A Generic Approach for Protecting Java Card™ Smart Card Against Software Attacks

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Outline

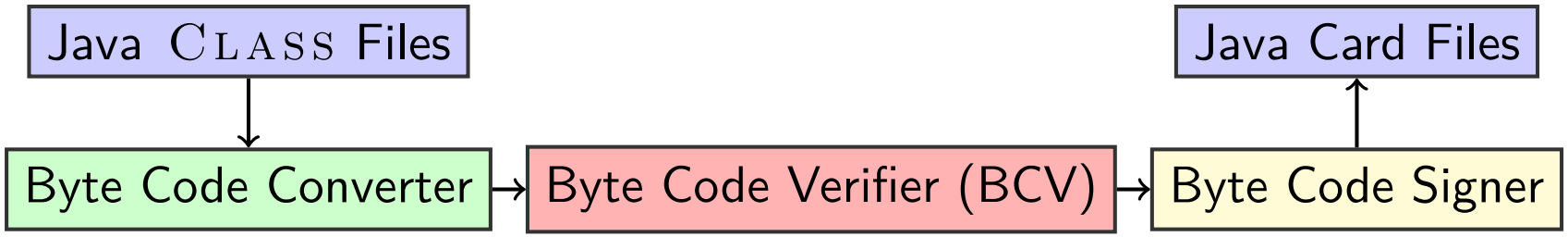
The Smart Card

- Used in our everyday life:
  - Credit Card;
  - (U)SIM Card;
  - Health Card (French Vitale card);
  - Pay TV;
  - ...
- Tamper-Resistant Computer;
- Securely stores and processes information;
- Most of the smart cards are based on Java Card technology.

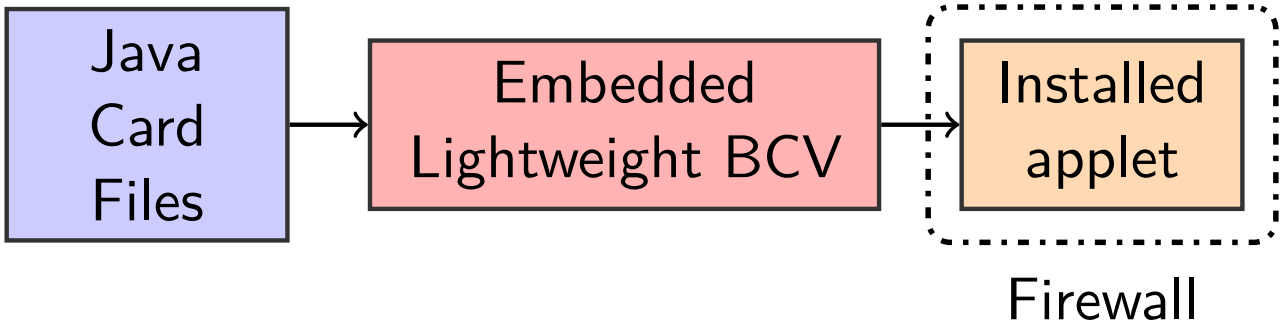
This device contains sensitive data

Java Card Security Model

- *Off-card* security



- *On-card* security



Java Card Attacks

Physical attacks

- Side Channel attacks (timing attacks, power analysis attack, etc.);
- Fault attacks (electromagnetic injection, laser beam injection, etc.).

Logical attacks

- Execution of malicious Java Card byte codes.

Combined attacks

- Mix of physical and logical attacks.

Problematic

- Inductive Approach:
  - 1 attack = 1 countermeasure;
  - **Bottom-up** approach.

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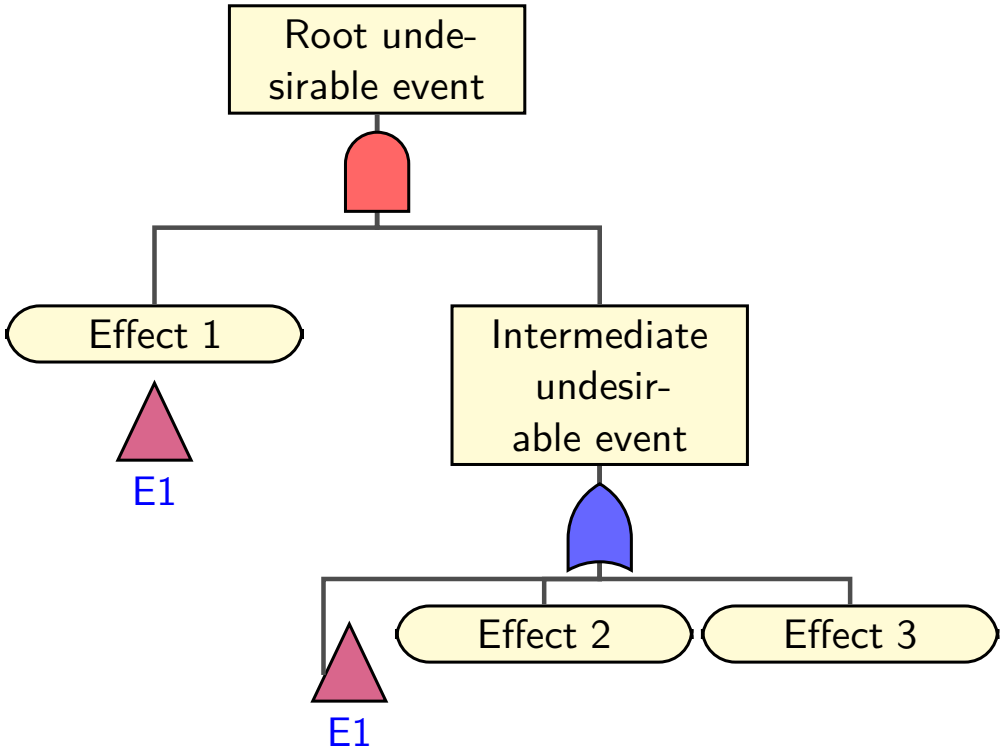
- Thesis Objectives:
  - Find and prevent each undesirable events;
  - Global vision to protect the smart card's assets;
  - Design a **top-down analytic approach**.

The Fault Tree Analysis (FTA)



- Undesirable events;
- Initial causes;
- Gate connectors.

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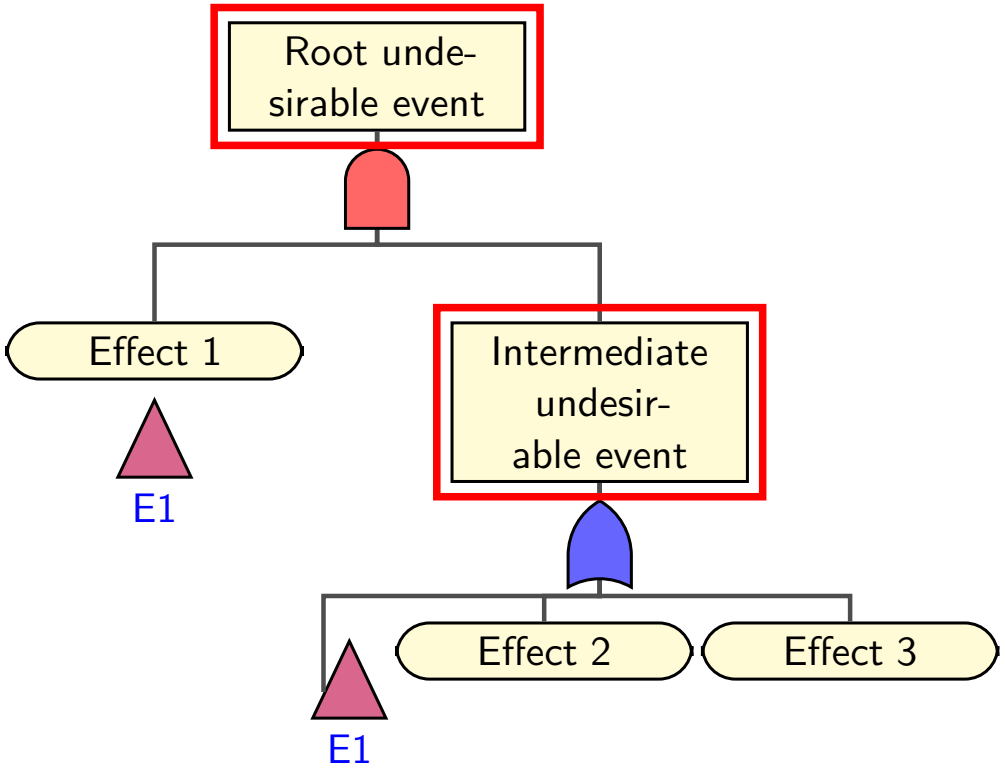

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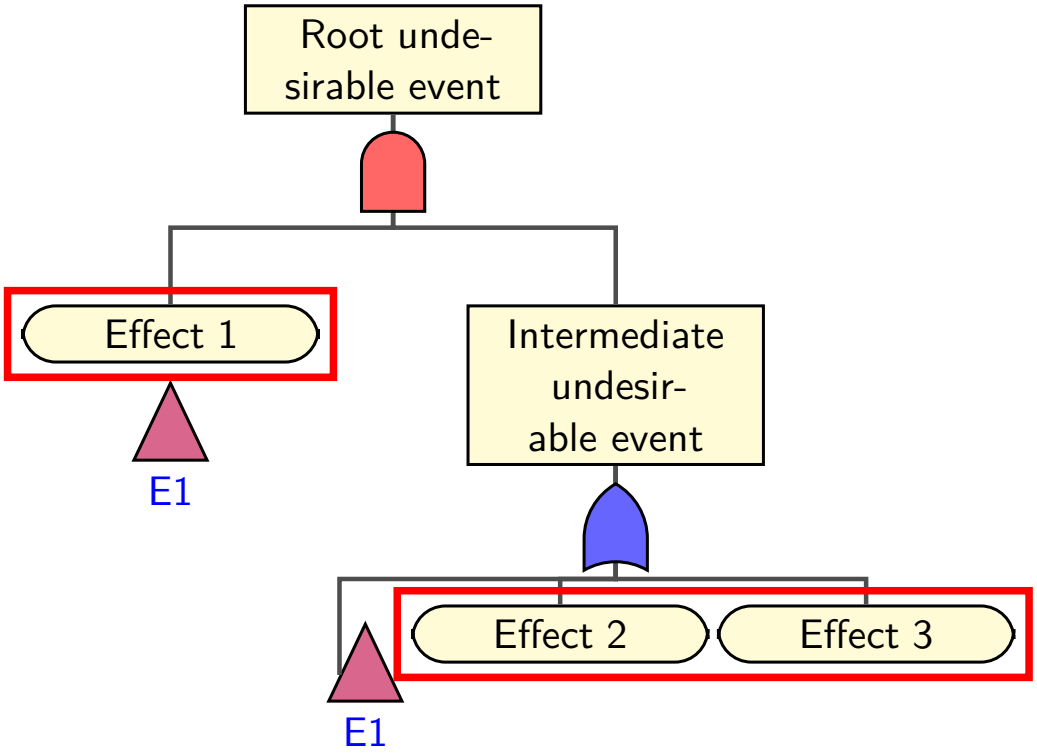

