Java Card Virtual Machine Memory Organization: a Design Proposal

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Abstract. The Java Card Virtual Machine (JCVM) platform is widely deployed on security-oriented components. JCVM implementations are mainly evaluated under security schemes. However, existing implementation are close-source without detail. We believe studying how to design JCVM will improve them and it can be reused by the community to improve Java Card security.
In 2018, Bouffard *et al.* [6] introduced an Operating System (OS) which aims at running JCVM compatible implementation. This OS is compatible with several Commercially available Off-The-Shelf (COTS) components. This is a first step to design a secure JCVM platform.
However, some important details are missing to design a secure-oriented Java Card platform. In this article, we focus on the JCVM memory. This memory contains everything required to run JCVM and applets. Currently, JCVM memory is out of the Java Card specification and each JCVM developer use his own approach. Based on the existing tools and documentation, we explain how to extract from the Java Card toolchain every data required by applets and JCVM. When data to store in memory are identified, this article introduces how to organize required data onto JCVM memory.

Keywords: Java Card, Virtual Machine, Design, Memory Organization

1 Introduction

Java Card [36] is a Java subset designed to run on resource-limited devices such as secure components or IoT devices. It implements a Virtual Machine (VM) to run Java applications in a portable and secure environment. Java Card platforms aim at running security-oriented applications where a high security level is required both on physical and software layout. Therefore, most of Java Card Virtual Machine (JCVM) implementations are evaluated within the Common Criteria scheme [37]. However, these implementations are closed source without details.

The Java Card platform implementations security has been studied against hardware [3,1,2,12] and software [10,7,17,31,40,21,27,20,22,23,28] attacks. For every attack, efficient countermeasures are presented. However, they are implementation-dependent. Currently, there is no public reference implementation to compare these countermeasures. Therefore, we think a JCVM public implementation design where the community can contribute will improve the Java Card security.

To propose implementation design to a community, one should target a platform easily accessible to evaluate and improve the existing solutions. For this purpose, Bouffard *et al.* [6] have introduced an Operating System (OS) designed to support JCVM specificity. Their OS exposes security features based on hardware mechanisms embedded on most Commercially available Off-The-Shelf (COTS) components. Therefore, the next step would be to design a secure-oriented JCVM which reuses the features provided by this OS.

In this article, we focus on how to organize the JCVM memory. The JCVM memory contains everything required to run the JCVM and Java Card applications. Therefore, the JCVM memory is composed of the Java Card standard and vendors' Application Programming Interface (API), GlobalPlatform manager and applications code and other data. How to organize the JCVM memory is not analysed by the literature and should be studied to improve the security JCVM. Based on the existing tools and the corresponding documentations, we propose a way to initialize and organize the Non-Volatile Memory (NVM) memory usable by a JCVM implementation.

1.1 Java Card Platform

Java Card technology is a secure-oriented platform designed to be embedded in resource-limited devices where a high security level is required. To ensure this, security mechanisms are embedded both inside and outside the JCVM. On the one hand, outside the JCVM, organizational security rules aim at preventing from loading malicious applications. On the other hand, the JCVM embeds several platform security features. The Java Card security model is described in section 1.1. However, before presenting it, an overview of the JCVM architecture is introduced in section 1.1.

Java Card Architecture The JCVM architecture shown in figure 1, is inspired by the Java Virtual Machine (JVM), where each application developed in Java runs onto the Java Card Runtime Environment (JCRE). Each application, named applet, can only execute functions from the Java Card API provided by the platform.

Calling native API from Java Card applet To call the native code from the Java code, the JVM has an interface, named Java Native Interface (JNI). Unlike JVM, calling native codes from Java Card applets is not allowed by the JCVM [36,

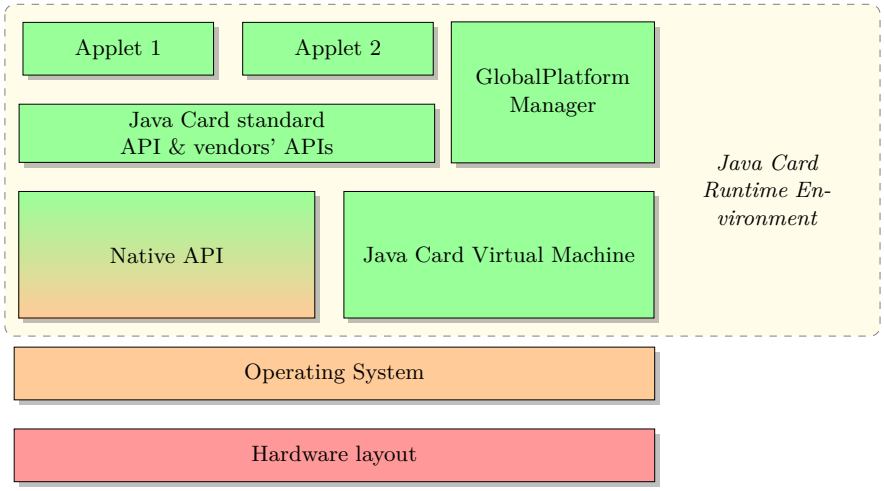

Fig. 1. Java Card architecture.

section 3.3]. There is no specified path to call this kind of code. However, specific features, like cryptographic aperations, needs to be run natively for security or efficiency matters.

Some Java Card platforms such as NXP JCOP allow the native code to be loaded. This native code is executed in a proprietary sandbox called SecureBox [32]. This feature is a proprietary implementation designed by the platform developers out of any public specifications.

GlobalPlatform Manager At the application level, a content manager is used to strengthen security in the environment. The GlobalPlatform specification [18] helps system developers who want to implement features widely spread across the market. Besides content and permission administration, such measures include platform and applications state management, internal and external communications protection, and inter-applications services supervision. These features are often integrated within a daemon, which must always be available at runtime. GlobalPlatform security managers tend to be useful to platform manufacturers and operators, since they allow them to specify their own policies and rules concerning the platform.

