MILCOM'12

TRUSTED COMMUNICATIONS...AWARENESS TO ACTION

Guest-Transparent Instruction Authentication for Self-Patching Kernels

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Outline

- Guest-Transparent Instruction Authentication for Self-Patching Kernels
  - Context
  - Problem
  - Approach
  - Evaluation
  - Summary

THE CONTEXT:
VMM-based prevention of kernel rootkits.

Context: Kernel Rootkits

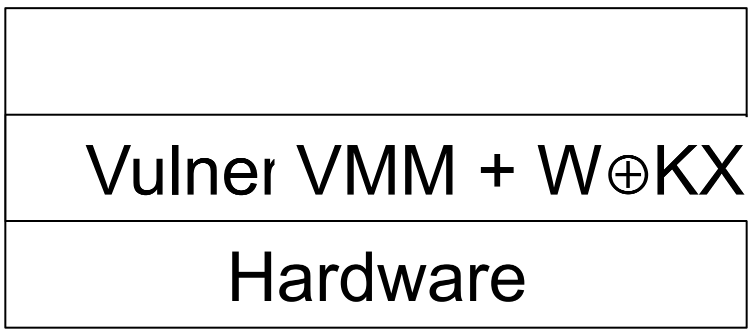
- Kernel rootkits operate with kernel-level permissions
  - Full control over the system
- In-kernel protection mechanisms are vulnerable to kernel rootkits
  - Ex. memory permission restrictions can be turned off by a rootkit

Context: Previous Work

- Security mechanisms have been created to prevent kernel rootkits by leveraging VMM capabilities such as introspection and memory protection
  - For our work, we build-upon one such mechanism: NICKLE
  - Other similar systems exist: hvmHarvard and SecVisor
- Though each system has its own unique contributions we refer to NICKLE, hvmHarvard, and SecVisor as “NICKLE-like systems.”

Context: VMM Enforced W⊕KX

- How does NICKLE prevent kernel rootkit infection?



- Run vulnerable system in a virtual machine
- Enforce W⊕KX kernel memory permissions from VMM

Context: Rootkit Prevention

- NICKLE Guarantee:
  - *No unauthorized code can be executed at the kernel level*
- Kernel rootkits typically need to introduce their own malicious code into a running kernel to gain control
- Because NICKLE does not allow memory to be both writable *and* kernel-executable:
  - The malicious code introduction will be prevented, or
  - The malicious code will be introduced but will not be executable

Context: Code Authentication

- The system must allow:
  - an authorized kernel to get loaded into place at boot
  - authorized kernel modules to get loaded during run-time
- Code introduced into the kernel is marked non-executable until it is authenticated
- If the code is authenticated:
  - The code is set to executable and read-only