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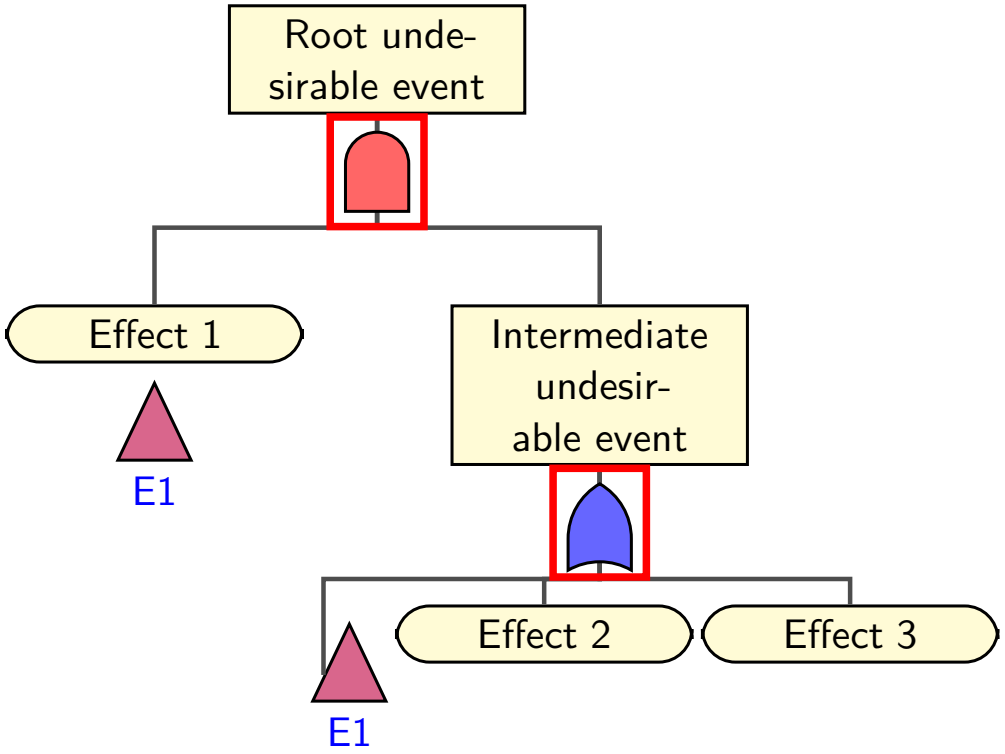

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- **Gate connectors.**

Smart Card's Assets

- The smart card's assets are the **code** and the **data**;
- Security properties:
  - Integrity;
  - Confidentiality;
- Undesirable events can affect:
  - Code integrity;
  - Data integrity;
  - Code confidentiality;
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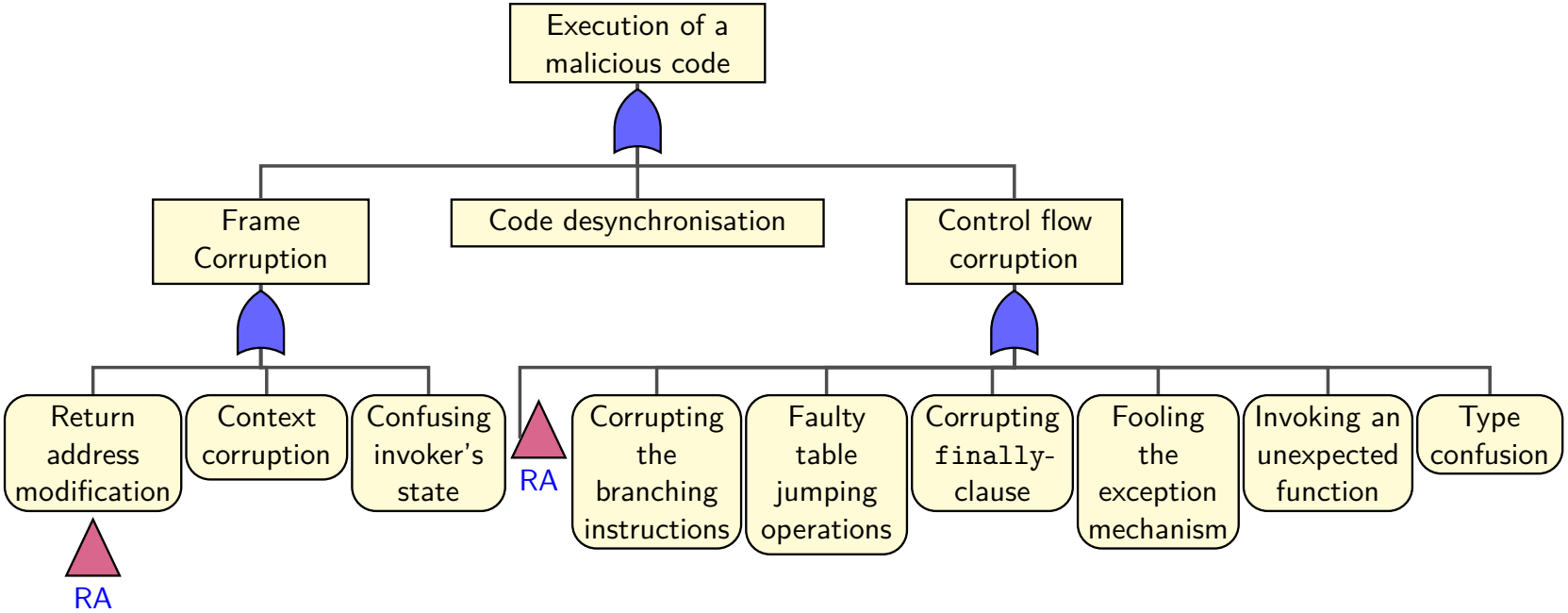
  - Data confidentiality;

An attack offers the execution of a malicious byte code.

Execution of a malicious code



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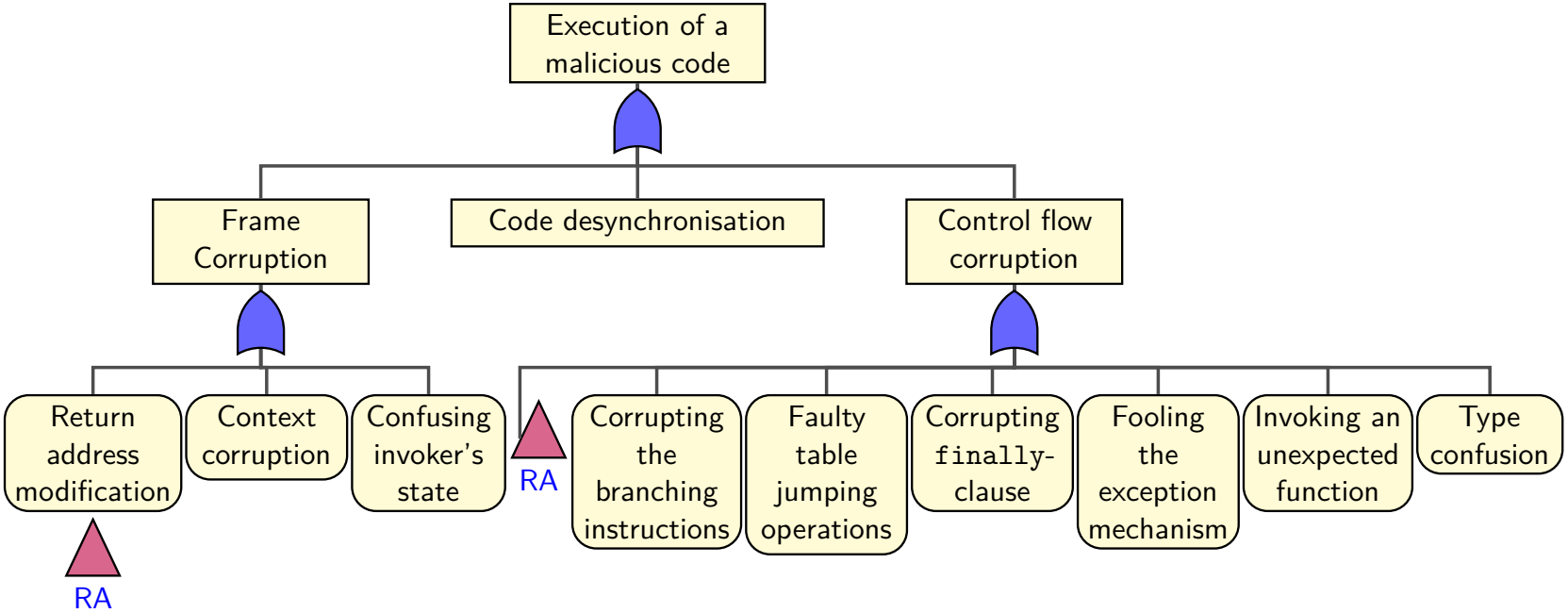

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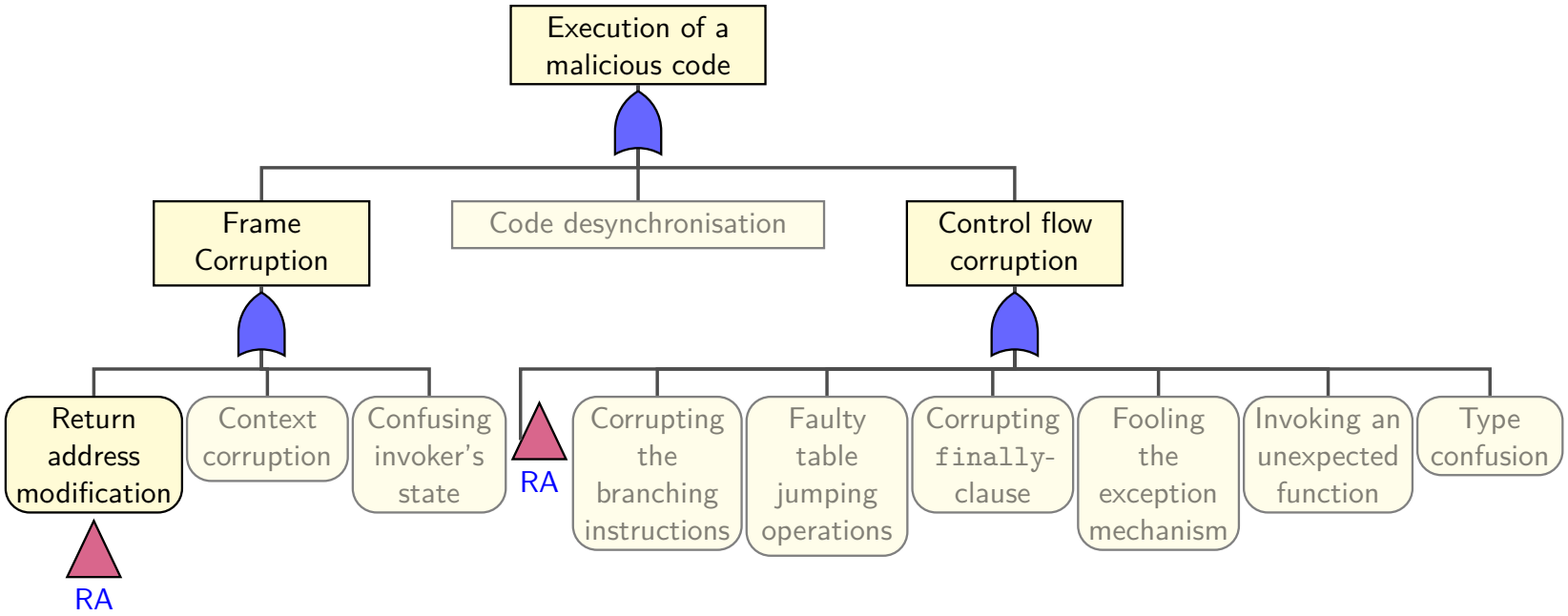

