Lec 22: Anti-malware

CSED415: Computer Security

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POSTECH

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Recap

- Malware: A malicious software
  - A program that is inserted into a system, usually covertly, with the intent of compromising the CIA of the victim's system
- Malware of our interests:
  - Virus, worm, trojan, rootkit, backdoor, spyware, bots, and ransomware
- Anti-malware (== Anti-virus) is a software or technique that aims to protect our systems from malware

Anti-virus (AV)

Fred Cohen’s problem

- Given an arbitrary program, can we design a Turing machine that determines whether the program is malicious or not?
  - In automata theory, a Turing machine computes a function

$$f, x \xrightarrow{\text{input}} \boxed{\text{TM}} \xrightarrow{\text{output}} f(x) = y$$

  - Can we define a function f, such that TM computes $f(x)$ as follows:

$$f(x) = \begin{cases} 1 & if\ x\ is\ malicious \\ 0 & otherwise \end{cases}\ ?$$

A paradox

- Let’s define a function named `is_virus`
  - Input: A program
  - Output: True if virus, False if not

```
def is_virus(prog):
    # test the prog and return 1 or 0
```

Assume such function actually exists

A paradox

- Write a program named `real_virus`

```
if __name__ == __main__:
    if is_virus(real_virus):
        return # do nothing

    else:
        infect_other_prog () # viral activity
        destroy_user_data()
        return
```

real_virus is a self-contradictory program!

Fred Cohen’s conclusion

- Virus detection is an undecidable problem
  - Undecidable: Proved to be impossible to construct an algorithm that always correctly determines the answer

- Since the detection is an undecidable problem, the removal of virus is not always guaranteed
  - You have to first detect a virus in order to remove it

How do detect malware then?

Naïve approach for malware detection

- Goal: Check if a file is identical to a known malware
- Approach: Signature matching
  - Collect malware samples (e.g., worm binaries)
  - Compute hashes of the malware samples
  - Compute the hash of the target file and compare it against the hashes of malware samples

What is wrong with this approach?

Naïve approach for malware detection

- Problem of hash matching: Too many ways to bypass
  - Add a dummy code (e.g., dead code)
    - A function that is not used
    - A function that does nothing significant
    - nop instructions
  - Change code order (e.g., define function A after B / B after A)
  - Replace instructions with semantically equivalent ones
    - e.g., inc eax → add eax, 1

A difference in a single bit results in totally different hash values

Another naïve approach for malware detection

- Pattern matching
  - Match using regular expression (RE)
  - e.g., bytecode of a execve(“/bin/sh”) shellcode

    -
      ```
      ...
      6a 0b  push 0xb
      58     pop eax
      cd 80  int 0x80
      ```
    - RE pattern: `(\x6a\x0b\x58)(.*)(\xcd\x80)`

(1) push 0xb
pop eax

(2) anything

(3) int 0x80

Matches any bytecode that has (1), (2), and (3)

Another naïve approach for malware detection

- Problem of RE matching: Still easy to bypass
  - RE pattern: `(\x6a\x0b\x58)(.*)(\xcd\x80)`
  - Easy to generate semantically identical code to `push 0xb; pop eax;`
    - `mov eax, 0xb;`
    - `mov eax, 0xa; inc eax;`
    - …

    → The above RE pattern misses these

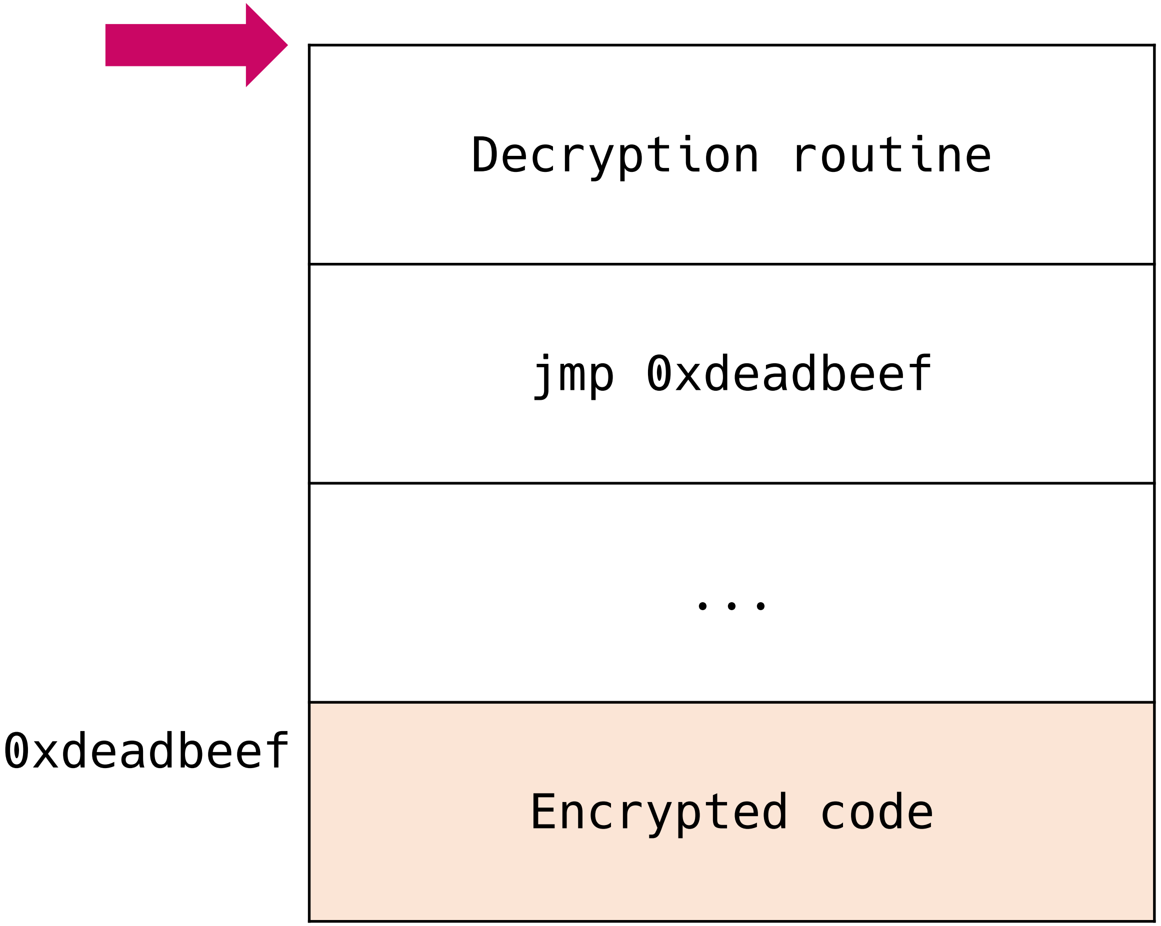
Recent malware utilize “self-modifying code” to make pattern-based detection even more challenging

