PV204 Security technologies

Protecting private key I.

- 10.3. Programming smartcards, management (Petr Svenda)
- 17.3. Practical threshold cryptography (Petr Svenda)
- 24.3. Secure Boot, TPM, SGX, AMD SEV (Petr Svenda)

JavaCard - programming secure elements

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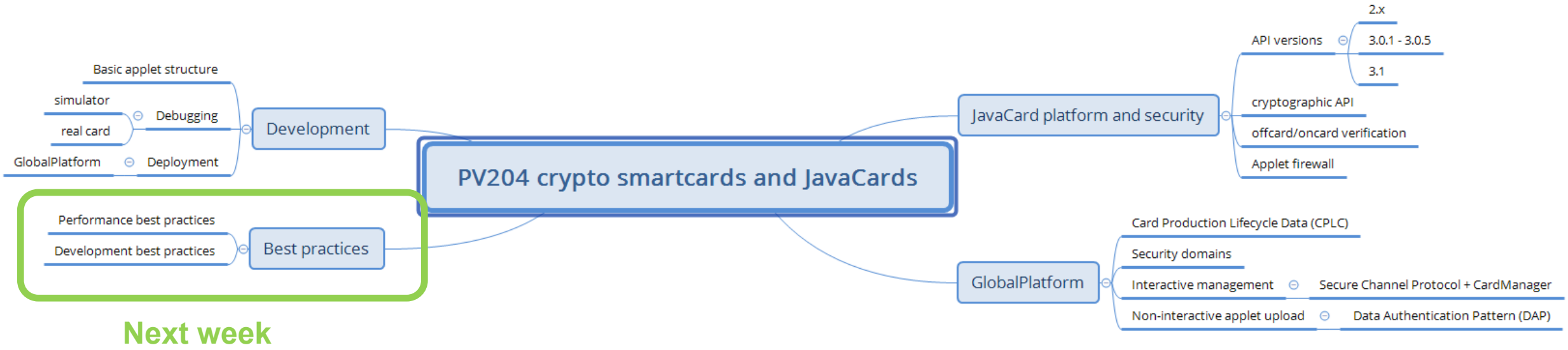
CROCS
Centre for Research on Cryptography and Security

Please comment on slides with anything unclear, incorrect or suggestions for improvement
https://drive.google.com/file/d/1wbHgjGEAYuxEC-kXUyW1SmOpf_crD_v0/view?usp=drive_link

Prerequisites

- Knowledge of basic smartcards technology is assumed (PV079)
- If you are not familiar yet, please read slides PV204_03___PV079_2023_smartcards.pdf from IS (uploaded for this course into PV204's course materials)


PV204 crypto smartcards and JavaCards
Development
Basic applet structure
Debugging
simulator
real card
Deployment
GlobalPlatform
Best practices
Performance best practices
Development best practices
JavaCard platform and security
API versions
2.x
3.0.1 - 3.0.5
3.1
cryptographic API
offcard/oncard verification
Applet firewall
GlobalPlatform
Card Production Lifecycle Data (CPLC)
Security domains
Interactive management
Secure Channel Protocol + CardManager
Non-interactive applet upload
Data Authentication Pattern (DAP)

Next week

Task: Difference between terms

- Use your favourite LLM chatbot (work within context of “security hardware”)
- Ask about difference between following topics:
  - Secure hardware
  - Cryptographic hardware
  - Trusted hardware
  - Trustworthy hardware
- Collaborative discussion

Motivation

- Usage security-relevant scenarios
  - Subscriber modules (SIMs), merchant payments, hardware wallets, authentication tokens, electronic IDs…
- Why not as another software application on your laptop?
  - Laptop not well portable, large trusted code base, many other applications (malware), lack of secure storage for cryptographic keys, user/attacker control platform, expensive to own…
- Mobile phone fixes only some of these issues
  - Is portable, some have better platform security (but not all!), still somewhat expensive…

Properties of “Ideal” hwsec platform

- Cheap, portable, no battery
- Good support from outer environment
- Fast enough for the task
- Easy to develop (securely)
- Apps portable between platform manufacturers
- Secure, even with physical access (keys extraction)
- Multiple apps from distrusting providers securely
- Secure remote management (new apps, update)
- …

Technology

crypto smartcards

PC/SC, phones with NFC

main CPU + crypto coprocessors

JavaCard API, tools, best practices

JavaCard bytecode, JCVM

tamper resistant, CC, FIPS140-2/3

Applet firewall, Security Domains

GlobalPlatform, SCP, DAP

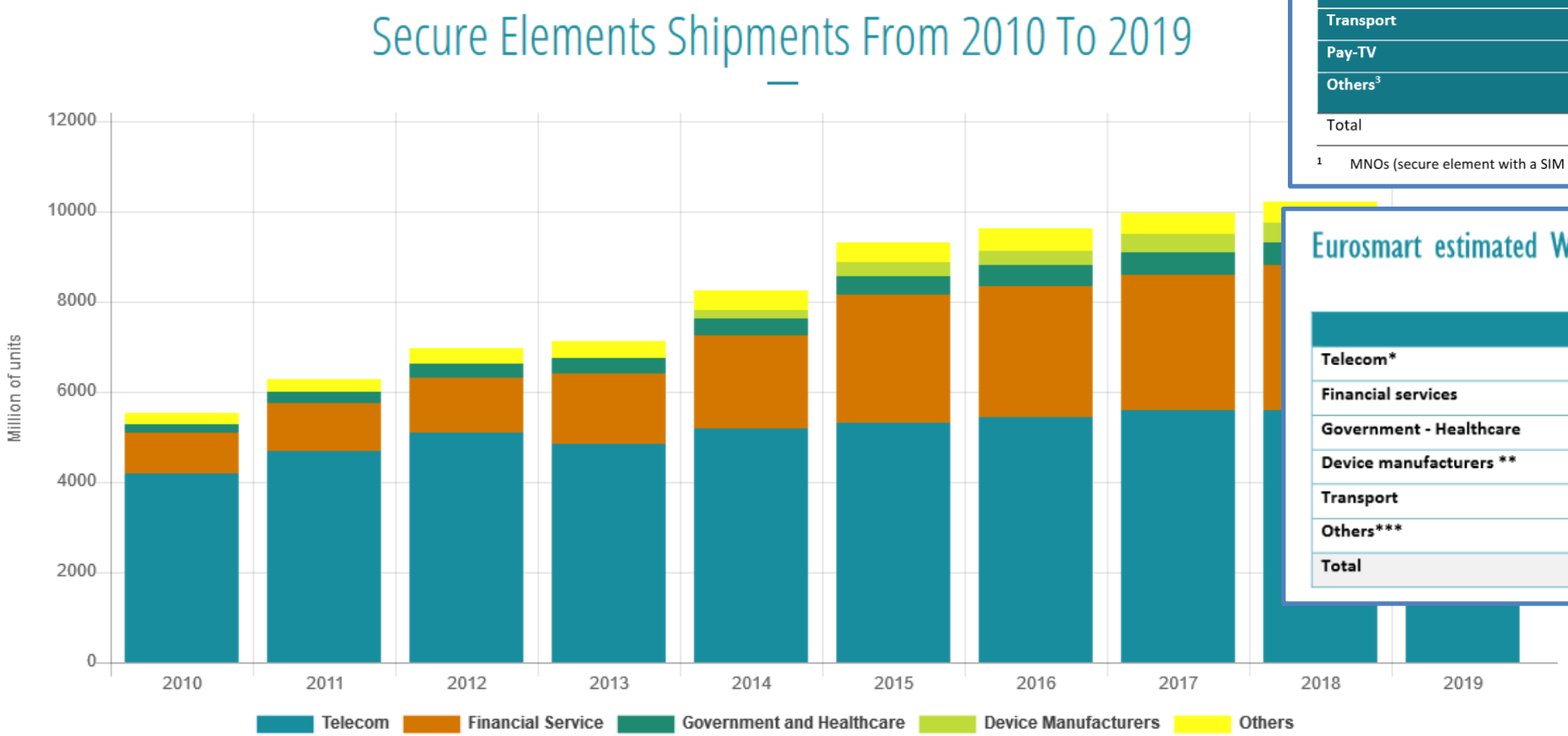
Primary markets for smartcards

January 2022

Eurosmart estimated WW µP market size - (Mu)

	2020	2021
Telecom[1]	5100	4900
Financial services	3170	3250
Government- Healthcare	425	490
Device manufacturers [2]	450	490
Transport	230	220
Pay-TV	75	65
Others[3]	90	90
Total	***9540***	***9505***

[1] MNOs (secure element with a SIM application)



Eurosmart estimated WW µP TAM - (Mu)

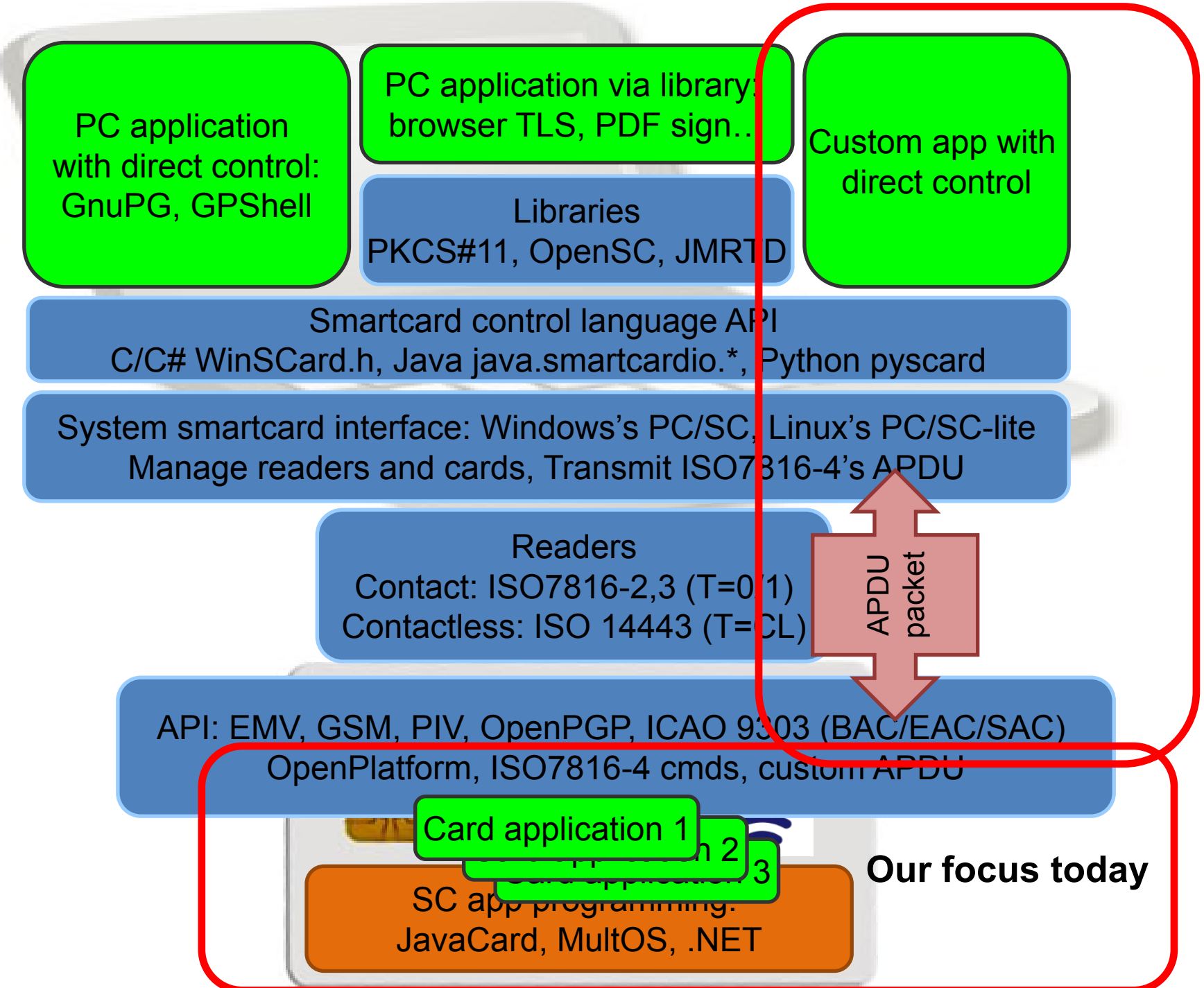
	2021	2022 forecasts
Telecom*	4700	4600
Financial services	3250	3200 - 3300
Government - Healthcare	510	550
Device manufacturers **	490	520
Transport	220	220-245
Others***	155	150
Total	**9325**	**9.240 - 9. 360**

https://www.eurosmart.com/eurosmarts-secure-elements-market-analysis-and-forecasts/
https://www.eurosmart.com/2021-secure-elements-global-market-and-2022-estimates/