Context: Code Authentication

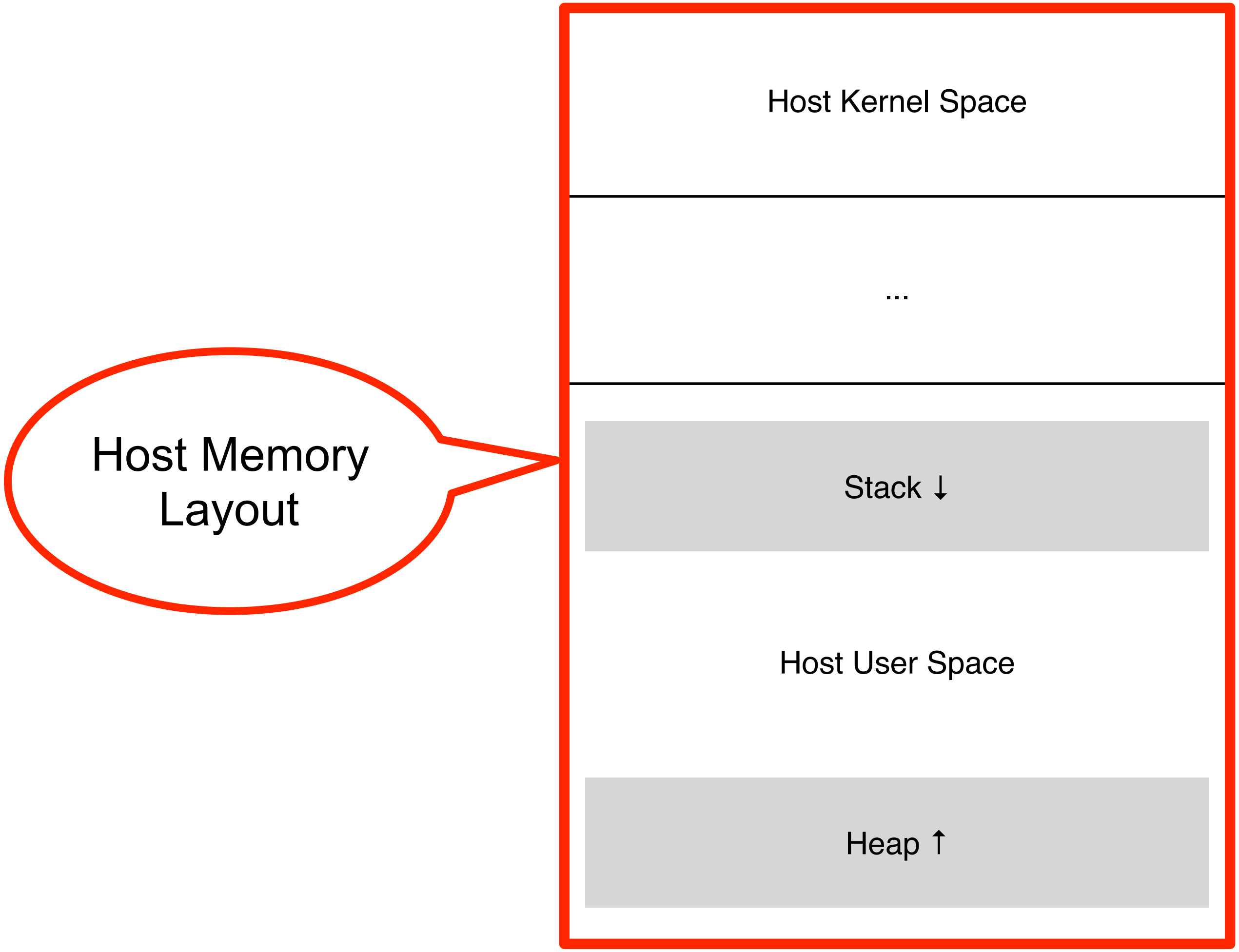
- To authenticate kernel code, previous works have used cryptographic hashes
  - Offline: a cryptographic hash is calculated for each piece of authorized code that *may* get loaded into the guest kernel
  - Online: the VMM intercepts each guest attempt to load new kernel code and calculates a hash for the code
  - If the online hash matches an offline hash, the load is allowed

THE PROBLEM:
How do we authenticate self-patching kernels?

Problem: Self-Patching Kernels

- Some kernels are self-patching; they modify their own code at runtime
  - CPU optimizations, multiprocessor compatibility adjustments, and advanced debugging
- In a NICKLE-like system:
  - If the patch is applied after hash verification
    - The memory will be read-only and the patching will fail
  - If the patch is applied before hash verification
    - The code authentication will fail