Polymorphism and Metamorphism

Polymorphic code

- Definition:
  - A code that mutates itself to change its appearance while keeping the original algorithm intact
  - Malware often employ polymorphism to bypass signature/pattern matching-based AVs
- Usage
  - Malicious use: Bypass malware detection
  - Benign use: Software protection
    - e.g., make reverse engineering tricky

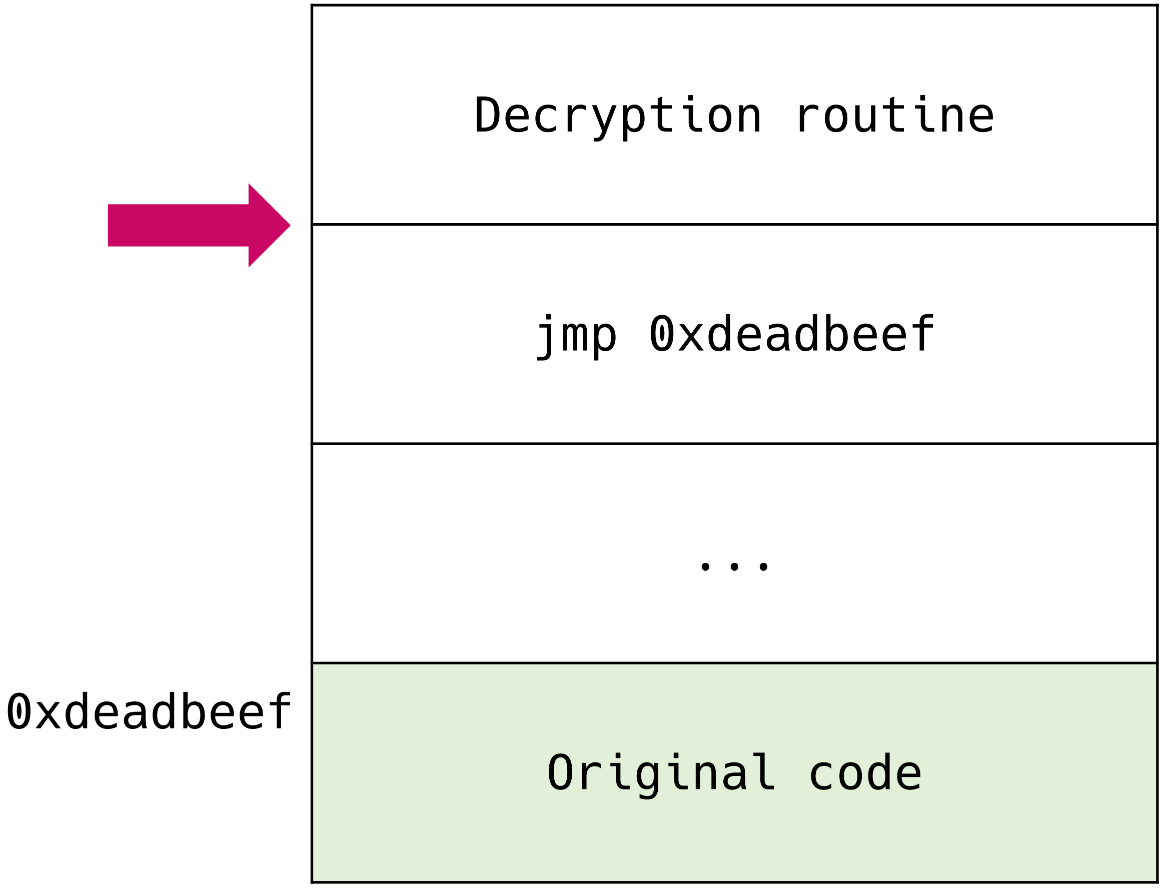
Polymorphism example



Reads the encrypted code and decrypts it