Old vs. current multi-application smart cards

- One program only
- Stored persistently in ROM or EEPROM
- Written in machine code
  - Chip specific

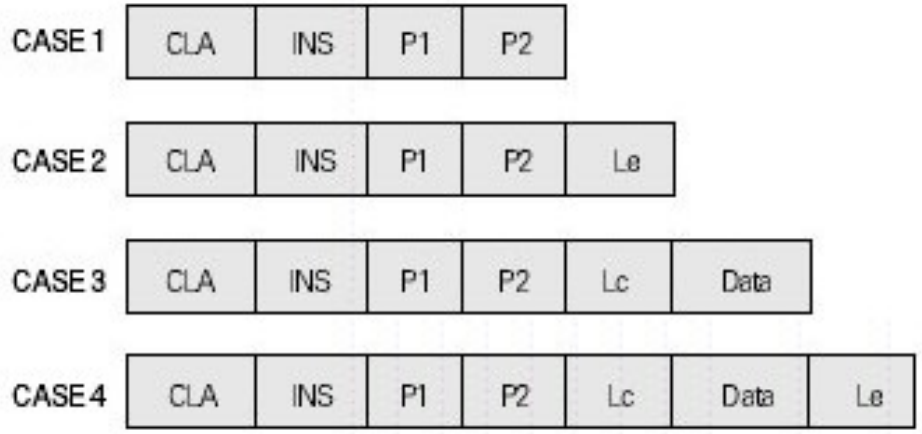
- Multiple applications at the same time
- Stored in EEPROM
- Written in higher-level language
  - Interpreted from bytecode (JavaCard)
  - Portable
- Application can be later managed (remotely OTA, GlobalPlatform)


PC application with direct control: GnuPG, GPShell
PC application via library: browser TLS, PDF sign…
Custom app with direct control
Libraries
PKCS#11, OpenSC, JMRTD
Smartcard control language API
C/C# WinSCard.h, Java java.smartcardio.*, Python pyscard
System smartcard interface: Windows's PC/SC, Linux's PC/SC-lite
Manage readers and cards, Transmit ISO7816-4's APDU
Readers
Contact: ISO7816-2,3 (T=0/1)
Contactless: ISO 14443 (T=CL)
APDU packet
API: EMV, GSM, PIV, OpenPGP, ICAO 9303 (BAC/EAC/SAC)
OpenPlatform, ISO7816-4 cmds, custom APDU
Card application 1
SC app programming:
JavaCard, MultOS, .NET
Our focus today

APDU packets were nested inside USB packets for HW02 (Yubikey interfaces)

APDU (Application Protocol Data Unit)

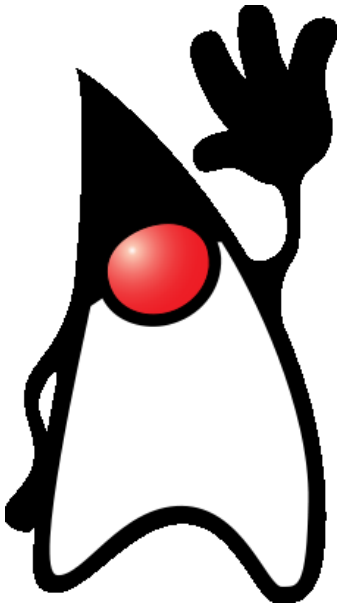
- APDU is basic logical communication datagram
  - header (5 bytes) and up to ~256 bytes of user data
- Format specified in ISO7816-4
- Header/Data format
  - CLA – instruction class
  - INS – instruction number
  - P1, P2 – optional data
  - Lc – length of incoming data
  - Data – user data
  - Le – length of the expected output data



- Some values of CLA/INS/P1/P2 standardized (better interoperability)
  - https://web.archive.org/web/20180721010834/http://techmeonline.com/most-used-smart-card-commands-apdu/
- Custom values used by application developer (your own API)

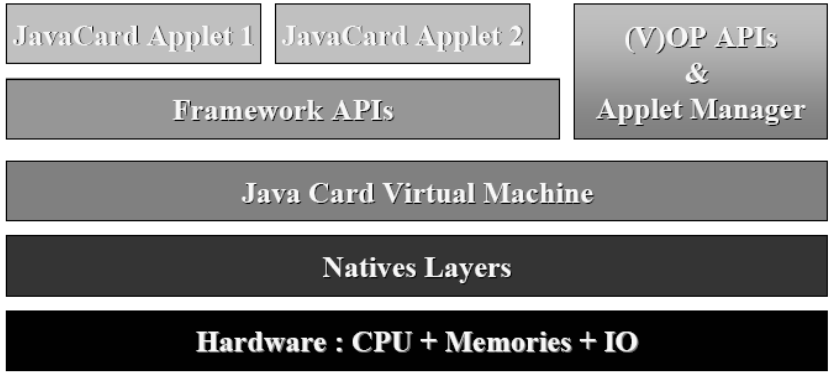
Command	Function	Instruction (INS)	Standard
ACTIVATE FILE	Reversibly unblock a file.	'44'	ISO/IEC 7816-9
APPEND RECORD	Insert a new record in a file with a linear fixed structure.	'E2'	ISO/IEC 7816-4
APPLICATION BLOCK	Reversibly block an application.	'1E'	EMV
APPLICATION UNBLOCK	Unblock an application.	'18'	EMV
ASK RANDOM	Request a random number from the smart card.	'84'	EN 726-3
		'24'	TS 51.011
		'24'	ISO/IEC 7816-8
		'AC'	EN 726-3
		'56'	EN 1546-3
		'E0'	ISO/IEC 7816-9
		'E2'	EN 726-3
		'52'	EN 1546-3
CREDIT PSAM	Pay from IEP to the PSAM.	'72'	EN 1546-3
DEACTIVATE FILE	Reversibly block a file.	'04'	ISO/IEC 7816-9
DEBIT IEP	Pay from the purse	'54'	EN 1546-
DECREASE	Reduce the value of a counter in a file.	'30'	EN 726-3
DECREASE STAMPED	Reduce the value of a counter in a file that is protected using a	'34'	EN 726-3

JavaCard basics



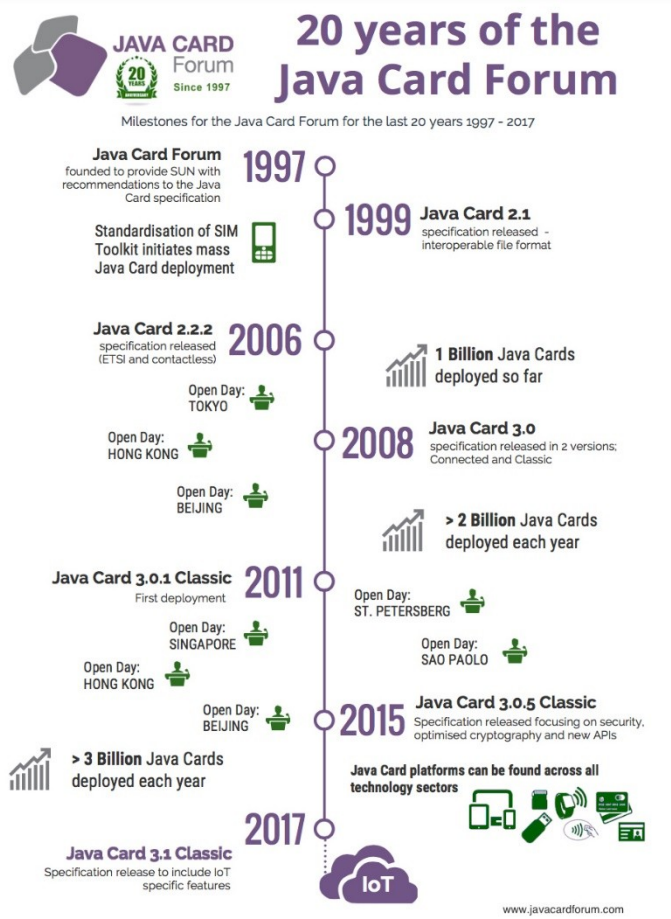
JavaCard

- Maintained by Java Card Forum (since 1997)
- Cross-platform and cross-vendor applet interoperability
- Freely available specifications and development kits
  - http://www.oracle.com/technetwork/java/javacard/index.html
- JavaCard applet is Java-like application
  - uploaded to a smart card
  - executed by the JCVM



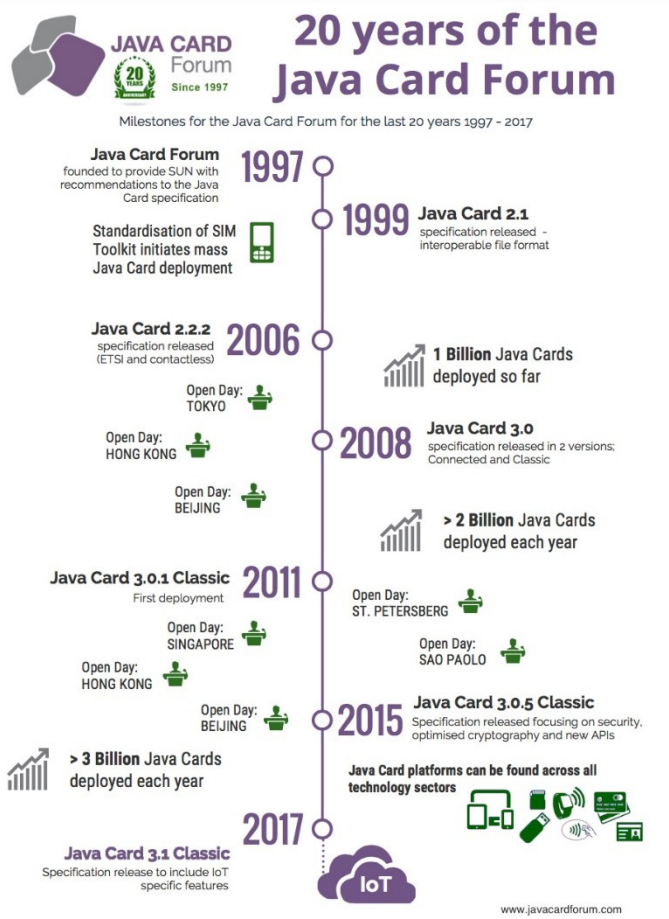
JavaCard 2.x is like Java but not supporting…

- No dynamic class loading
- No Security manager
- No Threads and synchronization
- No Object cloning, finalization
- No Large primitive data types
  - float, double, long and char
  - usually not even int (4 bytes) data type by default
    - specialized package javacardx.framework.util.intx for support
- Most of std. classes missing
  - most of java.lang, Object and Throwable in limited form
- Limited garbage collection
  - Newer cards supports, but slow and not always reliable



