Breaking Credit Cards with Tamarin

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based on Slides by Jorge Toro
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Tamarin Prover Tutorial, Summerschool on real-world crypto and privacy, v.1
June 4, 2024

EMV standard

- EMV (or "Chip & PIN") is the protocol standard for **smartcard payment**
- Founded by **E**uropay, **M**astercard, and **V**isa, other payment networks joined too
- **12+ billion** EMV cards in circulation worldwide
- EMV was advertised to offer the highest **security**

EMV security

Primary goal: protect cardholders

Low-value purchases do not require a PIN

High-value purchases **should** be protected by PIN

Some images from https://pngtree.com/so/

EMV security

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We'll show that they are **not**

Images from: https://pngtree.com/so/extend-a-finger
https://pngtree.com/so/emoji-icons

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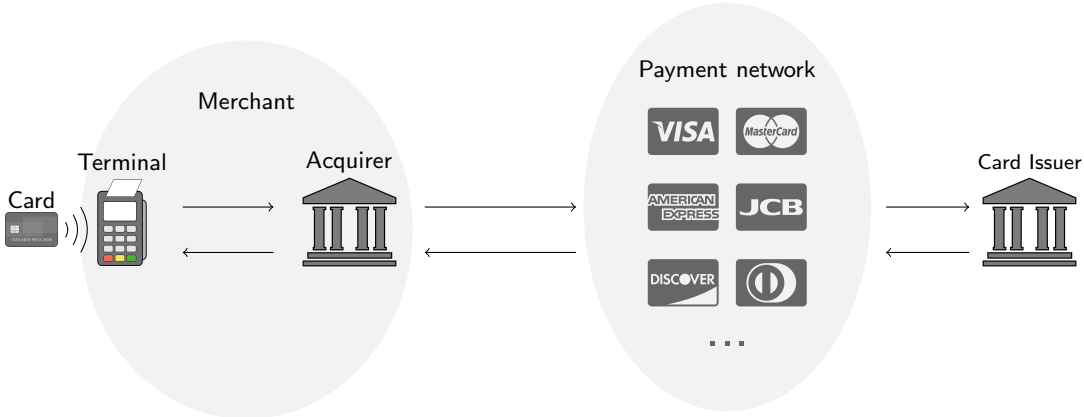
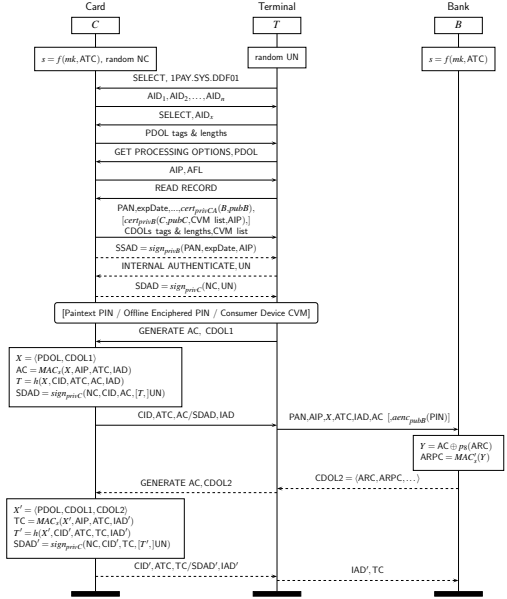
Involved parties

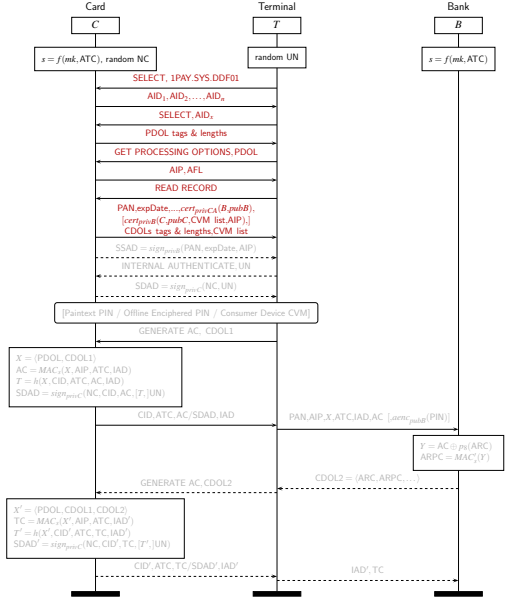


EMV protocol



EMV protocol

1. **Initialization**: card and terminal agree on application to use and exchange card and transaction data