Stores the result at the location where the encrypted code was stored

Polymorphism example



Decryption routine

jmp 0xdeadbeef

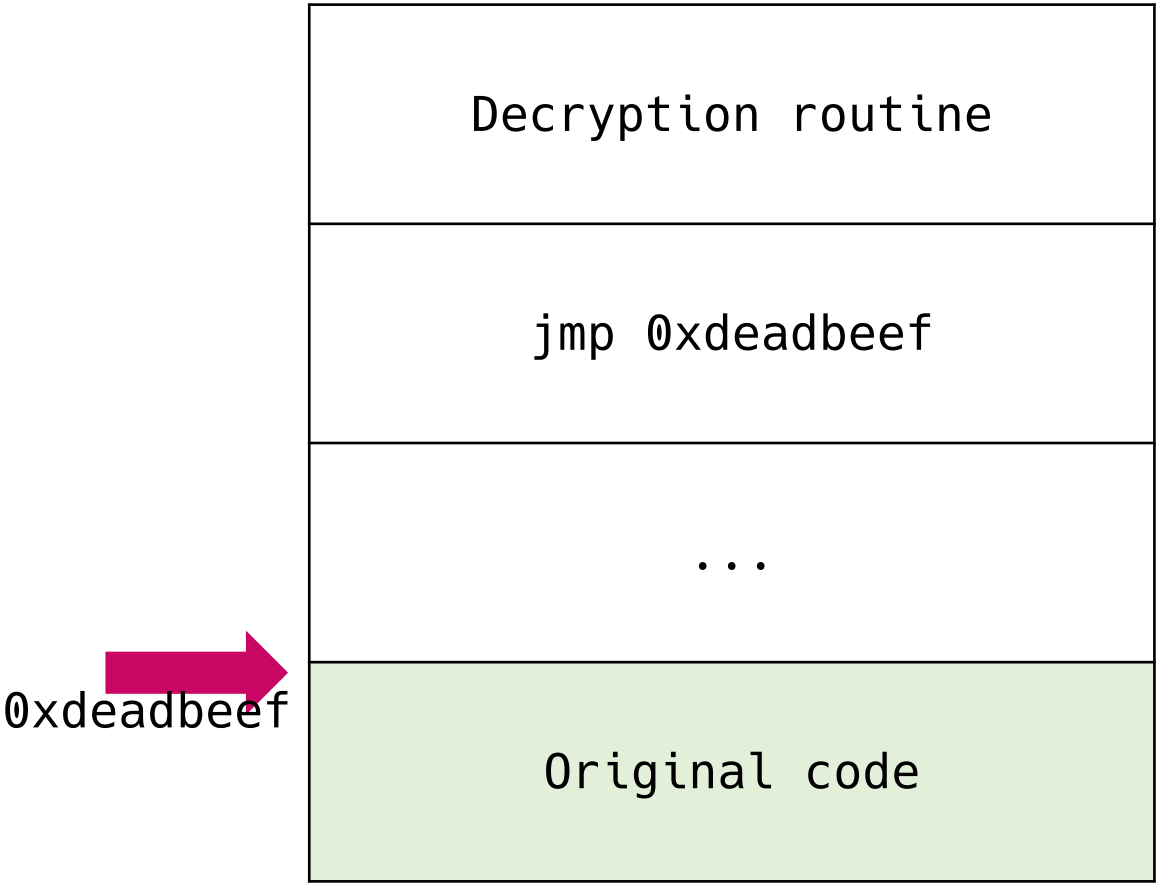
...

0xdeadbeef

Original code

Jumps to `0xdeadbeef`,
i.e., original entry point

Polymorphism example

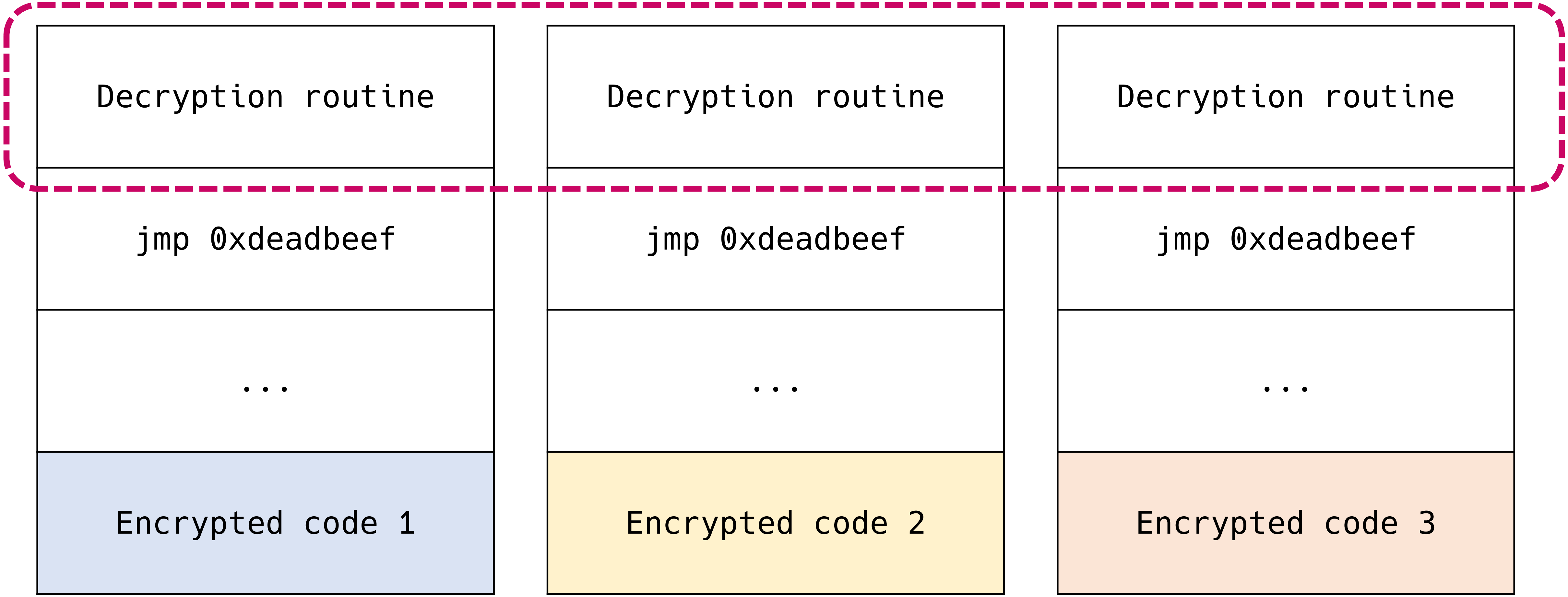


We can produce unlimited number of semantically identical binaries that have different signatures (e.g., hash) by just changing the encryption key