JavaCard 2.x supports

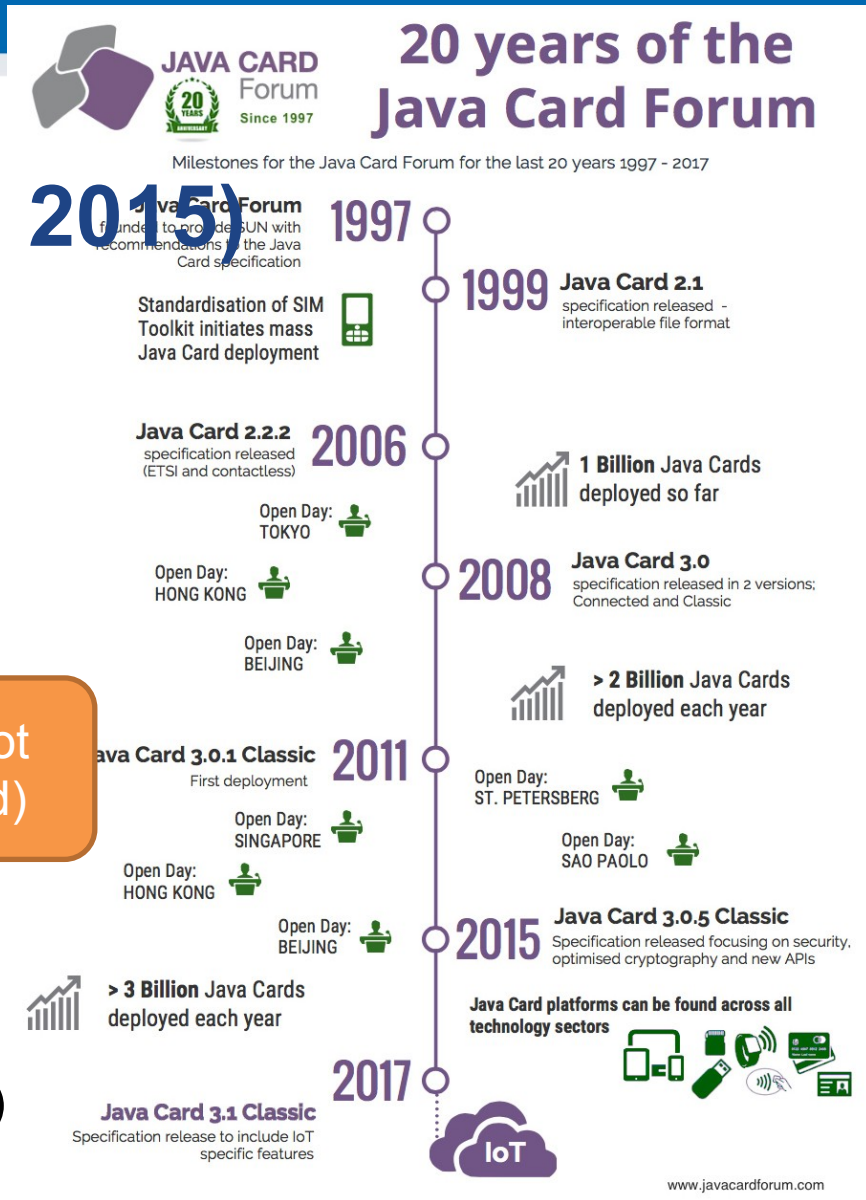
- Standard benefits of the Java language
  - data encapsulation, safe memory management, packages, etc.
- Applet isolation based on the JavaCard firewall
  - applets cannot directly communicate with each other
  - special interface (Shareable) for cross applets interaction
- Atomic operations using transaction mode
- Transient data (buffer placed in RAM)
  - fast and automatically cleared
- A rich cryptography API
  - accelerated by cryptographic co-processor
- Secure (remote) communication with the terminal
  - if GlobalPlatform compliant (secure messaging, security domains)



JavaCard 3.0.x (most recent 3.0.5 from 2015)

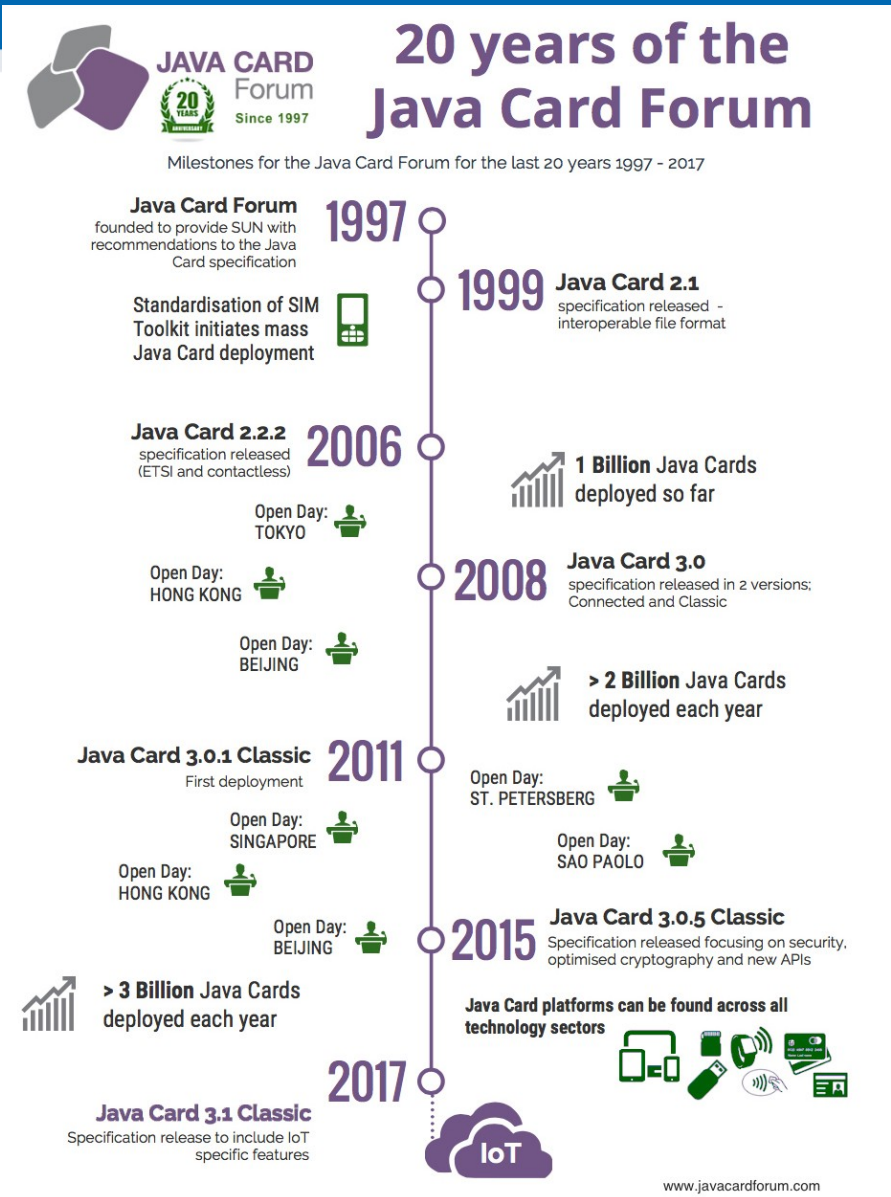
- Major release of JavaCard specification
  - significant changes in development logic
  - two separate branches – Classic and Connected edition
- JavaCard 3.x Classic Edition
  - legacy version, extended JC 2.x
  - APDU-oriented communication
- JavaCard 3.x Connected Edition
  - smart card perceived as web server (Servlet API)
  - TCP/IP network capability, HTTP(s), TLS
  - supports Java 6 language features (generics, annotations…)
  - move towards more powerful target devices
  - focused on different segment then classic smart cards

Connected edition is not used so far (likely dead)



JavaCard 3.1 (2018) and 3.2 (2023)

- JavaCard 3.1
  - Focus on IoT
  - Additional cryptographic algorithms, named curves
  - Not much practical experience yet (no devices available)
    - Some certified end of 2022 but not freely available
- JavaCard 3.2
  - Ext. EdDSA (edwards25519, edwards448 curves)
  - TLS1.3 and DTLS1.3 key schedule operations
  - Configuration for RSA-OAEP/PSS
- Conservative development of JavaCard specs
  - Only what is “widely” requested
  - Significantly lacking behind state of the art (e.g, PQC algs only via proprietary API)

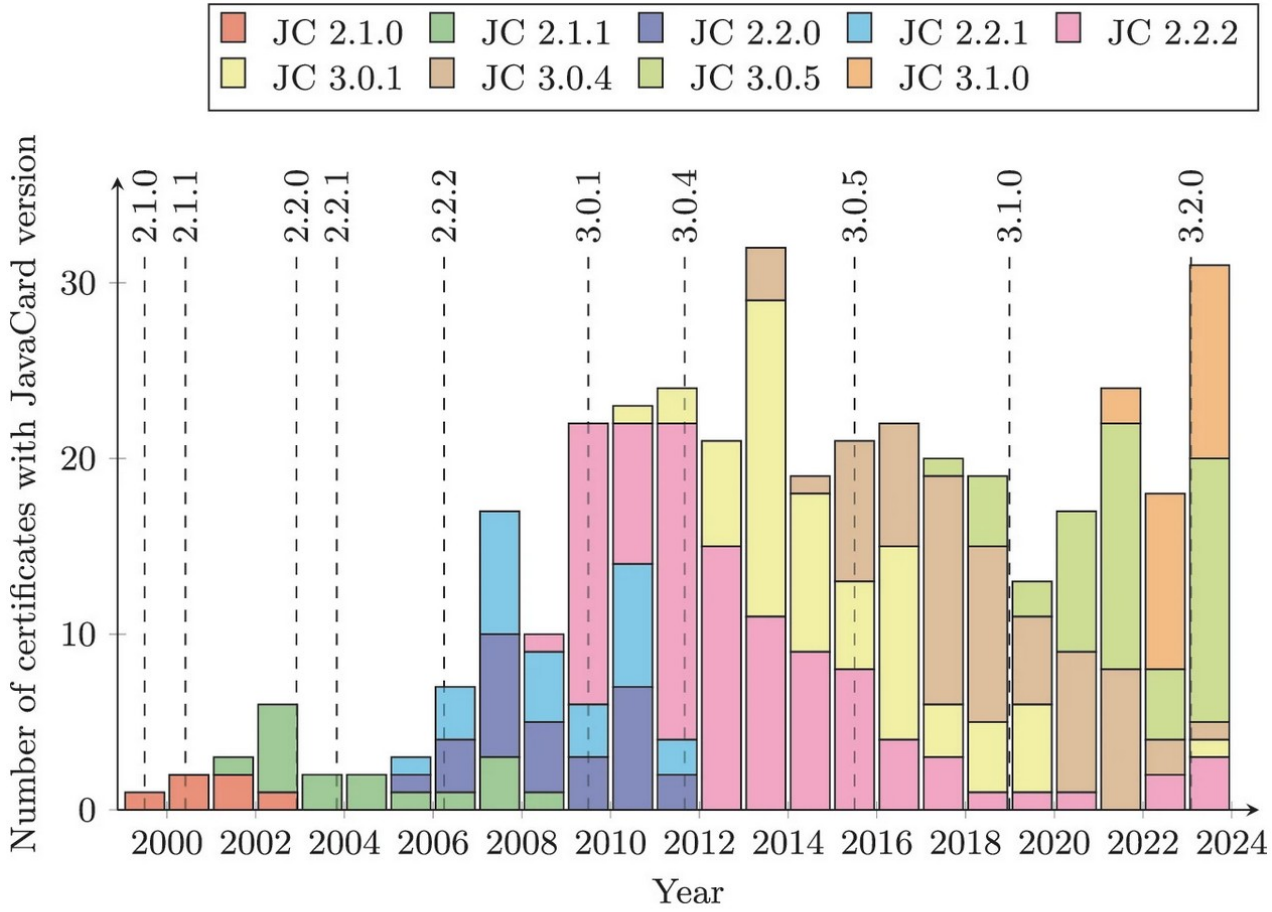


How to analyze real-world usage of technology X?

