Defending against Polymorphic Attacks: Recent Results and Open Questions

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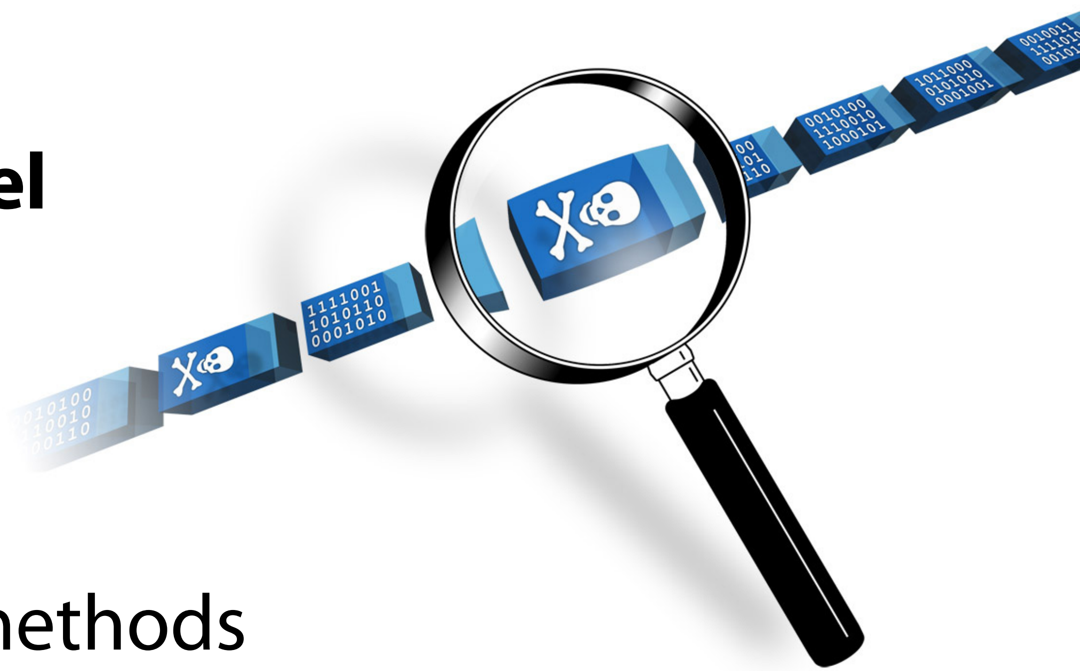
What this talk is about

0-day network-level attack detection



- Existing detection methods
- Evasion techniques
- A novel polymorphic attack detector
- Open issues

System Compromise

1 Place the attack code into a buffer

2 Divert the execution path of the vulnerable process (exploitation)

- Stack/heap/integer overflow
- Format string abuse
- Arbitrary data corruption

3 Execute the injected code (shellcode)

- Performs arbitrary operations under the privileges of the process that has been exploited

```
\xeb\x2a\x5e\x89\x76\x08\xc6\x46\x07\x00\xc7\x46\x0c\x00\x00\x00
```

Signature-based Detection (1/2)

- Known attacks
  - `GET default.ida?NNNNNNNNNNN...`
- Unknown attacks
  - Generic signatures for suspicious code sequences
  - NOP sleds, system calls, …

```
alert ip $EXTERNAL_NET $SHELLCODE_PORTS -> $HOME_NET any
(msg:"SHELLCODE Linux shellcode"; content:"|90 90 90 E8 C0 FF
FF FF|/bin/sh"; classtype:shellcode-detect; sid:652; rev:9;)

alert ip $EXTERNAL_NET $SHELLCODE_PORTS -> $HOME_NET any
(msg:"SHELLCODE x86 setuid 0"; content:"|B0 17 CD 80|";
classtype:system-call-detect; sid:650; rev:8;)
```

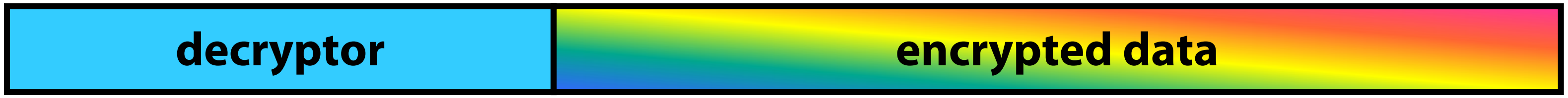
Signature-based Detection (2/2)

- Lots of work on automated signature generation
  - Honeycomb, Earlybird, Autograph, PADS, Polygraph, Hamsa, …
- Common idea: find invariant parts among multiple attack instances
  - Then turned into token subsequences ➔ **regular expressions**
- Limitations
  - Not effective for targeted attacks – only for worm-like attacks
  - Autograph/Polygraph/Hamsa need a pool of “suspect” flows: Which are suspect flows? What if the pool gets intentionally polluted?

```
alert tcp $EXTERNAL_NET any -> $HOME_NET 10202:10203 (msg:"CA
license GCR overflow attempt"; flow:to_server,established;
content:"GCR NETWORK<"; depth:12; offset:3; nocase;
pcre:"/^\S{65}|\S+\s+\S{65}|\S+\s+\S+\s+\S{65}/Ri"; sid:3520;)
```

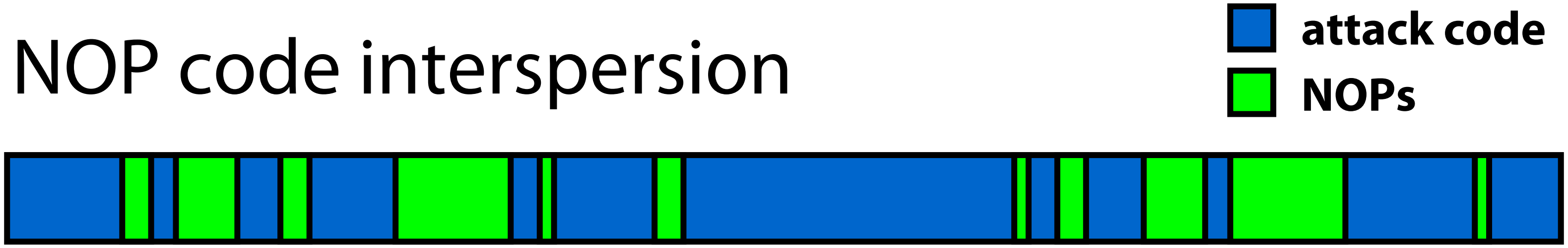
Polymorphism (1/2)