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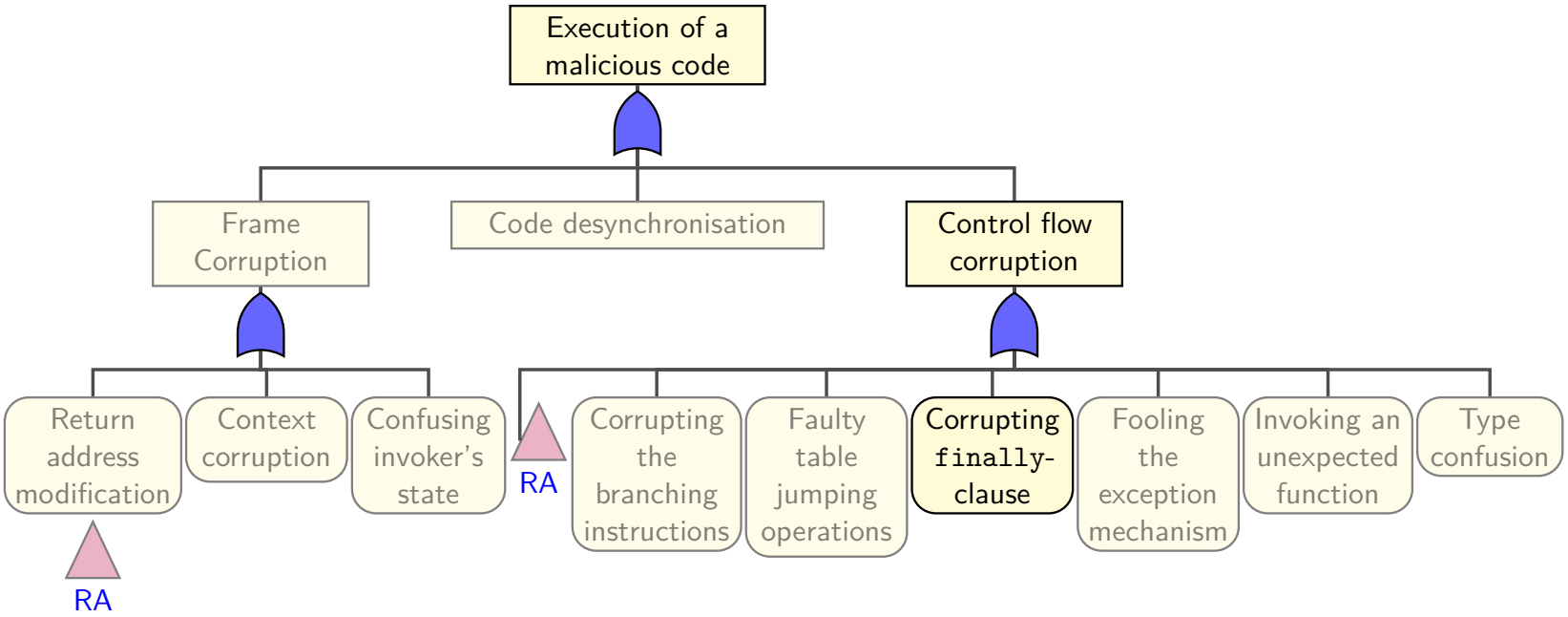

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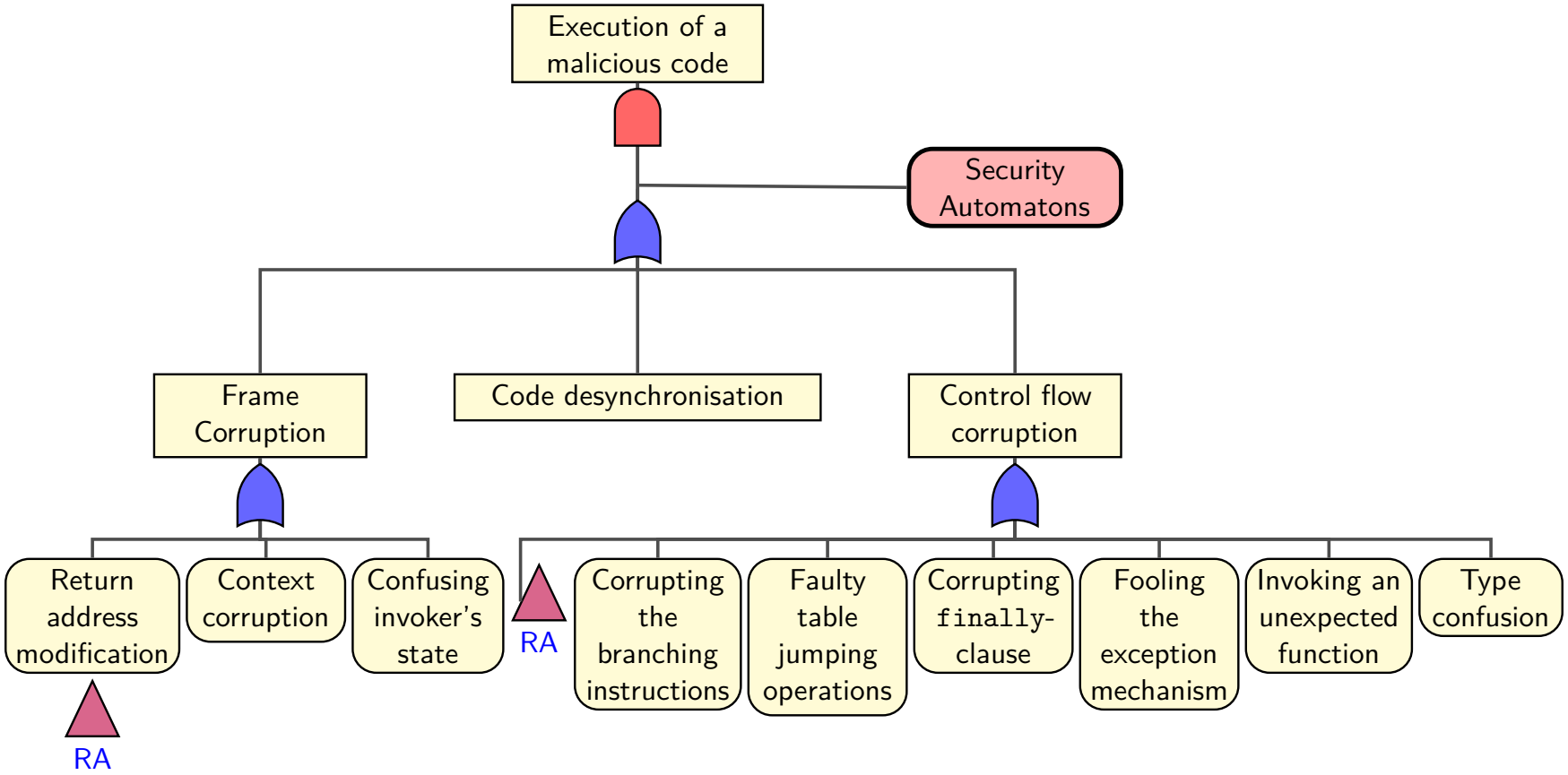

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The Java Method Return

> *The current frame is used in this case to* ***restore the state of the invoker****, including its local variables and operand stack, with the* ***program counter of the invoker*** *appropriately incremented to skip past the method invocation instruction. Execution then continues normally in the invoking method's frame with the returned value (if any) pushed onto the operand stack of that frame.* (source: Java 8 Virtual Machine Specification)

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  - Previous frame's size;
  - Program counter of the invoker (the return address) ;
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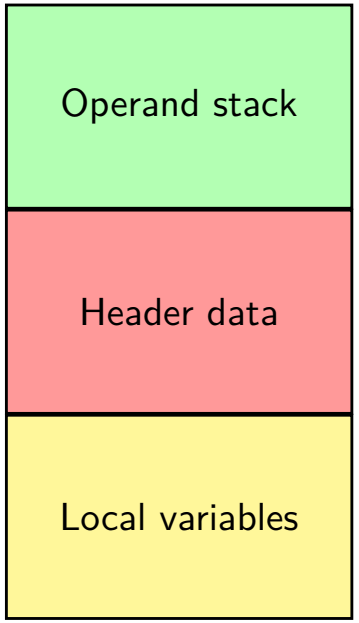
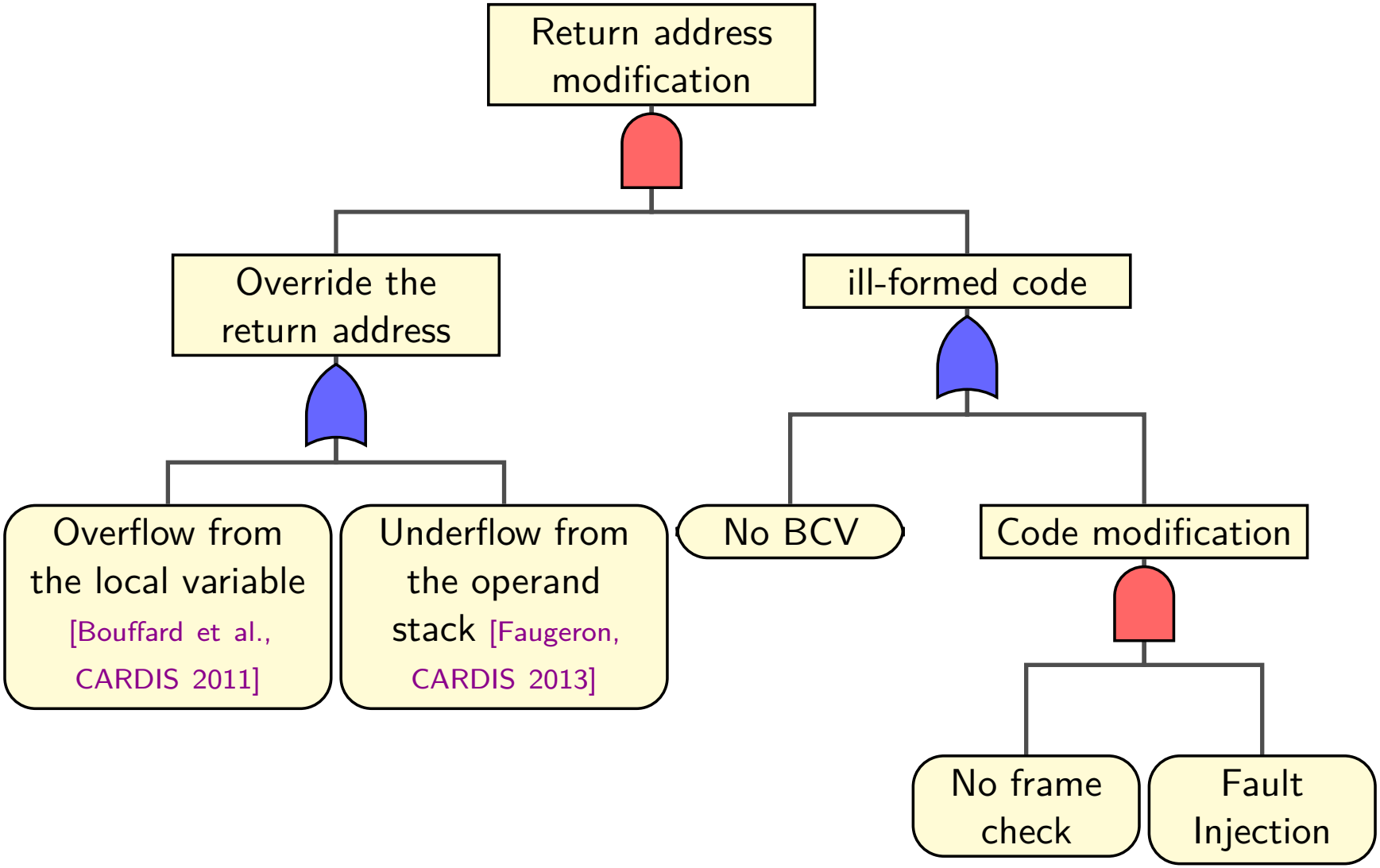