1. Collect representative sample of users / projects (ideally “all”)
   – E.g., all open-source JavaCard projects on GitHub
2. Establish significance of projects
   – E.g., Number of developers/forks/stars, search trends on Google, sales stats…
3. Analyze projects for the level and style of use of technology X
   – E.g., static code analysis of JavaCard keywords and constants
   – Ideally trends in time if possible (e.g., code state in time via git commits)

“The adoption rate of JavaCard features by certified products and open-source projects”, L. Zaoral, A. Dufka, P.Svenda, CARDIS’23
https://link.springer.com/chapter/10.1007/978-3-031-54409-5_9

Certified smartcards and JavaCard-related projects



The number of certification documents mentioning specific JavaCard API version per year (the year 2023 only till the end of October). In case multiple versions were detected in a document, only the latest one was included in the chart.

- Number of (expensively) certified JavaCard devices is increasing

Activity of open-source JavaCard applets in time

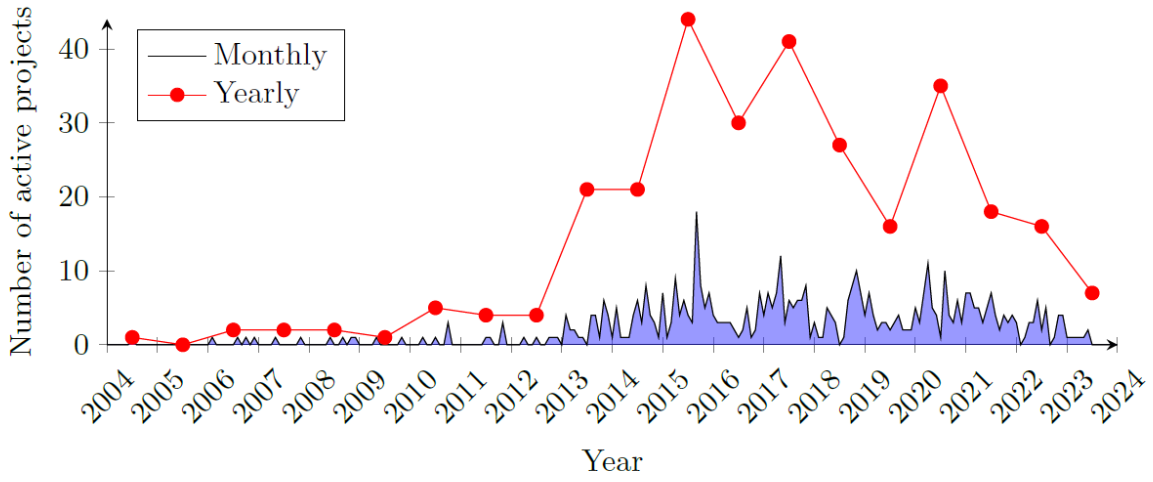
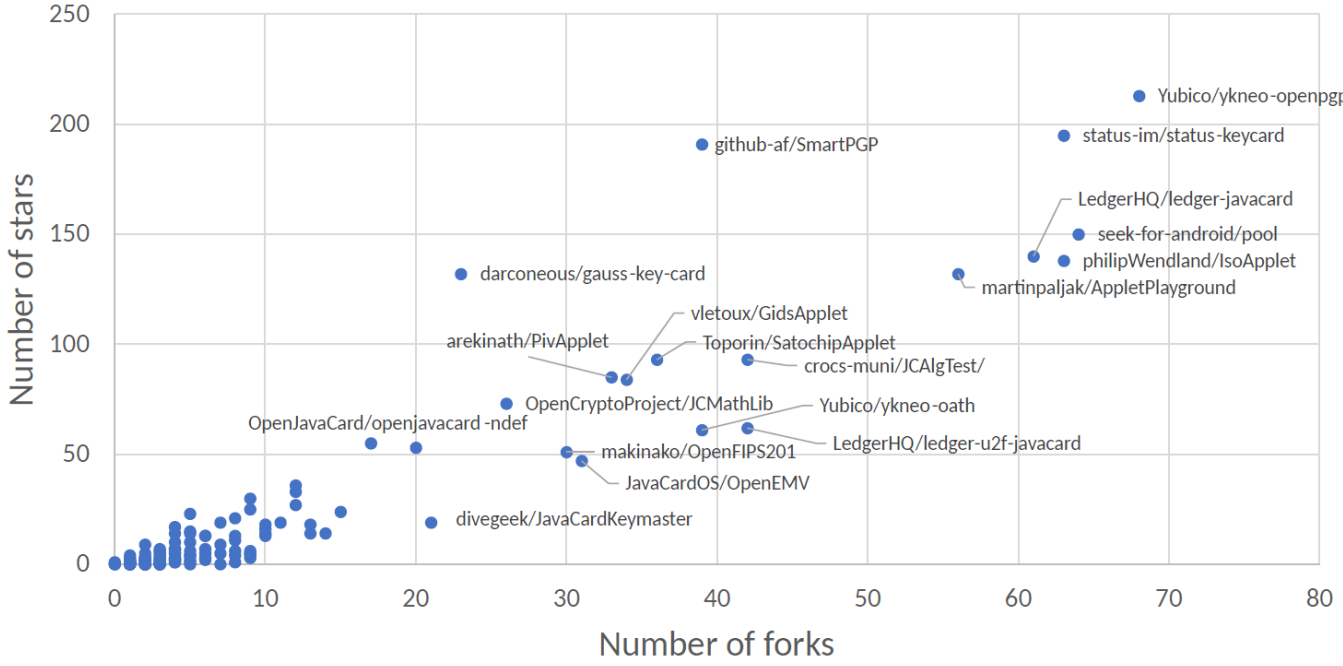


Fig. 3. Number of open-source projects with at least one commit per month (black line) or per year (red line) respectively. The year 2023 is only till end of June.

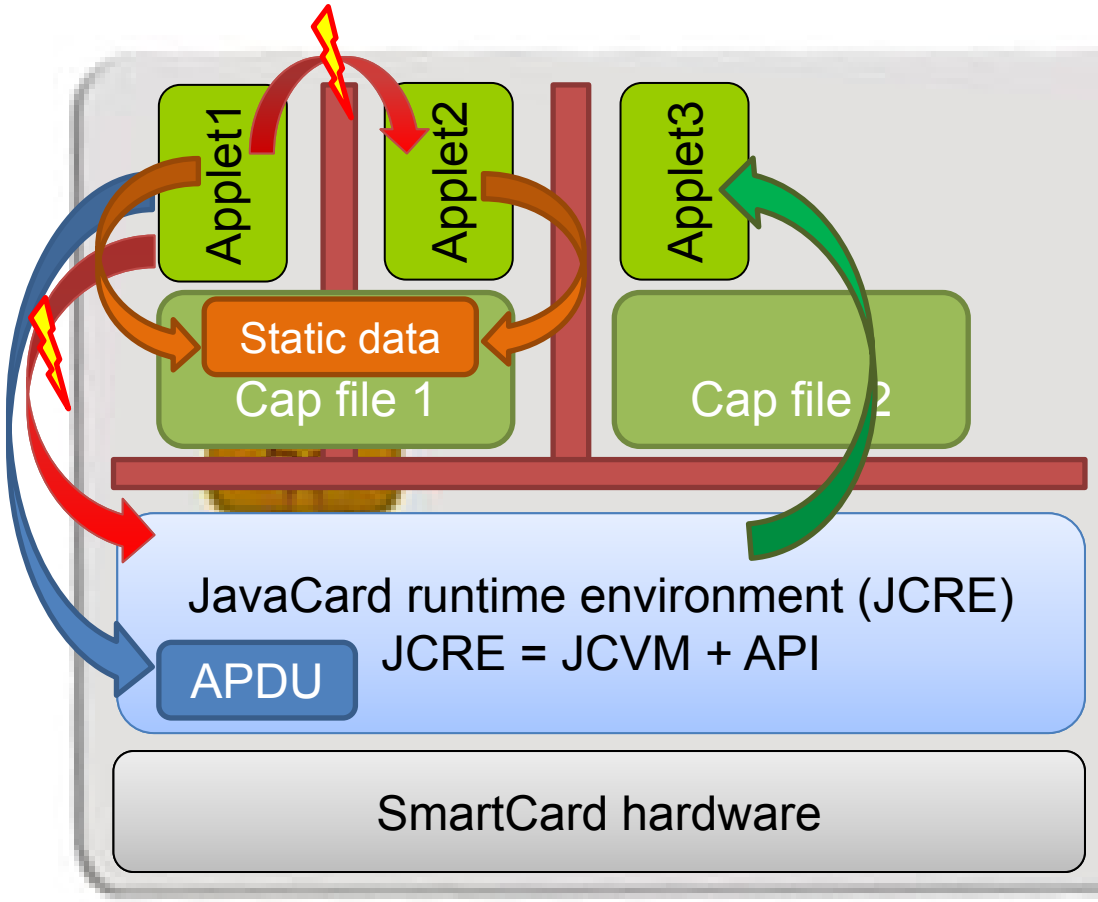


- Is open-source ecosystem representative of the whole domain?
  - Likely two orders of magnitude more developers in **non**-open source domain
  - Proprietary applets with access to proprietary API may be different

Version support

- Need to know supported version for your card
  - convertor adds version identification of packages used to binary cap file
  - If converted with unsupported version, upload to card fails
- Supported version can be (somewhat) obtained from card
  - JCSystem.getVersion() → [Major.Minor]
  - https://github.com/petrs/jcAIDScan
  - See https://www.fi.muni.cz/~xsvenda/jcsupport.html
- Available cards supports mostly 3.0.4 and 3.0.5 (newer cards)

JavaCard applet firewall – runtime checks



- Access to other applet's methods and attributes prevented
  - Even if `public`
- Applets can access specific JCRE objects
- JCRE can access all applets (no restriction)
- Static attributes of package accessible by all its applets!

Inspired by http://ekladata.com/lHWNXUB-yernblD2sdiK1zxxQco/5_javacard.pdf

Desktop vs. smart card

- Following slides will be marked with icon based on where it is executed

Process executed on host (PC/NTB…)

Process executed inside smart card

On-card, off-card code verification

- How to upload only “correct” applets?
- Off-card verification
  - Basic JavaCard constraints
  - Possibly additional checks (e.g., type consistency when using Shareable interface)
  - Full-blown static analysis possible
  - Applet can be digitally signed (and enforced by DAP – shown later)

- On-card verification
  - Limited resources available
  - Proprietary checks by JC platform implementation