- Naïve encryption



  - The decryptor remains the same in each attack instance
  - ***Easy to fingerprint using typical string signatures***

- NOP code interspersion



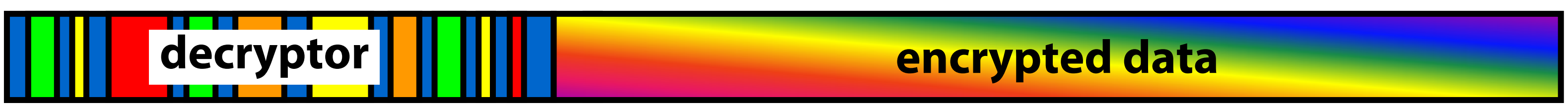
  - NOPs' type/position/number varies in each attack vector
  - ***Can be fingerprinted using regular expressions***

Polymorphism (2/2)

- Code obfuscation/metamorphism
  - Instruction substitution
  - Code block transposition
  - Register reassignment
  - Dead code insertion
  - ***Hard to fingerprint using regexps if applied extensively***

```
mov eax,0xF3   →   push 0xF3
                   pop eax
```

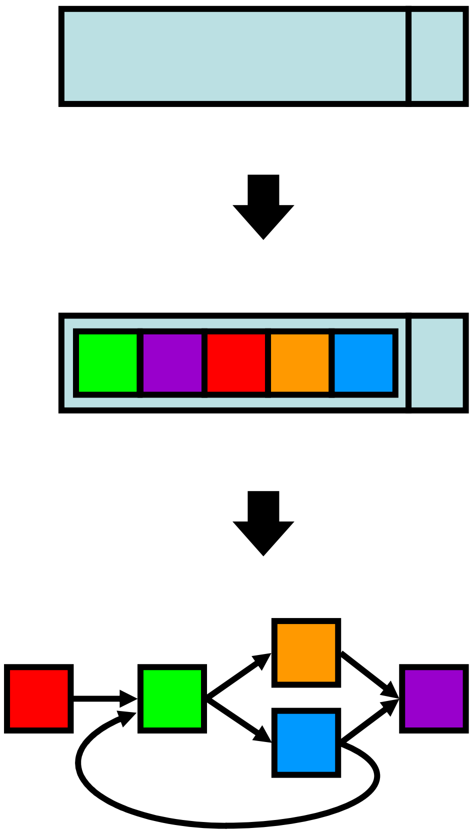
- **Combination of all techniques**



  - ***Signature extraction becomes infeasible***

Static Analysis Based Detection

- Recent proposals heuristically identify malicious code inside network flows using static binary code analysis
  - [Kruegel'05], [Chinchani'05], [Payer'05]
- Step forward – beyond pattern-matching
  - Do not depend on invariant content
- Basic steps
  1. **Disassembly**
  2. **Control Flow Graph extraction**
- Initial approaches focused on the shellcodes' sled component
  - Abstract Payload Execution [Kruegel'02]
    Pioneer network-level static analysis work
  - Orthogonal to above approaches



Static Analysis Resistant Shellcode (1/4)

- Static binary code analysis is generally accurate for compiled and well-structured binaries
- Shellcode is not normal code!
  - Written/tweaked at assembly level: complete freedom…
- The attacker can specially craft the shellcode to hinder disassembly and CFG extraction
  - Anti-disassembly tricks
  - Indirect addressing
  - **Self-modifying code**

Static Analysis Resistant Shellcode (2/4)

- Running example
  - Encrypted shellcode generated by the Countdown engine of the Metasploit Framework
  - Slightly modified with a self-modification

```
\x6A\x0F\x59\xE8\xFF\xFF\xFF\xFF\xC1\x5E\x80
\x46\x0A\xE0\x30\x4C\x0E\x0B\x02\xFA...
```

- Let's try to figure out what this code does

Static Analysis Resistant Shellcode (3/4)

- Linear disassembly can be easily tricked

Linear Disassembly

```
00   6A7F       push byte +0x7f
02   59         pop ecx
03   E8FFFFFFFF call 0x7
08   C15E8046   rcr [esi-0x80],0x46
0C   0AE0       or ah,al
0E   304C0E0B   xor [esi+ecx+0xb],cl
12   02FA       add bh,dl
14
... <encrypted shellcode>
93
```

Static Analysis Resistant Shellcode (3/4)

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Jumps to the middle of itself

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```

Recursive Traversal Disassembly

```
00   6A7F        push byte +0xf
02   59          pop ecx
03   E8FFFFFFFF  call 0x7
07   FFC1        inc ecx
09   5E          pop esi
0a   80460AE0    add [esi+0xa],0xe0
0e   304C0E0B    xor [esi+ecx+0xb],cl
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```

much better, but not the real code that will be eventually executed!

- Recursive traversal disassembly is still not enough…

Static Analysis Resistant Shellcode (4/4)

- Self-modifying code can hide the real CFG

Recursive Traversal Disassembly

```
00   6A7F         push byte +0x7f
02   59           pop ecx
03   E8FFFFFFFF   call 0x7
07   FFC1         inc ecx
09   5E           pop esi
0a   80460AE0     add [esi+0xa],0xe0
0e   304C0E0B     xor [esi+ecx+0xb],cl
12   02FA         add bh,dl
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...  <encrypted shellcode>
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```

Real Code Execution

```
push byte +0x7f
```

Static Analysis Resistant Shellcode (4/4)