Java Card security model As described in figure 2, to install an applet on the Java Card platform, one must first implement it in Java-language and then build it within Java compiler (`javac`) to obtain Java `class` files. Those `class` files are not designed to be embedded in a resource-limited device. Indeed, the Java `class` files are executed as-is with a link resolution by name. This kind of resolution is expensive. The adopted solution was to translate the Java-Class name to token during a step made by the Java Card converter, included in the

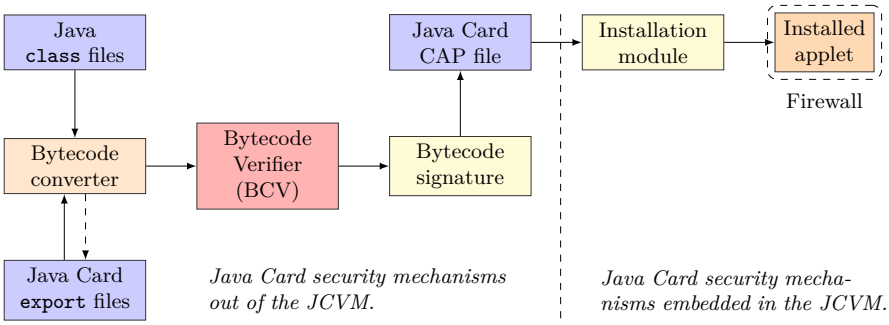

Fig. 2. Java Card security model.

public Java Card toolchain[1]. If the `class` file to convert shares features usable by other applications, a Java Card `export` file is also generated. The `export` file contains, for each Java name element, the associated token embedded on the device. Therefore, the `export` files are also used by the bytecode converter during the translation process. After this translation, the Java Card files are checked by the Bytecode Verifier (BCV) which statically verifies the compliance to the Java Card security rules. The translated Java `class` files are named the CAP (for Converted APplet) file. There is a unique CAP file by converted package, and it is signed to ensure its integrity and authenticity. On the device, the GlobalPlatform layer verifies the applet signature.

When the applet CAP file is obtained and signed, the applet developer needs GlobalPlatform loading keys to load their applet or API. During the installation process, an embedded security module checks some security elements. As this verification is not described by the Java Card specification [36] some works focus on reversing this process [9,30]. After the applet is installed, it runs in its context segregated by the Java Card Firewall. It ensures that the applet accesses only its data or specific shared features.

1.2 Related works

Contributions about Java Card mainly focus on about how to protect JCVM implementations by proposing countermeasures [41,13,38,7,1,5,43,16]. To improve Java Card, few works study how to develop JCVM from scratch.

To securely develop a JCVM, two approaches have been explored. On the one hand, some works design hardware blocks regarding Java Card security requirements. These hardware blocks aim at protecting the runtime environment. Lackner *et al.* designed mitigation to prevent type confusion onto the stack [24,25] and the heap [8]. In his master's thesis, Zelle [46] describes how to protect the

[1] The Java Card toolchain is available on the Oracle's website: `https://www.oracle.com/java/technologies/java-card-tech.html`

Java Card firewall through a Memory Protection Unit (MPU). However, these approaches are based on hardware mechanisms implemented on FPGA. Based on proprietary extensions, these approaches cannot be used on COTS components.

On the other hand, software approaches are also studied to securely design a JCVM. Dufay [14] has developed a formal proof of the JCVM platform design based in Coq-language able to generate compiled code. However, his work is based on an old version of Java Card and the developed formal model is partially available in his thesis and articles; it's not enough to generate a JCVM implementation. Lafer [26] develops a JCVM with x86 and 8051 implementations. This work seems interesting, however, the master thesis suffers from missing implementation details and no source code is provided. Recently, Bouffard *et al.* [6] introduce an OS in Rust-language to run a JCVM implementation. Their OS provides backend to support recent JCVM.

1.3 Contribution

Every listed article in section 1.2 introduces very little details on JCVM internals. These details are not enough to develop a JCVM and should be developed to improve the Java Card implementation security. In this article, we address the problem of memory organization usable by the JCVM to store and to manipulate data. This part is a first step to design a secure-oriented Java Card platform.

Based on public information, documentations and literature, this article targets how to generate JCVM memory and how to organize it regarding Java Card expectations. Figure 3 summarizes each step required to generate the JCVM initial memory state and dependences with JCVM implementation. Our contribution corresponds to the part (3). Parts (1) and (2) correspond to an extraction of the Java Card specifications [36,34,35,33] and GlobalPlatform specification [18]. Therefore, our contribution includes:

1. Which information should be extracted from every Java Card source code? Some information are the outputs of the Java Card toolchain. However, in case of native methods in Java source code, the Java Card toolchain cannot generate binary files. Indeed, the Java Card specification does not define how to handle Java native code [36, section 3.3]. Therefore, in every case, we described how to generate binary information to put in memory and how to organize inside them.
2. Based on results of case 1, we introduce how to organize the JCVM memory. We designed a filesystem adapted to Flash memory. This filesystem is designed to support the Java Card specificities where Java Card code and data are stored.

Figure 3 highlights the three parts that describes article's outline.

– Part (1) lists requirements to execute JCVM and applets. Based on the Java source code, section 2.1 introduces the Java Card API, GlobalPlatform manager and applets code architecture.

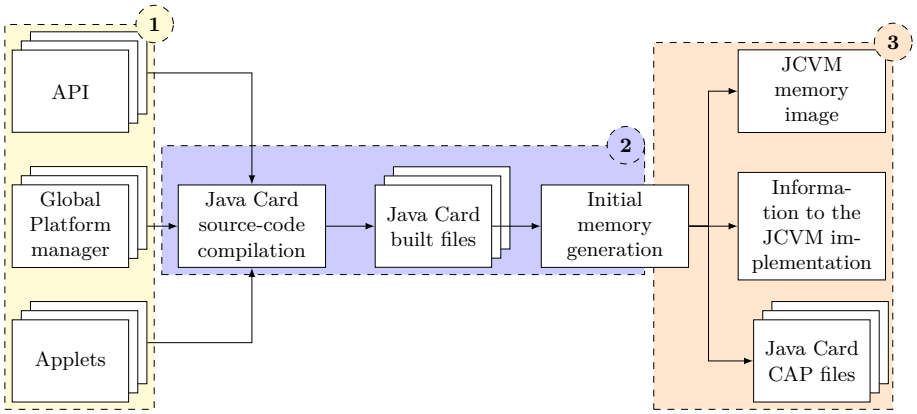

Fig. 3. Java Card initial memory generation overview.

- Part (2) introduces the compilation process. Since inputs introduced in part (1) are built, required information should be extracted and put in JCVM memory. This part is presented in the section 2.2.
- Part (3) is the article contribution. Based on the part (2) results, we define three outputs:
  - the JCVM memory image. This image aims at setting up the JCVM Flash memory. This image contains required elements (APIs, GlobalPlatform manager, applets and other data) to run the Java Card platform;
  - information requires by the JCVM to use the memory image. This information is a representation of elements stored in the memory image. This output should be linked to the JCVM source code during the compilation process. For instance, this information includes the list of native function tokens provided by the API;
  - and a way to check if the generated elements in the JCVM memory image are compliant with the Java Card security rules. This verification is done by the BCV.