DEVELOPING JAVACARD APPS

```
package example;
import javacard.framework.*;

public class HelloWorld extends Applet {
   protected HelloWorld()  {
     register();
   }
   public static void install(byte[] bArray, short bOffset, byte bLength) {
      new HelloWorld();
   }
   public boolean select() {
      return true;
   }
   public void process(APDU apdu) {
      // get the APDU buffer
      byte[] apduBuffer = apdu.getBuffer();
      // ignore the applet select command dispached to the process
      if (selectingApplet()) return;
      // APDU instruction parser
      if (apduBuffer[ISO7816.OFFSET_CLA] == CLA_MYCLASS) &&
          apduBuffer[ISO7816.OFFSET_INS] == INS_MYINS)) {
          MyMethod(apdu);
      }
      else ISOException.throwIt( ISO7816.SW_INS_NOT_SUPPOR
   }
   public void MyMethod(APDU apdu) { /* … */ }
}
```

include packages from javacard.*

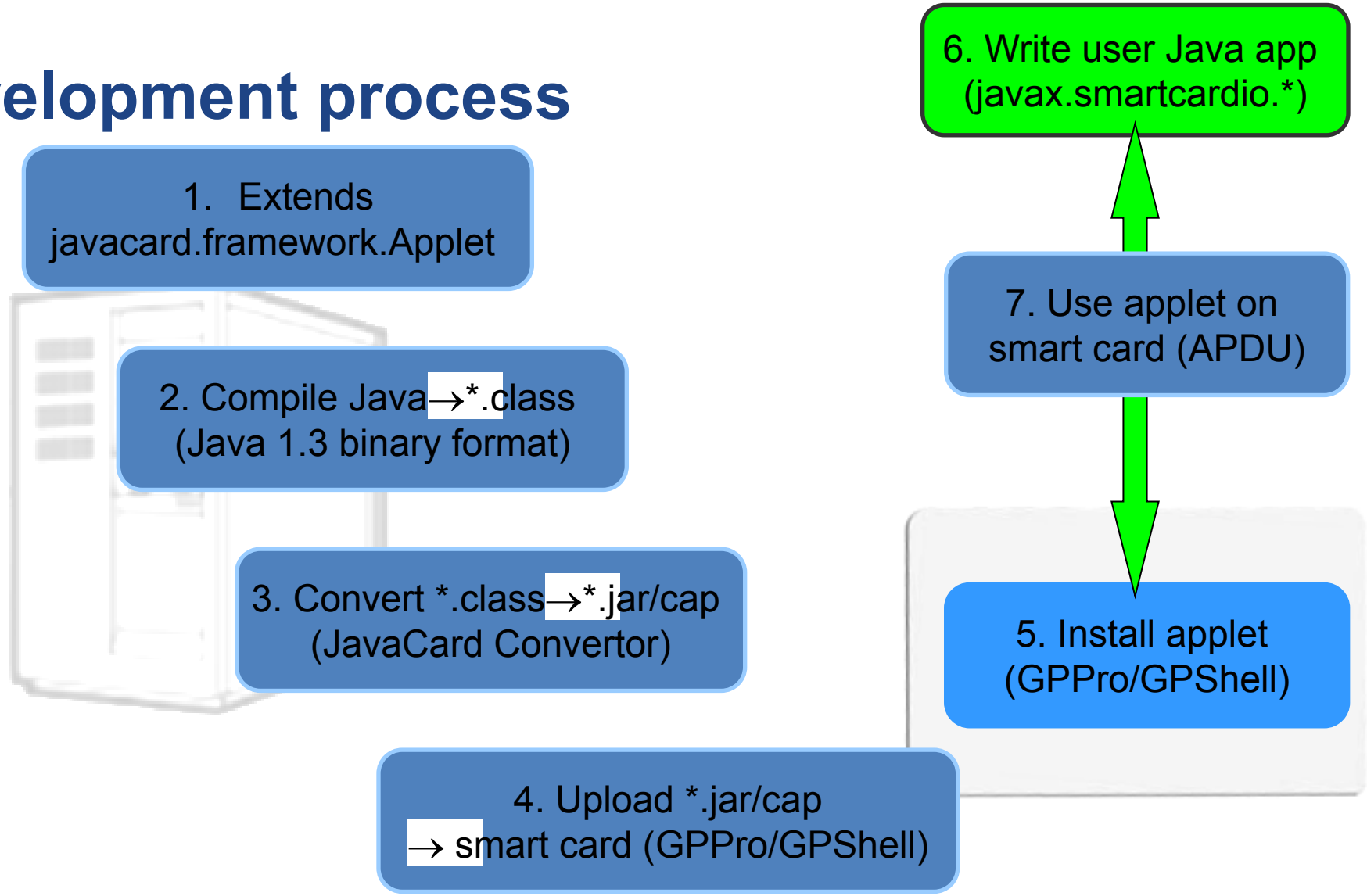
extends Applet

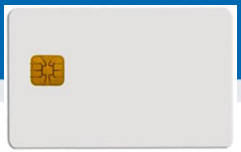
Called only once, do all allocations&init HERE

Called repeatedly on application select, do all temporaries preparation HERE

Called repeatedly for every incoming APDU, parse and call your code HERE

JC development process



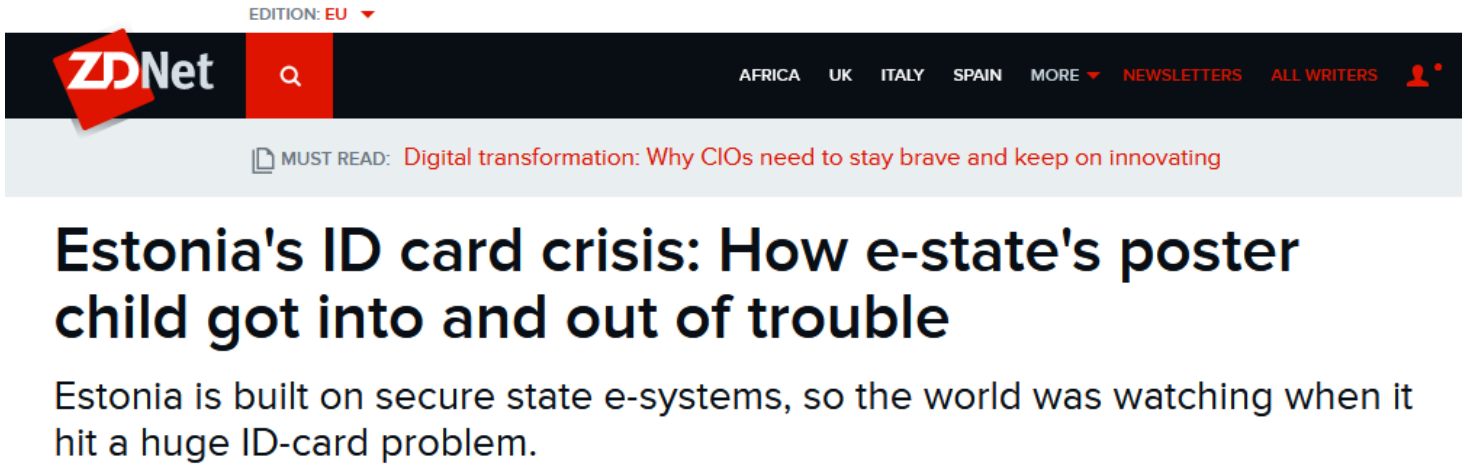


JavaCard application running model

1. Uploaded package – application binary
2. Installed applet from package – running application
3. Applet is “running” until deleted from card
4. Applet is suspended when power is lost
   - Transient data inside RAM are erased
   - Persistent data inside EEPROM remain
   - Currently executed method is interrupted
5. When power is resumed
   - Unfinished transactions are rolled back
   - Applet continues to run with the same persistent state
   - Applet waits for new command (does *not* continue with interrupted method)
6. Applet is deleted by service command

Managing applets on card

Motivation: Fix bug in electronic IDs for half of population


EDITION: EU

ZDNet

AFRICA UK ITALY SPAIN MORE NEWSLETTERS ALL WRITERS

MUST READ: Digital transformation: Why CIOs need to stay brave and keep on innovating

Estonia's ID card crisis: How e-state's poster child got into and out of trouble

Estonia is built on secure state e-systems, so the world was watching when it hit a huge ID-card problem.

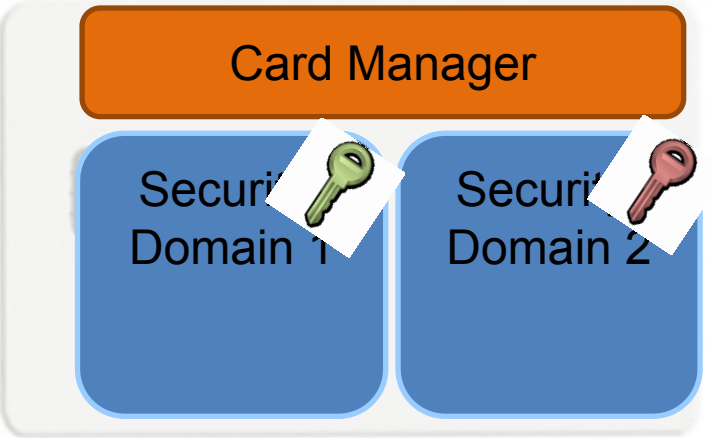
- Problem: how to remotely manage administrative access to token?
  - Smartcards, TEE (TrustZone) - same basic issues, but also some specifics
- Local/remote upload, configuration and removal of applications
- Authentication of manager, online vs. offline operations

GLOBALPLATFORM
THE STANDARD FOR MANAGING APPLICATIONS ON SECURE CHIP TECHNOLOGY

GlobalPlatform

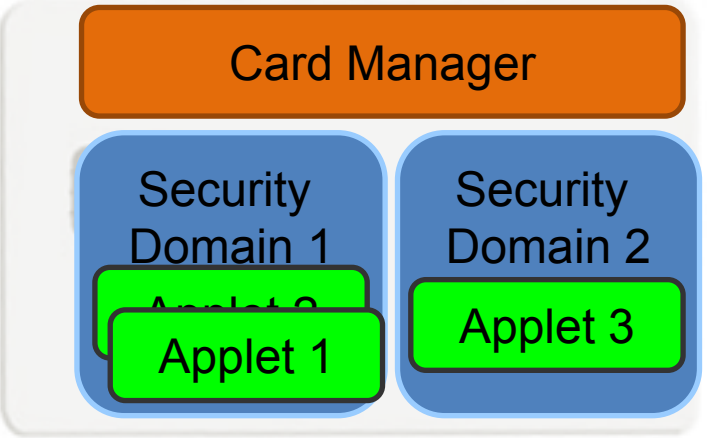
- Specification of API for card administration
  - Upload/install/delete applications
  - Card lifecycle management
  - Card security management
  - Security mechanisms and protocols
- Newest is GlobalPlatform Card Specification v2.3.1 (March 2018)
  - Previous versions also frequently used
  - http://www.globalplatform.org/specificationscard.asp
- Primary open API for Trusted Execution Environment (TEE)
  - ARM TrustZone…

GlobalPlatform – main terms



- Smart card life cycle
  - OP_READY, INITIALIZED (prepared for personalization)
  - SECURED (issued to user, use phase)
  - CARD_LOCKED (temporarily locked (attack), unlock to SECURED)
  - TERMINATED (logically destroyed)
- Card Manager (CM)
  - Special card component responsible for administration and card system service functions (cannot be removed)
- Security Domain (SD)
  - Logically separated area on card with own access control
  - Enforced by different authentication keys

GlobalPlatform – main terms



- Card Content (apps,data) Management
  - Content verification, loading, installation, removal
- Security Management
  - Security Domain locking, Application locking
  - Card locking, Card termination
  - Application privilege usage, Security Domain privileges
  - Tracing and event logging
- Command Dispatch
  - Application selection
  - (Optional) Logical channel management

Card Production Life Cycle (CPLC)

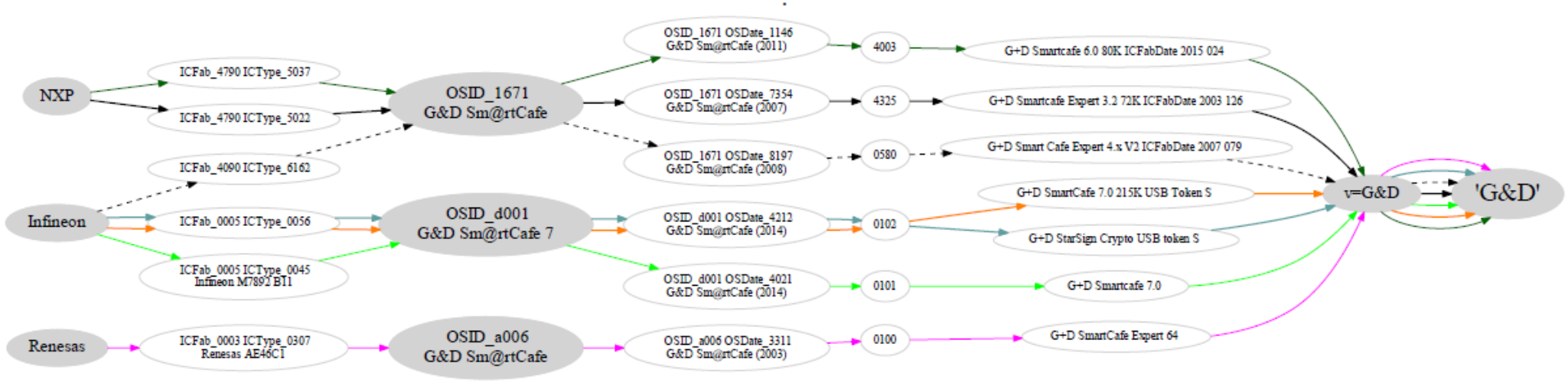
- Manufacturing metadata
- Dates (OS, chip)
- Circuit serial number
- (not mandatory)
- GlobalPlatform APDU
  - 80 CA 9F 7F 00
  - gppro --info
- ISO7816 APDU
  - 00 CA 9F 7F 00