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```
00   6A7F         push byte +0x7f
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```

Real Code Execution

```
push byte +0x7f
pop ecx                ecx = 0x7F
```

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Recursive Traversal Disassembly

```
00   6A7F        push byte +0x7f
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```

Real Code Execution

```
push byte +0x7f
pop ecx                  ecx = 0x7F
call 0x7                (push 0x8)
```

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```

Real Code Execution

```
push byte +0x7f
pop ecx                  ecx = 0x7F
call 0x7                (push 0x8)
inc ecx                  ecx = 0x80
```

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00   6A7F        push byte +0x7f
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push byte +0x7f
pop ecx               ecx = 0x7F
call 0x7             (push 0x8)
inc ecx               ecx = 0x80
pop esi               esi = 0x8
```

Static Analysis Resistant Shellcode (4/4)

- Self-modifying code can hide the real CFG

Recursive Traversal Disassembly			Real Code Execution	
00	6A7F	push byte +0x7f	push byte +0x7f	
02	59	pop ecx	pop ecx	ecx = 0x7F
03	E8FFFFFFFF	call 0x7	call 0x7	(push 0x8)
07	FFC1	inc ecx	inc ecx	ecx = 0x80
09	5E	pop esi	pop esi	esi = 0x8
0a	**80460AE0**	**add [esi+0xa],0xe0**	**add [esi+0xa],0xe0**	**ADD [12] 0xE0**
0e	304C0E0B	xor [esi+ecx+0xb],cl		
12	02FA	add bh,dl		
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...	<encrypted shellcode>			
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Static Analysis Resistant Shellcode (4/4)

- Self-modifying code can hide the real CFG

Recursive Traversal Disassembly			Real Code Execution	
00	6A7F	push byte +0x7f	push byte +0x7f	
02	59	pop ecx	pop ecx	ecx = 0x7F
03	E8FFFFFFFF	call 0x7	call 0x7	(push 0x8)
07	FFC1	inc ecx	inc ecx	ecx = 0x80
09	5E	pop esi	pop esi	esi = 0x8
0a	**80460AE0**	**add [esi+0xa],0xe0**	**add [esi+0xa],0xe0**	**ADD [12] 0xE0**
0e	304C0E0B	xor [esi+ecx+0xb],cl		
12	**E2FA**	**loop 0xe**		
14				
...	<encrypted shellcode>			
93				

Self-modification

0x02FA + 0xE0 = 0xE2FA

add bh,dl → loop 0xe

Static Analysis Resistant Shellcode (4/4)

- Self-modifying code can hide the real CFG

Recursive Traversal Disassembly

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00   6A7F        push byte +0x7f
02   59          pop ecx
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...  <encrypted shellcode>
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```

Real Code Execution

```
push byte +0x7f
pop ecx                     ecx = 0x7F
call 0x7                   (push 0x8)
inc ecx                     ecx = 0x80
pop esi                     esi = 0x8
add [esi+0xa],0xe0          ADD [12] 0xE0
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add [esi+0xa],0xe0          ADD [12] 0xE0
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Real Code Execution

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call 0x7                (push 0x8)
inc ecx                  ecx = 0x80
pop esi                  esi = 0x8
add [esi+0xa],0xe0       ADD [12] 0xE0
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loop 0xe                (ecx = 0x7F)
xor [esi+ecx+0xb],cl     XOR [92] 0x7F
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Real Code Execution

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push byte +0x7f
pop ecx                     ecx = 0x7F
call 0x7                   (push 0x8)
inc ecx                     ecx = 0x80
pop esi                     esi = 0x8
add [esi+0xa],0xe0          ADD [12] 0xE0
xor [esi+ecx+0xb],cl        XOR [93] 0x80
loop 0xe                   (ecx = 0x7F)
xor [esi+ecx+0xb],cl        XOR [92] 0x7F
loop 0xe                   (ecx = 0x7E)
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Real Code Execution

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push byte +0x7f
pop ecx                      ecx = 0x7F
call 0x7                    (push 0x8)
inc ecx                      ecx = 0x80
pop esi                      esi = 0x8
add [esi+0xa],0xe0           ADD [12] 0xE0
xor [esi+ecx+0xb],cl         XOR [93] 0x80
loop 0xe                    (ecx = 0x7F)
xor [esi+ecx+0xb],cl         XOR [92] 0x7F
loop 0xe                    (ecx = 0x7E)
xor [esi+ecx+0xb],cl         XOR [91] 0x7E
...
```
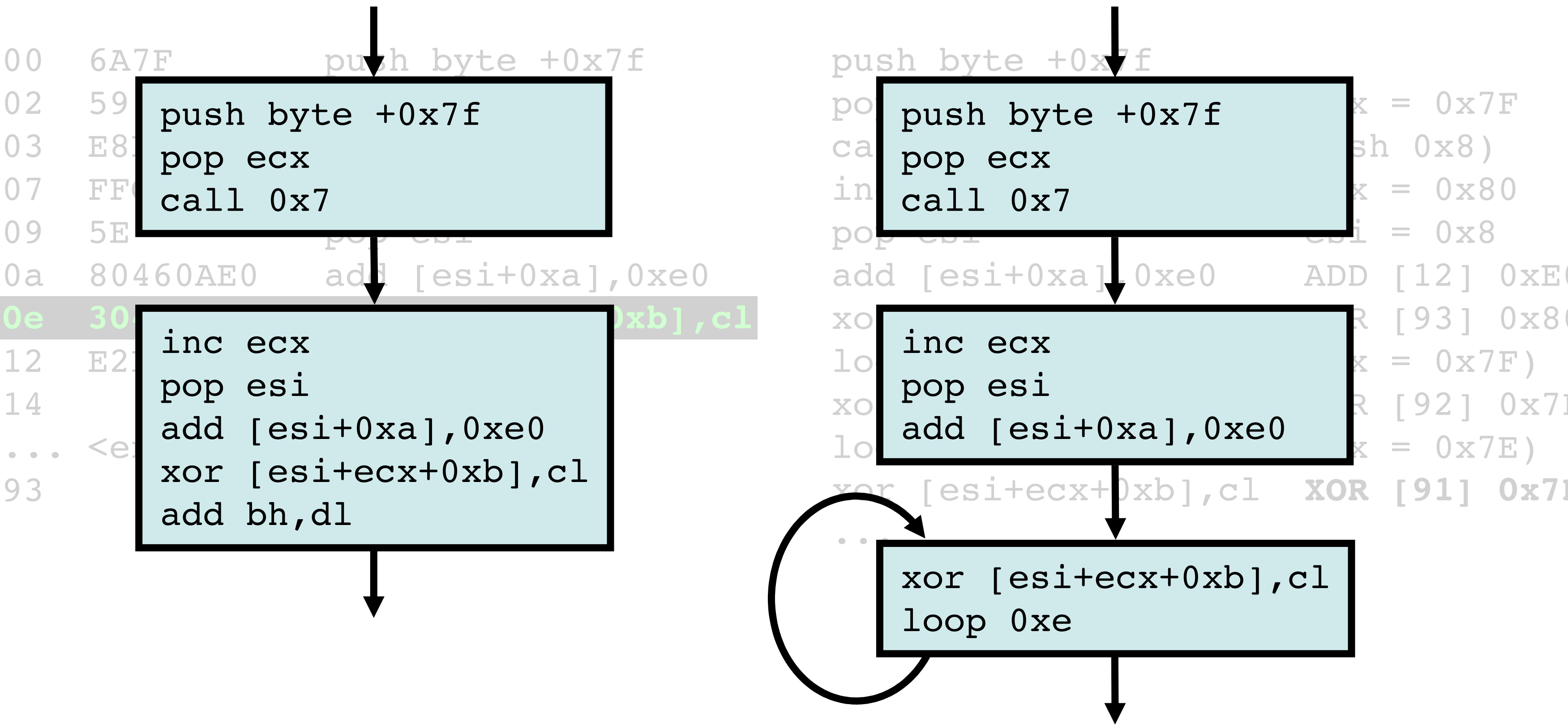