  Section 3 describes the information extracted from the Java Card built files. Section 4 explains how to organize this information in memory upon a filesystem. Section 5 presents our design on a ARM platform. Section 6 concludes this article with future works.

2 JCVM and Applets Requirements

The first step of our work is to design the JCVM requirements to run. From the figure 3, it is parts (1) and (2), that includes:

- the API required to execute each Java Card applets correctly,
- the GlobalPlatform manager

– and few applets can be included in the target's NVM. These applets may also be installed over the air through the platform installer if available.

In this section, we focus on how the Java Card source code is organized and how to build and to extract binary information required to generate initial memory.

2.1 Java Card Platform requirements

The Java Card platform is composed of the Java Card API, specified by Oracle [35], and the GlobalPlatform one [18]. To rely on the security provided by the Java Card platform, this API should be developed in Java-language. This section introduces the part (1) of figure 3.

Java Card API The Java Card API is a set of functions required to execute Java Card applets. The Java Card API is split into three packages: `java`, `javacard` and `javacardx`. First, the `java` package contains the Java required classes in order to run Java language baseline as `Exception` or remote methods. Next, the `javacard` package exposes the Java Card specific features as Application Protocol Data Unit (APDU) access or biometry functions. Finally, the `javacardx` package contains the Java Card features subject to export restrictions.

GlobalPlatform manager A GlobalPlatform-compatible security manager must provide an API capable of processing various types of requests. This API has to organize its functions and interfaces into several parts. Figure 4 represents some of these components in a correct, specification-compliant structure. All the API's content must be organized under the `org.globalplatform` package.

The framework is composed solely of interfaces, except for one class, `GPSystem`. It is frequently a starting point for third-party platform contents as it provides required instances to benefit from various features. It also allows an application to query information about itself or the platform in general, including life-cycle states.

`GlobalService` is an interface needed to query a service from an application offering global services. An instance of it must first be obtained from `GPSystem`, and then used to claim a Shareable Interface Object (SIO), which, itself, can provide the desired actions. While the `GlobalService` interface's content is known and specified, the content of the SIO is up to the global service application, and the receiver is expected to be aware of it.

In order to get information from the GlobalPlatform registry or even modify an entry, a third-party program must get an instance of the `GPRegistryEntry` interface from the `GPSystem` class. It will then be able to query data from the registry (such as its own life cycle state or the platform's one, its own Application Identifier (AID)), grant privileges to it or other applets, register services or

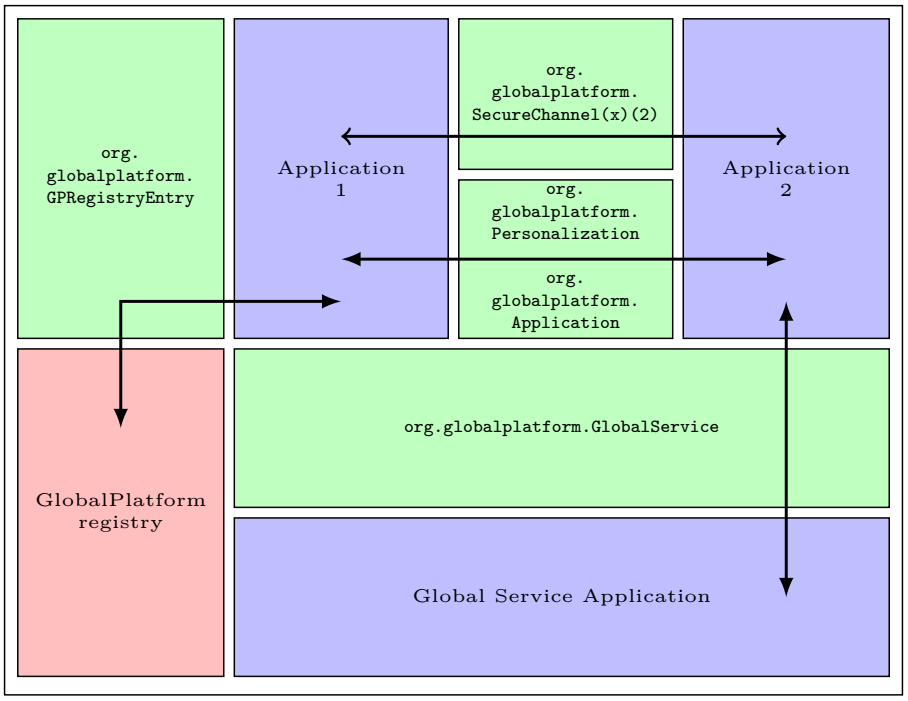

Fig. 4. Depiction of an accurate use of the GlobalPlatform API at runtime. Applications are represented in blue color, interfacing tools are in green, while the GlobalPlatform registry, as a database component, is red.

relationships with other embedded applications. Modifying entries can be possible depending on the type of affected data and the permission granted to the claimant.

Secure channels are an important feature designed by the GlobalPlatform specification. It allows applications to delegate security measures for communications, such as encryption or decryption, authentication, and security levelling. Therefore, the developer can rely on the trusted entity to take responsibility for all these aspects. An instance of the `SecureChannel` interface, or its two extensions `SecureChannelx` and `SecureChannelx2` can be obtained *via* `GPSystem`.

In case cross-application communication is needed, the `Application` and `Personalization` interfaces provide a mechanism where the implemented applet can simply receive data. The latter also allows outputting a response. In contrast to what the names might suggest, it can be used for any type of message.

As described in [15], an Hypertext Transfer Protocol (HTTP) session can be set up to simplify administration. An implementation of `HTTPAdministration` can ask for initialization and get notified with the end result if `HTTPReportListener` is also implemented.

A platform owner verification is usually required before conducting a sensitive operation. A Cardholder Verification Method (CVM) is generally provided as a global service through a `CVM` interface.

Finally, `Authority` and `AuthoritySignature` are interfaces that, once implemented, result in global services performing data signing and key recovery at the request of applications.

2.2 Building Java Card Source Code

After being developed, the Java Card API, GlobalPlatform manager and applets have to be built to be included into the JCVM memory. This step matches to figure 3 part (2) and aims at creating the initial state requirements used by the JCVM implementation.

Building API from Scratch The Java Card building process is summarized in figure 5. When an applet developer builds its code (its own API or applets), he must use the API provided information for the target to link his code. For instance, Oracle provides Java Card API `class`[2] and `export` files in the Java Card SDK. It is the API image used by the compiler to build Java `class` files and, according to the `export` files, the Java Card Assembly (JCA) files.

