{IAD}')$
$SDAD' = sign_{privC}(\text{NC}, \text{CID}', \text{TC}, [T',]\text{UN})$

CID', ATC, TC/SDAD', IAD'

IAD', TC

Main Properties Considered

1. **The bank accepts** transactions *t* accepted by the terminal

```
lemma bank_accepts:
  "All t #i.
    TerminalAccepts(t)@i
  ==>
    not (Ex #j. BankDeclines(t)@j) |
    Ex A #k. Honest(A)@i & Compromise(A)@k"
```

In Tamarin, protocol modeled as a labelled transition system giving rise to a (possibly infinite) set of traces.   Following trace would violate this property

…. BankDeclines(23581) … TerminalAccepts(23581) …

TerminalAccepts(t) iff Terminal satisfied with transaction.
BankDeclines(t) iff Bank receives authorization request with wrong cryptogram

Main Properties Considered

2. Transactions are **authenticated to the terminal** by the card and the bank

```
lemma auth_to_terminal: //injective agreement, r will be 'Card' or 'Bank'
  "All T P r t #i.
    Commit(T, P, <r, 'Terminal', t>)@i
  ==>
    ((Ex #j. Running(P, T, <r, 'Terminal', t>)@j & j < i) &
      not (Ex T2 P2 #i2. Commit(T2, P2, <r, 'Terminal', t>)@i2 & not(#i2 = #i))
    ) |
    Ex A #k. Honest(A)@i & Compromise(A)@k"
```

Whenever terminal *T Commits* to a transaction *t* with communication parter *P*, then either *P* in the role *r* ∈ {'card', 'Bank'} was previously *Running* the protocol with *T* and they agree on *t*, or an agent presumed honest was compromised. (Also there is a *unique Commit* for each pair of accepting transaction and accepting agent, so replay attacks are prevented. **)**

3. Transactions are **authenticated to the bank** by the card and the terminal. Property same as (2), but **'Terminal'** is now **'Bank'**.

Results for EMV Contact Protocol

Target Model	executable	bank accepts	auth. to terminal	auth. to bank
Contact_SDA_PlainPIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_PlainPIN_Offline	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_OnlinePIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_OnlinePIN_Offline	−	−	−	−
Contact_SDA_NoPIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_NoPIN_Offline	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_EncPIN_Online	−	−	−	−
Contact_SDA_EncPIN_Offline	−	−	−	−
Contact_DDA_PlainPIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_DDA_PlainPIN_Offline	✓	✗[2]	✗[1,2]	✗[1]
Contact_DDA_OnlinePIN_Online	✓	✗[2]	✗[2]	✓
Contact_DDA_OnlinePIN_Offline	−	−	−	−
Contact_DDA_NoPIN_Online	✓	✗[2]	✗[2]	✓
Contact_DDA_NoPIN_Offline	✓	✗[2]	✗[2]	✓
Contact_DDA_EncPIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_DDA_EncPIN_Offline	✓	✗[2]	✗[1,2]	✗[1]
Contact_CDA_PlainPIN_Online	✓	✓	✗[1]	✗[1]
Contact_CDA_PlainPIN_Offline	✓	✓	✗[1]	✗[1]
Contact_CDA_OnlinePIN_Online	✓	✓	✓	✓
Contact_CDA_OnlinePIN_Offline	−	−	−	−
Contact_CDA_NoPIN_Online	✓	✓	✓	✓
Contact_CDA_NoPIN_Offline	✓	✓	✓	✓
Contact_CDA_EncPIN_Online	✓	✓	✗[1]	✗[1]
Contact_CDA_EncPIN_Offline	✓	✓	✗[1]	✗[1]

Legend:
✓: property verified   ✗: property falsified   −: not applicable
(1): disagrees with card on CVM   (2): disagrees with card on last AC
bold: satisfies all 4 properties

- Only transactions using the **CDA** authentication method and **Online PIN** or **No PIN** as CVM are **secure**

- Transactions using **Plaintext PIN** or **Offline Enciphered PIN** as CVM admit the PIN bypass of [Murdoch et al., S&P 2010]

- Transactions using the **SDA** or **DDA** authentication methods admit an attack where the terminal accepts them but the bank declines them

- We also found other issues related to secrecy

- In general, weaponizing these issues in practice is challenging as one would need control of the contact chip channel

Decomposed analysis: contact(less), and methods for data authentication and cardholder verification

Results for EMV Contact Protocol

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Contact_SDA_NoPIN_Online	✓	✗(2)	✗(1,2)	✗(1)
Contact_SDA_NoPIN_Offline	✓	✗(2)	✗(1,2)	✗(1)
Contact_SDA_EncPIN_Online	–	–	–	–
Contact_SDA_EncPIN_Offline	–	–	–	–
Contact_DDA_PlainPIN_Online	✓	✗(2)	✗(1,2)	✗(1)
Contact_DDA_PlainPIN_Offline	✓	✗(2)	✗(1,2)	✗(1)
Contact_DDA_OnlinePIN_Online	✓	✗(2)	✗(2)	✓
Contact_DDA_OnlinePIN_Offline	–	–	–	–
Contact_DDA_NoPIN_Online	✓	✗(2)	✗(2)	✓
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Contact_CDA_OnlinePIN_Online	✓	✓	✓	✓
Contact_CDA_OnlinePIN_Offline	–	–	–	–
Contact_CDA_NoPIN_Online	✓	✓	✓	✓
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Contact_DDA_OnlinePIN_Online	✓	✗[2]	✗[2]	✓
Contact_DDA_OnlinePIN_Offline	–	–	–	–
Contact_DDA_NoPIN_Online	✓	✗[2]	✗[2]	✓
Contact_DDA_NoPIN_Offline	✓	✗[2]	✗[2]	✓
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Contact_CDA_PlainPIN_Offline	✓	✓	✗[1]	✗[1]
Contact_CDA_OnlinePIN_Online	✓	✓	✓	✓
Contact_CDA_OnlinePIN_Offline	–	–	–	–
Contact_CDA_NoPIN_Online	✓	✓	✓	✓
Contact_CDA_NoPIN_Offline	✓	✓	✓	✓
Contact_CDA_EncPIN_Online	✓	✓	✗[1]	✗[1]
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Attack: fake the Card's response, which is not authenticated