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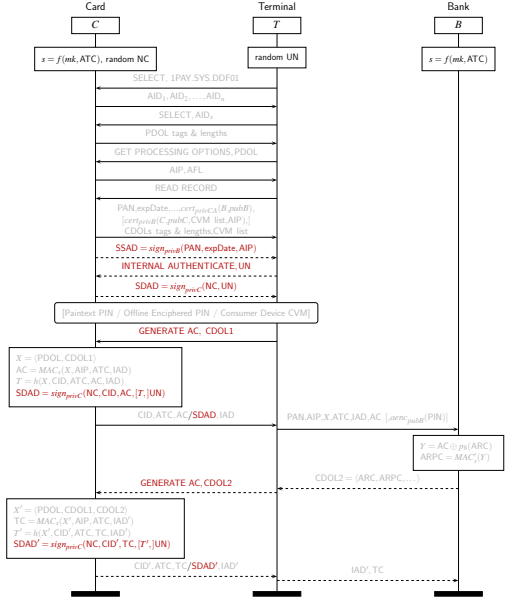
2. **Card Authenticates to the Terminal**: terminal performs a PKI-based validation of the card. Multiple methods exist.



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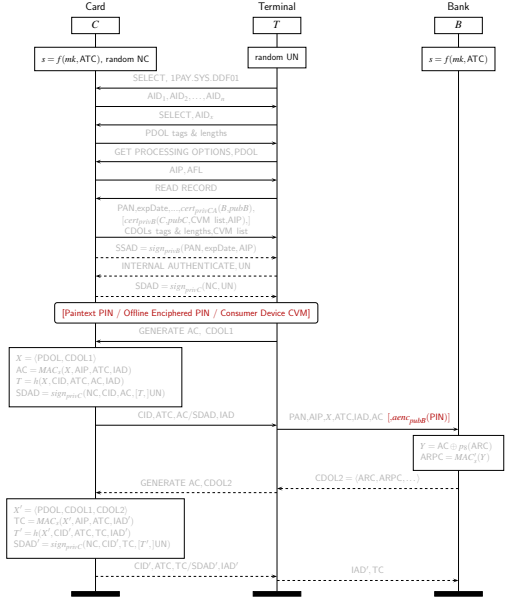
3. **Cardholder Verification**: terminal checks that person presenting the card is the legitimate cardholder. Four (digital) methods:
   - Signature
   - No CVM
   - Plaintext PIN
   - Offline Enciphered PIN
   - Online PIN
   - Consumer Device CVM



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   - Signature
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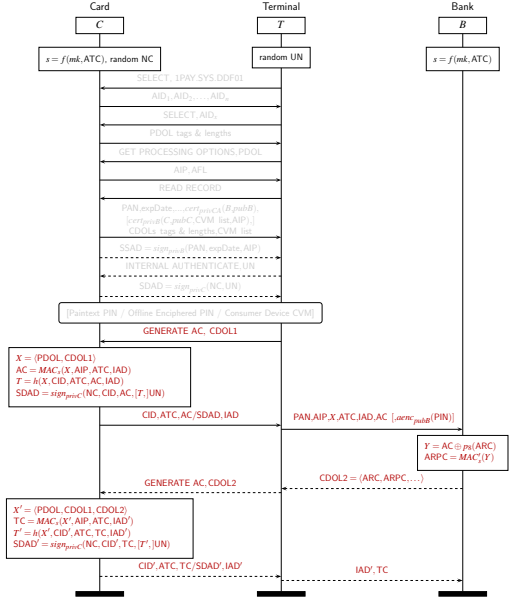
4. **Card Authenticates to the Bank**: The card generates an MAC for the card. The card and Bank share a symmetric key.