EMAN2: *A Ghost In the Stack*

- Modifying the return address;



EMAN2 and Its Avatars

- Stack **overflow** from the local variables [Bouffard et al., CARDIS 2011]
  - `sstore`, `sinc`, etc.;
- Stack **underflow** from the operand stack [Faugeron, CARDIS 2013]
  - `dup_x`, `swap_x`, etc.;
- Countermeasures from the literature:
  - Checking the integrity of the frame's header data;
  - Verifying each access to the frame's areas [Lackner et al., CARDIS 2012];
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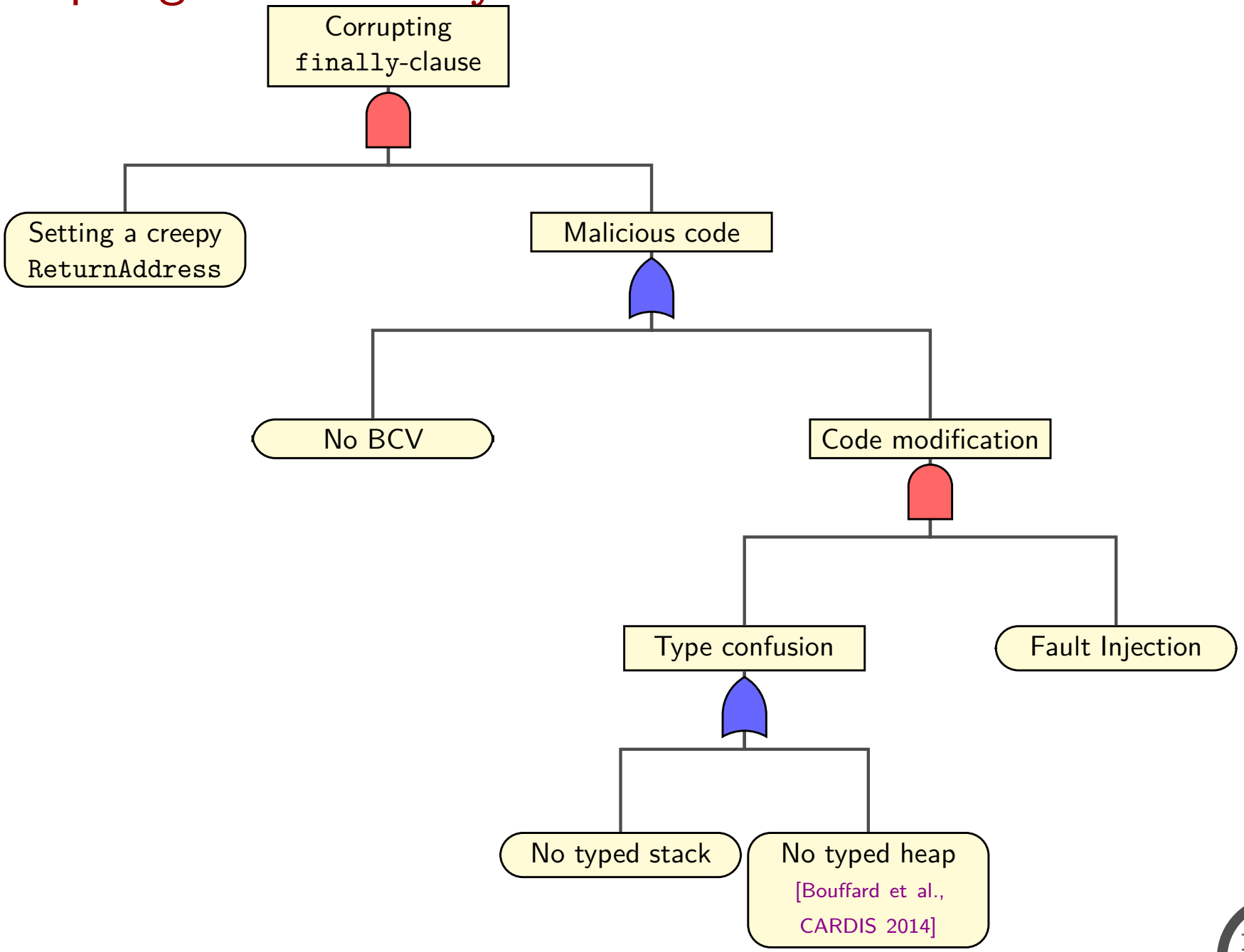
  - These countermeasures are at the same level than the attacks which they prevent;
- This attack modifies the Java Program Counter value upon the return address register. Recent smart cards embed countermeasures against this attack! ... **only the path is protected**;

The `finally`-Clause

- A `finally`-statement used the `jsr` ("***jump to subroutine***") and `ret` ("***return from subroutine***") instructions (deprecated since Java 6) ;
- The `jsr` pushes the address of the instruction immediately following it (typed as `ReturnAddress`);
- Saves the return value (if any) in a local variable;
- The `ret` instruction continues the execution from the value saved in the local variable.

Corrupting the `finally`-Clause



How to Exploit the jsr instruction?

- Hypothesis:
  - No verified by a BCV
  - No typed stack

```
short jsrAttack () {
  01 // flags: 0 max_stack : 1
  11 // nargs: 1 max_locals: 1
  /*0x53*/ L0: jsr L2
  /*0x56*/ L1: sspush 0xCAFE
  /*0x59*/     sreturn
  /*0x5A*/     sspush 0xBEEF
  /*0x5D*/     sreturn
  /*0x5E*/ L2: astore_1
  /*0x5F*/     sinc 0x1, 0x4
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```

Cheating the BCV component

- The BCV checks the structure and the semantics of the application;
- To verify the byte code semantics, the BCV starts its analyse from an **entry point**;
- Unreachable code has no entry point ⇒ ⚠ it is **not checked** by the BCV!
- A malicious byte code can be hidden through the BCV verification!

An Unreachable Code...

```
void cheatingBCV () {
  04 // flags: 0 max_stack : 4
  03 // nargs: 0 max_locals: 3
  /*0x05B*/ L0: jsr L1
  // ...
  /*0x066*/ L1: astore_3
            L2: ... // Set of instructions
  /*0x163*/     if_scmpeq_w 0xFF05 // -> L2
  /*0x166*/     return
  /*0x167*/     sinc 0x3, 0x4
  /*0x16A*/     ret 0x3
}
```

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Checked by the BCV

Unchecked by the BCV

```
verifycap api_export_files/**/*.exp maliciousCAPFile.cap
[ INFO: ] Verifier [v3.0.5]
[ INFO: ]  Copyright (c) 2015, Oracle and/or its affiliates.
           All rights reserved.

[ INFO: ] Verifying CAP file maliciousCAPFile.cap
[ INFO: ] Verification completed with 0 warnings and 0 errors.
```

... Can Be Executed

- EMAN4 [Bouffard et al., CARDIS 2011] introduced a way to change an instruction's parameter upon a laser beam injection;
  - This attack focuses on wide instructions;
  - `goto_w`, `if_*_w`, ...

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  - This attack focuses on wide instructions;
  - `goto_w`, `if_*_w`, ...
- `if_scmpeq_w 0xFF05` ⇒ `if_scmpeq_w 0x0005`
- That can be viewed as a logical attack enabler.

Protecting the Execution Flow

- Direct modification:
  - Integrity → can be bypassed when the JPC is updated by the JCVM;
- Transient fault:
  - Executing twice the same piece of code;
  - It is a very expensive solution;
- Solution: dynamically check the applet's CFG:
  - Séré's countermeasures [Séré's PhD thesis, 2010] based on Field of bits, Basic block method or Path check technique;
  - This kind of countermeasure can be **computed in the card**?

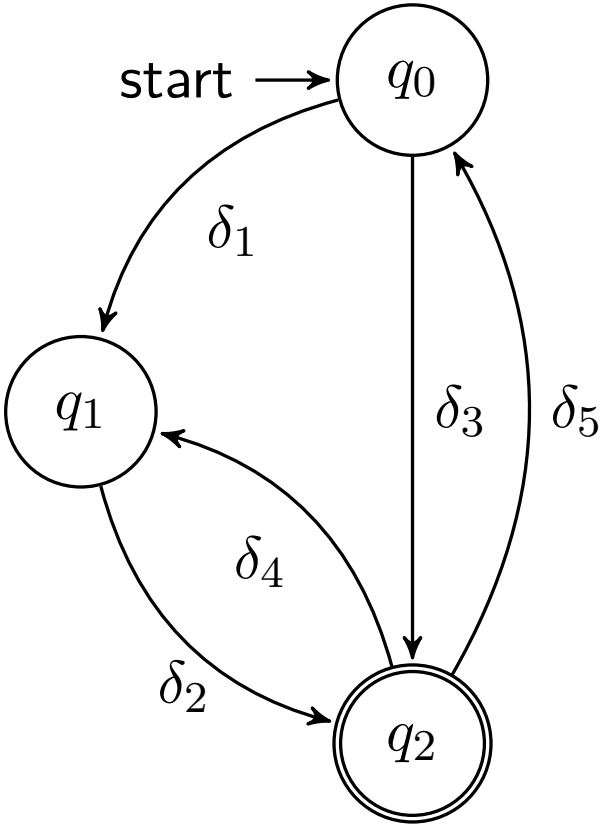
Security Automatons and Execution Monitor

Principle

- Detecting a deviant behaviour $\Rightarrow$ **safety property** "*nothing bad happens*";
- Preventing some attacks: several partial traces of events are defined:
  - Property can be encoded by a finite state automaton;
- Schneider automatons: (Q, q_0, δ), where Q is a set of states, q_o is the initial state and δ is a transition function $(Q \cdot I) \rightarrow 2^Q$);
- The CFG can be computed during the loading process;
- When interpreting a byte code, the monitor checks:
  - If the transition generates an authorized partial trace;
  - If not, it takes an appropriate countermeasure.

Security Automatons and Execution Monitor (Cont.)

Principle



Security automaton
(computed inside the card)

State	q_0	q_1	q_2
q_0		δ_1	δ_3
q_1			δ_2
q_2	δ_5	δ_4	

State matrix (binary implementation of the security automaton)

- [Bouffard et al., SSCC 2013], [Bouffard et al., SAR-SSI 2013] and extended in [Bouffard et al., IJTMCC 2014].

Security Automaton in Practice