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Contact_DDA_OnlinePIN_Offline	–	–	–	–
Contact_DDA_NoPIN_Online	✓	✗ [2]	✗ [2]	✓
Contact_DDA_NoPIN_Offline	✓	✗ [2]	✗ [2]	✓
Contact_DDA_EncPIN_Online	✓	✗ [2]	✗ [1,2]	✗ [1]
Contact_DDA_EncPIN_Offline	✓	✗ [2]	✗ [1,2]	✗ [1]
Contact_CDA_PlainPIN_Online	✓	✓	✗ [1]	✗ [1]
Contact_CDA_PlainPIN_Offline	✓	✓	✗ [1]	✗ [1]
Contact_CDA_OnlinePIN_Online	✓	✓	✓	✓
Contact_CDA_OnlinePIN_Offline	–	–	–	–
Contact_CDA_NoPIN_Online	✓	✓	✓	✓
Contact_CDA_NoPIN_Offline	✓	✓	✓	✓
Contact_CDA_EncPIN_Online	✓	✓	✗ [1]	✗ [1]
Contact_CDA_EncPIN_Offline	✓	✓	✗ [1]	✗ [1]

Legend:
✓ : property verified   ✗ : property falsified   – : not applicable
(1): disagrees with card on CVM   (2): disagrees with card on last AC
bold: satisfies all 4 properties

- Only transactions using the **CDA** authentication method and **Online PIN** or **No PIN** as CVM are secure

- Transactions using **Plaintext PIN** or **Offline Enciphered PIN** as CVM admit the PIN bypass of [Murdoch et al., S&P 2010]

- **Transactions using the SDA or DDA authentication methods admit an attack where the terminal accepts them but the bank declines them**

- We also found other issues related to secrecy

- In general, weaponizing these issues in practice is challenging as one would need control of the contact chip channel

Attack: transaction cryptogram modified, which goes undetected by terminal and is only later detected by bank

Results for EMV Contact Protocol

Target Model	executable	bank accepts	auth. to terminal	auth. to bank
Contact_SDA_PlainPIN_Online	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_SDA_PlainPIN_Offline	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_SDA_OnlinePIN_Online	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_SDA_OnlinePIN_Offline	–	–	–	–
Contact_SDA_NoPIN_Online	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_SDA_NoPIN_Offline	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_SDA_EncPIN_Online	–	–	–	–
Contact_SDA_EncPIN_Offline	–	–	–	–
Contact_DDA_PlainPIN_Online	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_DDA_PlainPIN_Offline	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_DDA_OnlinePIN_Online	✓	✗ (2)	✗ (2)	✓
Contact_DDA_OnlinePIN_Offline	–	–	–	–
Contact_DDA_NoPIN_Online	✓	✗ (2)	✗ (2)	✓
Contact_DDA_NoPIN_Offline	✓	✗ (2)	✗ (2)	✓
Contact_DDA_EncPIN_Online	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_DDA_EncPIN_Offline	✓	✗ (2)	✗ (1,2)	✗ (1)
Contact_CDA_PlainPIN_Online	✓	✓	✗ (1)	✗ (1)
Contact_CDA_PlainPIN_Offline	✓	✓	✗ (1)	✗ (1)
Contact_CDA_OnlinePIN_Online	✓	✓	✓	✓
Contact_CDA_OnlinePIN_Offline	–	–	–	–
Contact_CDA_NoPIN_Online	✓	✓	✓	✓
Contact_CDA_NoPIN_Offline	✓	✓	✓	✓
Contact_CDA_EncPIN_Online	✓	✓	✗ (1)	✗ (1)
Contact_CDA_EncPIN_Offline	✓	✓	✗ (1)	✗ (1)

Legend:
✓: property verified   ✗: property falsified   –: not applicable
(1): disagrees with card on CVM   (2): disagrees with card on last AC
bold: satisfies all 4 properties

- Only transactions using the **CDA** authentication method and **Online PIN** or **No PIN** as CVM are **secure**

- Transactions using **Plaintext PIN** or **Offline Enciphered PIN** as CVM admit the PIN bypass of [Murdoch et al., S&P 2010]

- Transactions using the **SDA** or **DDA** authentication methods admit an attack where the terminal accepts them but the bank declines them

- We also found other issues related to secrecy

- In general, weaponizing these issues in practice is challenging as one would need control of the contact chip channel