Problem: Self-Patching Kernels



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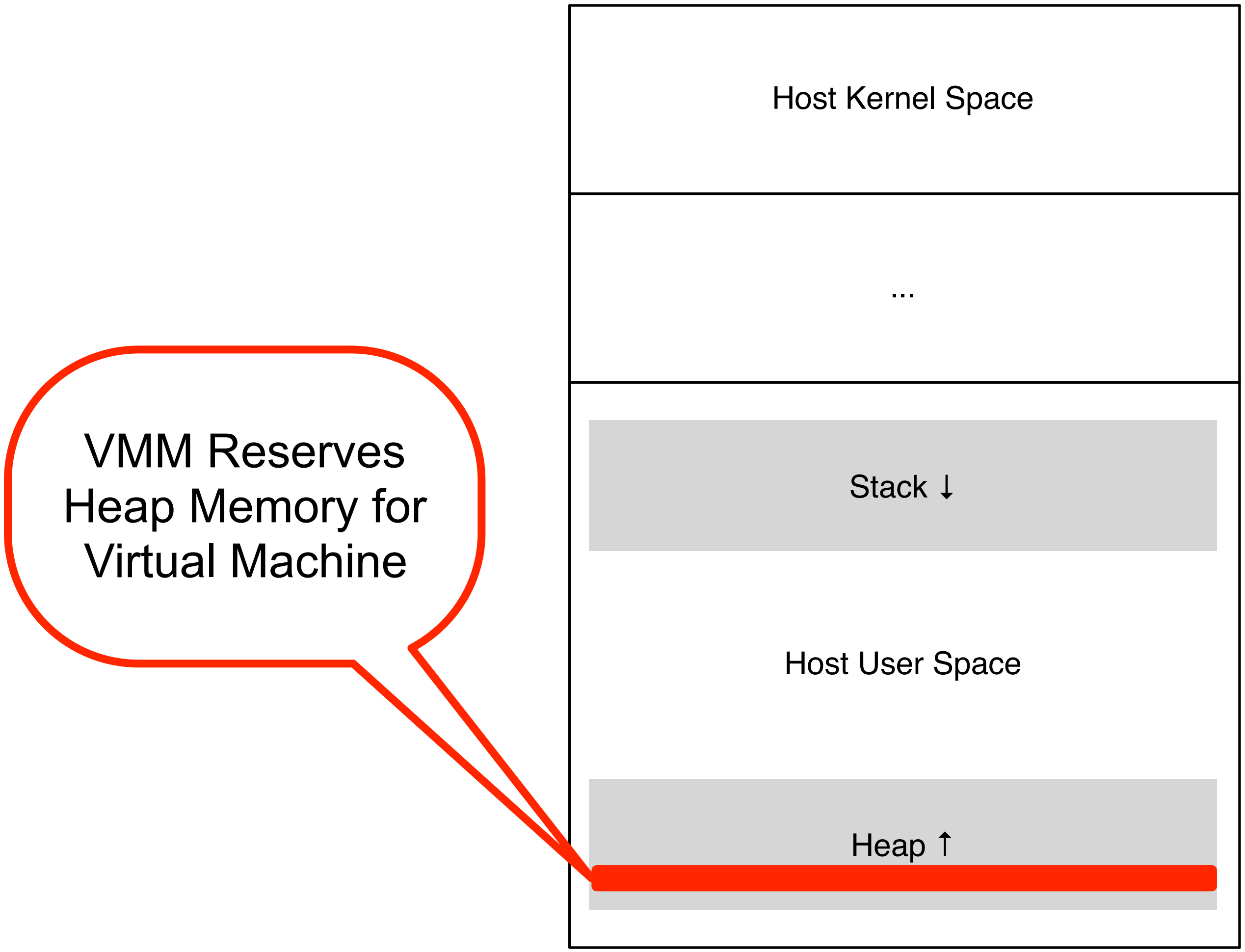

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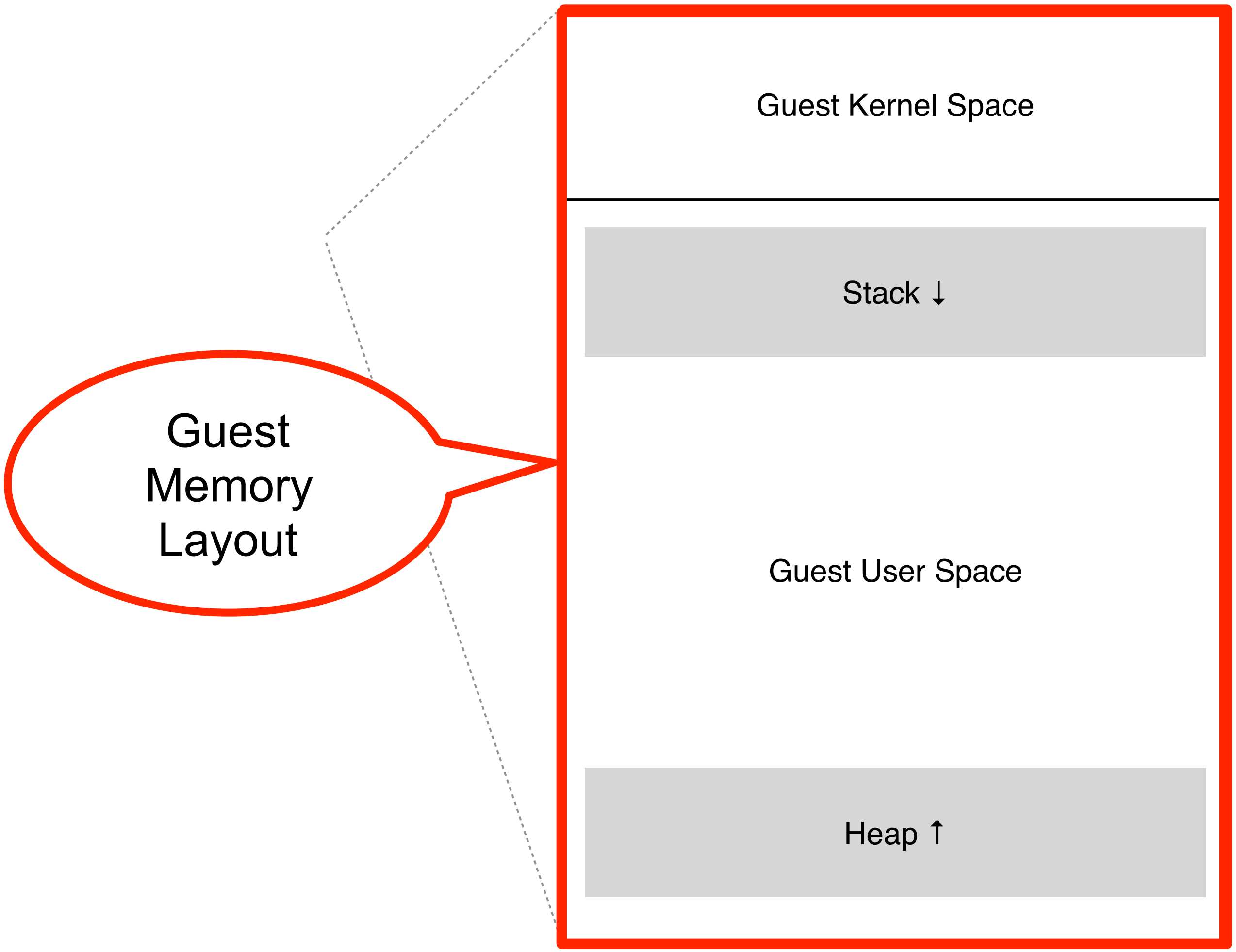