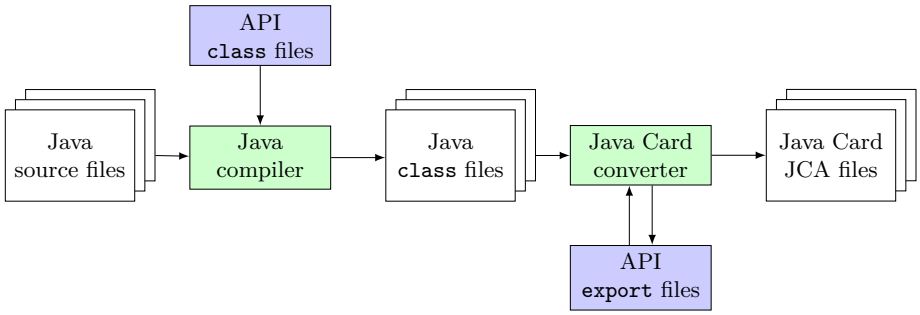

Fig. 5. Java Card building process from Java source files.

In this work, we aim at having a reproducible compilation process with minimal external dependencies. Decreasing the external dependencies reduces the risk to import buggy code. However, the code to build should be analysed to avoid security issues.

Most of the Java Card API packages are dependent between them. In order to find the best compilation order, we analyse their dependencies. It turns out that the Java Card API must be built in this order:

[2] These `class` files only contain the method signatures.

1. `java.lang`
2. `java.io`
3. `java.rmi`
4. `javacard.framework`
5. `javacard.framework.service`
6. `javacard.security`
7. `javacardx.crypto`
8. `javacardx.biometry`
9. `javacardx.external`
10. `javacardx.biometry1toN`
11. `javacardx.security`
12. `javacardx.framework.util`
13. `javacardx.framework.math`
14. `javacardx.framework.tlv`
15. `javacardx.framework.string`
16. `javacardx.apdu`
17. `javacardx.apdu.util`

The `export` files need building just after compiling the `class` files. The Java Card converter next translates `class` files to Java Card file using information contained in the `export` files. As indicated in section 1.1, the Java Card converter outputs CAP by default. However, as native methods declaration may have been declared in the Java Card API, CAP files cannot be built. Native methods are not supported in the CAP file [36]. Therefore, an intermediate file format must be used: the JCA files. So, for each API and GlobalPlatform package, a JCA file is obtained.

Parsing the JCA Files Now that the pool of JCA files is obtained, it should be parsed to extract required information to generate the JCVM initial memory.

The JCA file is a text file generated by the Java Card converter as a human representation of the CAP file. This file is not executable as is.

A syntax analyser must be developed to exploit the information contained in this file. The JCA file can be compiled into a CAP file using the Java Card converter.

Oracle publicly and partially defines the JCA file in the Java Card development kit [33] through a simple example. As introduced in the development kit, the JCA file contains the following information for a Java Card package:

- imported packages: the package Identifier (ID) required by the current one;
- declared applets references;
- constant pool with type of each element used in each class's methods;
- classes and interfaces associated with the current package. For each class or interface, we have:
  - fields declaration;
  - virtual methods tables;
  - interfaces table;
  - remote interfaces table;
  - implemented methods with their bytecodes.

To parse the JCA file, we propose to use the `javacc` lexer [19]. This tool, developed in Java, generates, from a Backus-Naur form (BNF) grammar, a Javaparser library. So, to parse the JCA file, the grammar must be defined. In the Oracle's development kit [33], Oracle points out that this grammar is available

in the "*source release*" version. As this version is not public, we do not have access to it.

To write the BNF grammar of the JCA file, we have played with the compilation parameters and the program to build. We analyse how the Java method accessors (`native`, `final`, *etc.*) and tokens are organized and so on. Therefore, we developed a set of Java Card application codes where each Java keywords are used. Next, we analyse the obtained JCA files to understand the relationship between each keyword and its representation in the JCA file. Listing 1.1 gives the big picture of the JCA file grammar.

Listing 1.1. An overview of the JCA file.

```
.package PACKAGE_NAME {
  .aid PACKAGE_ID
  .version MAJOR.MINOR
  .imports { [LIST OF (PACKAGE_ID VERSION_MAJOR.MINOR)] }
  .applets { [LIST OF (CLASS_ID classname)] }

  .constant pool
    { [ENTRIES OUT OF CURRENT PACKAGE] [ENTRIES IN THE CURRENT
        PACKAGE] }

  .class [ACCESSOR] [abstract] [final]
                    classname [extends (NAME | TOKEN)]
    { [IMPLEMENTED SHAREABLE INTERFACES]
      [IMPLEMENTED REMOTE INTERFACES]
      [FIELDS LIST]
      [PUBLIC & PACKAGE METHOD TABLES]
      [IMPLEMENTED INTERFACE METHODS LIST]
      [IMPLEMENTED REMOTE METHOD INTERFACE METHODS LIST]
      .method [ACCESSOR] [abstract] [static] [final] [native]
        METHOD_SIGNATURE [token]
          { METHOD HEADER [METHOD BYTECODES]
                          [METHOD EXCEPTION HANDLER] }
} }
```

To understand this grammar, let's us explain how to read it:

- words in uppercase signify a set of different information hidden for better reading;
- words in lowercase define the constant string value used as-is in the JCA file;
- Sentences between square brackets point optional elements;
- Sentences between parentheses refer to mandatory element;
- The `|` indicates a logical OR between the occurrence of each element as (A|B) for (A or B).

Since this grammar is given to `javacc`, we obtain a Java library which allows us to parse JCA files.

3 Extracting Information from Java Card API

Since we can parse JCA files, we should analyse it to generate the initial data. This section aims at introducing the figure 3 part (3) to define efficient initial state outputs.

The initial memory generator has three outputs:

- Information to the JCVM implementation given as a C-header file, named `jni.h`. This file contains a generated native method dispatcher, declaration of native methods to implement and the triple (package ID, class ID, method ID) to call the starter. A part of this file is described in section 3.1;
- The Java Card CAP files. This output offers a way to verify generated CAP files with the Java Card BCV. The initial state generator fills the CAP file structures from the parsed JCA files. To ensure the correctness of this translation, CAP files are generated to verify them as explained in section 3.2.
- The JCVM initial state memory image via a binary file used to set the target's NVM. This output is introduced in section 4;

A JCA file is a comprehensible human version of the CAP file and contains the same information. When building a binary version of all the JCA files, the simple solution is to translate each of them to a CAP file. As the CAP file is executable as-is by the JCVM, this translation may be enough. However, some elements such as Java native method cannot be represented in the CAP file.