Attack: downgrade to plain PIN verification, and read PIN via MITM

Results for EMV Contact Protocol

Target Model	executable	bank accepts	auth. to terminal	auth. to bank
Contact_SDA_PlainPIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_PlainPIN_Offline	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_OnlinePIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_OnlinePIN_Offline	–	–	–	–
Contact_SDA_NoPIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_NoPIN_Offline	✓	✗[2]	✗[1,2]	✗[1]
Contact_SDA_EncPIN_Online	–	–	–	–
Contact_SDA_EncPIN_Offline	–	–	–	–
Contact_DDA_PlainPIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_DDA_PlainPIN_Offline	✓	✗[2]	✗[1,2]	✗[1]
Contact_DDA_OnlinePIN_Online	✓	✗[2]	✗[2]	✓
Contact_DDA_OnlinePIN_Offline	–	–	–	–
Contact_DDA_NoPIN_Online	✓	✗[2]	✗[2]	✓
Contact_DDA_NoPIN_Offline	✓	✗[2]	✗[2]	✓
Contact_DDA_EncPIN_Online	✓	✗[2]	✗[1,2]	✗[1]
Contact_DDA_EncPIN_Offline	✓	✗[2]	✗[1,2]	✗[1]
Contact_CDA_PlainPIN_Online	✓	✓	✗[1]	✗[1]
Contact_CDA_PlainPIN_Offline	✓	✓	✗[1]	✗[1]
Contact_CDA_OnlinePIN_Online	✓	✓	✓	✓
Contact_CDA_OnlinePIN_Offline	–	–	–	–
Contact_CDA_NoPIN_Online	✓	✓	✓	✓
Contact_CDA_NoPIN_Offline	✓	✓	✓	✓
Contact_CDA_EncPIN_Online	✓	✓	✗[1]	✗[1]
Contact_CDA_EncPIN_Offline	✓	✓	✗[1]	✗[1]

Legend:
✓: property verified   ✗: property falsified   –: not applicable
(1): disagrees with card on CVM   (2): disagrees with card on last AC
bold: satisfies all 4 properties

- Only transactions using the **CDA** authentication method and **Online PIN** or **No PIN** as CVM are **secure**

- Transactions using **Plaintext PIN** or **Offline Enciphered PIN** as CVM admit the PIN bypass of [Murdoch et al., S&P 2010]

- Transactions using the **SDA** or **DDA** authentication methods admit an attack where the terminal accepts them but the bank declines them

- We also found other issues related to secrecy

- In general, weaponizing these issues in practice is challenging as one would need control of the contact chip channel

Results for EMV Contactless Protocol

Target Model	exec.	bank accepts	auth. to terminal	auth. to bank
Visa_EMV_Low	✓	✓	✗[1]	✗[1]
Visa_EMV_High	✓	✓	✗[1]	✗[1]
Visa_DDA_Low	✓	✗[2]	✗[2]	✓
Visa_DDA_High	✓	✓	✓	✓
Mastercard_SDA_OnlinePIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_SDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_SDA_NoPIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_SDA_NoPIN_High	–[3]	–	–	–
Mastercard_DDA_OnlinePIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_DDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_DDA_NoPIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_DDA_NoPIN_High	–[3]	–	–	–
Mastercard_CDA_OnlinePIN_Low	✓	✓	✓	✓
Mastercard_CDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_CDA_NoPIN_Low	✓	✓	✓	✓
Mastercard_CDA_NoPIN_High	–[3]	–	–	–

Legend:

✓: property verified   ✗: property falsified   –: not applicable

(1): disagrees with card on CVM   (2): disagrees with card on AC

(3): high-value transactions without CVM are not completed contactless

bold: satisfies all 4 properties

- Most common Mastercard transactions are **secure**

- Most common Visa transactions are **not secure**

Results for EMV Contactless Protocol

Target Model	exec.	bank accepts	auth. to terminal	auth. to bank
Visa_EMV_Low	✓	✓	✗[1]	✗[1]
Visa_EMV_High	✓	✓	✗[1]	✗[1]
Visa_DDA_Low	✓	✗[2]	✗[2]	✓
Visa_DDA_High	✓	✓	✓	✓
Mastercard_SDA_OnlinePIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_SDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_SDA_NoPIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_SDA_NoPIN_High	–[3]	–	–	–
Mastercard_DDA_OnlinePIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_DDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_DDA_NoPIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_DDA_NoPIN_High	–[3]	–	–	–
Mastercard_CDA_OnlinePIN_Low	✓	✓	✓	✓
Mastercard_CDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_CDA_NoPIN_Low	✓	✓	✓	✓
Mastercard_CDA_NoPIN_High	–[3]	–	–	–

Legend:

✓: property verified   ✗: property falsified   –: not applicable

(1): disagrees with card on CVM   (2): disagrees with card on AC

(3): high-value transactions without CVM are not completed contactless

bold: satisfies all 4 properties

- Most common Mastercard transactions are **secure**

- Most common Visa transactions are **not secure**

**Recall: CDA is what is commonly used in practice
(We return to this result for Mastercard later!)**

Results for EMV Contactless Protocol

Target Model	exec.	bank accepts	auth. to terminal	auth. to bank
Visa_EMV_Low	✓	✓	✗ [1]	✗ [1]
Visa_EMV_High	✓	✓	✗ [1]	✗ [1]
Visa_DDA_Low	✓	✗ [2]	✗ [2]	✓
Visa_DDA_High	✓	✓	✓	✓
Mastercard_SDA_OnlinePIN_Low	✓	✗ [2]	✗ [2]	✓
Mastercard_SDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_SDA_NoPIN_Low	✓	✗ [2]	✗ [2]	✓
Mastercard_SDA_NoPIN_High	– [3]	–	–	–
Mastercard_DDA_OnlinePIN_Low	✓	✗ [2]	✗ [2]	✓
Mastercard_DDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_DDA_NoPIN_Low	✓	✗ [2]	✗ [2]	✓
Mastercard_DDA_NoPIN_High	– [3]	–	–	–
Mastercard_CDA_OnlinePIN_Low	✓	✓	✓	✓
Mastercard_CDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_CDA_NoPIN_Low	✓	✓	✓	✓
Mastercard_CDA_NoPIN_High	– [3]	–	–	–