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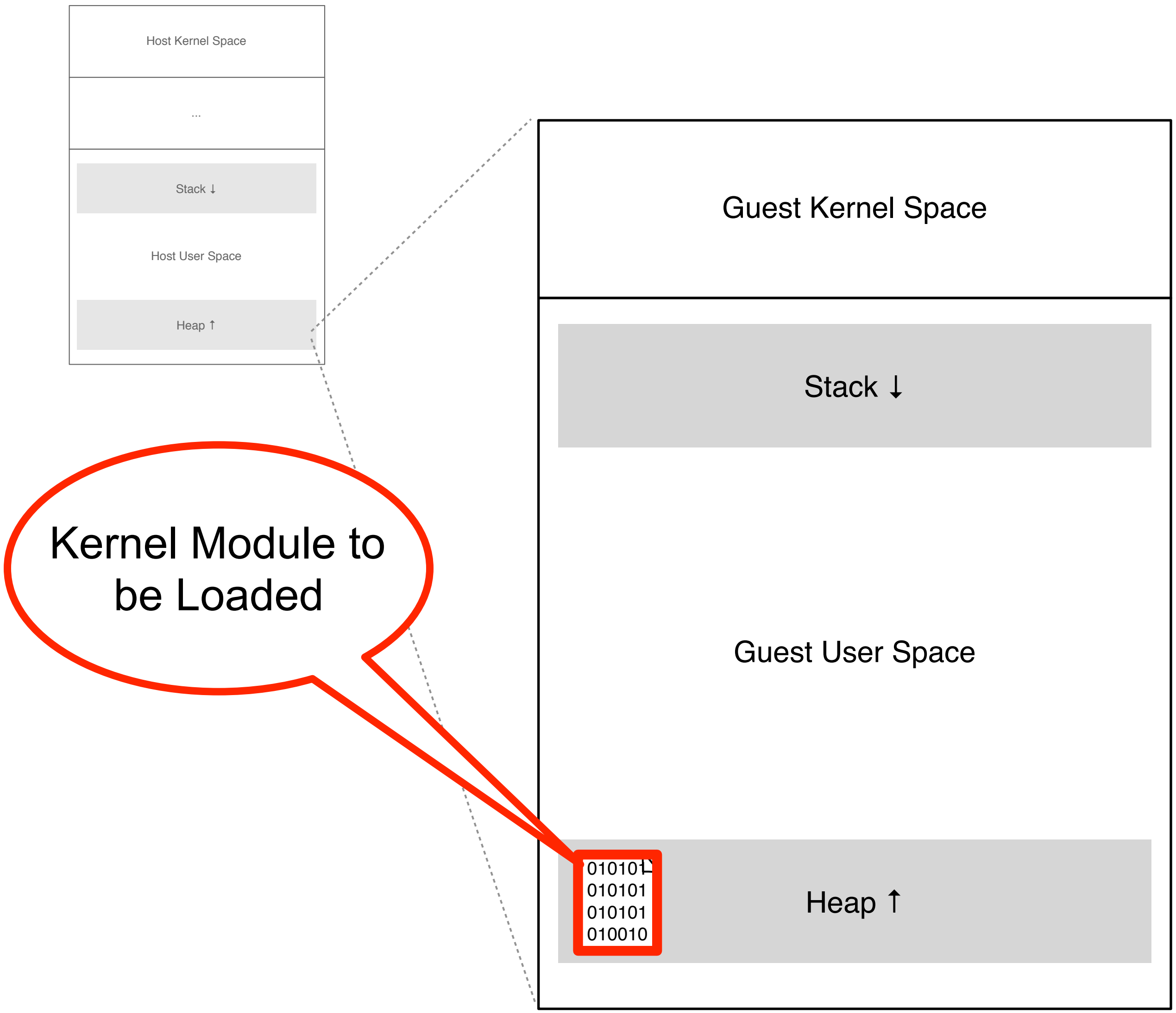