Static Analysis Resistant Shellcode (4/4)

- Self-modifying code can hide the real CFG

Recursive Traversal Disassembly **Real Code Execution**



Attacks – Defenses Coevolution

Plain Shellcode

String Signatures

Simple Obfuscation

Regexp Signatures

Polymorphism

Static Analysis

SARS

?

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Emulation

Network-level Polymorphic Shellcode Detection

- **Motivation:** Highly obfuscated code will not reveal its actual form until it is executed
- **Main idea:** execute each TCP stream as if it was executable code
- **Goal:** identify the specific behavior inherent in polymorphic shellcodes

Network-level Emulation (1/2)

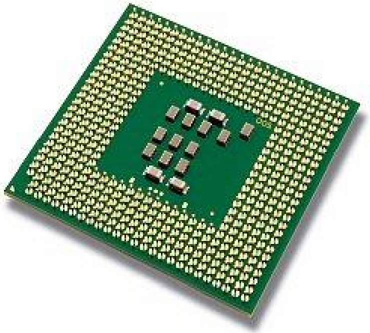
- Is it possible to execute the shellcode using only information available at the network level?
  - No access to the vulnerable host
- The execution of a polymorphic shellcode consists of two sequential parts
  1. Decryption
  2. Actual shellcode execution
- Focus on the decryption process
  - Generic, independent of the exploit/vulnerability/OS

Network-level Emulation (2/2)

- Polymorphic shellcode engines (so far) produce *self-contained* decryptor code
  - **Position-independent:** will run from any location in the vulnerable process' address space
  - **Mandatory GetPC code:** for finding its absolute address in memory (x86 has no indirect memory addressing)
  - **Known operand values:** operands are initialized before use (encrypted payload size, decryption key, …)
- Can be executed using merely a CPU emulator
  - Without any host-level information

Detector

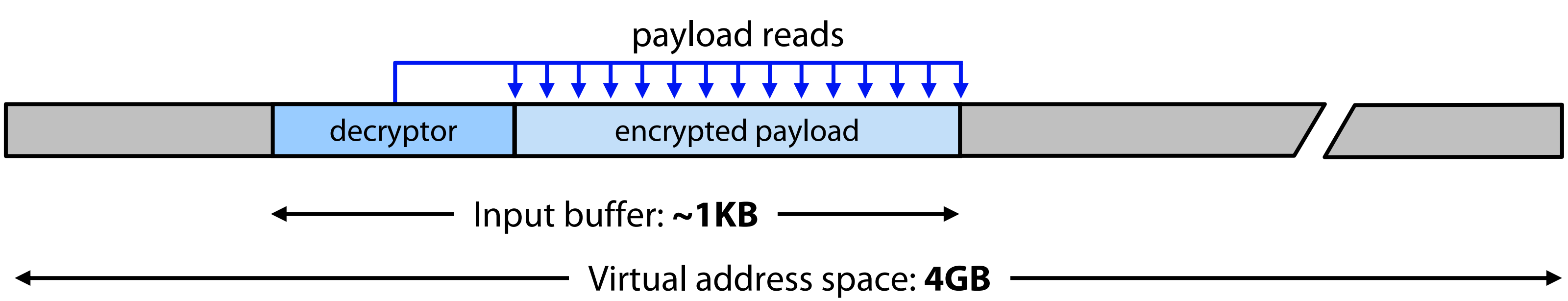
- Input: reassembled TCP streams or UDP packets
- CPU emulator
  - Randomized state before each new execution