Legend:

✓: property verified   ✗: property falsified   –: not applicable

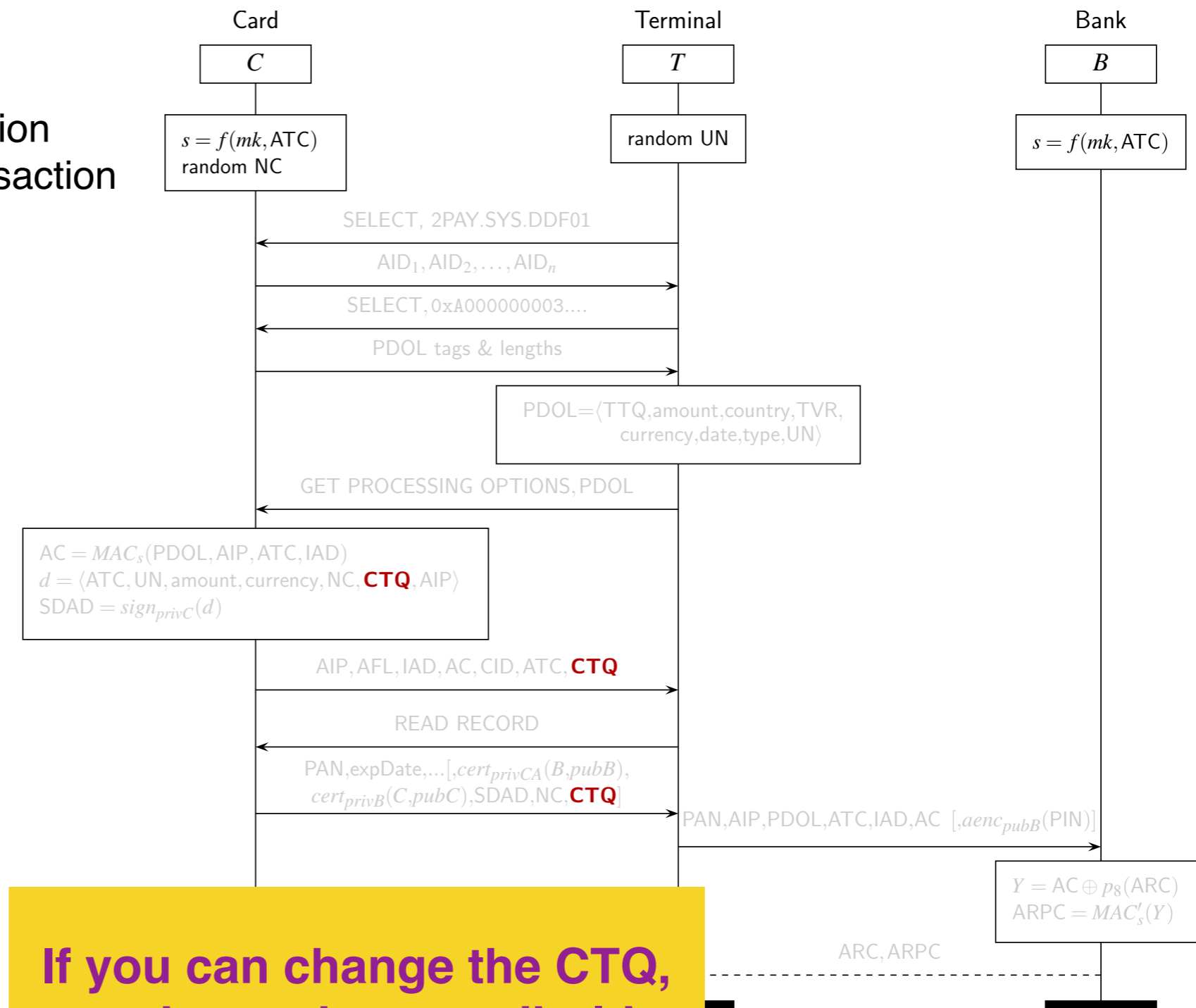(1): disagrees with card on CVM   (2): disagrees with card on AC