Original malware code is executed

Creating partial signatures

This part does not change → AVs can create signatures of the decryption routine



`Decryption routine`	`Decryption routine`	`Decryption routine`
`jmp 0xdeadbeef`	`jmp 0xdeadbeef`	`jmp 0xdeadbeef`
`...`	`...`	`...`
`Encrypted code 1`	`Encrypted code 2`	`Encrypted code 3`

Creating partial signatures

`Decryption routine`

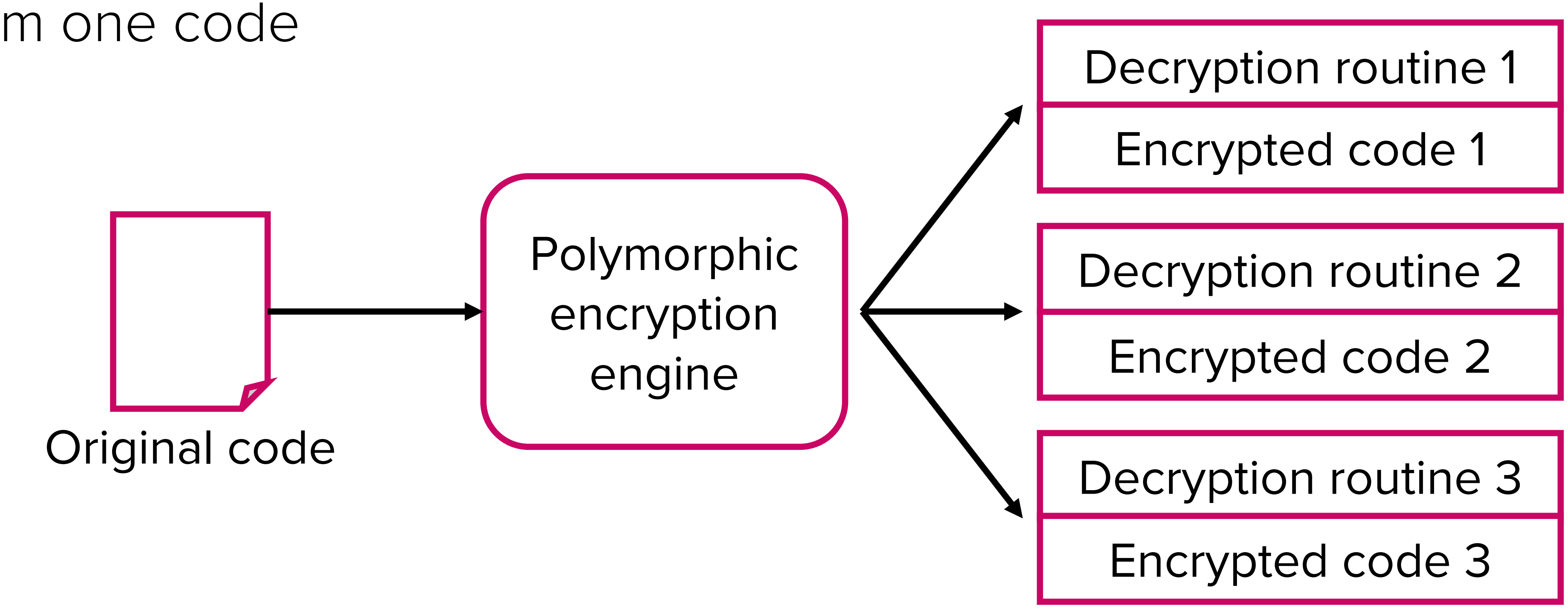
`Decryption routine`

`Decryption routine`

Can polymorphism be applied even to the decryption routine?

Polymorphic encryption

- Goal:
  - Creating multiple unique pairs of encryption and decryption routines from one code



Original code

Polymorphic encryption engine

Decryption routine 1

Encrypted code 1

Decryption routine 2

Encrypted code 2

Decryption routine 3

Encrypted code 3

Polymorphic encryption example

```
for (int i = 0; i < code_len / 4; ++i) {
  v = obc[i]; // obc: int array containing the original bytecode
  key[i] = random_int(); // random 4-byte integer
  op[i] = random_op(); // random operation
  switch (op[i]) {
    case ADD: v += key[i]; break;
    case SUB: v -= key[i]; break;
    case XOR: v ^= key[i]; break;
    ...
  }
  enc[i] = v; // enc: int array containing the encrypted code
}
```

Polymorphic decryption example

```
for (int i = 0; i < code_len / 4; ++i) {
  v = enc[i]; // for every 4-byte of the encrypted code
  k = key[i]; // retrieve the key
  switch (op[i]) {
    case ADD: v -= k; break;
    case SUB: v += k; break;
    case XOR: v ^= k; break;
    ...
  }
  dec[i] = v; // store decrypted (original) code in dec
}
```

→ Unroll (i.e., flatten) the loop and embed to malware as decryption routine

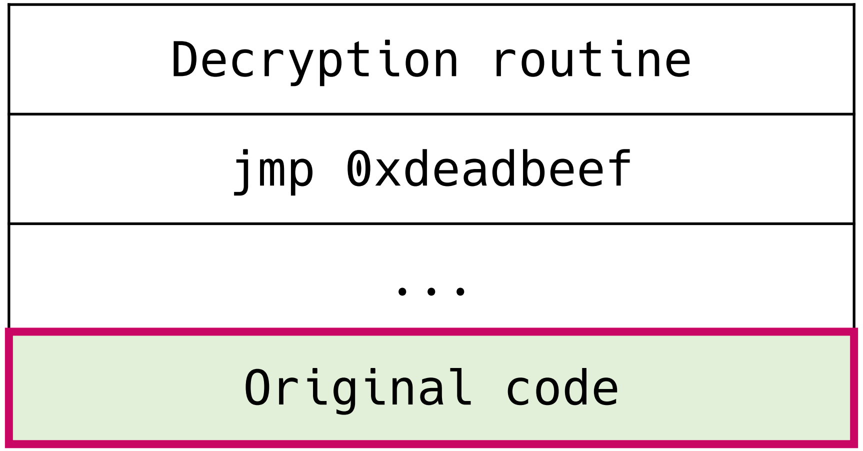
Signatures for polymorphic encryption

- Using polymorphic encryption, millions of variants can be created from a single malware
- Signature database of an AV will rapidly expand if all possible variants are considered
- Signature-based pattern matching does not help anymore

What can be done?