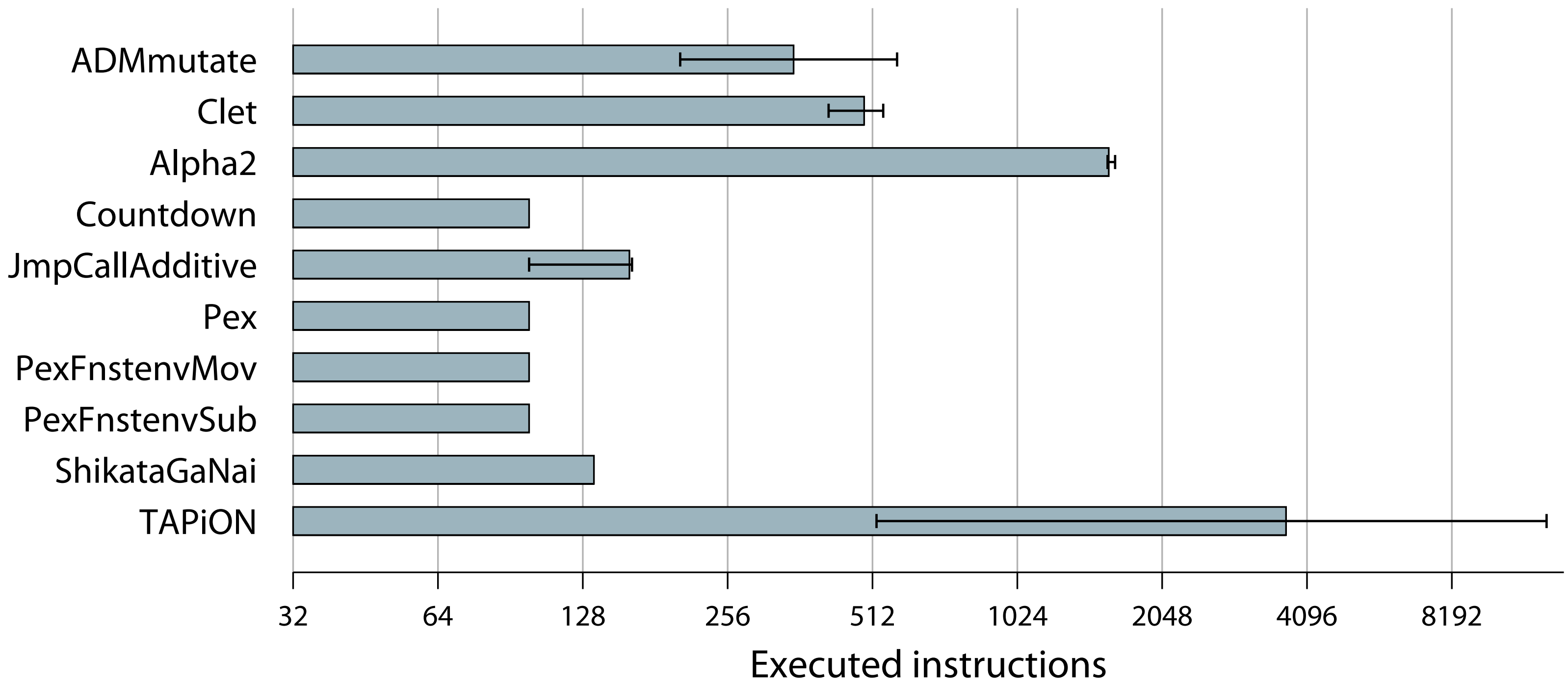
- We don't know the starting position of the shellcode in the input stream
  - Start execution from each byte
  - Performance optimization: skip NULL-byte-delimited regions smaller than 50 bytes
- Execution Threshold
  - Sometimes *endless* or *infinite* loops occur in random code
  - Dynamic infinite loop detection and squashing

Detection Heuristic

1. GetPC code (just a hint)
   - Execution of a suspicious instruction: `call`, `fstenv/fnstenv`, `fsave/fnsave`
2. Memory reads from *distinct* locations of the input buffer (*Payload reads)*
   - Low probability of payload reads in random data (~1KB vs 4GB)
   - For each execution, the buffer is mapped to a random location



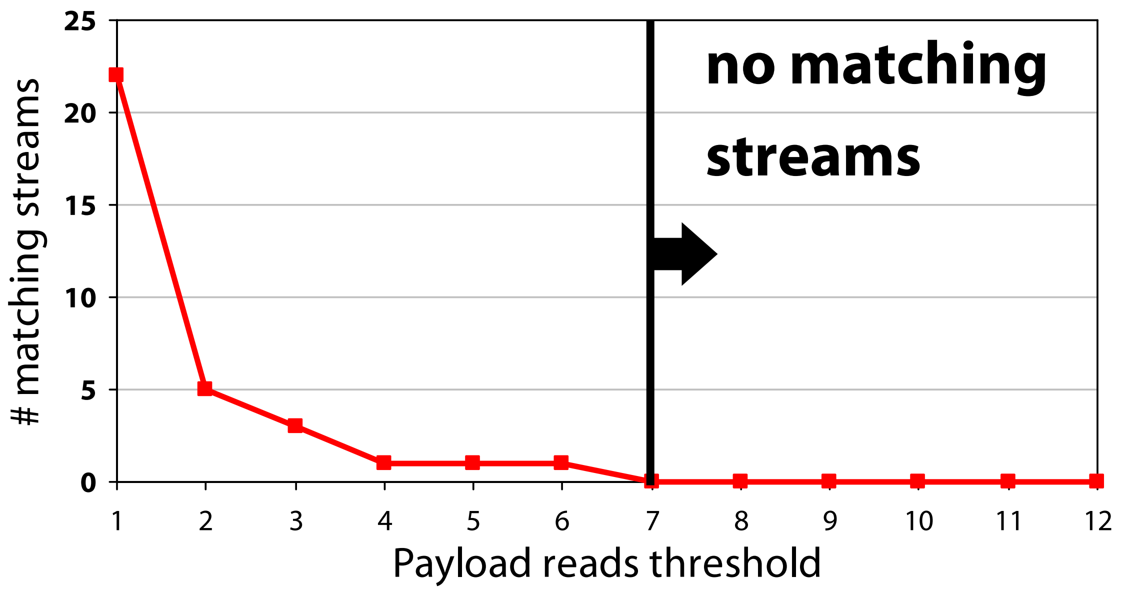
Evaluation: Correct Execution



- Off-the-shelf polymorphic shellcode engines
- Original shellcode is 128 bytes, 1000 mutations with each engine
- ***In all cases the shellcode is decrypted correctly***