(3): high-value transactions without CVM are not completed contactless

bold: satisfies all 4 properties

- Most common Mastercard transactions are secure

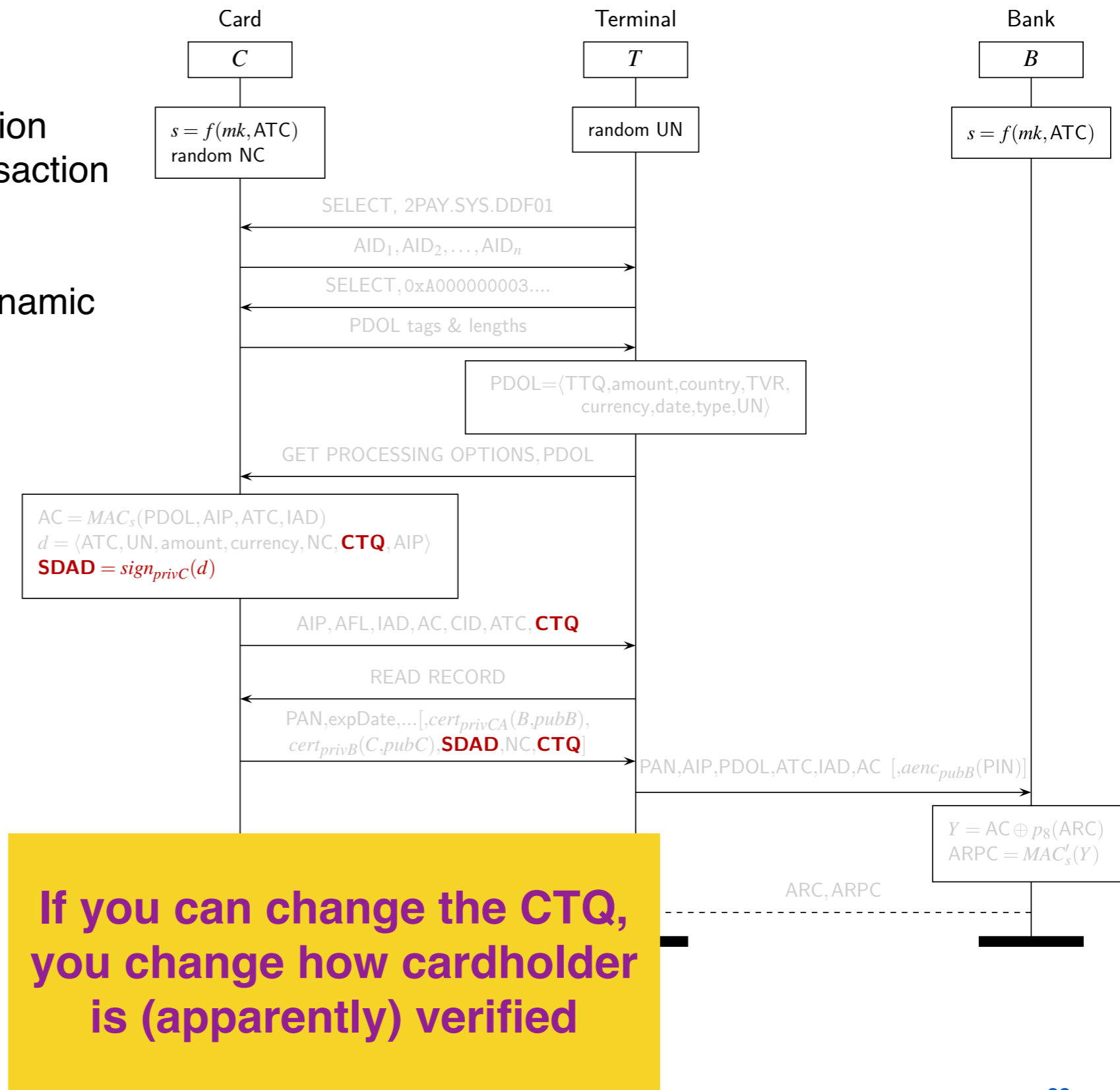- Most common Visa transactions are **not secure**

Problem with Visa Contactless

- Card's choice for Cardholder Verification Method (CVM) encoded in Card Transaction Qualifiers (CTQ)

Card

C

$s = f(mk, \text{ATC})$
random NC

Terminal

T

random UN

Bank

B

$s = f(mk, \text{ATC})$

SELECT, 2PAY.SYS.DDF01

$\text{AID}_1, \text{AID}_2, \ldots, \text{AID}_n$

SELECT, 0xA000000003....

PDOL tags & lengths

$\text{PDOL} = \langle \text{TTQ}, \text{amount}, \text{country}, \text{TVR}, \text{currency}, \text{date}, \text{type}, \text{UN} \rangle$

GET PROCESSING OPTIONS, PDOL

$\text{AC} = MAC_s(\text{PDOL}, \text{AIP}, \text{ATC}, \text{IAD})$
$d = \langle \text{ATC}, \text{UN}, \text{amount}, \text{currency}, \text{NC}, \textbf{CTQ}, \text{AIP} \rangle$
$\text{SDAD} = sign_{privC}(d)$

$\text{AIP}, \text{AFL}, \text{IAD}, \text{AC}, \text{CID}, \text{ATC}, \textbf{CTQ}$

READ RECORD

$\text{PAN}, \text{expDate}, \ldots [, cert_{privCA}(B, pubB),$
$cert_{privB}(C, pubC), \text{SDAD}, \text{NC}, \textbf{CTQ}]$

$\text{PAN}, \text{AIP}, \text{PDOL}, \text{ATC}, \text{IAD}, \text{AC} \ [, aenc_{pubB}(\text{PIN})]$