3.1 Native Methods Call

The Java Card specification does not define any way to call the native method. However, it defines two bytecodes, `impdep1` and `impdep2`, as:

> "*The two reserved opcodes, numbers 254 and 255, have the mnemonics* ***`impdep1`*** *and* ***`impdep2`****, respectively. These instructions are intended to provide "back doors" or traps to implementation-specific functionality implemented in software and hardware, respectively.*"
>
> (JCVM specification [36, Section 7.2])

`impdep1` and `impdep2` instructions offer a standard way to execute a piece of code outside the JCVM sandbox. To the best of our knowledge, none of JCVM developers use these instructions on their VM implementation. Thus, we choose these instructions to be a part of the mechanism to call native code from the JCVM.

Therefore, in order to call native code, an offset of the native method to execute should be pushed on the Java Card stack before executing the `impdep` instruction. As the Java Card stack contains 2-byte words, we can thus encode native method offset on 2-byte without footprint overweight. Therefore, we

choose to push a 2-byte offset to have enough index. With 2-byte offset, we can call up to 65 535 native methods. The associated native methods will be called through a switch-case statement. Figure 6 gives a global overview of the process we have developed. If an unused token is called, the `default` statement will be executed, and a security exception will be thrown.

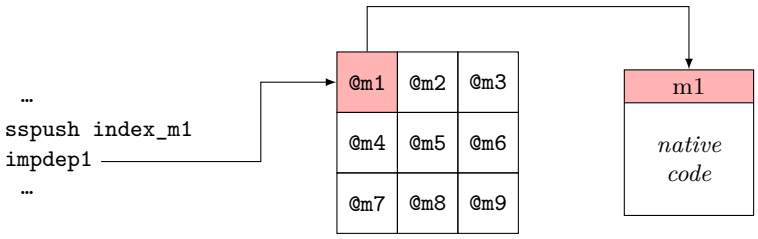

Fig. 6. Calling native code.

For this behaviour to be obtained, a dispatcher method named `callJCNativeMethod` is generated. It requires as parameters the current Java Card context and an index to the native method to call. The index is arbitrarily determined by the initial state generator where the first native method found by the parser has the index 1 and so on. We rely on the JCVM implementation to check whether the current Java Card context is allowed to execute the associated native method.

As an example, let's consider the Java native `myNativeMethod` method in listing 1.2. This method is called by `executeNative` method which has two-byte parameters.

Listing 1.2. Calling native method from Java point of view.

```
class MyClass {
  native short myNativeMethod(byte p1, byte p2);

  void executeNative() {
    byte p1 = 0xCA, p2 = 0xFE;
    short ret = myNativeMethod(p1, p2);
} }
```

After building `MyClass`, the `jni.h` file is generated and contains the JCVM to native methods dispatcher and native methods signature to implement. A part of the `jni.h` file is shown in the listing 1.3.

Listing 1.3. Native method dispatcher and native method to implement in `jni.h`.

```
1 extern jshort_t MyClass_myNativeMethod (jbyte_t p1,
2                                         byte_t p2);
3 // ...
4 void callJCNativeMethod(Context& context, jshort_t index) {
5   Stack& stack = context.getStack();
```

```
6   Heap& heap = context.getHeap();
7   switch(index) {
8     case MYCLASS_MYNATIVEMETHOD: {
9       jbyte_t p2 = stack.pop_Byte();
10      jbyte_t p1 = stack.pop_Byte();
11      jshort_t ret = MyClass_myNativeMethod(p1, p2);
12      stack.push_Short(ret);
13      break;
14    // ...
15    default:
16      // If the native method index is unknown, a Java Security
            Exception must be thrown!
17      throw SecurityException();
18 } } }
```

In listing 1.3, the `myNativeMethod` method execution is made from line 9 to 12. The first two lines (9 and 10) push all parameters from the Java Card stack to the C-stack required to execute the native method. On line 11, the native method is executed and its returned value is saved and pushed on the Java Card stack (line 12). For each native Java method, our tool generates this kind of fragment of the code required to jump from the Java Card side to the native one. As the native method is declared as `extern`, we rely on the JCVM developer for implementing it. Thus, the C-compiler will link the dispatcher calls to the native method implementations.

As this piece of code is executed out of the Java Card sandbox, it should be segregated by the OS to protect the system if malicious code is running. Bouffard *et al.* [6] proposed to use the component MPU to ensure this security property.

3.2 Creating the CAP Files Structures

As introduced in section 1.1, the CAP file is designed to be executed as-is by the JCVM. To be compliant with this architecture, we parse the JCA files to fill the CAP structures.

The CAP File The CAP file is based on components. It possesses ten standard components: Header, Directory, Import, Applet, Class, Method, Static Field, Export, Constant Pool, Reference Location and one optional: Descriptor. Moreover, the targeted JCVM may support user custom components. We exclude the Debug component because it is only used on the debugging step and it is not loaded in the platform. Each component is interconnected. Figure 7 summarizes the dependencies between each component.

From the JCA to the CAP File From the JCA file grammar in listing 1.1, one sees that this file contains partial information to build the CAP file. This information should be parsed and analysed to fill the CAP component. From the

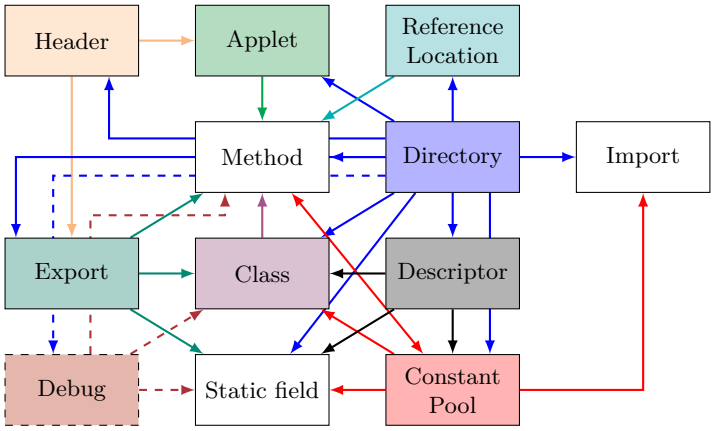

Fig. 7. CAP components dependencies. A component pointed is referenced by the component at the other extremity of the arrow. Only the Method component has a double dependency on Constant Pool component. A token in the Method component refers to an entry in the Constant Pool component which may refer to a method in the Method component. Dashed arrows link dependencies to or from debug component.

JCA file, we can build Static Field, Import, Method, Constant Pool and Class components. The Export component is built from the Static, Method and Class components. The Descriptor component is constructed based on the content of Constant Pool and Class components. Reference Location component is generated based on the Method component. Applet component is built from the JCA file and the offset of the Method component. The Header component is based on Applet, Class and Export components state. Finally, the Directory component contains the size of all other components. Figure 8 synthesizes the CAP components construction order.