CPLC info

IC Fabricator: **4790**
IC Type: **5167**
OS ID: **4791**
OS Release Date: **2081**
OS Release Level: **3b00**
IC Fabrication Date ((Y DDD) date in that year): **4126**
IC Serial Number: **00865497**
IC Batch Identifier: **3173**
IC Module Fabricator: **4812**
IC Module Packaging Date: **4133**
IC Manufacturer: **0000**
IC Embedding Date: **0000**
IC Pre Personalizer: **1017**
IC Pre Personalization Equipment Date: **4230**
IC Pre Personalization Equipment ID: **38363534**
IC Personalizer: **0000**
IC Personalization Date: **0000**
IC Personalization Equipment ID: **00000000**

Example CPLC results from several G&D cards

ICFabricator → ICFab_ICType → OperatingSystemID → OperatingSystemID_OSReleaseDate → OSReleaseLevel → CardName → Original vendor → Current vendor



GlobalPlatform package/applet upload - SCP

A. Security domain selection
B. Secure channel establishment (SCP) – security domain
C. Package (cap file) upload
   – Local upload in trusted environment
   – Remote upload with relayed secure channel
D. Applet installation
   – Separate instance from package binary with unique AID
   – Applet privileges and other parameters passed
   – Applet specific installation data passed

- `gp --install file_with_applet.cap`

GlobalPlatform package/applet upload - Data Authentication Pattern (DAP)

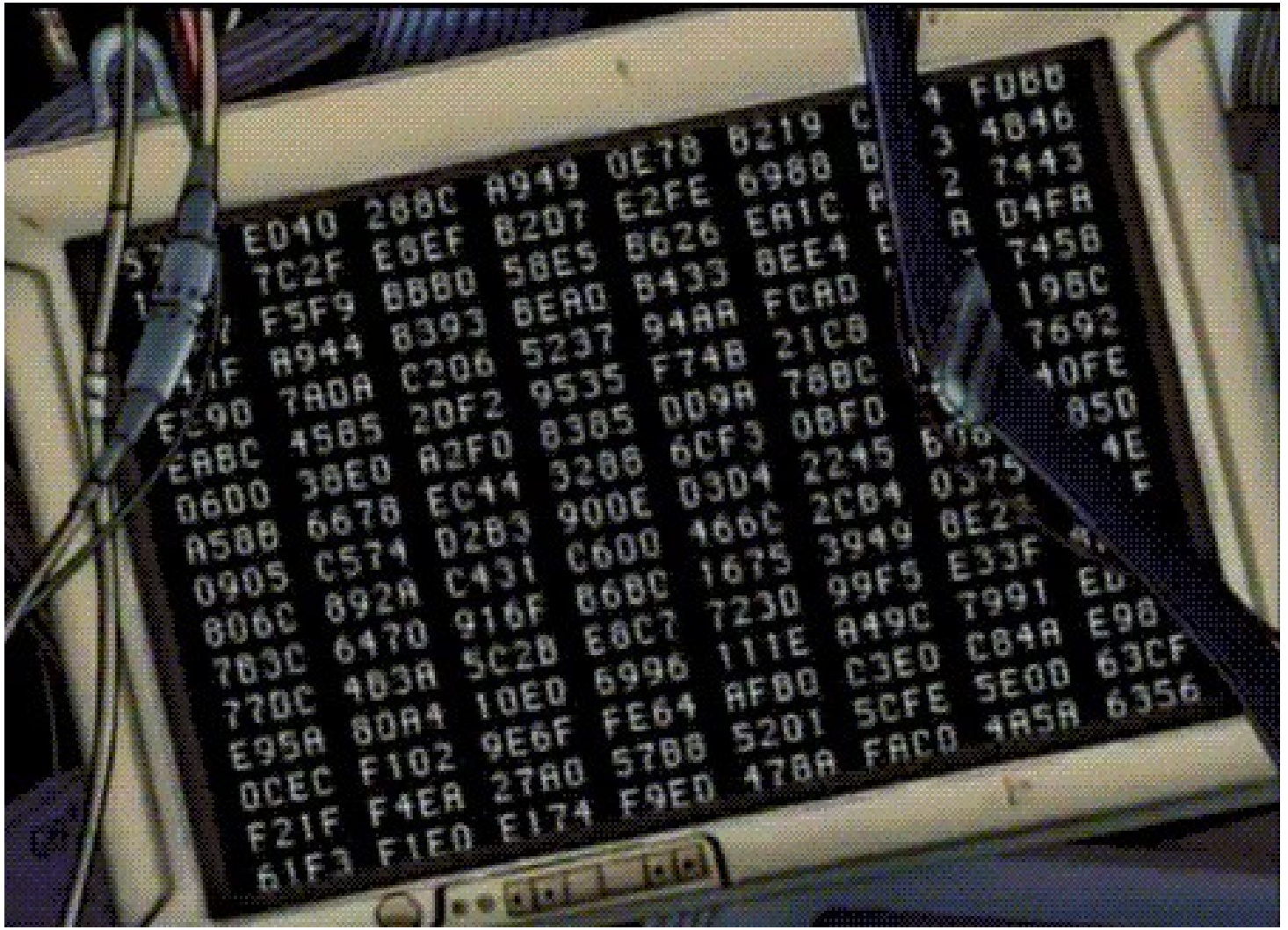
- Generate cap signing keypair (RSA, OpenSSL)
- Sign applet (file with cap, capfile tool)
- Create policy domain (SSD) with MandatedDAPVerification
- Set personalization keys for the SSD (secret symmetric crypto keys)
- Upload verification key for this domain (key version 0x73, public key of your signing keypair)
- Verify that SSD is prepared (DOM, DAPVerification privilage)
- Upload signed applet (*.cap file)
- https://github.com/martinpaljak/GlobalPlatformPro/blob/next/tests/sce70.sh

DEBUGGING APPLET

Martin Paljak
@martinpaljak

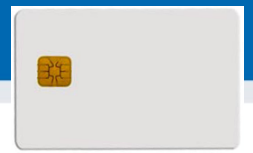
Following

How does smart card programming look like in real life? Here's a typical scenario...



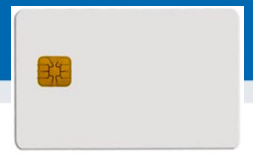
1. Debugging applets: simulator

- The smartcard is designed to protect application
  - Debugger cannot be connected to running application
- Option 1: use card simulator (jcardsim.org)
  - Simulation of JavaCard 3.0.5 (based on BouncyCastle)
  - Very helpful, allows for direct debugging (will be covered in labs)
  - Catch of logical flaws etc.
  - Allows to write automated unit and integration tests!
- Problem: Real limitations of cards are missing
  - supported algorithms, memory, execution speed…



2. Debugging applets: real cards

- Option 2: use real cards
  - Cannot directly connect debugger, no logging strings…
- Debugging based on error messages
  - Use multiple custom errors rather than ISO7816 errors
  - Distinct errors tell you where problem (might) happened
- Problem: operation may end with unspecific 0x6f00
  - Any uncaught exception on card (other than ISOException)
  - Solution1: Capture on card, translate to ISOException
  - Solution2: Locate problematic command by insertion of ISOException.throwIt(0x666); and recompile



Possible causes for exception on card

- Writing behind allocated array
- Using Key that was Key.clear() before
- Insufficient memory to complete operation
- Cipher.init() with uninitialized Key
- Import of RSA key into real card generated by software outside card (e.g., getP() len == 64 vs. 65B for RSA1024)
- Storing reference of APDU object localAPDU = origAPDU;
- Decryption of value stored in byte[] array with raw RSA with most significant bit == 1 (set first byte of array to 0xff to verify)
- Set CRT RSA key using invalid values for given part - e.g. setDP1()
- Too many nested calls, no free space on stack for arguments
- … and many more ☺

Getting more than 0x6f00

```
public void process(javacard.framework.APDU apdu) {
    // ignore the applet select command dispatched to the process
    if (selectingApplet()) return;
    try {
        //
        // ... Standard APDU command dispatching...
        //
    } catch (ISOException e) {
        throw e; // Our exception from code, just re-emit
    } catch (ArrayIndexOutOfBoundsException e) {
        ISOException.throwIt(SW_ArrayIndexOutOfBoundsException);
    } catch (ArithmeticException e) {
        ISOException.throwIt(SW_ArithmeticException);
    } catch (ArrayStoreException e) {
        ISOException.throwIt(SW_ArrayStoreException);
    } catch (NullPointerException e) {
        ISOException.throwIt(SW_NullPointerException);
    } catch (NegativeArraySizeException e) {
        ISOException.throwIt(SW_NegativeArraySizeException);
    } catch (CryptoException e) {
        ISOException.throwIt((short) (SW_CryptoException_prefix | e.getReason()));
    } catch (SystemException e) {
        ISOException.throwIt((short) (SW_Sy
    } catch (PINException e) {
        ISOException.throwIt((short) (SW_PI
    } catch (TransactionException e) {
        ISOException.throwIt((short) (SW_Tr
    } catch (CardRuntimeException e) {
        ISOException.throwIt((short) (SW_Ca
    } catch (Exception e) {
        ISOException.throwIt(Consts.SW_Exce
    }
}
```

Our exception, just re-emit

Some exceptions provide additional information (code). Propagate it further

```
final short SW_Exception                        = (short) 0xff01;
final short SW_ArrayIndexOutOfBoundsException   = (short) 0xff02;
final short SW_ArithmeticException              = (short) 0xff03;
final short SW_ArrayStoreException              = (short) 0xff04;
final short SW_NullPointerException             = (short) 0xff05;
final short SW_NegativeArraySizeException       = (short) 0xff06;
final short SW_CryptoException_prefix           = (short) 0xf100;
final short SW_SystemException_prefix           = (short) 0xf200;
final short SW_PINException_prefix              = (short) 0xf300;
final short SW_TransactionException_prefix      = (short) 0xf400;
final short SW_CardRuntimeException_prefix      = (short) 0xf500;
```

Debugging using custom commands

- Addition of custom commands to “dump” interesting parts of data
  - Intermediate values of internal arrays, unwrapped keys…
- Should obey to *Secure by default principle*
  - Debugging possibility should be enabled only on intention
  - E.g., specific flag in installation data which cannot be enabled later (by an attacker)
  - Don’t let debugging code into release!