Break, Fix, Verify

- Developed first comprehensive model of EMV (Used Tamarin to analyze 2,000+ pages of paper specification)
- Found both known and new security issues
- Proposed and machine-checked fixes (disclosed to relevant vendors)

Modelling the configurations

- Different Kernels, configurations in one model:
  - Allow for different configurations in parallel
  - Using branching

Analysing Configurations seperately

- Generate one model for each configuration
- The lemmas analyze only one configuration: Configuration models differ in the action facts for the lemmas
- Results in 24 Models for Contact and 17 for contactless
- Analyze each lemma for each configuration model
- We can identify secure and vulnerable configurations

Security of EMV contactless

Target Model	exec.	bank accepts	auth. to terminal	auth. to bank
Visa_EMV_Low	✓	✓	×(1)	×(1)
Visa_EMV_High	✓	✓	×(1)	×(1)
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Legend:

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

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

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bold: satisfies all 4 properties

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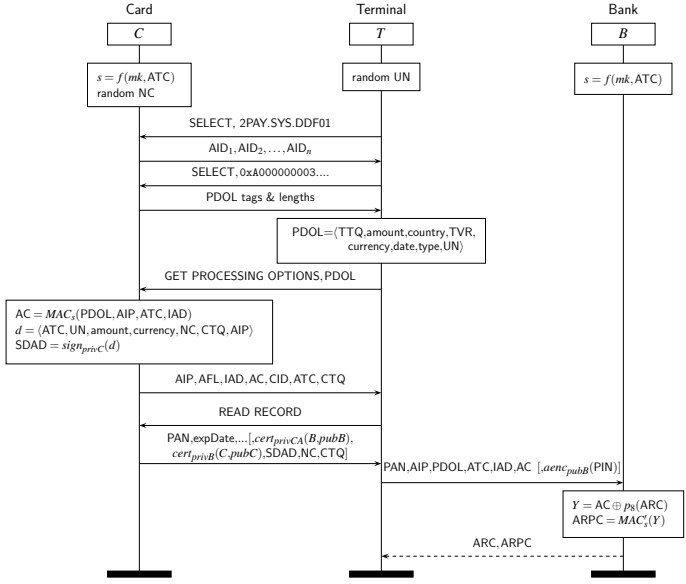
- Common Mastercard transactions are **secure**
- Common Visa transactions are **not secure**

Visa protocol: A look at the problem



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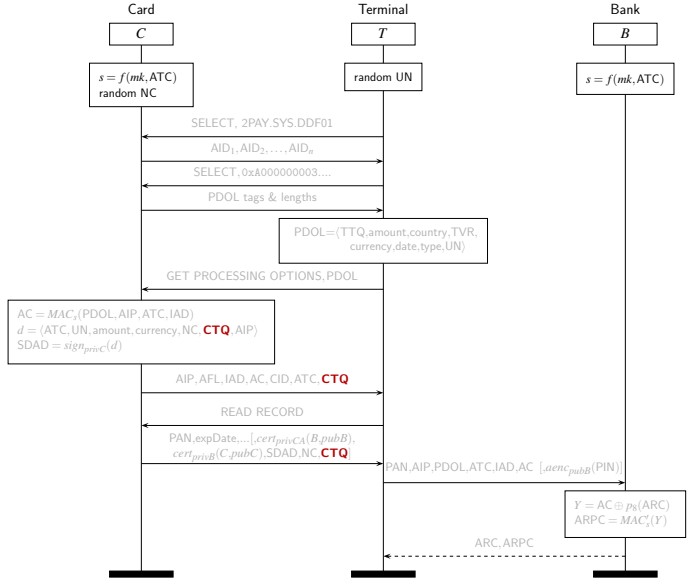

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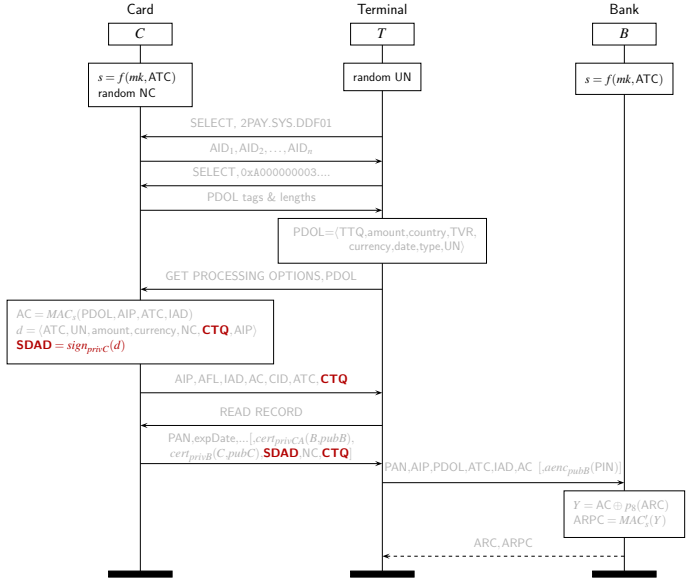