To fill the CAP structures and to ensure the coherence between components, we base this step on the Java-library CapMap[3].

Testing the Generated CAP Components To verify the coherence of the generated CAP components, each of them must be verified by the Java Card BCV. Included in the Java Card SDK, the BCV aims at checking the structure and the semantic for the input CAP file. An `export` files for each imported package is required to process this analyse.

In our setup, CapMap gives us CAP files to be verified by the BCV. The `export` files are obtained during the compilation of the Java source files. However, the CAP files which contain `impdep1` or `impdep2` bytecodes cannot be verified. Indeed, the BCV does not know the associated semantics of these in-

[3] Available on: `https://bitbucket.org/ssd/capmap-free`

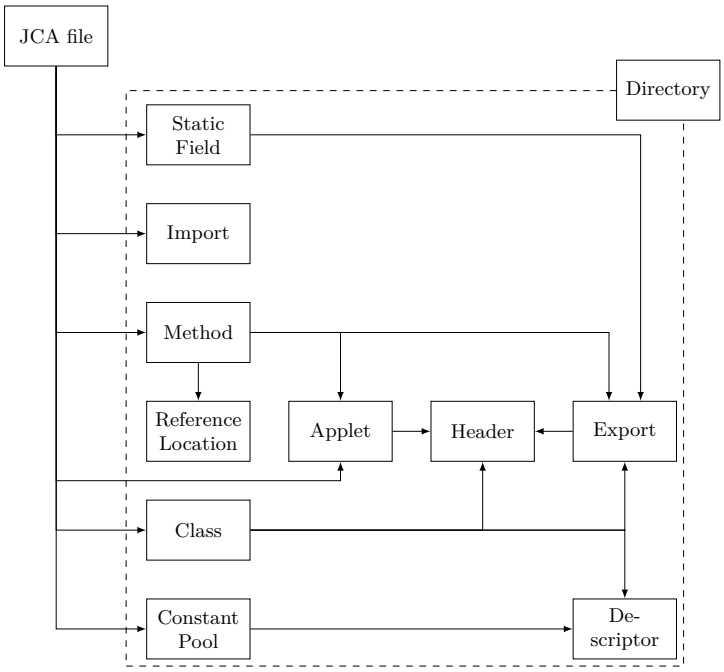

Fig. 8. CAP components construction order. Arrows specify information propagation from the JCA file to each CAP components.

structions nor which values are popped and pushed.

To decrease the number of unchecked packages by the BCV, we recommend separating native methods in a specific package which only contains signature of native methods to implement. Therefore, except for this package, each other must be successfully validated by the BCV.

4 Java Card Initialization Memory Image

The Java Card initialization image is a binary blob which contains enough data to set the target's NVM and start the JCVM instance. That includes at least:

- Packages table where each installed package is listed. This table should be used to check if a package is present or not. This table is mainly provided for optimization;
- Applications (API, GlobalPlatform manager and applets) serialized data: the data to serialize were obtained as explained in the previous section;
- Non-null static fields initial values: on Java Card, static fields are accessible (read and write) by all contexts. Therefore, we decided to put this data out of the application memory area to rely on the JCVM implementation for

checking access rights. Indeed, application code can only be read whereas the static fields which can be read and written;

For each of these elements to be stored, a file system has been designed. This file system aims at providing an easy access to NVM organization. On recent microcontrollers, the NVM is mainly Flash memory.

4.1 File System Constraints on Flash Memory

The Flash memories embedded in the microcontroller are divided by sectors. Each sector might not have the same size, nonetheless it is always a power of 2. Each Flash bit can move from 1 to 0 when a writing operation happens. However, to shift a bit from 0 to 1, all the sector must first be erased, then set to 1.

On an advanced microcontroller, Flash memory can be split in two same size banks, divided in same number of same size sectors. The banks can be exchanged to roll back to the previous system state when an error on a sensitive operation occurs. For instance, the Wookey project [4] uses this functionality on the update system to restore the previous version when an update fails. Flash memory banks are out of the scope of this work and we rely on the JCVM implementation for switching between them. Therefore, the initial state generation aims at generating the initial state of the main Flash bank.

4.2 Related Works on File System for Flash Memories

For efficient storage of data in Flash memory, a file system should be adapted. A first step is to check the state-of-the-art Flash file system to find the best ratio metadata length to data access speed.

Included in the Linux kernel, several file systems designed for the Flash memory have been developed. For instance, we can cite JFFS2 [45], YAFFS [44], UBIFS [42] or LogFS [11] developed to access to the Flash memory directly. These file systems are the main ones used to manage the content of Flash memories. However, they require more memory than limited-resource IoT devices have. For this reason, we developed a small-memory footprint file system according to the Java Card requirements.

4.3 Design of the File System

The file system we designed requires a hash table, stored only in Random Access Memory (RAM), and rebuilt at each microcontroller starts by scanning the entire Flash memory. This hash table is a structure contains the size and the address of each valid block in Flash memory. This approach is possible due to its small size.

The writing operation consists in adding a block in Flash memory with the new key and content value and updating the hashtable in RAM. The update

of the content value will then be automatically taken into account at the next startup, thanks to the full scan of the Flash memory. In order to make the operation atomic, few details should be taken into account. First, a block will be written in memory and it is tagged as an invalid data. Next, block is tagged as valid when the block writing process is finished. Moreover, each block is assigned a checksum to manage a card withdrawal risk in the middle of an erasure operation, which could leave the platform in an undetermined state.

Since the only operations available are to add a new block in a sector and to erase a whole sector, sectors will naturally fill-up. It is therefore necessary to remove the blocks marked invalid at some point. The method chosen to carry out this operation is to copy each block that is still valid into another sector; as if the block had been modified, and, therefore, benefiting from the same atomicity guarantees. Then, one erases the Flash sector that no longer contains a valid block.

It is necessary to ensure we always have enough Flash space to perform this "defragmentation" operation, so a sector is reserved for this.

Format of a Sector A sector is the concatenation of blocks. A block consists in either a written block, as defined below, or an empty block (*i.e.* not yet written: all bits are set to 1) or of an erased block; *i.e.* all the bits are set to 0.

Format of a Block The block format is introduced in figure 9.