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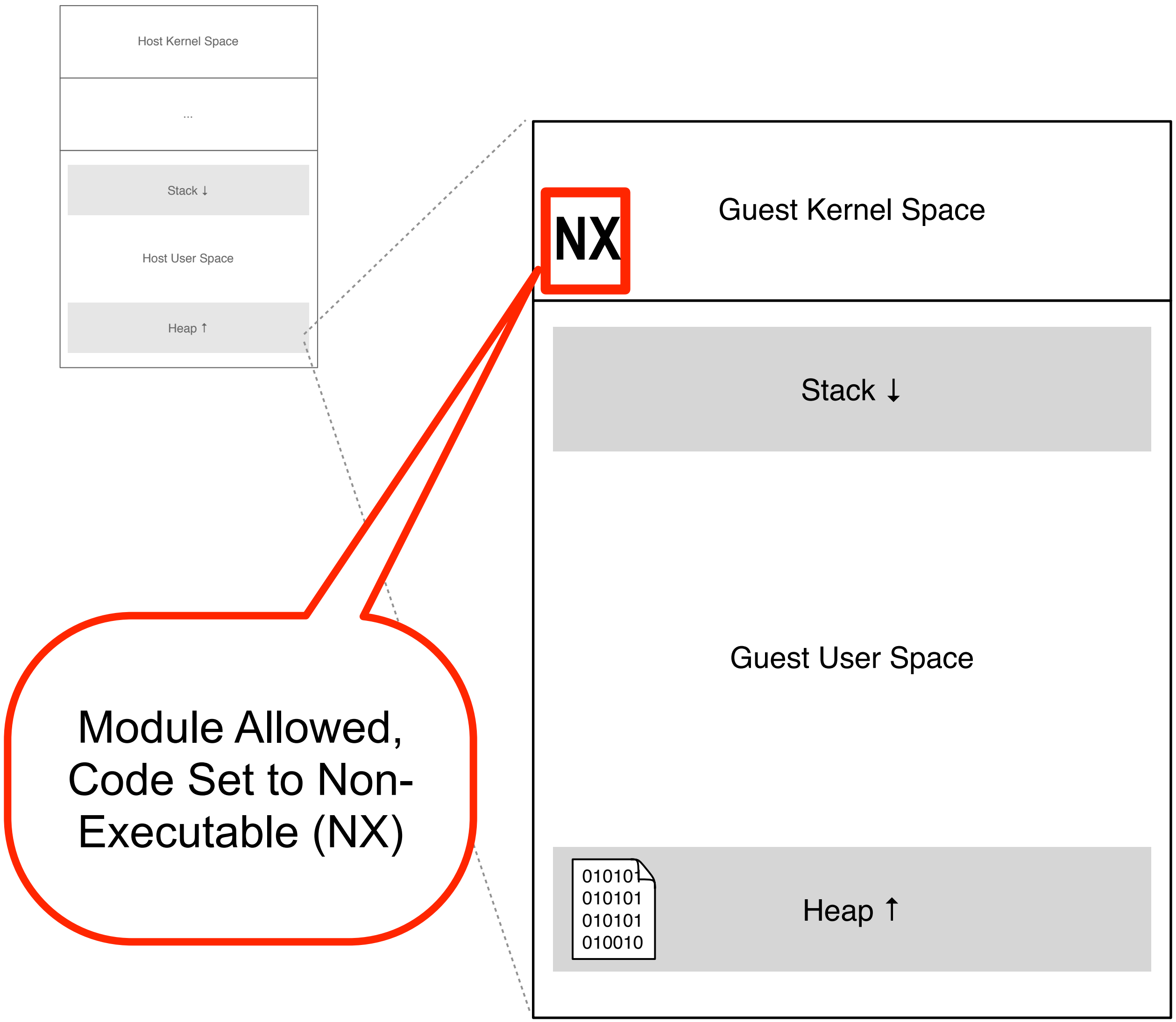