$Y = \text{AC} \oplus p_8(\text{ARC})$
$\text{ARPC} = MAC'_s(Y)$

ARC, ARPC

If you can change the CTQ, you change how cardholder is (apparently) verified
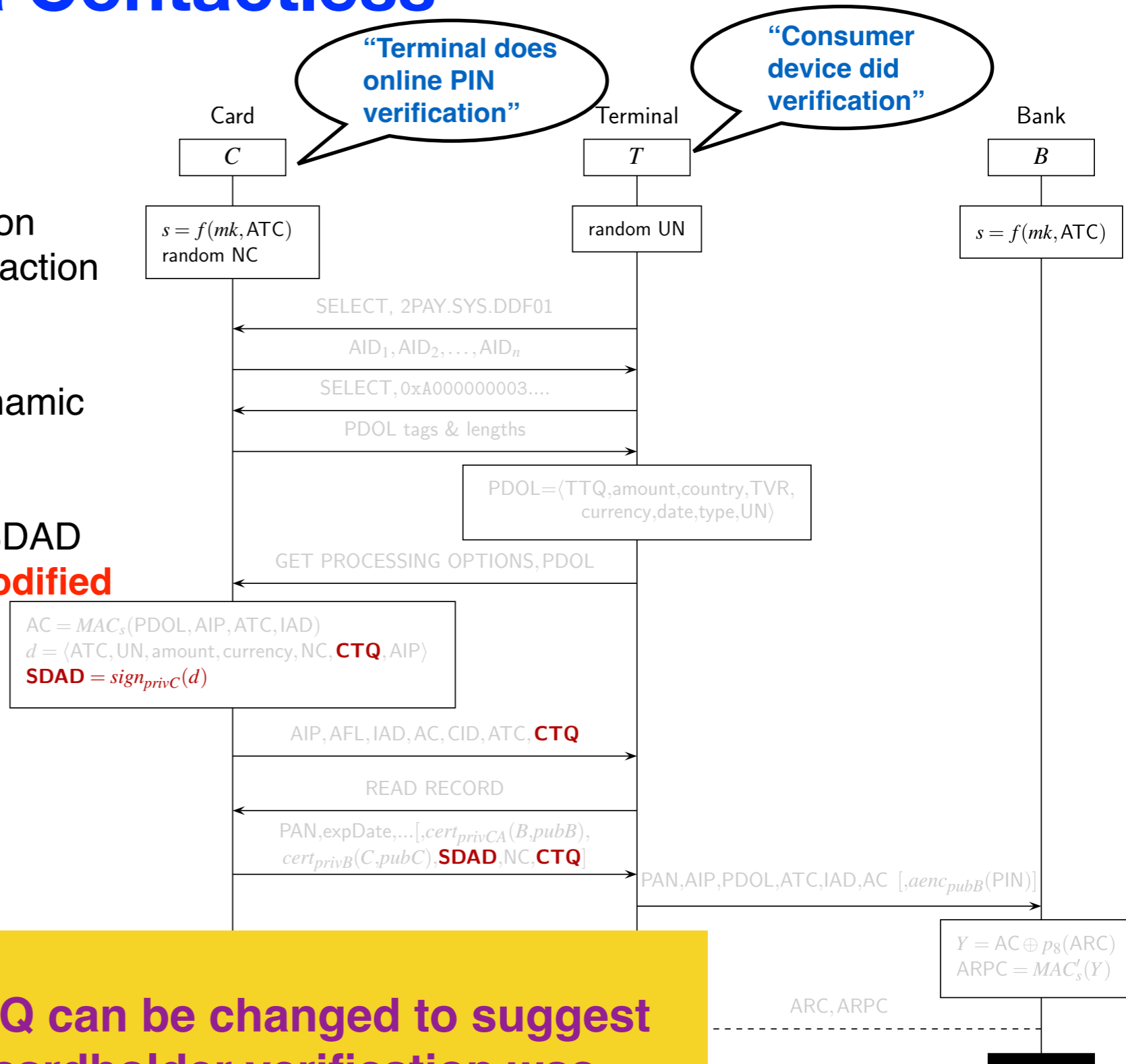
Problem with Visa Contactless

- Card's choice for Cardholder Verification Method (CVM) encoded in Card Transaction Qualifiers (CTQ)

- CTQ authenticated via the Signed Dynamic Authentication Data (SDAD)

Card — C

Terminal — T

Bank — B

$s = f(mk, \text{ATC})$
random NC

random UN

$s = f(mk, \text{ATC})$

SELECT, 2PAY.SYS.DDF01

$\text{AID}_1, \text{AID}_2, \ldots, \text{AID}_n$

SELECT, 0xA000000003....

PDOL tags & lengths

$\text{PDOL} = \langle \text{TTQ}, \text{amount}, \text{country}, \text{TVR}, \text{currency}, \text{date}, \text{type}, \text{UN} \rangle$

GET PROCESSING OPTIONS, PDOL

$\text{AC} = MAC_s(\text{PDOL}, \text{AIP}, \text{ATC}, \text{IAD})$
$d = \langle \text{ATC}, \text{UN}, \text{amount}, \text{currency}, \text{NC}, \textbf{CTQ}, \text{AIP} \rangle$
$\textbf{SDAD} = sign_{privC}(d)$

$\text{AIP}, \text{AFL}, \text{IAD}, \text{AC}, \text{CID}, \text{ATC}, \textbf{CTQ}$

READ RECORD

$\text{PAN}, \text{expDate}, \ldots [, cert_{privCA}(B, pubB), cert_{privB}(C, pubC), \textbf{SDAD}, \text{NC}, \textbf{CTQ}]$

$\text{PAN}, \text{AIP}, \text{PDOL}, \text{ATC}, \text{IAD}, \text{AC} \ [, aenc_{pubB}(\text{PIN})]$

$Y = \text{AC} \oplus p_8(\text{ARC})$
$\text{ARPC} = MAC'_s(Y)$

ARC, ARPC

If you can change the CTQ, you change how cardholder is (apparently) verified

Problem with Visa Contactless

"Terminal does online PIN verification"

"Consumer device did verification"

Card C

Terminal T

Bank B

- Card's choice for Cardholder Verification Method (CVM) encoded in Card Transaction Qualifiers (CTQ)

- CTQ authenticated via the Signed Dynamic Authentication Data (SDAD)

- Most Visa transactions don't use the SDAD ⇒ CTQ and therefore **CVM can be modified**

$s = f(mk, \text{ATC})$
random NC

random UN

$s = f(mk, \text{ATC})$

SELECT, 2PAY.SYS.DDF01

$\text{AID}_1, \text{AID}_2, \ldots, \text{AID}_n$

SELECT, 0xA000000003....