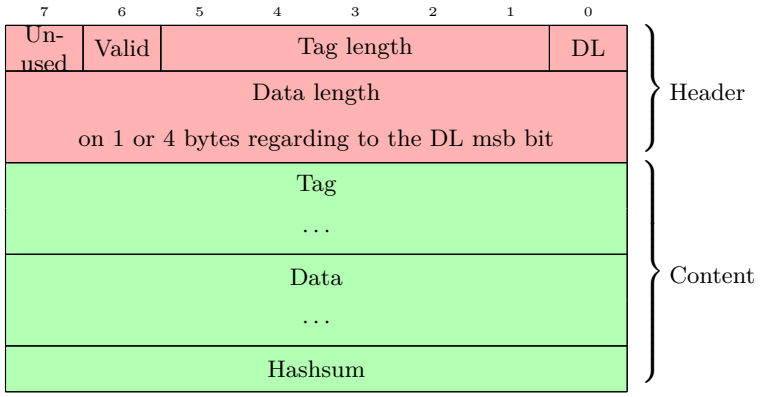

Fig. 9. File system block

Figure 9 shows header and block content. The header is made up of several fields:

– *Unused*: bit-size field consists in adding by default to 1 during a block writing. When this block is written, this bit is set to 0;

- *valid*: bit-size field initially sets to 1 during a block writing operation, it is set to 0 when another block with the same tag is written;
- *Tag length*: this 5-bit size field contains the data tag length. The binary values `0b11111` and `0b00000` are forbidden because they indicate an empty block or an erased block;
- *DL (data length)*, bit-size field sets to 1 if the data length is encoded on 4 bytes, otherwise 0 when the data length is encoded on 1 byte.

In the block content, one will find:

- The *data length field*: it contains the length of the data field, which is either 1 or 4 bytes depending on DL. If it is stored on 4 bytes, then it is stored with the most significant byte on the left;
- The tag and data fields;
- The *hashsum field*: it is the result of the CRC-8 of all other fields except *Unused* and *Valid* ones.

4.4 Using File System for Java Card Serialized Data

Global overview Now that we have specified the file system designed to serialize Java Card data, we focus on how to structure data using this file system. We want it to store a package list, CAP structures (for API, GlobalPlatform manager and applets), static and applet fields. The tag field is used to encode the type of stored data. More specifically the first byte of the tag is dedicated of this purpose. Formally, we have for the different types:

- For the package list, the tag value is (0) and its content is a binary array where each bit marks whether if the package is installed (bit set) or not (bit reset);
- The CAP structures have the tag value (`1`, `package number`) and its content is the result of the JCA file translation obtained in section 3.2;
- The static field tag value is (`2`, `package number`, `static field number`). Its content can be statically computed regarding the CAP static field component. This component is the initial vector of all static fields. For static objects, the default value is `null` and it must be instantiated upon a class field owner constructor;
- The applets field tag value is (`3`, `package number`, `class number`, `applet field number`). The applet field content is not statically computable. Those data must be created during the runtime by the `Applet` class constructor. So, we rely on the JCVM to serialize the field data;
- all other tag values are reserved for futur uses.

By encoding the tag element on 1-Byte, our solution limit the number of packages to 256[4]. For the class, applet field and static field number, this size is

[4] The Java Card specification does not limit the number of packages

compliant with the one defined by the Java Card specification [36].

When a field is stored in Flash memory, we save its type for security reasons, to prevent type confusion. In the Flash block data part for static and applet field, we encoded the field type in the first byte. We use the values introduced in Listing 1.4.

Listing 1.4. Fields type values.

```
byte FIELD_TYPE_BYTE    = 0;
byte FIELD_TYPE_BOOLEAN = 1;
byte FIELD_TYPE_SHORT   = 2;
byte FIELD_TYPE_INT     = 3;
byte FIELD_TYPE_OBJECT  = 4;

byte FIELD_TYPE_ARRAY_BYTE   = ((1 << 7)|FIELD_TYPE_BYTE);
byte FIELD_TYPE_ARRAY_BOOLEAN= ((1 << 7)|FIELD_TYPE_BOOLEAN);
byte FIELD_TYPE_ARRAY_SHORT  = ((1 << 7)|FIELD_TYPE_SHORT);
byte FIELD_TYPE_ARRAY_INT    = ((1 << 7)|FIELD_TYPE_INT);
byte FIELD_TYPE_ARRAY_OBJECT = ((1 << 7)|FIELD_TYPE_OBJECT);

byte FIELD_TYPE_TRANSIENT_ARRAY_BYTE
                       = ((1 << 6)|FIELD_TYPE_ARRAY_BYTE);
byte FIELD_TYPE_TRANSIENT_ARRAY_BOOLEAN
                       = ((1 << 6)|FIELD_TYPE_ARRAY_BOOLEAN);
byte FIELD_TYPE_TRANSIENT_ARRAY_SHORT
                       = ((1 << 6)|FIELD_TYPE_ARRAY_SHORT);
byte FIELD_TYPE_TRANSIENT_ARRAY_INT
                       = ((1 << 6)|FIELD_TYPE_ARRAY_INT);
byte FIELD_TYPE_TRANSIENT_ARRAY_OBJECT
                       = ((1 << 6)|FIELD_TYPE_ARRAY_OBJECT);
```

Using this File System Since the file system is designed, see how to used it. Suppose the partial Java Card class shows in Listing 1.5. This class is a Java Card applet, named `Example`, associated to the `sample` package.

Listing 1.5. A part of Java Card Applet to serialized.

```
package Sample;

class Example {
   static byte[]  static_field = new byte[]
                                    {0x01, 0x02, 0x03, 0x04};
   private short  class_field1 = (short) 0x4567;
   private Object class_field2 = new Object();
   // ...
}
```

As the file system is a set of blocks parsed in Flash memory. We will describe, in this section, which value has the blocks stored in memory regarding

the example.

`Example` class will be serialized with 4 block: one for the `Example` class representation and ones for every class field. `Example` class and `static_field` blocks are statically computed during the Java Card initialization memory image generation. However, `class_field1` and `class_field2` blocks are computed during the `Example` class constructor when fields are instantiated.