Potential countermeasure

- In-memory detection
  - At some point of time, the original code will be “unpacked” and stored in the memory to be executed
  - Scanning the **memory** for the original malware code pattern is a working solution



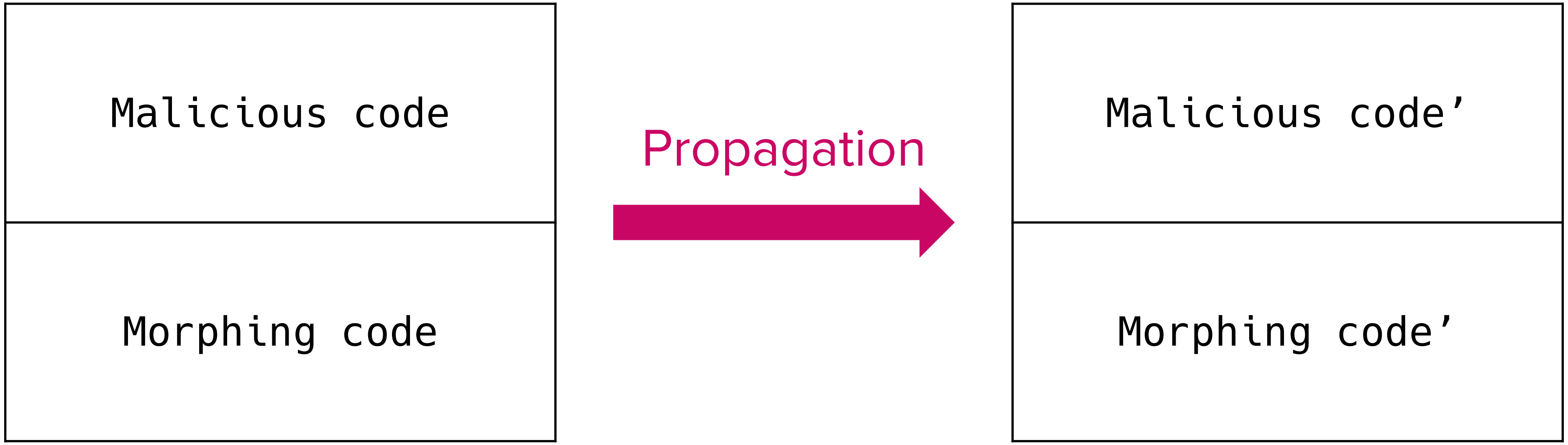
Memory

Potential countermeasure

- Polymorphic malware ends up exposing the unpacked code
  - Attacker: Can we completely remove packing/unpacking to bypass detection?