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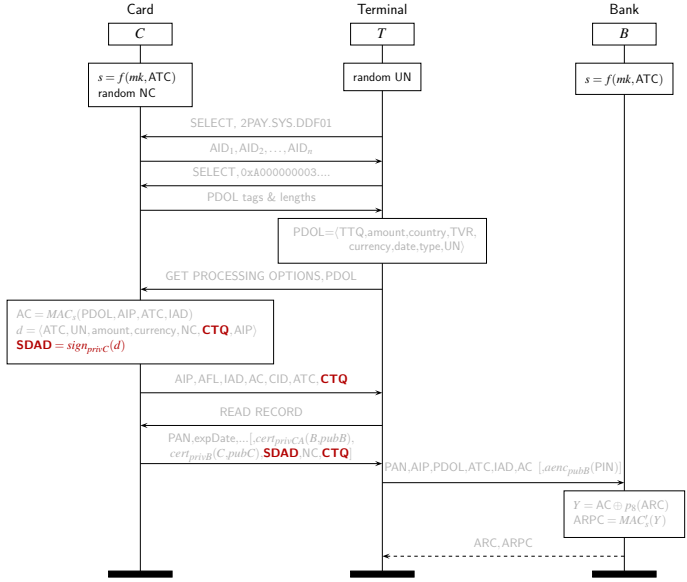

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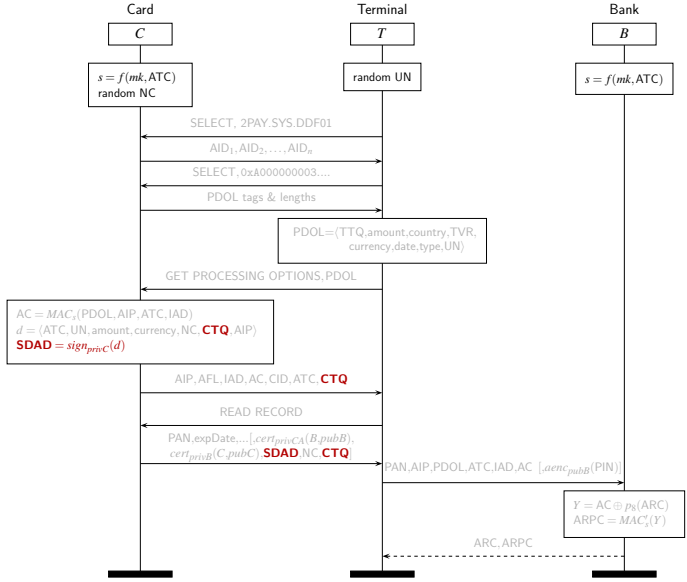
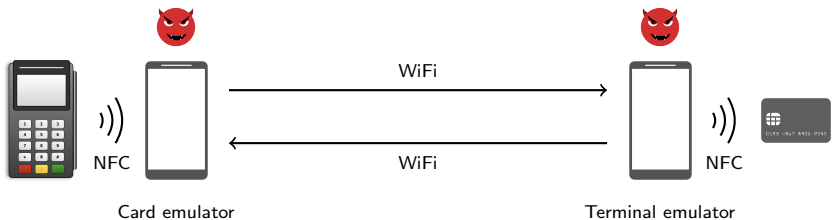
- Most Visa transactions **don't use** the SDAD
- Thus CTQ and **CVM can be modified**!