NEXT WEEK:
BEST PRACTICES FOR JAVACARD (SECURE MULTIPARTY COMPUTATION)

Summary

- Smart cards are programmable (JavaCard)
  - reasonable cryptographic API
  - coprocessor for fast cryptographic operations
  - multiple applications coexist securely on single card
  - Secure execution environment
- Standard Java 6 API for communication exists
- PKI applet can be developed with free tools
  - PIN protection, on-card key generation, signature…
- JavaCard is not full Java – optimizations, security

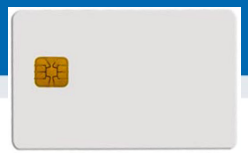
Mandatory reading

- Mandatory
  - IS, Gemalto_JavaCard_DevelGuide.pdf
- Optional
  - Java Card lecture, Erik Poll, Radboud Uni
    - http://ekladata.com/IHWNXUB-yernblD2sdiK1zxxQco/5_javacard.pdf

BEST PRACTICES (FOR APPLET DEVELOPERS)

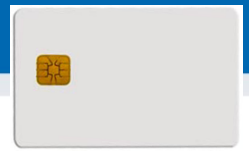
Quiz

1. Expect that your device is leaking in time/power channel. Which option will you use?
   - AES from hw coprocessor or software re-implementation?
   - Short-term sensitive data stored in EEPROM or RAM?
   - Persistent sensitive data in EEPROM or encrypted object?
   - Conditional jumps on sensitive value?
2. Expect that attacker can successfully induct faults (random change of bit(s) in device memory).
   - Suggest defensive options for applet's source code
   - Change in RAM, EEPROM, instruction pointer, CPU flags…



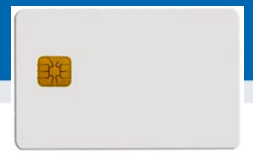
Security hints (1)

- Use API algorithms/modes rather than your own
  - API algorithms fast and protected in cryptographic hardware
  - general-purpose processor leaks more information (side-channels)
- Store session data in RAM
  - faster and more secure against power analysis
  - EEPROM has limited number of rewrites (10^5 - 10^6 writes)
- Never store keys, PINs or sensitive data in primitive arrays
  - use specialized objects like OwnerPIN and Key
  - better protected against power, fault and memory read-out attacks
  - If not possible, generate random key in Key object, encrypt large data with this key and store only encrypted data
- Make checksum on stored sensitive data (=> detect fault)



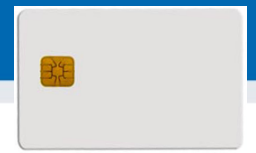
Security hints (2)

- Erase unused keys and sensitive arrays
  - use specialized method if exists (Key.clearKey())
  - or overwrite with random data (Random.generate())
  - Perform always before start of new session
- Use transactions to ensure atomic operations
  - power supply can be interrupted inside code execution
  - be aware of attacks by interrupted transactions - rollback attack
- Do not use conditional jumps with sensitive data
  - branching after condition is recognizable with power analysis => timing/power leakage



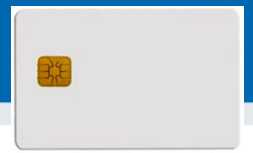
Security hints (3)

- Allocate all necessary resources in constructor
  - applet installation usually in trusted environment
  - prevent attacks based on limiting available resources
- Don’t use static attributes (except constants)
  - Static attribute is shared between multiple instances of applet (bypass applet firewall)
  - Static ptr to array/engine filled by dynamic allocation cannot be removed until package is removed from card (memory “leak”)
- Use automata-based programming model
  - well defined states (e.g., user PIN verified)
  - well defined transitions and allowed method calls



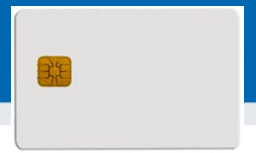
Security hints (4)

- Treat exceptions properly
  - Do not let uncaught native exceptions to propagate from the card
  - Do not let your code to cause basic exceptions like OutOfBoundsException or NullPointerExceptions…



Security hints: fault induction (1)

- Cryptographic algorithms are sensitive to fault induction
  - Single signature with fault from RSA-CRT may leak the private key
  - Perform operation twice and compare results
  - Perform reverse operation and compare (e.g., verify after sign)
- Use constants with large hamming distance
  - Induced fault in variable will likely cause unknown value
  - Use 0xA5 and 0x5A instead of 0 and 1 (correspondingly for more)
  - Don’t use values 0x00 and 0xff (easier to force all bits to 0 or 1)
- Check that all sub-functions were executed [Fault.Flow]
  - Fault may force program stack or stack to skip some code
  - Idea: Add defined value to flow counter inside target sub-function, check later for expected sum. Add also in branches.



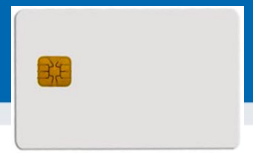
Security hints: fault induction (2)

- Replace single condition check by complementary check
  - **`conditionalValue`** is sensitive value
  - Do not use boolean values for sensitive decisions

```
if (conditionalValue == 0x3CA5965A) { // enter critical path
  // . . .
  if (~conditionalValue != 0xC35A69A5) {
    faultDetect(); // fail if complement not equal to 0xC35A69A5
  }
  // . . .
}
```

- Verify number of actually performed loop iterations

```
int i;
for ( i = 0; i < n; i++ ) { // important loop that must be completed
//. . .
}
if (i != n) { // loop not completed
  faultDetect();
}
```



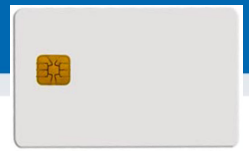
Security hints: fault induction (3)

- Insert random delays around sensitive operations
  - Randomization makes targeted faults more difficult
  - for loop with random number of iterations (for every run)
- Monitor and respond to detected induced faults
  - If fault is detected (using previous methods), increase fault counter.
  - Erase keys / lock card after reaching some threshold (~10)
    - Natural causes may occasionally cause fault => > 1

How and when to apply protections

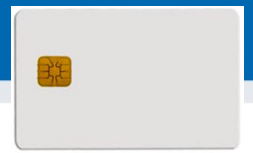
- ✓ Does the device need protection?
- ✓ Understand the resistance of the hardware
- ✓ Identify potential weakness in design
- ✓ Select patterns to use
- ✓ Understand your compiler
- ✓ Code it
- ✓ Test the resistance of the device

Riscure



Execution speed hints (1)

- Big difference between RAM and EEPROM memory
  - new allocates in EEPROM (persistent, but slow)
    - do not use EEPROM for temporary data
    - do not use for sensitive data (keys)
  - JCSystem.getTransientByteArray() for RAM buffer
  - local variables automatically in RAM
- Use algorithms from JavaCard API and utility methods
  - much faster, cryptographic co-processor
- Allocate all necessary resources in constructor
  - executed during installation (only once)
  - either you get everything you want or not install at all



Execution speed hints (2)

- Garbage collection limited or not available
  - do not use **`new`** except in constructor
- Use copy-free style of methods
  - foo(byte[] buffer, short start_offset, short length)
- Do not use recursion or frequent function calls
  - slow, function context overhead
- Do not use OO design extensively (slow)
- Keep Cipher or Signature objects initialized
  - if possible (e.g., fixed master key for subsequent derivation)
  - initialization with key takes non-trivial time

JCPROFILERNEXT – PERFORMANCE PROFILING, NON-CONSTANT TIME DETECTION

JCProfilerNext: on-card performance profiler

- Open-source on-card performance profiler (L. Zaoral)
  - https://github.com/lzaoral/JCProfilerNext
- Automatically instrumentation of provided JavaCard code
  - Conditional exception emitted on defined line of code
  - Spoon tool used https://spoon.gforge.inria.fr/
- Measures time to reach specific line (measured on client-side)
- Fully automatic, no need for special setup (only JavaCard + reader)
- Goals:
  - Help developer to identify parts for performance optimizations
  - Help to detect (significant) timing leakages
  - Insert “triggers” visible on side-channel analysis
  - Insert conditional breakpoints…

Instrumented code (Spoon)

```
// if m_perfStop equals to stopCondition, exception is thrown (trap hit)
public static void check(short stopCondition) {
    if (PM.m_perfStop == stopCondition) {
        ISOException.throwIt(stopCondition);
    }
}
```

```
private void example(APDU apdu) {
  PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_1);
  short count = Util.getShort(apdu.getBuffer(), ISO7816.OFFSET_CDATA);
  PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_2);
  for (short i = 0; i < count; i++) {
    PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_3);
    short tmp = 0;
    PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_4);
    for (short k = 0; k < 50; k++) {
      PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_5);
      tmp++;
      PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_6);
    }
    PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_7);
  }
  PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_8);
}
```

JCProfilerNext – timing profile of target line of code

example.Example.example2(javacard.framework.APDU)

TRAP_example_Example_example2_argb_javacard_framework_APDU_arge_12

Card ATR: 3BFA1800008131FE454A434F5033315632333298
Number of rounds: 1000
APDU header: 80010000
Input regex: 00[0-9A-F]{2}
Elapsed time: 0 days 00:00:02.814
Source measurements: measurements.csv

☐ Show explicit traps

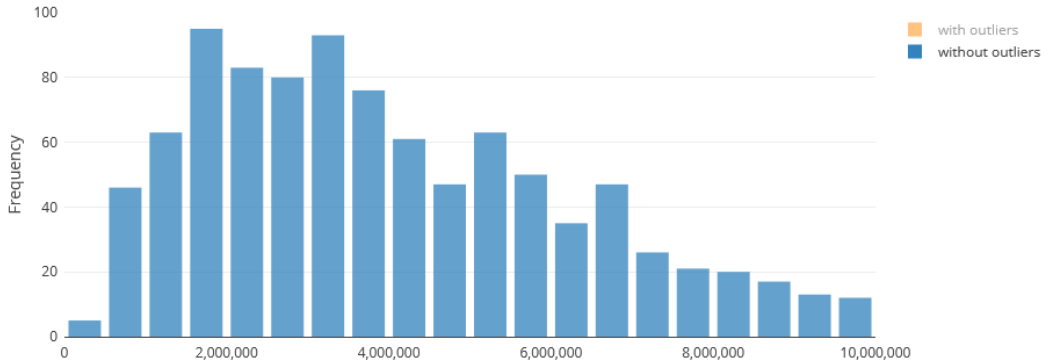
Avg µs

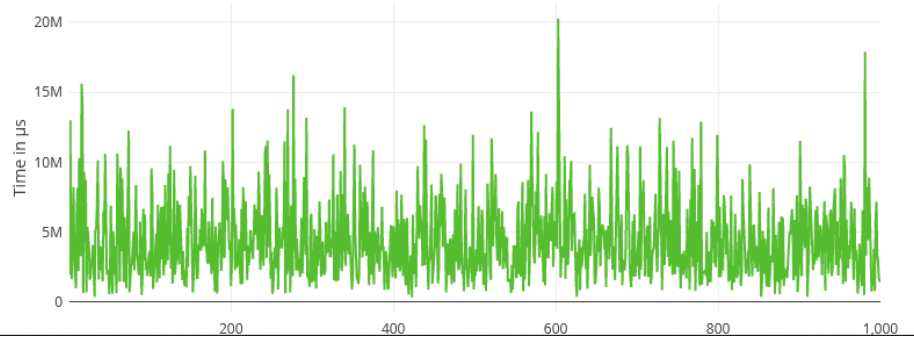
```
1  private void example2(APDU apdu) {
2      byte[] apdubuf = apdu.getBuffer();
3      short dataLen = apdu.setIncomingAndReceive();
4      // SET KEY VALUE
5      m_aesKey.setKey(apdubuf, ISO7816.OFFSET_CDATA);
6      // INIT CIPHERS WITH NEW KEY
7      m_encryptCipher.init(m_aesKey, Cipher.MODE_ENCRYPT);
8      m_decryptCipher.init(m_aesKey, Cipher.MODE_DECRYPT);
9      m_encryptCipher.doFinal(apdubuf, ISO7816.OFFSET_CDATA, ((short) (0x10)), m_ramArray, ((short) (0)));
10     m_decryptCipher.doFinal(apdubuf, ISO7816.OFFSET_CDATA, ((short) (0x10)), m_ramArray, ((short) (0)));
11     // Hash input
12     m_hash.doFinal(apdubuf, ISO7816.OFFSET_CDATA, dataLen, m_ramArray, ((short) (0)));
13     // GENERATE DATA
14     m_secureRandom.generateData(apdubuf, ISO7816.OFFSET_CDATA, ((short) (0x10)));
15     // Sign data
16     short signLen = m_sign.sign(apdubuf, ISO7816.OFFSET_CDATA, ((byte) (dataLen)), m_ramArray, ((byte) (0)));
17     // Generate fresh key pair on-card
18     m_keyPair.genKeyPair();
19     m_publicKey = m_keyPair.getPublic();
20     m_privateKey = m_keyPair.getPrivate();
21     // INIT WITH PRIVATE KEY
22     m_sign.init(m_privateKey, Signature.MODE_SIGN);
23 }
```

Colour explanation

Currently selected trap | Trap was never reached | Trap was reached only sometimes

Click on a bin to get a list of corresponding inputs.