PDOL tags & lengths

PDOL = ⟨TTQ, amount, country, TVR, currency, date, type, UN⟩

GET PROCESSING OPTIONS, PDOL

$AC = MAC_s(\text{PDOL, AIP, ATC, IAD})$
$d = \langle \text{ATC, UN, amount, currency, NC,} \textbf{CTQ}, \text{AIP} \rangle$
$\textbf{SDAD} = sign_{privC}(d)$

AIP, AFL, IAD, AC, CID, ATC, **CTQ**

READ RECORD

PAN, expDate, ... [, $cert_{privCA}(B, pubB)$, $cert_{privB}(C, pubC)$, **SDAD**, NC, **CTQ**]

PAN, AIP, PDOL, ATC, IAD, AC [, $aenc_{pubB}(\text{PIN})$]

$Y = AC \oplus p_8(\text{ARC})$
$ARPC = MAC'_s(Y)$

ARC, ARPC

CTQ can be changed to suggest cardholder verification was performed on the Consumer Device

23

Weaponizing PIN bypass Attack

Man-in-the-middle attack on top of a relay attack architecture

WiFi

WiFi

NFC

NFC

Card emulator

POS emulator
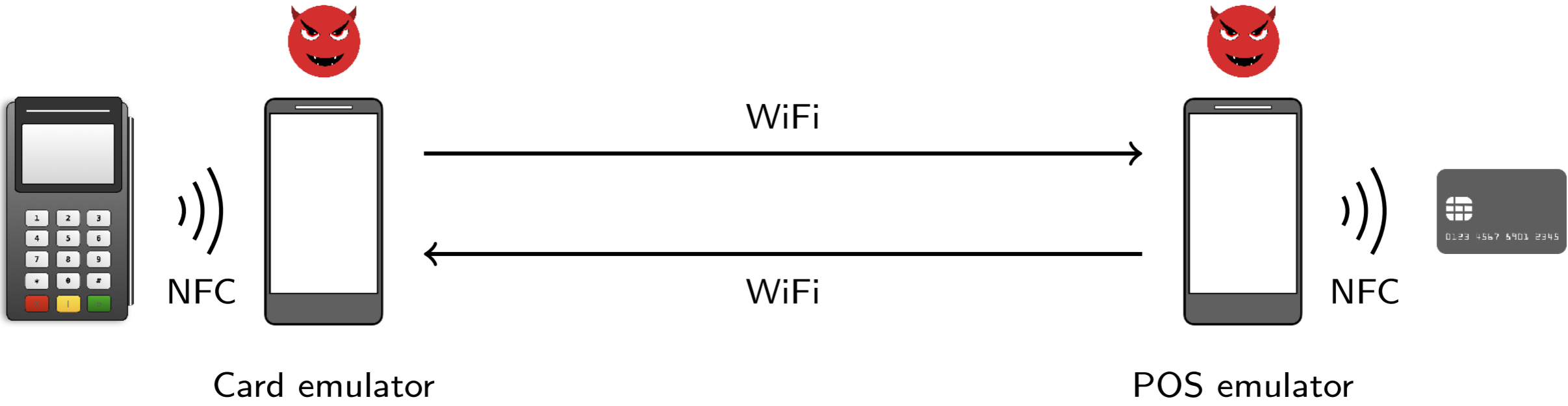
Weaponizing PIN bypass Attack

Man-in-the-middle attack on top of a relay attack architecture

(a) Terminal sends command indicating *Cardholder Verification* required

(b) Card sends response indicating *Online PIN required*

(c) Attacker changes Card Transaction Qualifier (CTQ) to 0x028 indicating that
Online PIN not required and Consumer Device CVM was performed

Card emulator

POS emulator

Media Coverage

Countermeasure to PIN Bypass

- **Recall the problem**: Most VISA transactions do not use the Signed Dynamic Authentication Data (SDAD), which is the only protection to the Card Transaction Qualifiers (CTQ)

- **Easy Fix:** always have the card supply the SDAD and the terminal verify it

- Having the card supply it is as easy as setting bit 1 of byte 1 of the Terminal Transaction Qualifiers (TTQ)

- Fixes can be deployed on terminals without reissuing cards!

Card — C Terminal — T Bank — B

$s = f(mk, \text{ATC})$
random NC

random UN

$s = f(mk, \text{ATC})$

SELECT, 2PAY.SYS.DDF01

$\text{AID}_1, \text{AID}_2, \ldots, \text{AID}_n$

SELECT, 0xA000000003....