Weaponizing: PIN bypass attack

Machine-in-the-middle attack built on top of a **relay attack** architecture:



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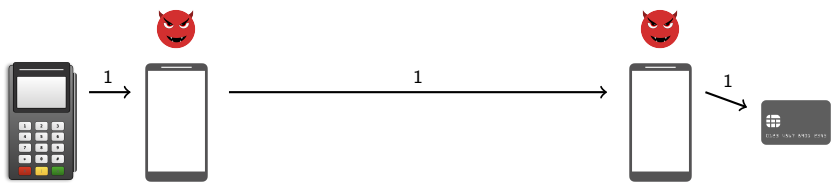

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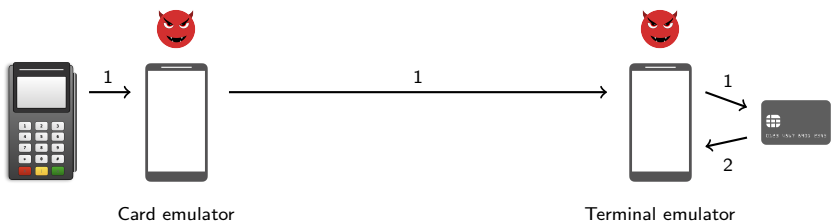

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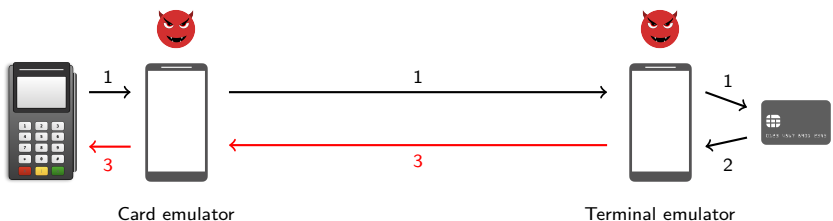
3. Attacker modifies CTQ to indicate that
   Online PIN is not Required and **Consumer Device CVM was Performed**



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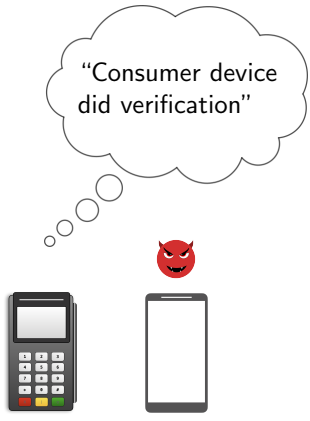

Card emulator

Terminal emulator

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What about Mastercard?

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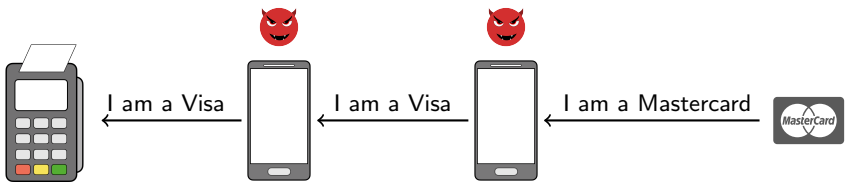
- **NO**: There is another attack!

PIN bypass attack targeting masteracard

Problem: lack of integrity protection for card data (AIDs) that determines the EMV protocol version (a.k.a. kernel) to use.
Attack idea: replace card's AIDs with the Visa AID to deceive the terminal into activating the Visa kernel.



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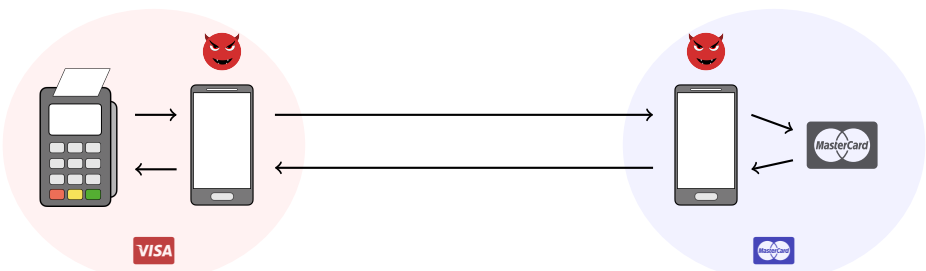
- Simultaneously perform a Visa transaction with the terminal and a Mastercard transaction with the card.
- For Visa transaction, apply previously described attack on Visa!