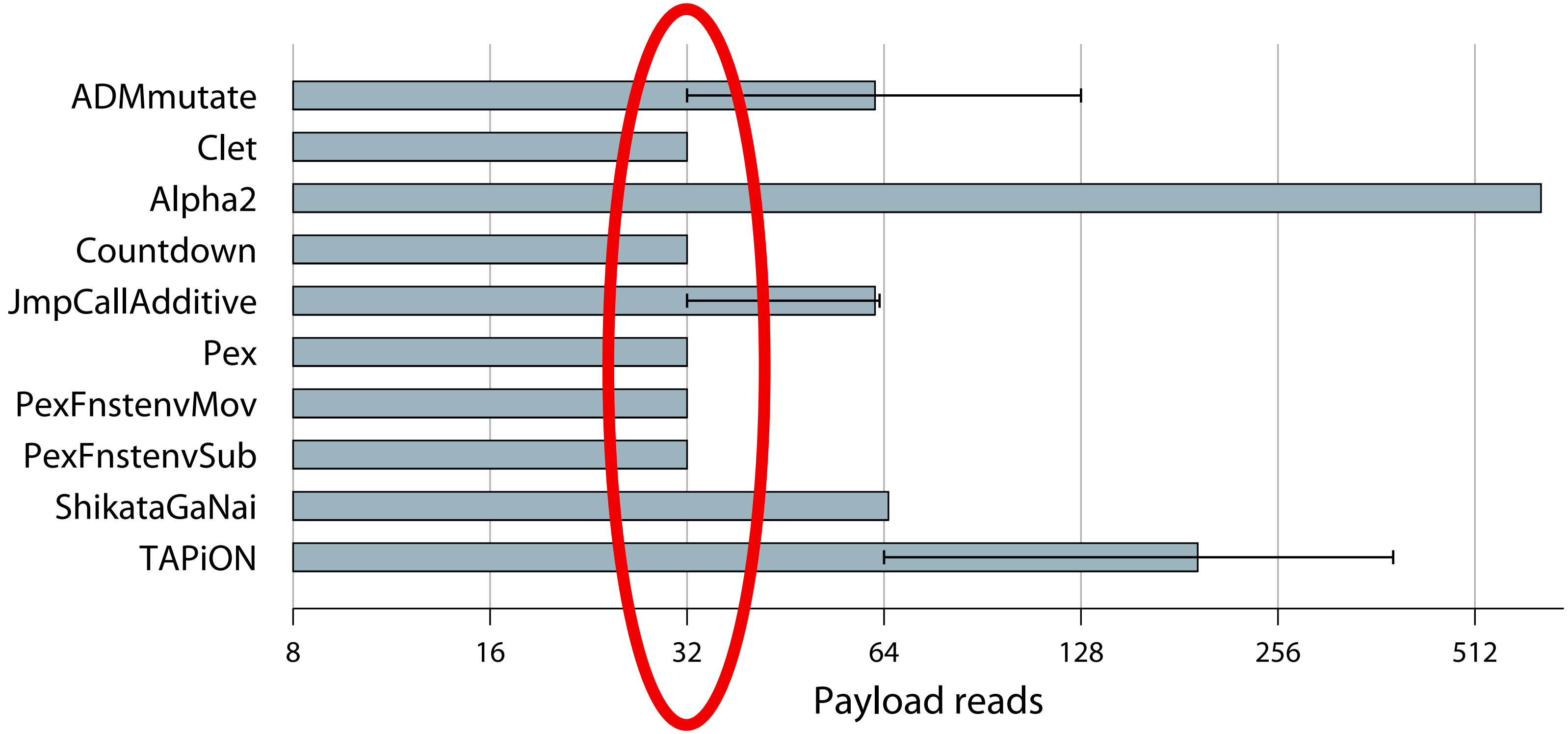
Evaluation: False Positives / Heuristic Tuning