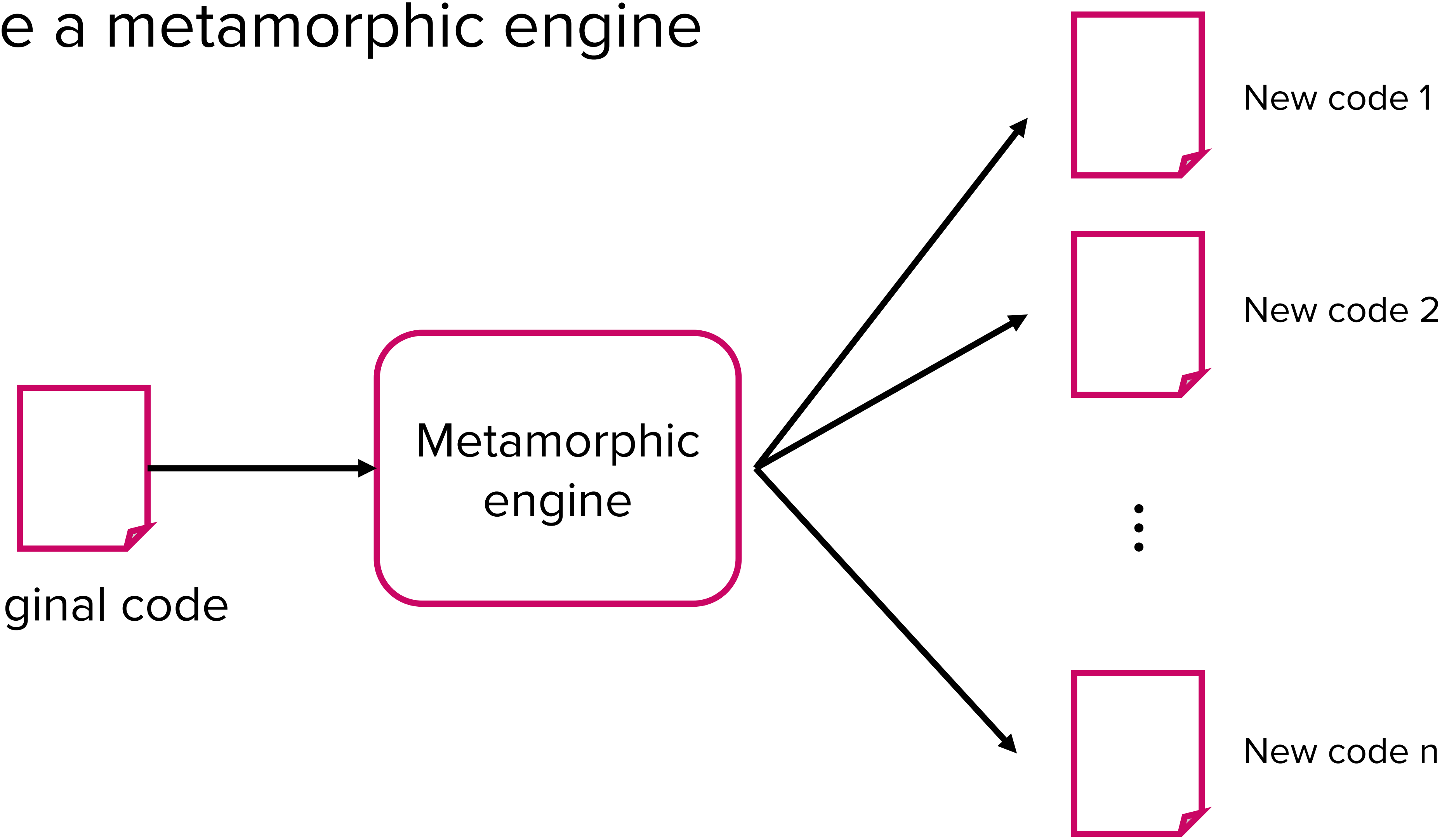
Metamorphic malware

- Concept
  - Do not rely on encryption or decryption (== packing and unpacking)
  - Code automatically modifies itself each time it propagates



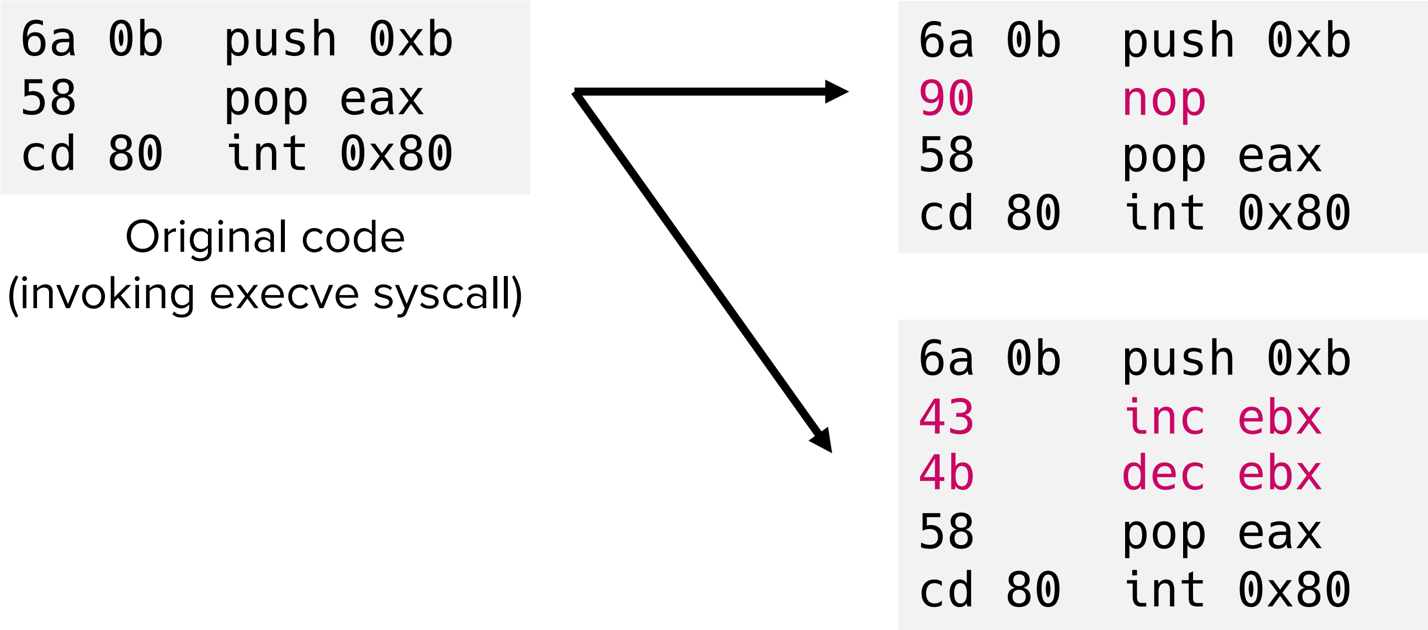
Metamorphic malware

- Idea: Use a metamorphic engine



Metamorphic malware

- Metamorphic engine
  - Adding dead code



```
6a 0b   push 0xb
58      pop eax
cd 80   int 0x80
```