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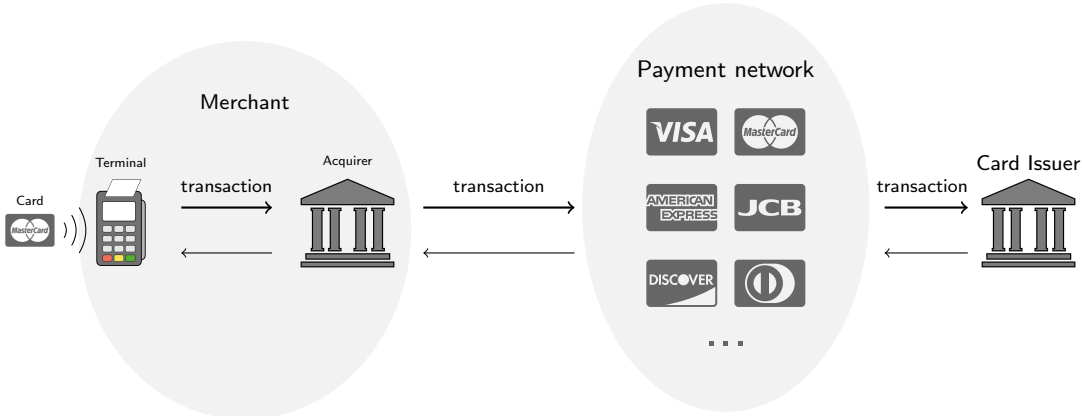
Why did we not capture the Card Brand Mixup attack previously?

Online authorization and routing



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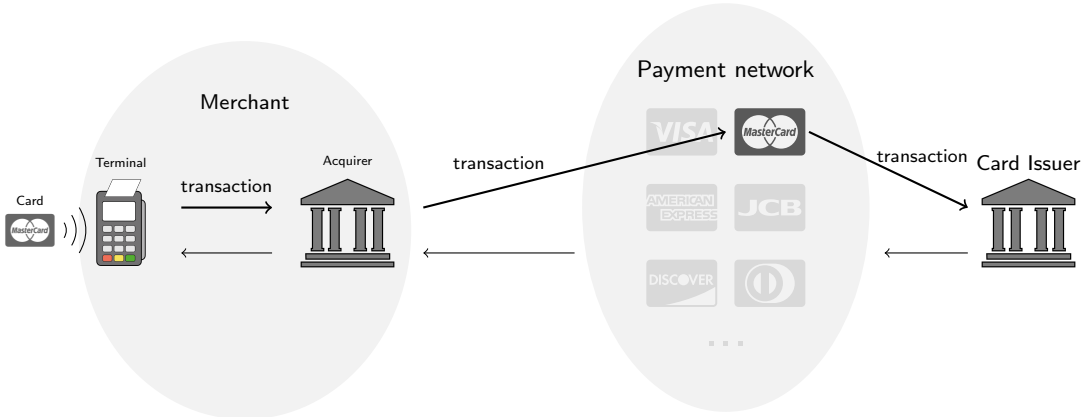

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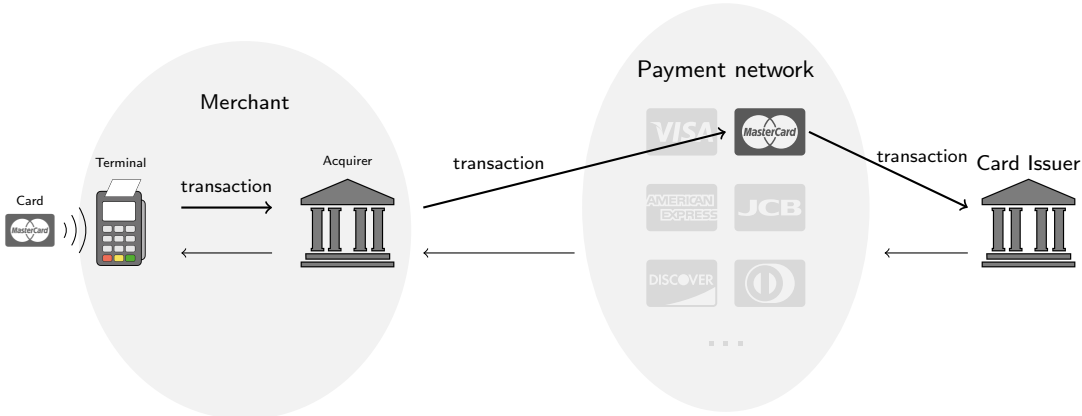