```
protected Protocolpayment (byte[] buffer, short offset, byte length) {
  A[0] = 0; // initialisation of array A
  for (byte j = 0; j < buffer[(byte)(offset+12)]; j++) {
    D[j] = 0; // initialisation of array D
  }
  pin = new OwnerPIN((byte) TRY_LIMIT, (byte) MAX_PIN_SIZE);
  // Initialisation of pin
  pin.update(myPin, (short) START_OFFSET, (byte) myPin.length);
  register(); // registering this instance
} // source: (Girard et al., CRiSIS 2010)
```

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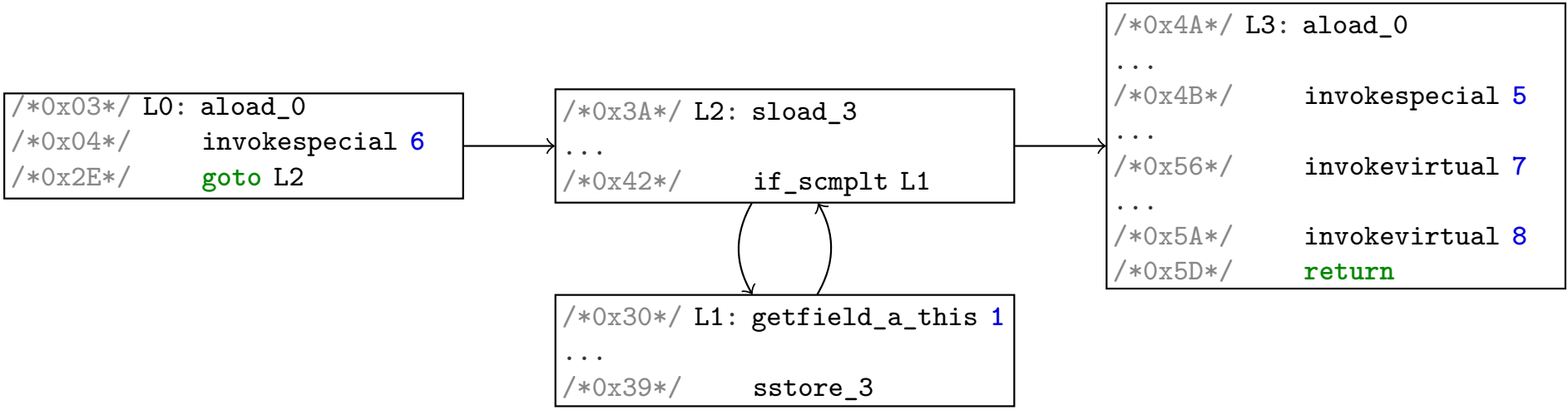
- To create the security automaton:
  - Local view of the method's CFG;
  - The set S contains the element of a language which expresses the control flow integrity policy:
    - `ifeq`, `ifne`, `goto`, `invoke`, `return`, etc.;
    - plus the dummy instruction `join` representing any other instruction pointed by a label.

Security Automaton included in the JCVM



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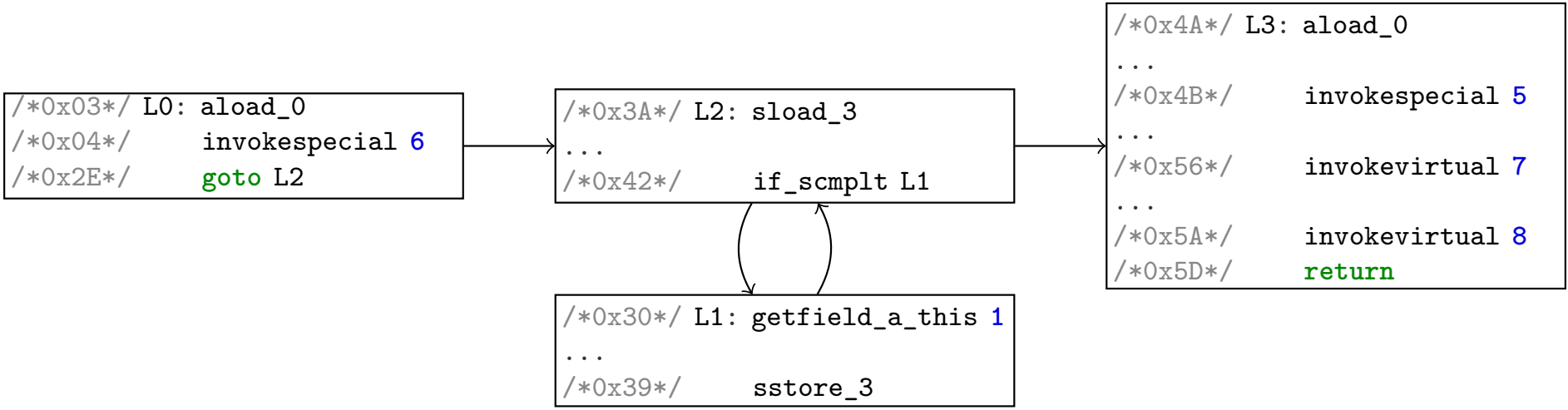

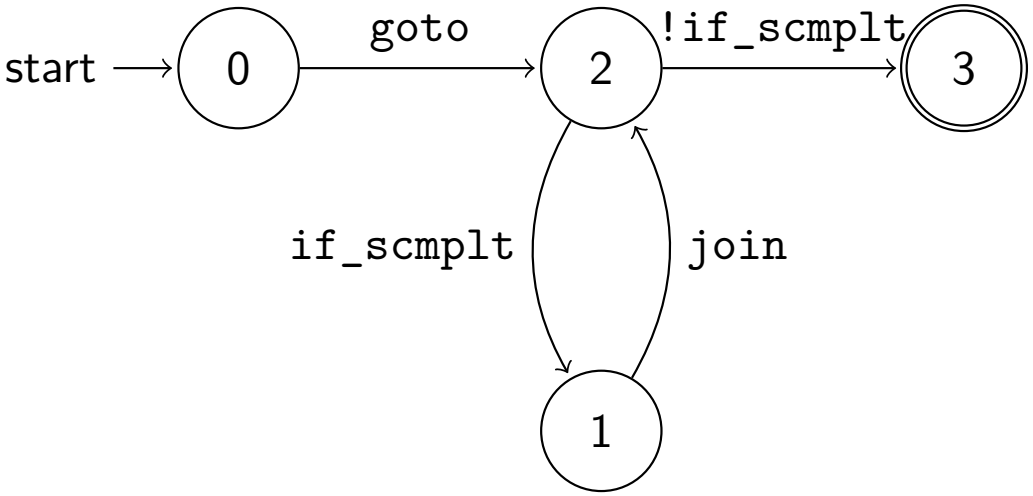