- Benign traffic traces and 61GB of random data
  - More than 2 million streams



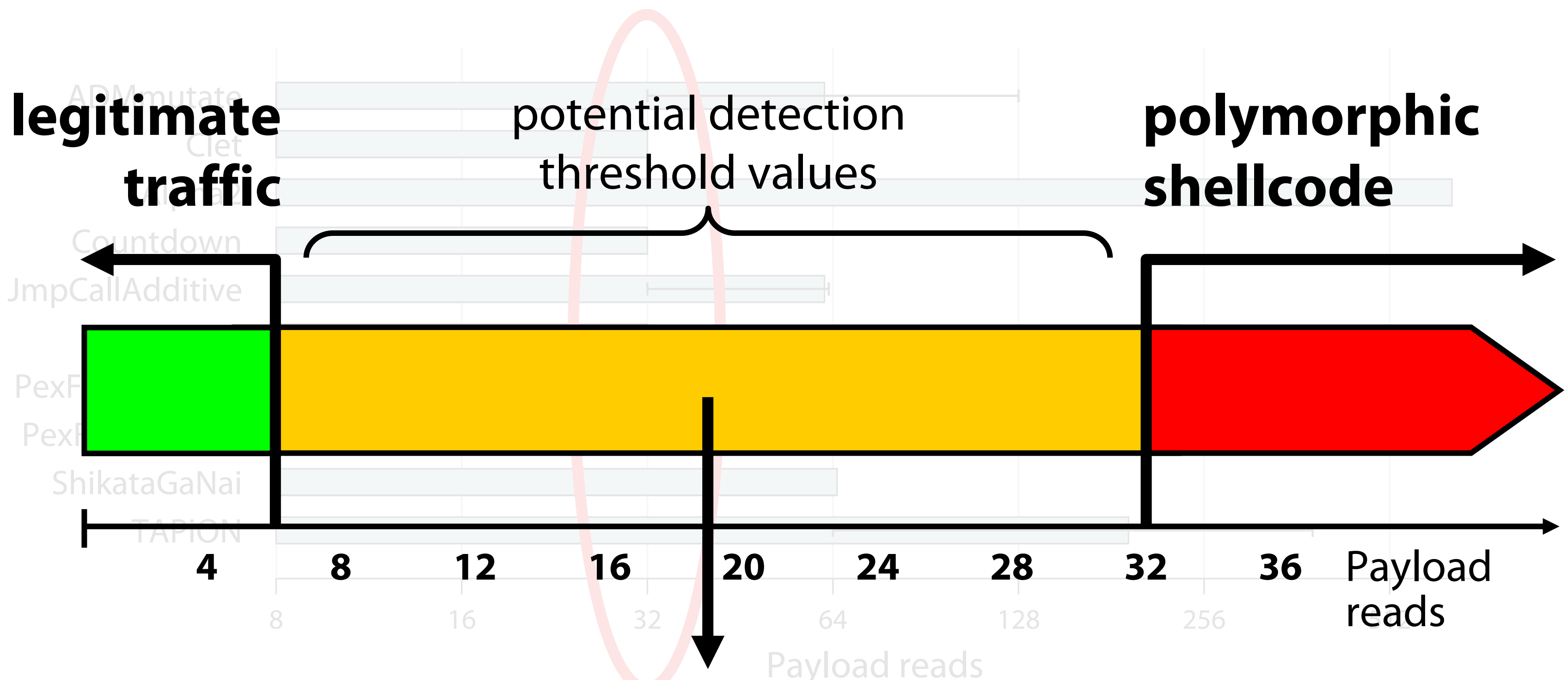
- Requiring the execution of some GetPC code followed by 7 or more payload reads gives zero false positives

Payload Reads for Complete Decryption



- Benign data: 1-6 accidental payload reads in extremely rare cases
- Polymorphic shellcodes: **at least 32** payload reads for a conservatively small 128-byte shellcode

Payload Reads for Complete Decryption



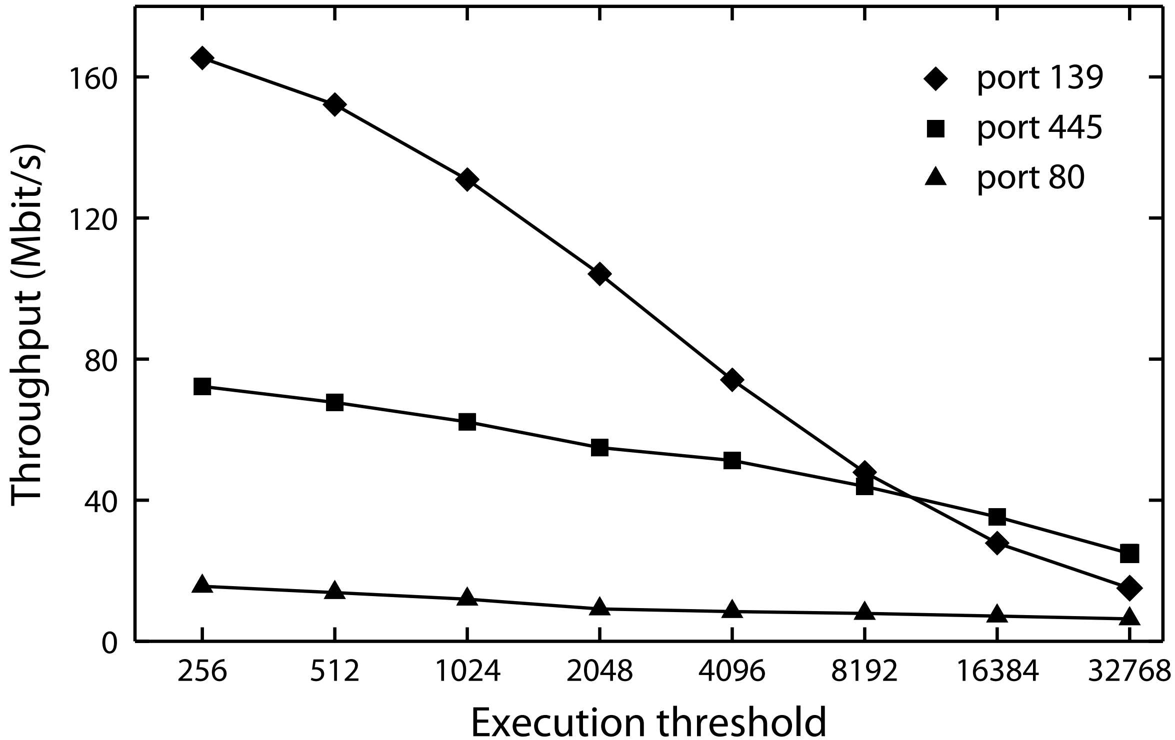
Choose the median

→ *Even more increased resilience to false positives*

→ Benign data: 1-6 accidental payload reads in extremely rare cases

→ Polymorphic shellcodes: **at least 32** payload reads for a conservatively small 128-byte shellcode