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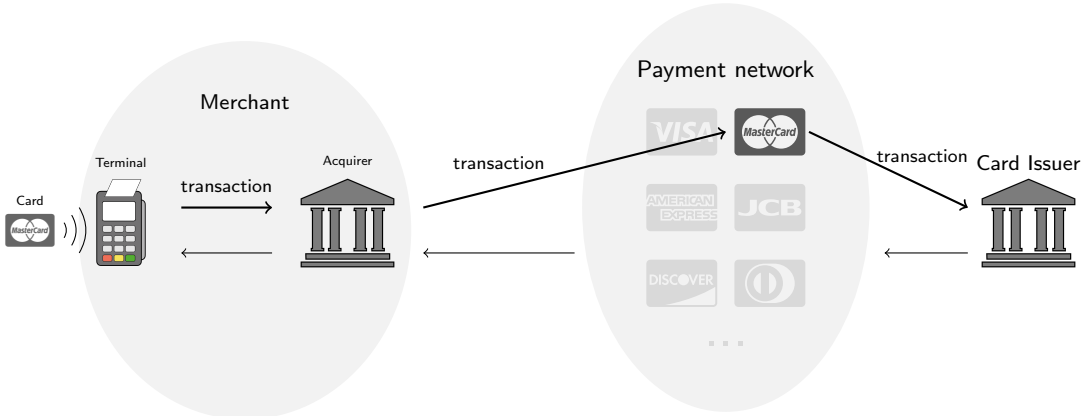

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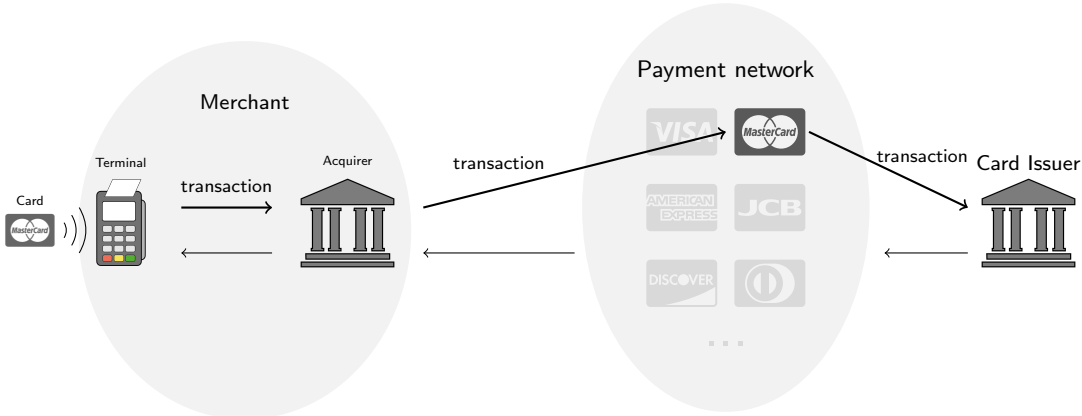

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Previous model: AID, New model: PAN

Good News

Following our disclosure, Mastercard deployed countermeasures at network level!

Mastercard Cards are now secure

Right?...

Mastercard Cards are now secure

Right?...

Well....

Bypassing Cardholder Verification for Mastercard

- Card announces **supported CVMs** in the `CVM List`
- The card authenticates the `CMV List` to the terminal using its signature which is authenticated by the **card's certificate** (signed by the issuer)
- What if this authentication fails?

Certificate verification

- Terminal has a **list of root certificates**
- Root CAs provide certificate for card issuers
- Card issuers provide **certificates stored on cards**
- Card sends signature, certificates, and information on CA to Terminal
- Terminal **looks up the root CA certificate** in its database according to:
  - Registered Application Provider Identifier, which is derived from the Application Identifier (AID)
  - the **CA Public Key Index**

Hidden in the Specifications...