JCProfilerNext – memory consumption

opencrypto.jcmathlib.OCUnitTests()

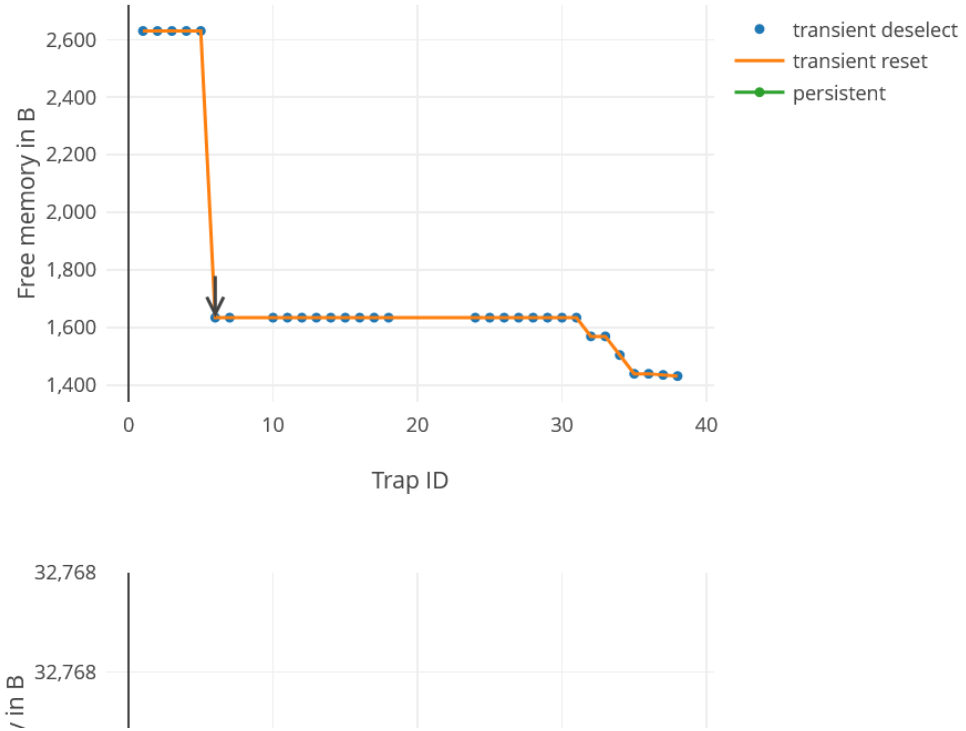
TRAP_opencrypto_jcmathlib_OCUnitTests_argb_arge_6

Mode: memory
Card ATR: 3B80800101
APDU header: measured during installation
Input: measured during installation
Elapsed time: 0 days 00:00:00.294
Source measurements: measurements.csv

☐ Show explicit traps

Diff in B

```
1   public OCUnitTests() {
2       OperationSupport.getInstance().setCard(OperationSupport.SIMULATOR);// TC
3       m_memoryInfo = new short[((short) (7 * 3))];// Contains RAM and EEPROM r
4       m_memoryInfoOffset = snapshotAvailableMemory(((short) (1)), m_memoryInfo
5       if (bTEST_256b_CURVE) {
6           m_ecc = new ECConfig(((short) (256)));
7       }
8       if (bTEST_512b_CURVE) {
9           m_ecc = new ECConfig(((short) (512)));
10      }
11      m_memoryInfoOffset = snapshotAvailableMemory(((short) (2)), m_memoryInfo
12      // Pre-allocate test objects (no new allocation for every tested operat
13      if (bTEST_256b_CURVE) {
14          m_testCurve = new ECCurve(false, SecP256r1.p, SecP256r1.a, SecP256r1
15          m_memoryInfoOffset = snapshotAvailableMemory(((short) (3)), m_memory
16          // m_testCurveCustom and m_testPointCustom will have G occasionally
17          m_customG = new byte[((short) (SecP256r1.G.length))];
18          Util.arrayCopyNonAtomic(SecP256r1.G, ((short) (0)), m_customG, ((sho
19          m_testCurveCustom = new ECCurve(false, SecP256r1.p, SecP256r1.a, Sec
20      }
21      if (bTEST_512b_CURVE) {
```



JCProfilerNext – checking for non-constant behavior

opencrypto.jcmathlib.OCUnitTests#test_BN_MOD(javacard.framework.APDU,short)

TRAP_opencrypto_jcmathlib_OCUnitTests_hash_test_BN_MOD_argb_javacard_framework_APDU__short_arge_10

Mode: time
Card ATR: 3B80800101
Number of rounds: 1000
APDU header: B0252100
Input regex: 00[0-9A-F]{64}[4-7][0-9A-F]{63}
Elapsed time: 0 days 00:58:39.803
Source measurements: measurements.csv

Show explicit traps

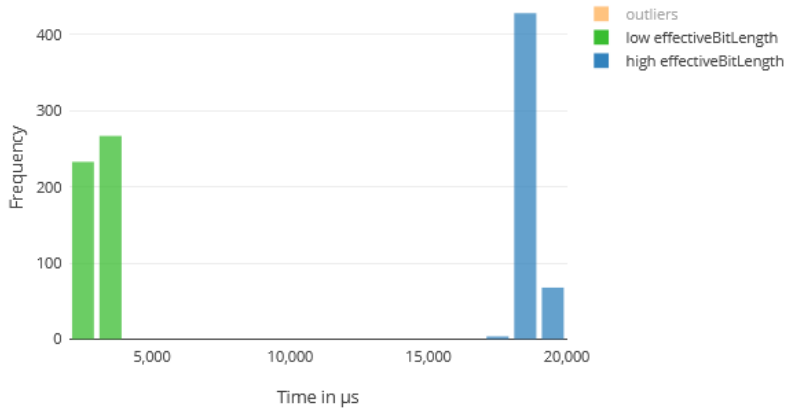
Avg µs

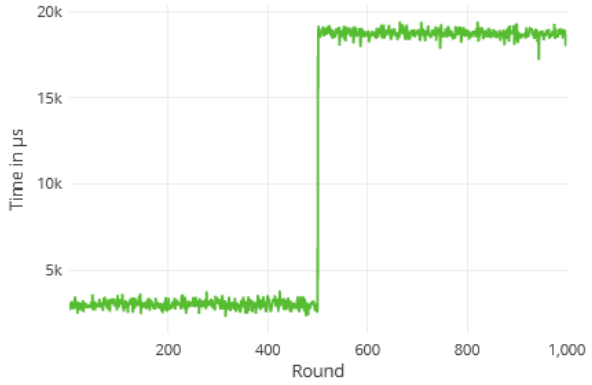
```
1  void test_BN_MOD(APDU apdu, short dataLen) {
2      byte[] apdubuf = apdu.getBuffer();
3      short p1 = ((short) (apdubuf[ISO7816.OFFSET_P1] & 0xff));
4      Bignat num = m_testBN1;
5      num.set_size(p1);
6      Bignat mod = m_testBN2;
7      mod.set_size(((short) (dataLen - p1)));
8      num.from_byte_array(p1, ((short) (0)), apdubuf, ISO7816.OFFSET_CDATA);
9      mod.from_byte_array(((short) (dataLen - p1)), ((short) (0)), apdubuf,
10     num.mod(mod);
11     short len = num.copy_to_buffer(apdubuf, ((short) (0)));
12     apdu.setOutgoingAndSend(((short) (0)), len);
13 }
```

Colour explanation

Currently selected trap | Trap was never reached | Trap was reached only sometimes

Click on a graph item to get a list of corresponding inputs.

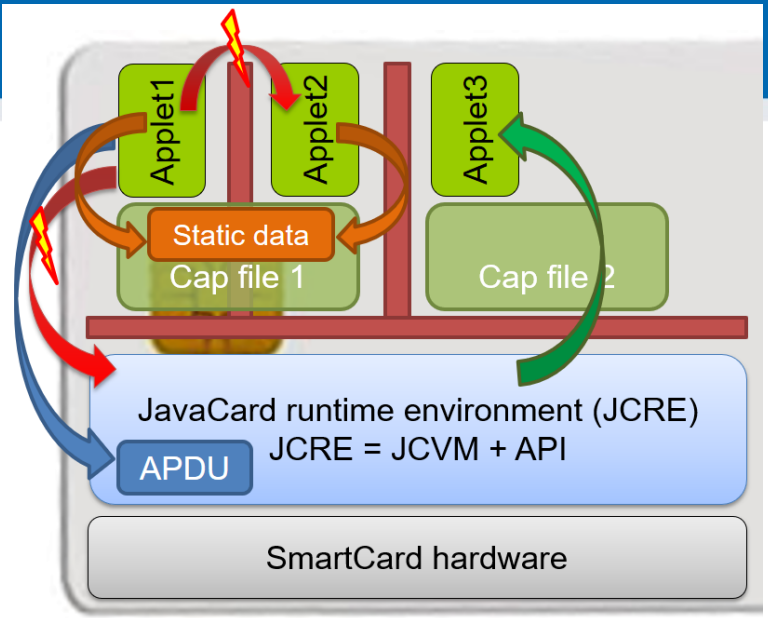




JCProfilerNext – profiling via power measurement

- The default measurement option is host-based timer => imprecise
  - Exception thrown after every line of code, measured with whole roundtrip
- Idea: insert distinct operation visible in powertrace after every line
  - Original code is instrumented with 3xRNG.generateData() instead of exception
  - Powertrace of whole method is captured
  - RNG operations are detected and used as separators
  - Precise timing of operation is obtained
  - Visualization is performed using standard JCProfilerNext pipeline
- More elaborate setup (oscilloscope), but very precise measurement
  - better detection of non-constant-time operations

JavaCard applet firewall issues



- Main defense for separation of multiple applets
- Platform implementations differ
  - Usually due to the unclear and complex specification
- If problem exists then is out of developer's control
- Firewall Tester project (W. Mostowski)
  - Open and free, the goal is to test the platform
  - http://www.sos.cs.ru.nl/applications/smartcards/firewalltester/

```
short[] array1, array2; // persistent variables
short[] localArray = null; // local array
JCSystem.beginTransaction();
        array1 = new short[1];
        array2 = localArray = array1; // dangling reference!
JCSystem.abortTransaction();
```

Relevant open-source projects

- Easy building of applets
  - https://github.com/martinpaljak/ant-javacard
  - https://github.com/ph4r05/javacard-gradle-template
- AppletPlayground (ready to “fiddle” with applets)
  - https://github.com/martinpaljak/AppletPlayground
- Card simulator https://jcardsim.org
- Profiling performance
  - https://github.com/crocs-muni/JCAlgTest
  - https://github.com/OpenCryptoProject/JCProfiler
- Curated list of JavaCard applets
  - https://github.com/crocs-muni/javacard-curated-list
- Low-level ECPoint library
  - https://github.com/OpenCryptoProject/JCMathLib

Summary

- Smart cards are programmable (JavaCard)
  - reasonable cryptographic API
  - coprocessor for fast cryptographic operations
  - multiple applications coexist securely on single card
  - Secure execution environment
- Standard Java 6 API for communication exists
- PKI applet can be developed with free tools
  - PIN protection, on-card key generation, signature…
- JavaCard is not full Java – optimizations, security