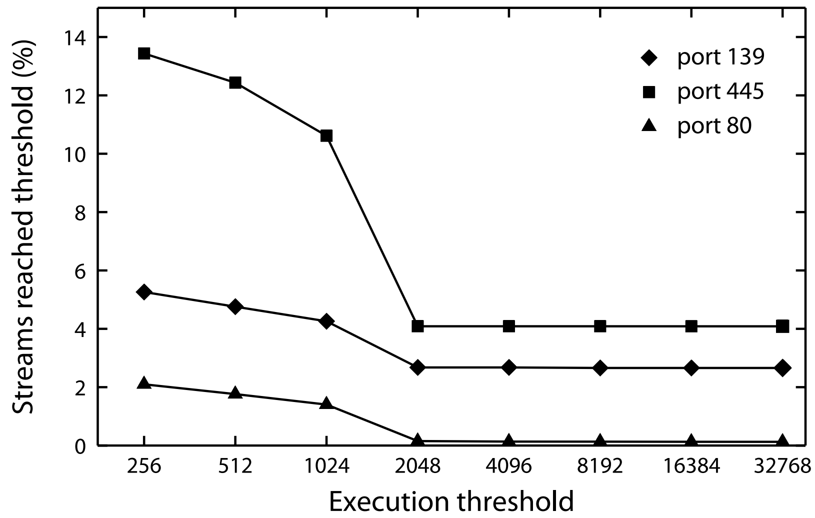
Evaluation: Processing Cost



- Higher XT ➔ longer processing time per input ➔ lower throughput
- NULL-byte optimization not effective for port 80 (mostly ASCII data)
  - Could take advantage of other delimiters (CRLF, protocol framing)

Open Issues: Endless Loops

- Evasion by placing endless loops before/within the decryptor code
  - The execution threshold is reached before any sign of polymorphic behavior
- Endless loops occur in less than 5% of the benign traffic
  - Even if loops are used for evasion, useful as a first-level detector
  - Send all traffic reaching XT to a honeypot
- Infinite loop squashing provides some mitigation



- Can we do better than this? Can we also skip the execution of **endless** (but not infinite) loops?
  - The loop can compute something useful, like the decryption key
  - Static analysis strikes back?

Open Issues: Non-Polymorphic Shellcode

- What about plain or completely metamorphic code?
  - Does not decrypt its body
  - No self modifications
- Existing methods: search for exposed system calls, suspicious code sequences, …
- Shellcode "packing" is becoming essential
  - Evasion!
  - Avoidance of restricted bytes

  http://www.metasploit.com/projects/Framework/exploits.html

Payload Info:

Room for **512** bytes of payload

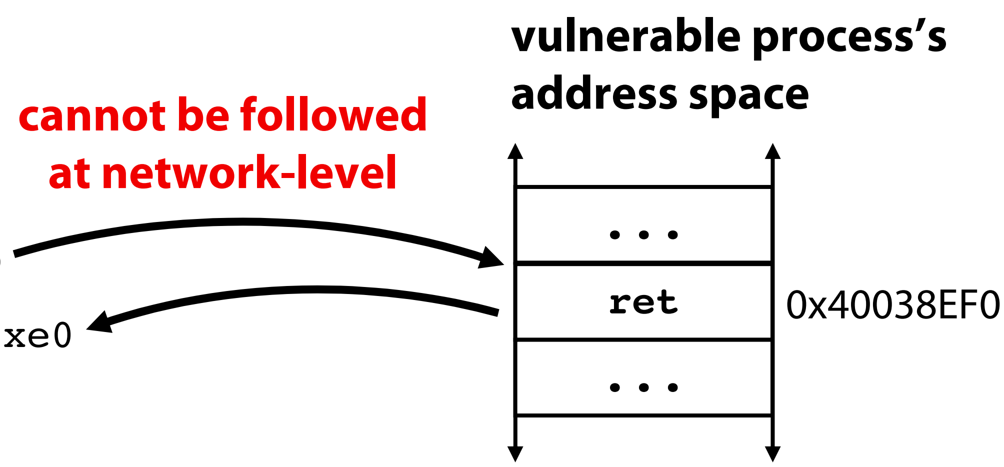
Restricted bytes: **0x00 0x3a 0x26 0x3f 0x25 0x23 0x20 0x0a 0x0d 0x2f 0x2b 0x0b 0x5c**

Open Issues: Non-Self-Contained Code

- Although current polymorphic/encryption engines produce self-contained code, non-self-contained code is possible
- Take advantage of addresses with a priori known contents
  - e.g., initialize registers or jump to existing code
  - Should remain constant across all vulnerable systems (not always feasible)

shellcode

```
...
inc ecx
call 0x40038EF0
add [esi+0xa],0xe0
...
```



- Augment the network-level detector with host-level information
  - e.g., invariant parts of the address space of each protected process

Summary

- Pattern matching and static analysis are not enough
  - Highly polymorphic and self-modifying code
- Network-level emulation
  - Detects self-modifying polymorphic shellcode
- Preliminary experimental results are promising
  - Network-level detection of all known off-the-shelf polymorphic shellcode engines at 10-100 Mbps
- Open issues that have to be explored

Defending against Polymorphic Attacks: Recent Results and Open Questions

thank you!

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fallback slides

Network-Level Emulation

GET /ind | ex.php HT | TP/1.1 Hos …

GET /index.php HTTP/1.1 Host: www.foo.com …

```
G
E
T
 /
index.p
hp HT
T
P

1.
1
...
```

```
inc edi
inc ebp
push esp
and [edi],ch
imul ebp,[esi+0x64],dword 0x702e7865
push dword 0x54482070
push esp
push eax
das
xor [esi],ebp
xor [eax],esp
...
```

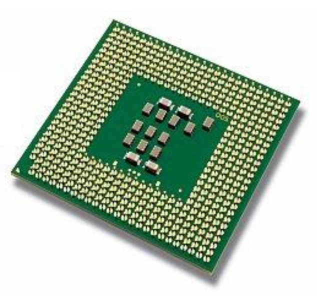
✓ **benign request**

Network-Level Emulation

\x6A\x0F\x59 | \xE8\xFF\xFF | \xFF\xFF\xC1 | …

\x6A\x0F\x59\xE8\xFF\xFF\xFF\xFF\xC1\x5E\x80… …

```
6A07
59
E8FFFFFFFF
FFC1
5E
80460AE0
304C0E0B
E2FA
...
```



```
push byte +0x7f
pop ecx
call 0x7
inc ecx
pop esi
add [esi+0xa],0xe0
xor [esi+ecx+0xb],cl
loop 0xe
xor [esi+ecx+0xb],cl
loop 0xe
xor [esi+ecx+0xb],cl
...
```

✘ **malicious request!**

Payload Reads vs Execution Threshold