PDOL tags & lengths

$\text{PDOL} = \langle \textbf{TTQ}, \text{amount}, \text{country}, \text{TVR}, \text{currency}, \text{date}, \text{type}, \text{UN} \rangle$

GET PROCESSING OPTIONS, PDOL

$\text{AC} = MAC_s(\text{PDOL}, \text{AIP}, \text{ATC}, \text{IAD})$
$d = \langle \text{ATC}, \text{UN}, \text{amount}, \text{currency}, \text{NC}, \textbf{CTQ}, \text{AIP} \rangle$
$\textbf{SDAD} = sign_{privC}(d)$

$\text{AIP}, \text{AFL}, \text{IAD}, \text{AC}, \text{CID}, \text{ATC}, \textbf{CTQ}$

READ RECORD

$\text{PAN}, \text{expDate}, \ldots [, cert_{privCA}(B, pubB),$
$cert_{privB}(C, pubC), \textbf{SDAD}, \text{NC}, \textbf{CTQ}]$

$\text{PAN}, \text{AIP}, \text{PDOL}, \text{ATC}, \text{IAD}, \text{AC} \; [, aenc_{pubB}(\text{PIN})]$

$Y = \text{AC} \oplus p_8(\text{ARC})$
$\text{ARPC} = MAC'_s(Y)$

ARC, ARPC

Other Issues found

Target Model	exec.	bank accepts	auth. to terminal	auth. to bank
Visa_EMV_Low	✓	✓	✗[1]	✗[1]
Visa_EMV_High	✓	✓	✗[1]	✗[1]
Visa_DDA_Low	✓	✗[2]	✗[2]	✓
Visa_DDA_High	✓	✓	✓	✓
Mastercard_SDA_OnlinePIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_SDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_SDA_NoPIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_SDA_NoPIN_High	–[3]	–	–	–
Mastercard_DDA_OnlinePIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_DDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_DDA_NoPIN_Low	✓	✗[2]	✗[2]	✓
Mastercard_DDA_NoPIN_High	–[3]	–	–	–
Mastercard_CDA_OnlinePIN_Low	✓	✓	✓	✓
Mastercard_CDA_OnlinePIN_High	✓	✓	✓	✓
Mastercard_CDA_NoPIN_Low	✓	✓	✓	✓
Mastercard_CDA_NoPIN_High	–[3]	–	–	–

Legend:

✓: property verified   ✗: property falsified   –: not applicable

(1): disagrees with card on CVM   (2): disagrees with card on AC

(3): high-value transactions without CVM are not completed contactless

bold: satisfies all 4 properties

- Low-value **offline** transactions with Visa or old Mastercard are **not secure**

- **Weaponize**: MITM fools terminal into accepting a transaction where bank declines, only after attacker is long gone

- Didn't test in the wild for ethical reasons

- **Fix**: Change the SDAD input to authenticate additional data, e.g., the AC (cryptogram) and its input. So changes detected by terminals.

- Requires reissuing cards!

Mastercard can be attacked too!

After previous work, we **enriched our model** to account for the fact that there are different **payment networks**.

Terminal → Acquirer → Payment Network → Card Issuer
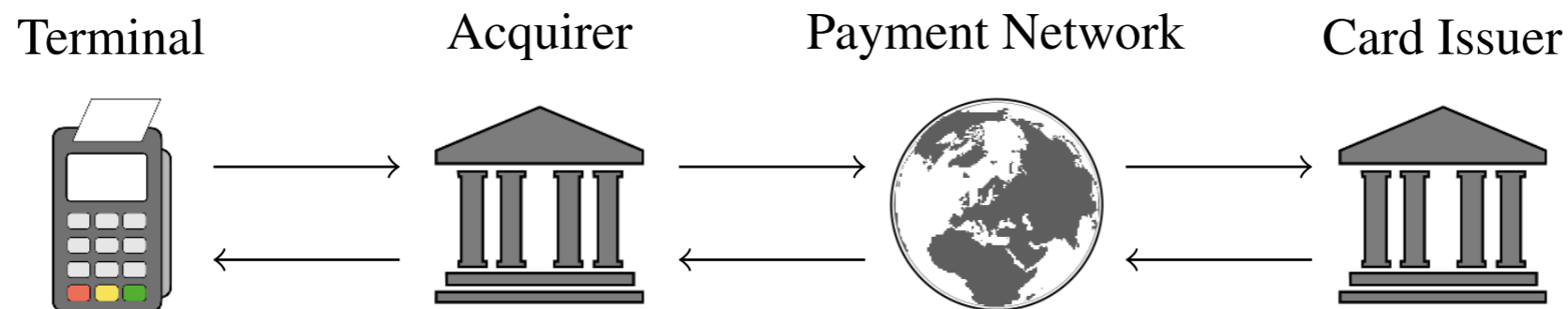
Attack idea: replace card's Application Identifiers (AIDs) with the Visa AID `A0000000031010` to deceive the terminal into activating the Visa kernel.

— Simultaneously perform a Visa transaction with the terminal and a Mastercard transaction with the card.

— For Visa transaction, apply previously described attack on Visa!

Current work: verification project with an EMV partner to analyze upcoming changes to standard.

Conclusions

Formal Methods matter!
- You can rob the bank with a theorem prover.

Tools sufficiently advanced that they can and should be used
- Good hygiene: be explicit about protocol, adversary, and properties

- Find errors or produce proofs

- Follow standardization efforts: check modifications for upcoming releases
  EMV not a standard but Tamarin is being used now as part of its development

Research challenges
- **COMPLEXITY, Complexity**, **complexity**

- Improving scope and accuracy

- Education: getting the message out and training engineers

References   (including background)

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