By supposing the `sample` package is identified with number 3, and each field is initialized, we will have:

1. `sample` CAP file block value, this CAP has the `Example` class representation:
   - Header: tag length is 2 bytes and data length depends on the `Example` class length.
   - Data:
     - tag value is `[0x01, 0x03]` where:
       - `0x01` for CAP structure block
       - `0x03` points package `0x03` (here `sample` package)
     - data contains the binary representation of `Example` class.
2. `static_field` block value:
   - Header: tag length is 3 bytes and data length is 5 bytes.
   - Data:
     - tag value is `[0x02, 0x03, 0x00]` where:
       - `0x02` for static field block
       - `0x03` points package `0x03` (here `sample` package)
       - `0x00` static field 0
     - data contains `[FIELD_TYPE_ARRAY_BYTE, 0x01, 0x02, 0x03, 0x04]`
3. `class_field1` block value:
   - Header: tag length is 4 bytes and data length is 3 bytes.
   - Data:
     - tag value is `[0x03, 0x03, 0x00, 0x00]` where:
       - `0x03` for applet field block
       - `0x03` points package `0x03` (here `sample` package)
       - `0x00` class 0 (here `Example` class) of package `sample`
       - `0x00` class field 0
     - data contains `[FIELD_TYPE_SHORT, 0x45, 0x67]`
4. `class_field2` block value:
   - Header: tag length is 4 bytes. Data length depends on the `Object` instance size. In our API implementation, `Object` class has no field. Therefore, there instance size is 0. So, the data length is 1 byte.
   - Data: tag value is `[0x03, 0x03, 0x00, 0x01]` where:
     - `0x03` for applet field block
     - `0x03` points package `0x03` (here `sample` package)
     - `0x00` class 0 (here `Example` class) of package `sample`
     - `0x01` class field 1
     - data contains `[FIELD_TYPE_OBJECT]`

5 Experimental Results

For our experimentation, we target an STM32F401RE microcontroller. This microcontroller embeds an ARM Cortex M4 with 512 kB Flash memory. The STM32F401RE Flash memory is split into 8 sectors of 16, 16, 16, 16, 64, 128, 128 and 128 kB in one bank.

Our Java-source code is based on the Java Card API implementations, GlobalPlatform manager and SmartPGP applet, an open-source GPG implementation[5]. The Java-source code is composed of 146 Java files split into 23 packages with 8040 Java lines of code. Building the entire Java-source code from Figure 3 part (1) gives around 51 kB of data with:

- A packages table where each installed packages are listed: 8 Bytes;
- Applications (API, GloablPlatform manager and applet) code: 51 198 Bytes;
- Non-null static fields initial values: 0 Byte. Our implementation has not non-null static fields initial values. Static object fields need a construct method, called by the JCRE, to be initialized.

The compilation process does neither optimize the code nor compress it. This will require future work to obtain a more compact binary output.

Regarding the data size to write, two possibilities are open to us. On the one hand, we can split data through each sector regarding their size and the data size to write. This approach may create defragmentation over the sector. On the other hand, we can write all data in the same sector and rely on the target OS to optimize data location during the JCVM lifetime. We choose the latter solution.

So, at least a 64 kB sector has to store the entire binary blob where all API, GlobalPlatform manager and applet are to write. We arbitrarily selected the sector 5. Such as the file system was designed, the location of data inside the Flash memory is not important. Indeed, the target OS must parse the memory to find all valid blocks during the hash table generation.

After generating the Java Card initialization image, as introduced in section 4 and in Figure 3 part (3), we will need to set the sector 5 of the STM32F401RE Flash memory. So this can happen, our initial state generator outputs an Intel Hex file format. This file is commonly used for programming microcontroller and memory[6].

To setup the STM32F401RE Flash memory, we use `openocd`[7] with the command:

[5] This implementation is the one available there: `https://github.com/ANSSI-FR/SmartPGP`.

[6] The complete file format explanation is available on Wikipedia `https://en.wikipedia.org/wiki/Intel_HEX`

[7] `openocd` is available here `http://openocd.org/`

```
flash write_image erase flash.hex
```

where `flash.hex` is the file given by the initial state generator.

With the initial state, the `jni.h` file is also generated (403 lines length). This file contains the `callJCNativeMethod` function. An overview of this file is listed in Listing 1.6.

Listing 1.6. An overview of the `jni.h` file.

```
1  /* STARTING METHOD PARAMETERS */
2  #define STARTING_JAVACARD_PACKAGE 0x01
3  #define STARTING_JAVACARD_CLASS   0x00
4  #define STARTING_JAVACARD_METHOD  0x01
5
6  /**
7   * Java types to provide by the JCVM implementation:
8   *   - jref_t: for Java Card reference
9   *   - jshort_t: for Java Card short value
10  *   - jbyte_t: for Java Card byte value
11  *   - jbool_t: for Java Card boolean value
12  *   - jint_t: for Java Card integer value
13  */
14
15 /* METHOD SIGNATURES TO IMPLEMENT */
16 extern jshort_t
17 NativeImplementation_arrayCopyRepack(jref_t,jshort_t,jshort_t,
       jref_t,jshort_t);
18 // ...
19
20 #define NATIVEIMPLEMENTATION_ARRAYCOPYREPACK         0x0000
21 // ...
22 #define NATIVEIMPLEMENTATION_MAKETRANSIENTINTARRAY   0x0021
23
24 void callJCNativeMethod(Context& context, jshort_t index) {
25   Stack& stack = context.getStack();
26   Heap& heap = context.getHeap();
27   switch(index) {
28     case NATIVEIMPLEMENTATION_ARRAYCOPYREPACK: {
29       jshort_t param_04 = stack.pop_Short();
30       jref_t   param_03 = stack.pop_Reference();
31       jshort_t param_02 = stack.pop_Short();
32       jshort_t param_01 = stack.pop_Short();
33       jref_t   param_00 = stack.pop_Reference();
34
35       stack.push_Short
36          (NativeImplementation_arrayCopyRepack
37               (param_00, param_01, param_02,
38                          param_03, param_04);
39       break; /* ... */ }}}
```

Listing 1.6, lines 2 to 4, contains a tuple (package, class, method) which defines the entry point of the first Java Card method called by the JCRE on startup. This method initialized the Java Card platform and call the GlobalPlatform daemon.

The native method dispatcher, line 24, is a switch-case statement where the native method `arrayCopyRepack()` is called (line 28 to 39). As introduced in the line 17, the `arrayCopyRepack()` method is declared as a C-`extern` method and must be implemented by the JCVM developers. In our API implementation, 34 native methods must be implemented.

6 Conclusion and Future Works

In this article, we introduced a design proposal to organize NVM memory where every data required for running JCVM implementation and applets are stored. The JCVM memory organization is not studying by the state of the art. To improve the security of JCVM implementation, every part of the Java Card platform should be studied to have an open design where the scientific community can contribute.

This work is partial but it is a new step for designing a JCVM implementation. The next step consists in studying how the whole JCVM based on this JCVM memory organization and the OS introduced by Bouffard *et al.* [6] can be secured designed.

Another possible future enhancement would be to optimize the generated data. Indeed, the current Java Card initialization image is based on the result of Java compiler. This compiler does not optimize the built bytecodes. Code optimization may reduce the built code size and, *in fine*, reduce the size of the resulting binary output. This could allow ones to remove, for instance, unreachable or useless fragments of code. Security of this optimization must also be studied.

Also based on the code optimization, code compression can be another approach to have a smaller data. Code compression replaces several frequently used pack of instructions by another one. Future research work could study this compression to obtain a generic and optimized compressing method.

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