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...
/*0x42*/     if_scmplt L1
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```
/*0x30*/ L1: getfield_a_this 1
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/*0x39*/     sstore_3
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/*0x4A*/ L3: aload_0
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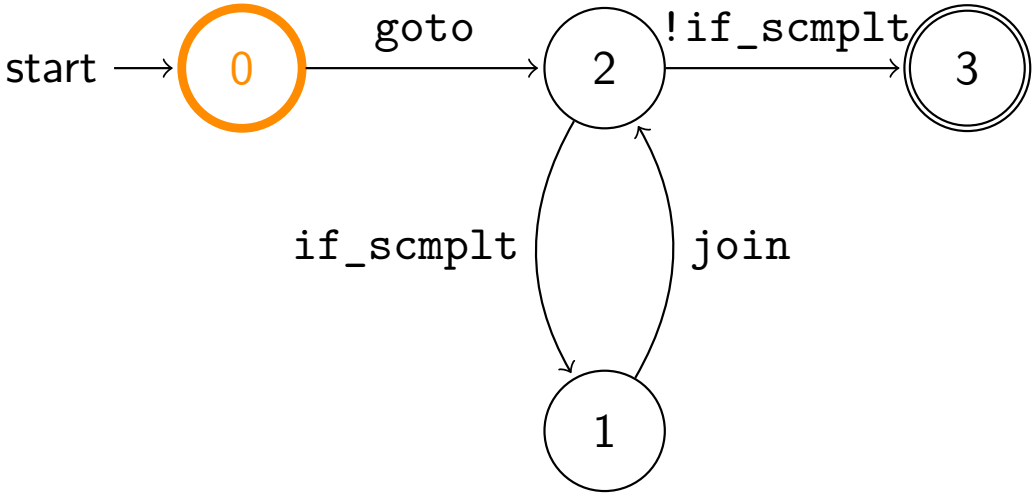

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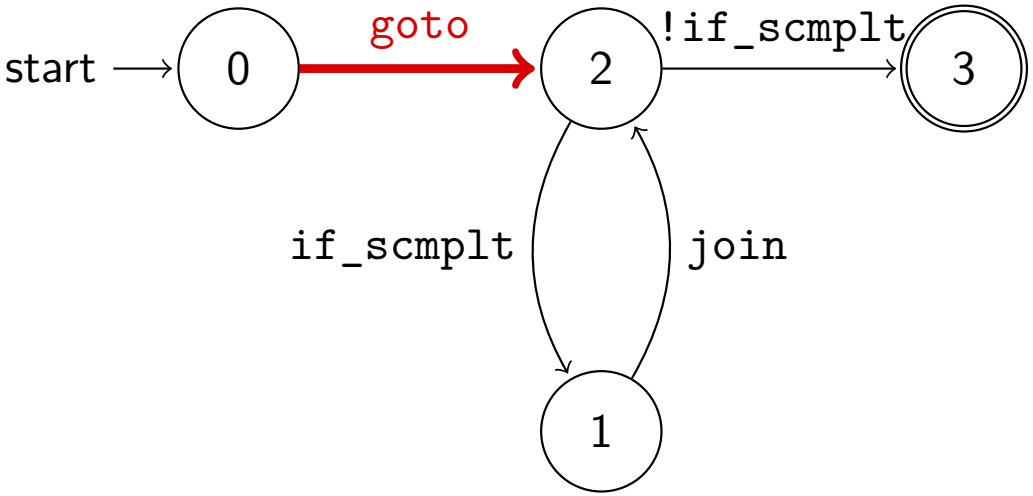

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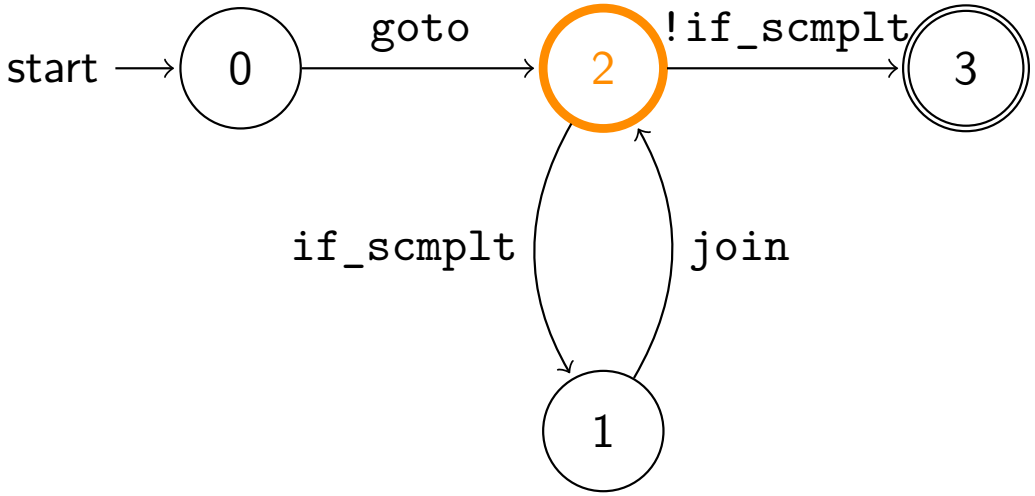

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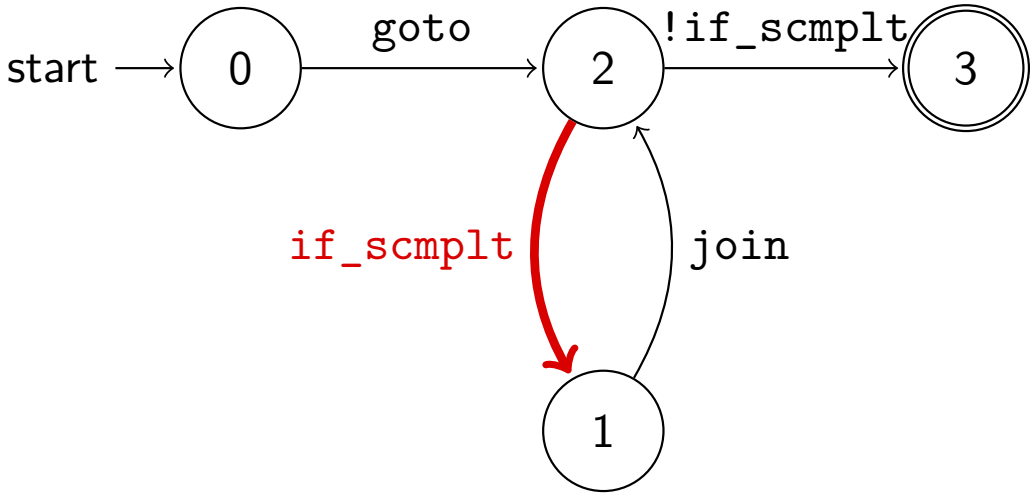

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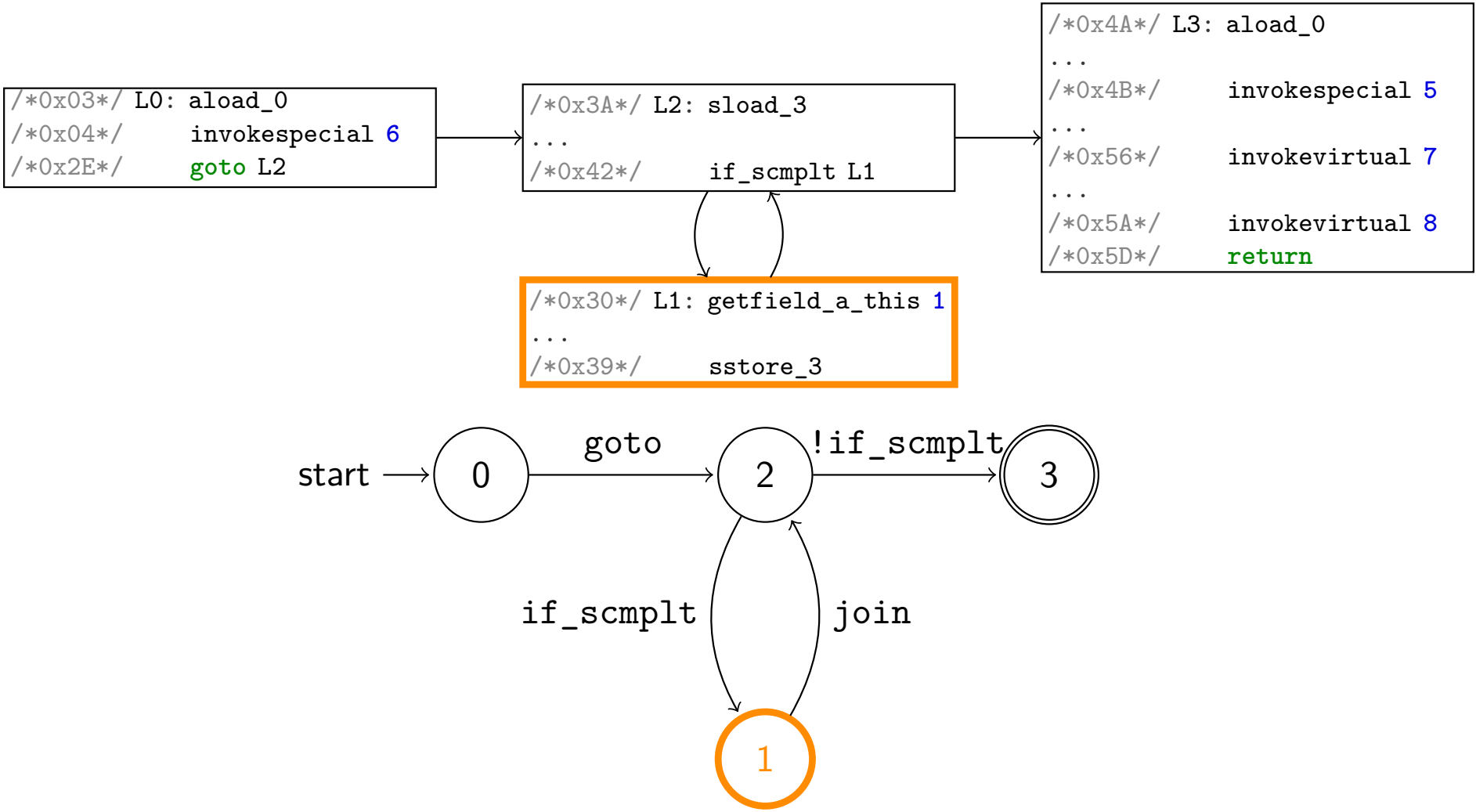

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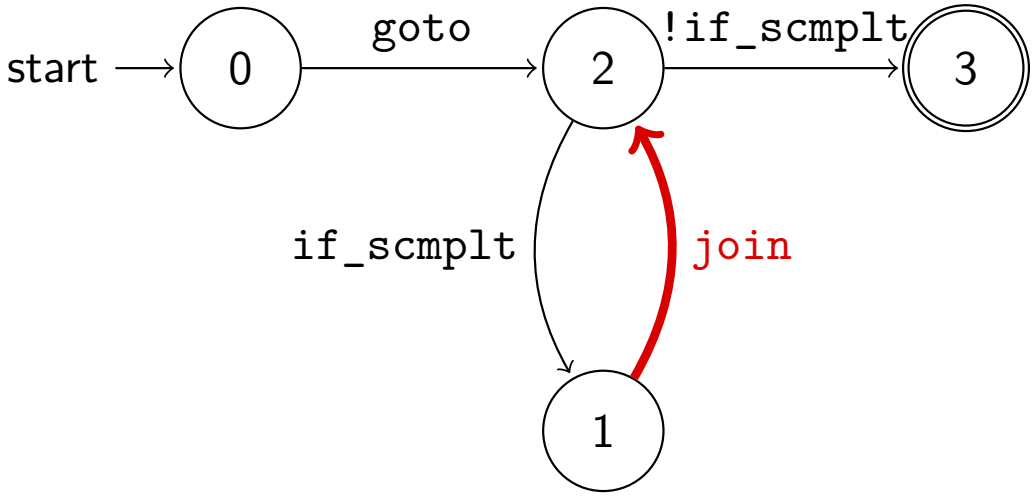
```

```
/*0x30*/ L1: getfield_a_this 1
...
/*0x39*/     sstore_3
```

```
/*0x4A*/ L3: aload_0
...
/*0x4B*/     invokespecial 5
...
/*0x56*/     invokevirtual 7
...
/*0x5A*/     invokevirtual 8
/*0x5D*/     return
```