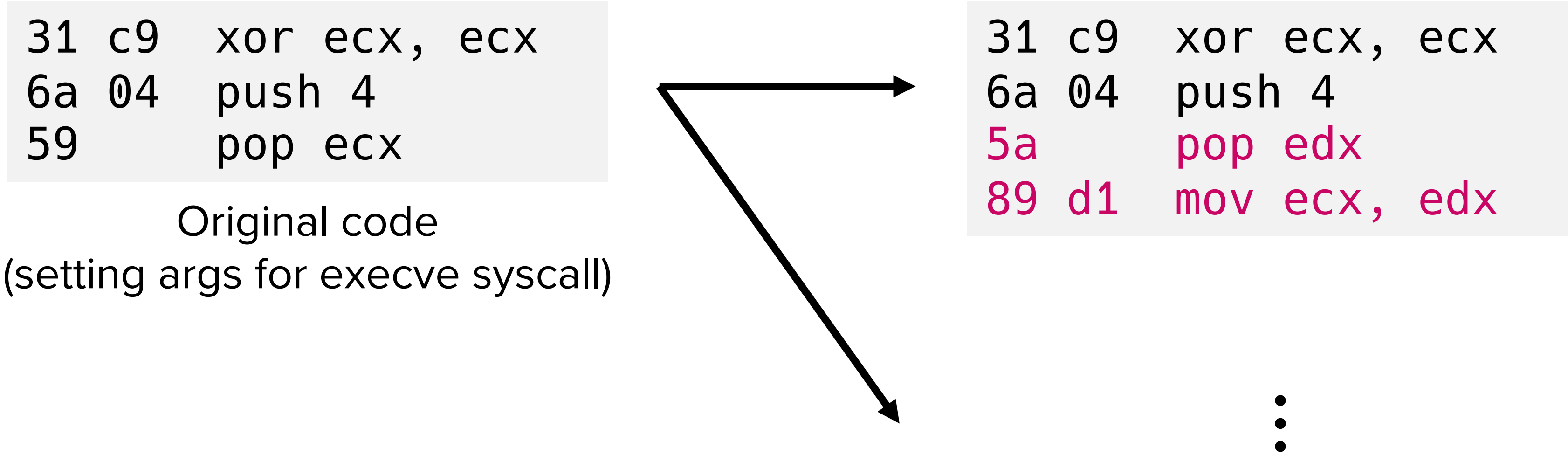
Original code
(invoking execve syscall)

```
6a 0b   push 0xb
90      nop
58      pop eax
cd 80   int 0x80
```

```
6a 0b   push 0xb
43      inc ebx
4b      dec ebx
58      pop eax
cd 80   int 0x80
```

Metamorphic malware

- Metamorphic engine
  - Register renaming



```
31 c9   xor ecx, ecx
6a 04   push 4
59      pop ecx
```

Original code
(setting args for execve syscall)

```
31 c9   xor ecx, ecx
6a 04   push 4
5a      pop edx
89 d1   mov ecx, edx
```

⋮

Metamorphic malware

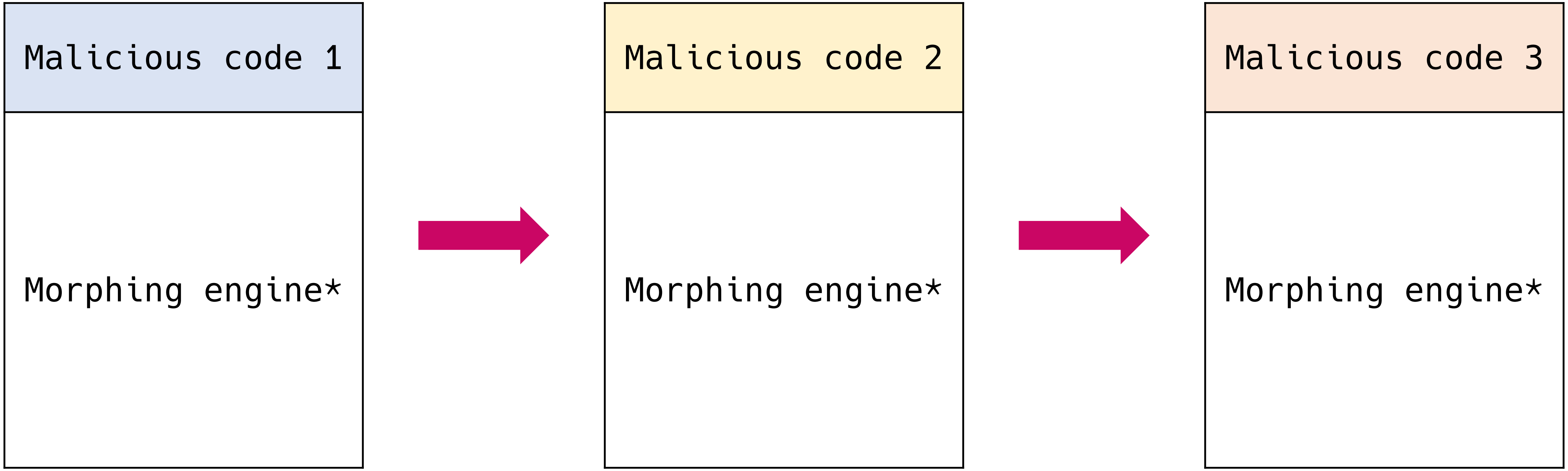
- Metamorphic engine
  - Function reordering
    - Reorder the order of invocations for functions that do not affect each other

```
setvbuf(stdin, NULL, _IONBF, 0);
setvbuf(stdout, NULL, _IONBF, 0);
```

```
setvbuf(stdout, NULL, _IONBF, 0);
setvbuf(stdin, NULL, _IONBF, 0);
```

  - Code permutation
  - Randomizing
  - Compressing and decompressing
  - …

Metamorphic malware



* The morphing engine itself could also be metamorphic

In-memory detection no longer works!
Malicious code 1, 2, 3, … (not the unpacked original code)
are loaded onto the memory and get executed

Dynamic Analysis

Dynamic Analysis

- Problem:
  - Static analysis (e.g., pattern matching) cannot reliably detect signatures of self-changing code
- Idea:
  - Whether malware is polymorphic or metamorphic, it will eventually exhibit the same malicious behavior
  - We can execute the program and **observe the behavior** to see if it matches malicious behaviors

Two categories of behaviorial analysis

- Rule-based approach (== heuristic-based)
  - Detect malicious behavior
  - e.g., malware-specific behavior (reading sensitive files)

- Anomaly-based approach
  - Detect abnormal behavior
  - “Normal” and “Abnormal” behaviors should be defined

Rule-based dynamic analysis

- Monitor malicious behaviors with a set of rules
  - Attempts to open, view, delete, and/or modify files
  - Attempts to format disk drives
  - Modifications to the logic of executable files
  - Moidification of critical system settings, e.g., start-up scripts
  - Initiation of network communications