- On Page 255 of the Mastercard kernel, there are some suspicious lines:

IF [The *CA Public Key Index (Card)* is not present in the CA Public Key Database]
THEN
SET 'CDA failed' in *Terminal Verification Results*
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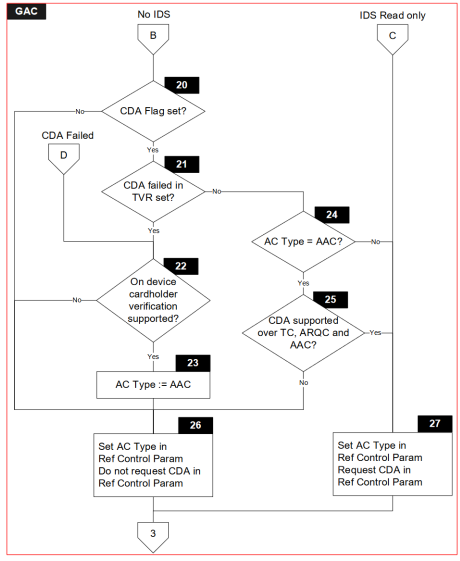

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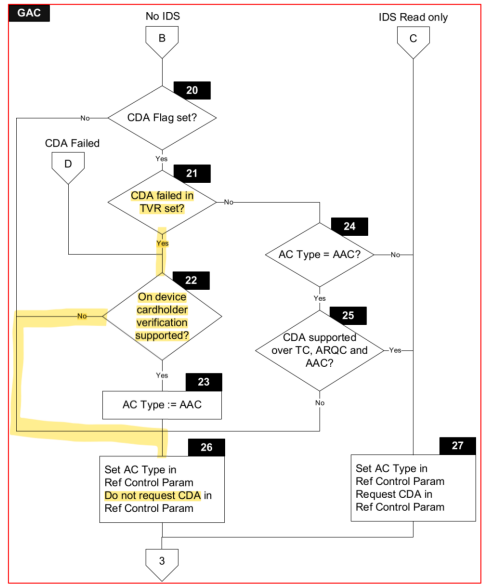

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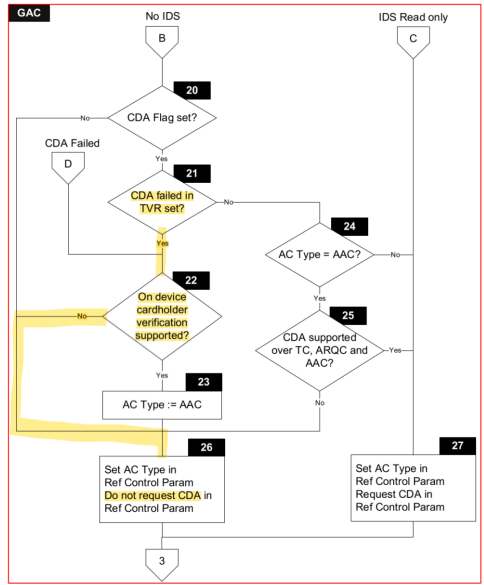
- "Do not request CDA" $\Leftrightarrow$ "No signature verificaiton is performed"
- This can happen, because the CA Public Key Index is not cryptographically protected



Inducing Authentication Failure

Providing an **invalid CA Public Key Index** and some additional changes will result in the **terminal accepting** the transaction **without verifying the PIN** although the card would require it.

Role of Tamarin

- Previous models did not capture this attack as they abstracted the terminal's decision tree.
- Tamarin was used to verify proposed counter measures.

Conclusion

- **If you are building critical infrastructure, you have to get it right!**
- **Formal automated verification is a necessity**
  We (humans) cannot cover the full execution space that complex systems have
- **Existing verification tools are up to the task**
  Tamarin, ProVerif, etc... have been used to analyse TLS, 5G AKA, etc...
- **Systems must be verified as a whole and not by parts separately**
  Separate system parts may be secure but composition may be insecure
- **Ambiguity and redundancy should be avoided in system specification**
  Critical mechanisms (e.g. routing) of the system should be unambiguously specified

About this work

- **The EMV Standard: Break, Fix, Verify**, published at the 42nd IEEE Symposium on Security and Privacy (S&P 2021)
- **Card Brand Mixup Attack: Bypassing the PIN in non-Visa cards by Using Them for Visa Transactions**, published at the 30th USENIX Security Symposium (USENIX Security 21)
- **Inducing Authentication Failures to Bypass Credit Card PINs**, published at the 32nd USENIX Security Symposium (USENIX Security 23)
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