Security Automaton included in the JCVM

```
/*0x03*/ L0: aload_0
/*0x04*/     invokespecial 6
/*0x2E*/     goto L2
```

```
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...
/*0x42*/     if_scmplt L1
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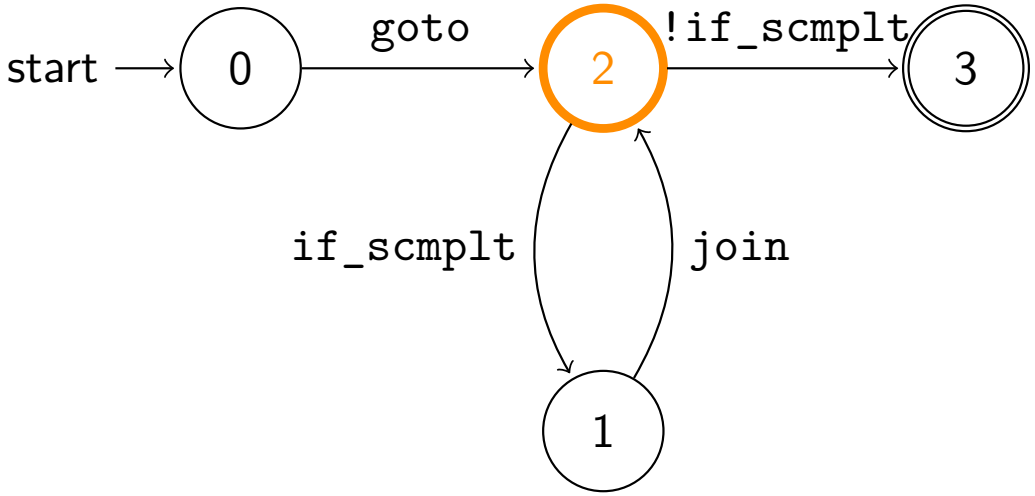

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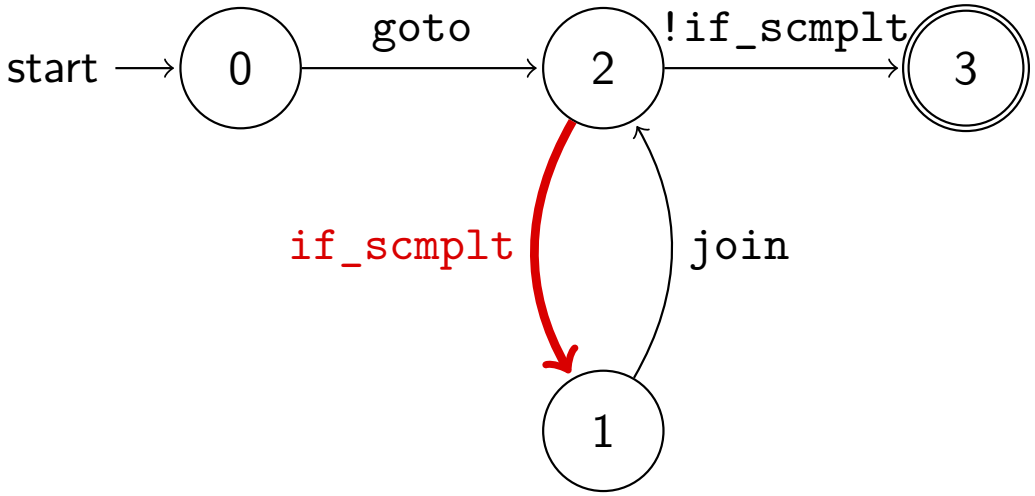
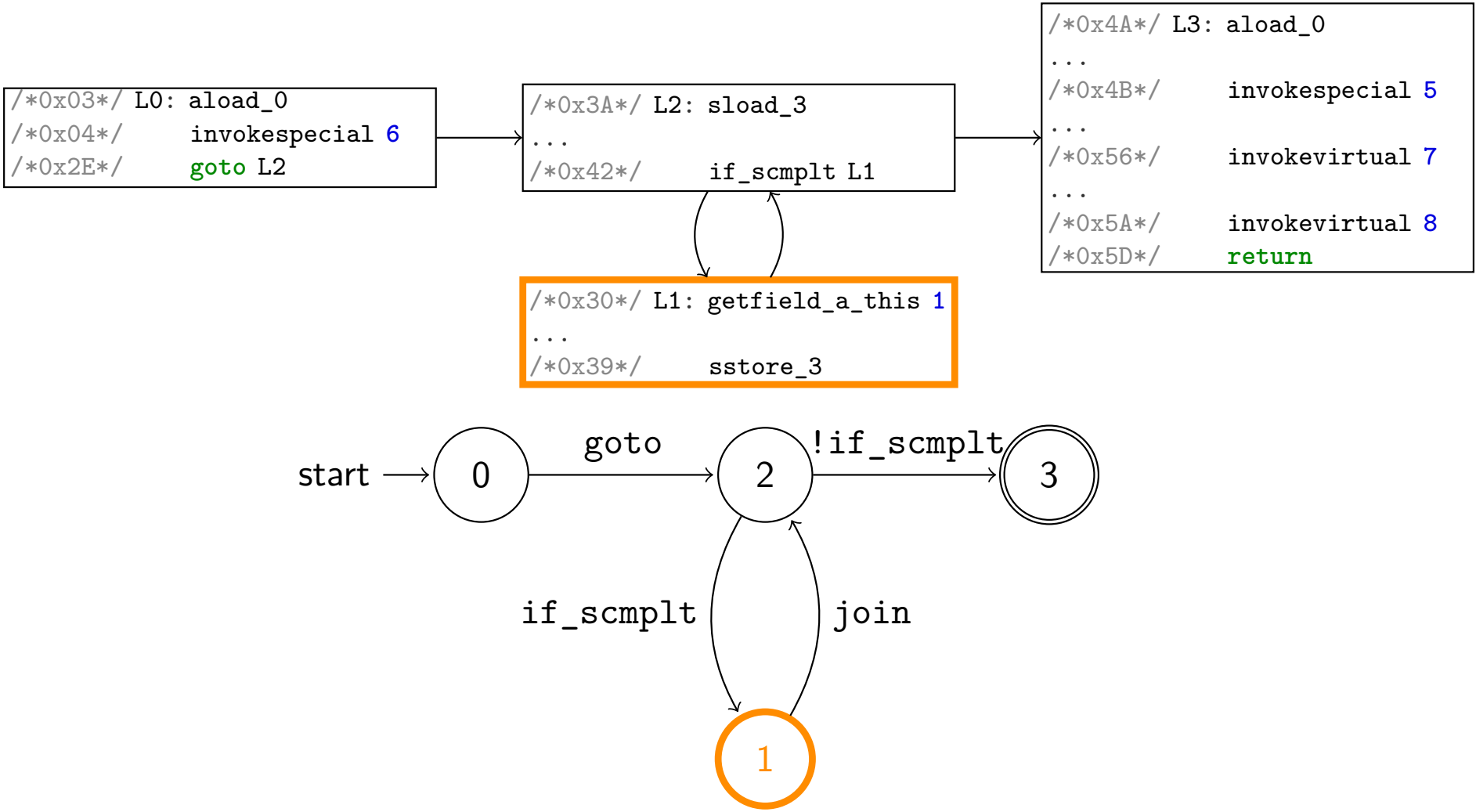


Security Automaton included in the JCVM



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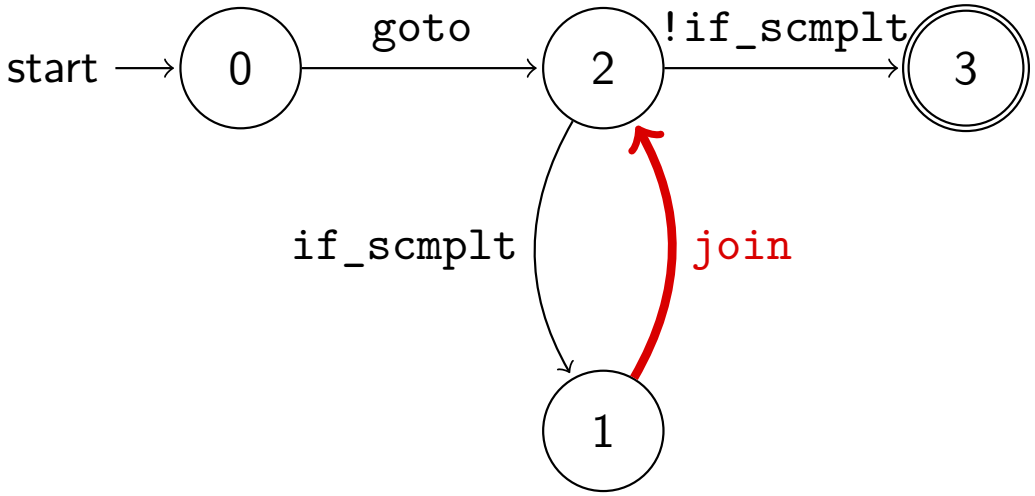

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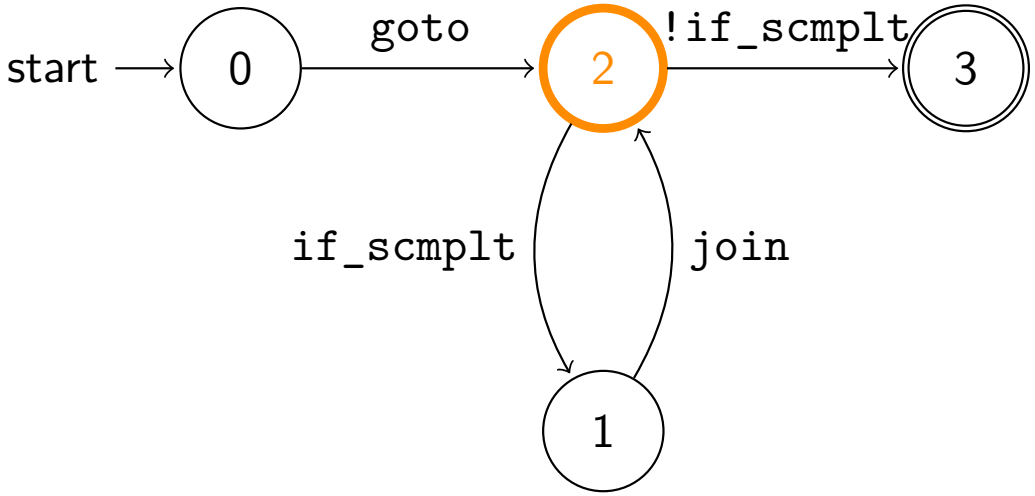

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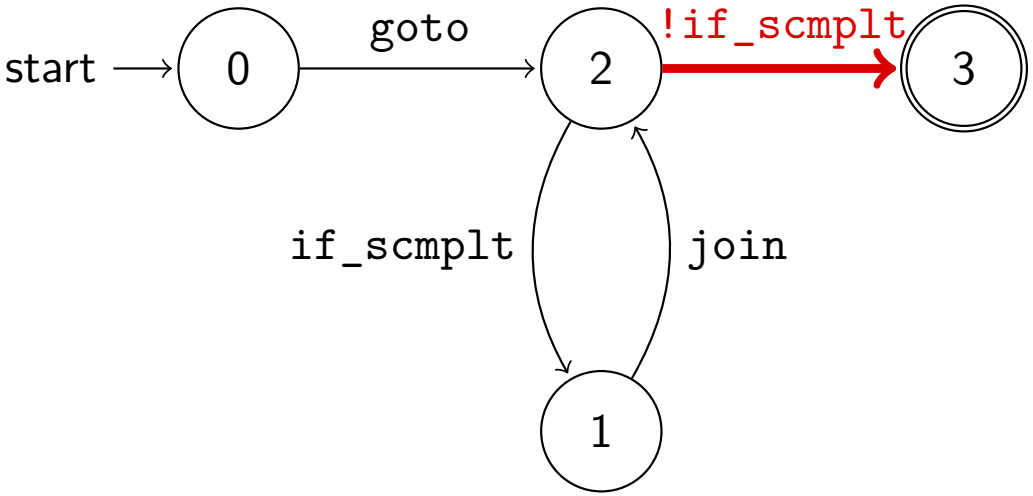

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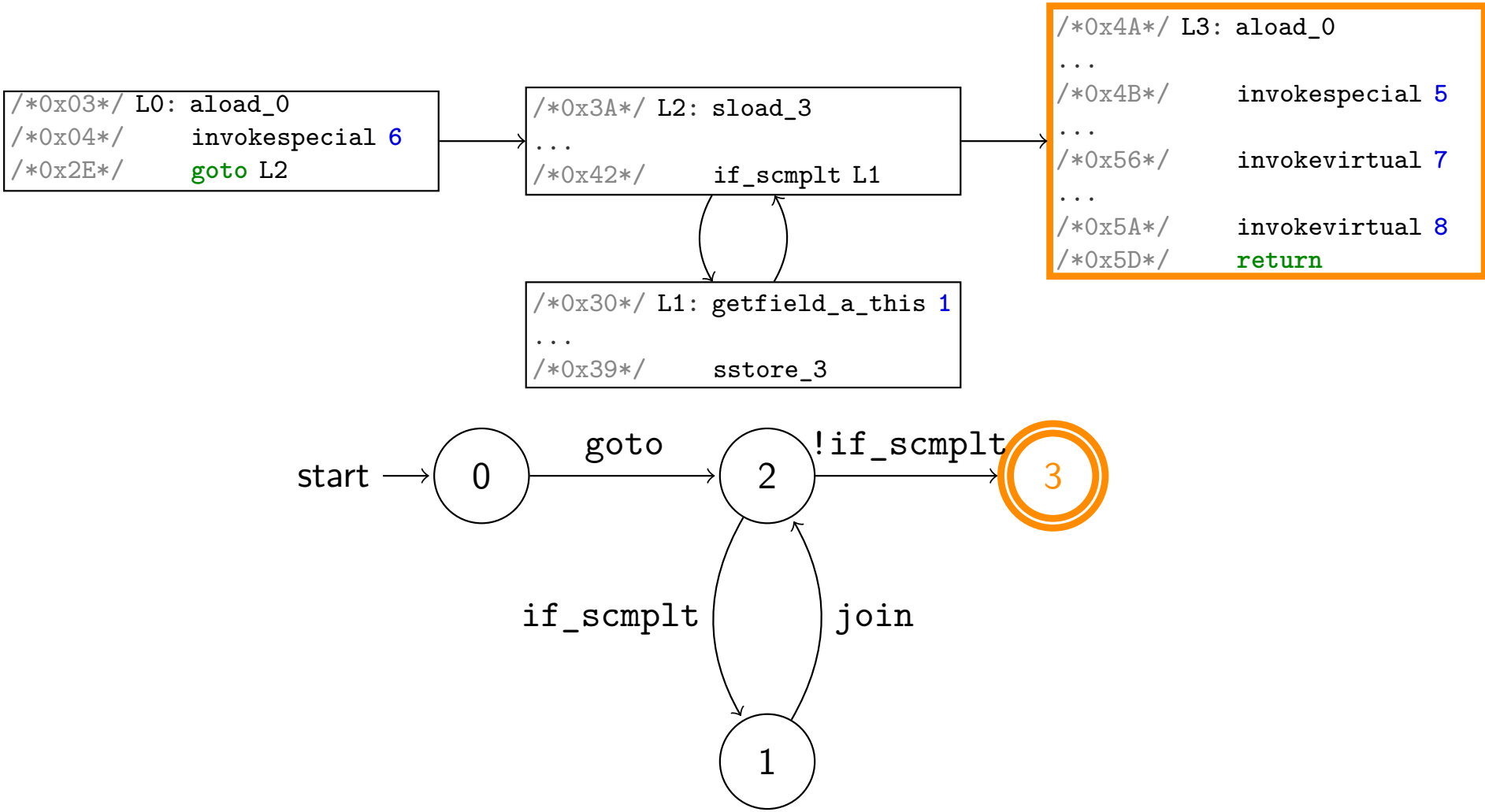

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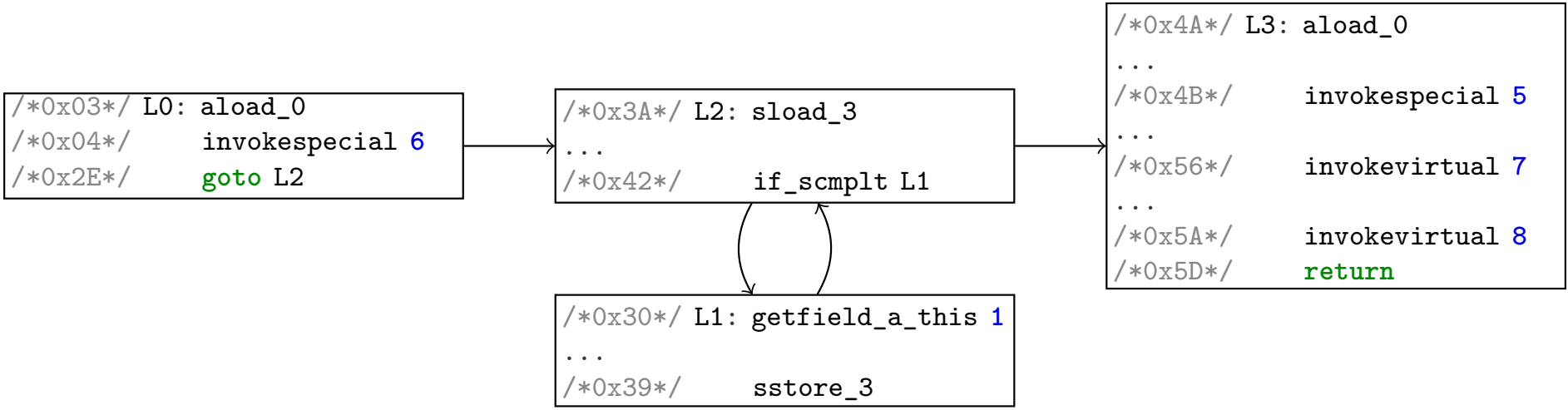
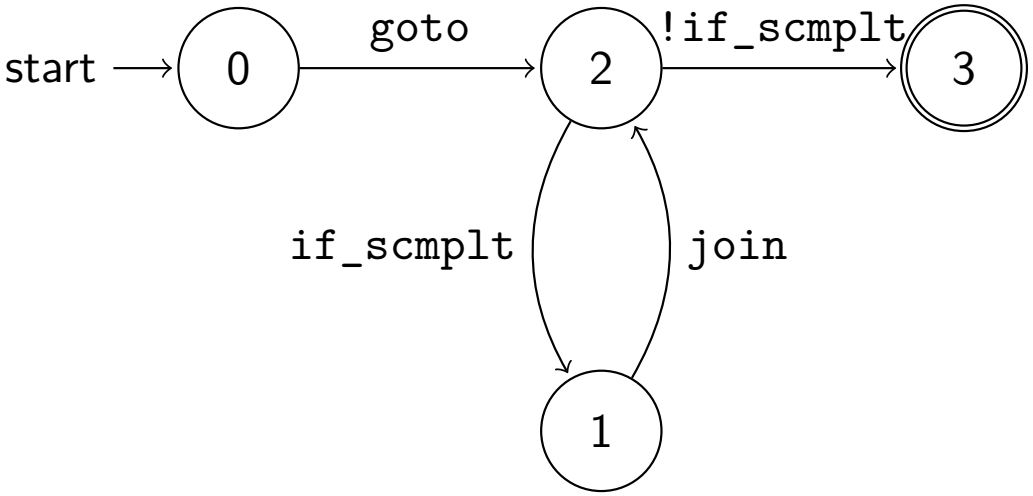
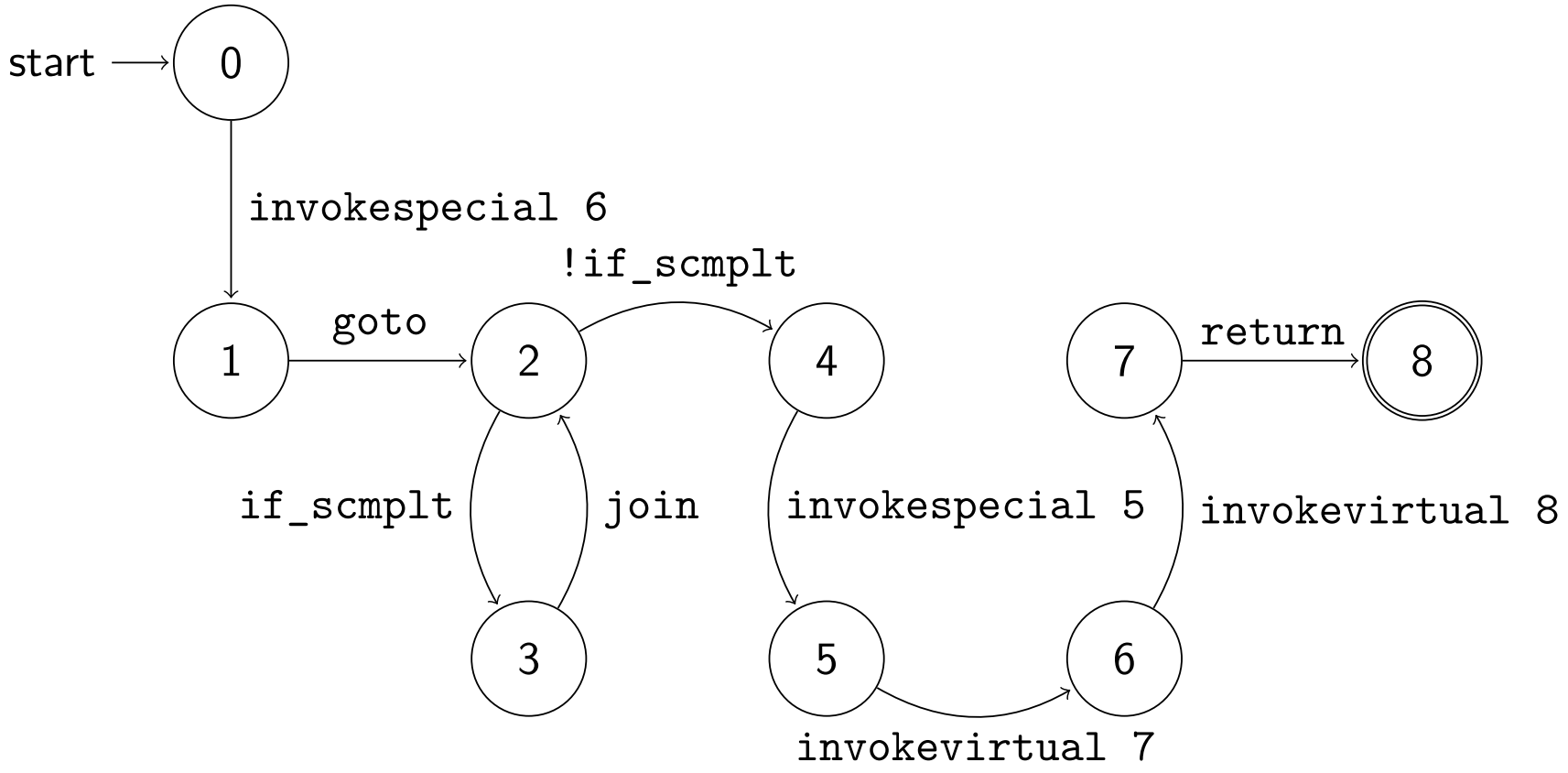




The trace recognised would be:

(goto, (if_scmplt, join)*,!if_scmplt, return)

Security Automaton included in the JCVM (Cont.)



Security Automaton included in the JCVM (Cont.)

δ \ q	q_0	q_1	q_2	q_3	q_4	q_5	q_6	q_7
`invokespecial 6`	q_1							
`goto`		q_2						
`join`				q_2				
`if_scmplt`			$q_{3,4}$					
`invokespecial 5`					q_5			
`invokevirtual 7`						q_6		
`invokevirtual 8`							q_7	
`return`								$+$

The Security Automaton

- The execution flow is checked by the security automaton upon a finite state machine;