→ Many AV solutions have their own collection of rules

Anomaly-based dynamic analysis

- Idea:
  - Define normal (== expected) behavior to identify malicious behavior
- Three types of anomalies
  - Point anomalies: Defined with an individual data point
  - Contextual anomalies: Defined within a context
  - Collective anomalies: Defined with a collection of related data

Anomaly-based dynamic analysis

- Point anomalies
  - If an individual data instance can be considered as anomalous with respect to the rest of data, then the instance is termed as a point anomaly
  - Example: Credit card fraud detection
    - Alice typically spends 5~40 USD per transaction
    - A transaction (i.e., data instance) for which the amount spent is 20,000 USD is anomalous

Anomaly-based dynamic analysis

- Contextual anomalies
  - If a data instance is anomalous only in a specific context, then it is termed as a contextual (or conditional) anomaly
  - Example: Temperature
    - 30 ℃ (86 ℉) at Pohang in December is abnormal
    - Totally normal in Singapore or Abu Dhabi (hot all year round)

Anomaly-based dynamic analysis

- Collective anomalies
  - If a collection of related data instances is anomalous with respect to the entire dataset, it is termed as a collective anomaly
  - Example: Money transfer
    - Alice transfers 200 USD to Mallory - normal
    - Bob transfers 200 USD to Mallory - normal
    - Claire transfers 200 USD to Mallory - normal
    - Dave transfers 200 USD to Mallory - normal
    - …
    - Zuckerberg transfers 200 USD to Mallory - normal

Abnormal

Anomaly-based dynamic analysis

- Example: Self-immune system
  - Collect a sequence of system calls for normally operating programs
  - Build a profile of normal behavior based on the sequence
  - When we observe discrepancies, we flag them as anomalous

Anomaly-based dynamic analysis

- Example: Self-immune system
  - System call sequences of normal execution

```
open-read-mmap-mmap-open-getrlimit-mmap-close
```

```
open-getrlimit-close
```

```
open-getrlimi-mmap-close
```

```
open-read-mmap-mmap-open
```

Anomaly-based dynamic analysis

- Example: Self-immune system
  - Pairwise syscall profile using sliding window of 4

Syscall	pos 1	pos 2	pos 3
`open`	`read`	`mmap`	`mmap`
	`getrlimit`	-	`close`
`read`	`mmap`	`mmap`	`open`
`mmap`	`mmap`	`open`	`getrlimit`
	`open`	`getrlimit`	`mmap`
	`close`	-	-
`getrlimit`	`mmap`	`close`	-

Anomaly-based dynamic analysis

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- Example: Self-immune system
  - Checking a behavior against the profile

Syscall	pos 1	pos 2	pos 3
`open`	`read`	`mmap`	`mmap`
	`getrlimit`	`-`	`close`
`read`	`mmap`	`mmap`	`open`
`mmap`	`mmap`	`open`	`getrlimit`
	`open`	`getrlimit`	`mmap`
	`close`	`-`	`-`
`getrlimit`	`mmap`	`close`	`-`

Behavior to check: `open-read-mmap-open-open-getrlimit-mmap-close`

No match

Anomaly-based dynamic analysis

- Example: Self-immune system
  - Checking a behavior against the profile

Syscall	pos 1	pos 2	pos 3
`open`	`read`	`mmap`	`mmap`
	`getrlimit`	-	`close`
`read`	`mmap`	`mmap`	`open`
`mmap`	`mmap`	`open`	`getrlimit`
	`open`	`getrlimit`	`mmap`
	`close`	-	-
`getrlimit`	`mmap`	`close`	-

Behavior to check: `open-read-mmap-open-open-getrlimit-mmap-close`

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Anomaly-based dynamic analysis

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`read`	`mmap`	`mmap`	`open`
`mmap`	`mmap`	`open`	`getrlimit`
	`open`	`getrlimit`	`mmap`
	`close`	`-`	`-`
`getrlimit`	`mmap`	`close`	`-`

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`mmap`	`mmap`	`open`	`getrlimit`
	`open`	`getrlimit`	`mmap`
	`close`	`-`	`-`
`getrlimit`	`mmap`	`close`	`-`

Behavior to check: `open-read-mmap-open-open-getrlimit-mmap-close`

No match

Anomaly-based dynamic analysis

- Example: Self-immune system
  - Checking a behavior against the profile

Syscall	pos 1	pos 2	pos 3
`open`	`read`	`mmap`	`mmap`
	`getrlimit`	`-`	`close`
`read`	`mmap`	`mmap`	`open`
`mmap`	`mmap`	`open`	`getrlimit`
	`open`	`getrlimit`	`mmap`
	`close`	`-`	`-`
`getrlimit`	`mmap`	`close`	`-`

Behavior to check: `open-read-mmap-open-open-getrlimit-mmap-close`

Match

Mismatch rate: 4/5 = 80% → Anomalous!

Anomaly-based dynamic analysis

- How to obtain execution profile?
  - Using tracers
    - Tracers allow you to observe and/or intercept syscalls
    - Ptrace, strace, ltrace, …
  - Attaching debuggers to running process
    - GDB, LLDB, WinDbg, …
  - Code instrumentation
    - Inject additional code into programs to track behavior
      - Adding printf()s for debugging is a naïve form of instrumentation!
    - Pin, DynamoRio, Valgrind, …

Anomaly-based dynamic analysis

- Running potential malware is a bad idea
  - Sandboxing is recommended
    - e.g., Dynamically analyze a file in a virtual machine

Summary

- Malware detection is an undecidable problem
- Static analysis
  - Fast - pattern matching w/o execution
  - Safe - no execution
  - Prone to false negatives - may miss self-modifying malware
- Dynamic analysis
  - Slow - need to execute
  - Potentially unsafe - need to execute potential malware
  - Better detection - resilient to poly/metamorphism

Questions?