- Each transition is verified by the execution monitor;
- The CFG can be automatically computed by the loading process;
- The CFG can be encoded upon a sparse matrix $\rightarrow$ optimised solution to store the CFG
- The JCVM and the loader should be modified to handle automatons.

Conclusion

- This thesis aimed at designing **efficient** and **affordable** countermeasure using a **top-down** approach;
- It is based on the **Fault Tree Analysis** which this approach aims at being **generic**;
- We identified major undesirable events:
  - We discovered new attack paths, someones are generic;
  - And introduced high level-countermeasures.

Conclusion (Cont.)

- We focused on the **code integrity**:
  - Modification of the control flow;
  - Corruption of the Java Card Linker [Hamadouche et al., SAR-SSI 2012], [Razafindralambo et al., SNDS 2012] and [Bouffard et al., CRiSIS 2013];
- Each evaluated attacks succeeded on different cards
  - Bottom-up approach ?
  - We wear a white hat;
- Our approach aims at helping card manufacturers to clearly identify the assets to protect.

Thank you for your attention!
Questions?

Publications

During my PhD thesis, I have co-written **27 publications**:

- 2 book chapters;
- 5 journal articles;
- 3 invited conferences;
- 12 articles in international conferences with review and proceedings;
- 4 articles in national conferences with review and proceedings;
- 1 articles in national conferences with review and without proceeding;
- 1 posters.