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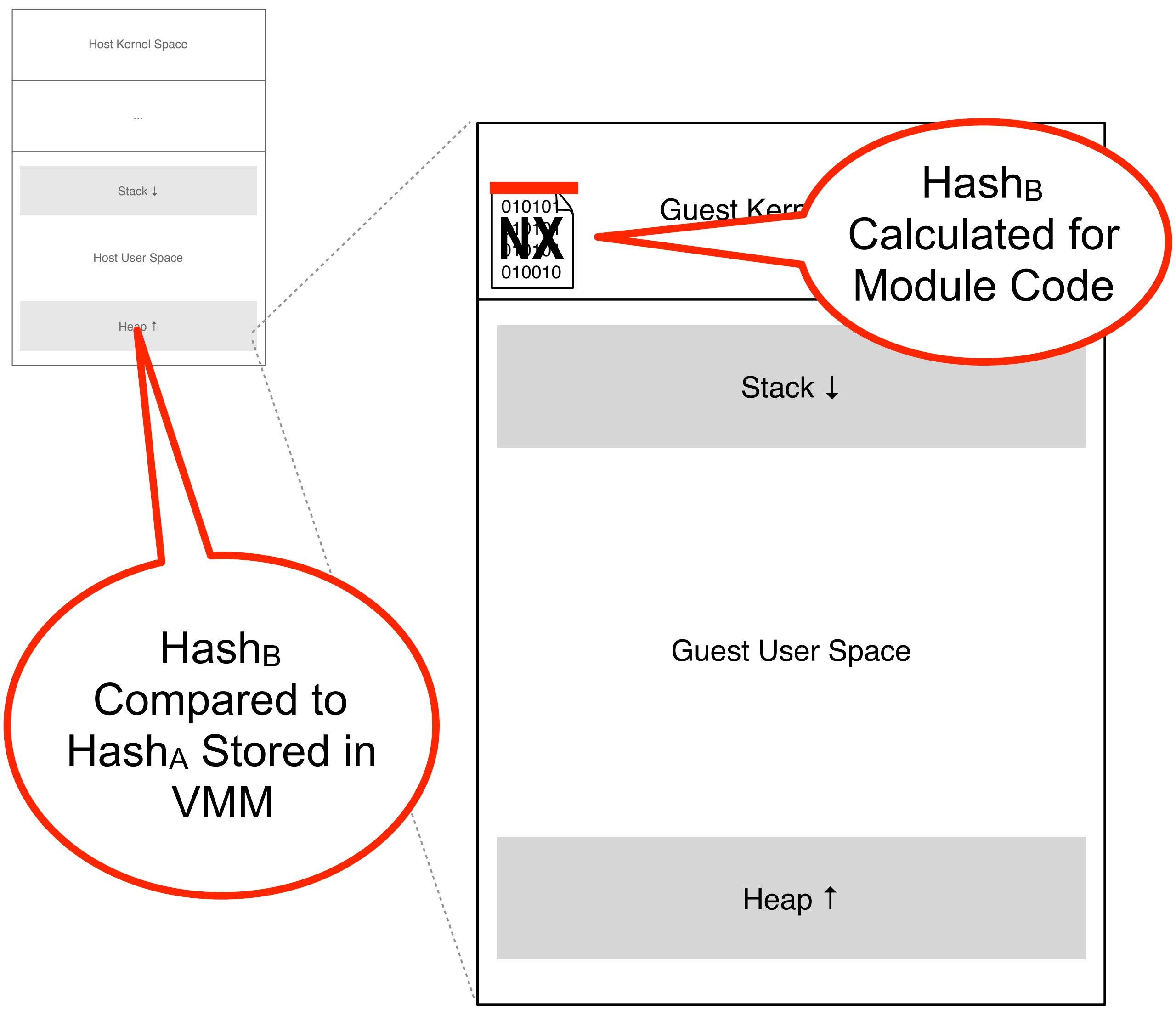

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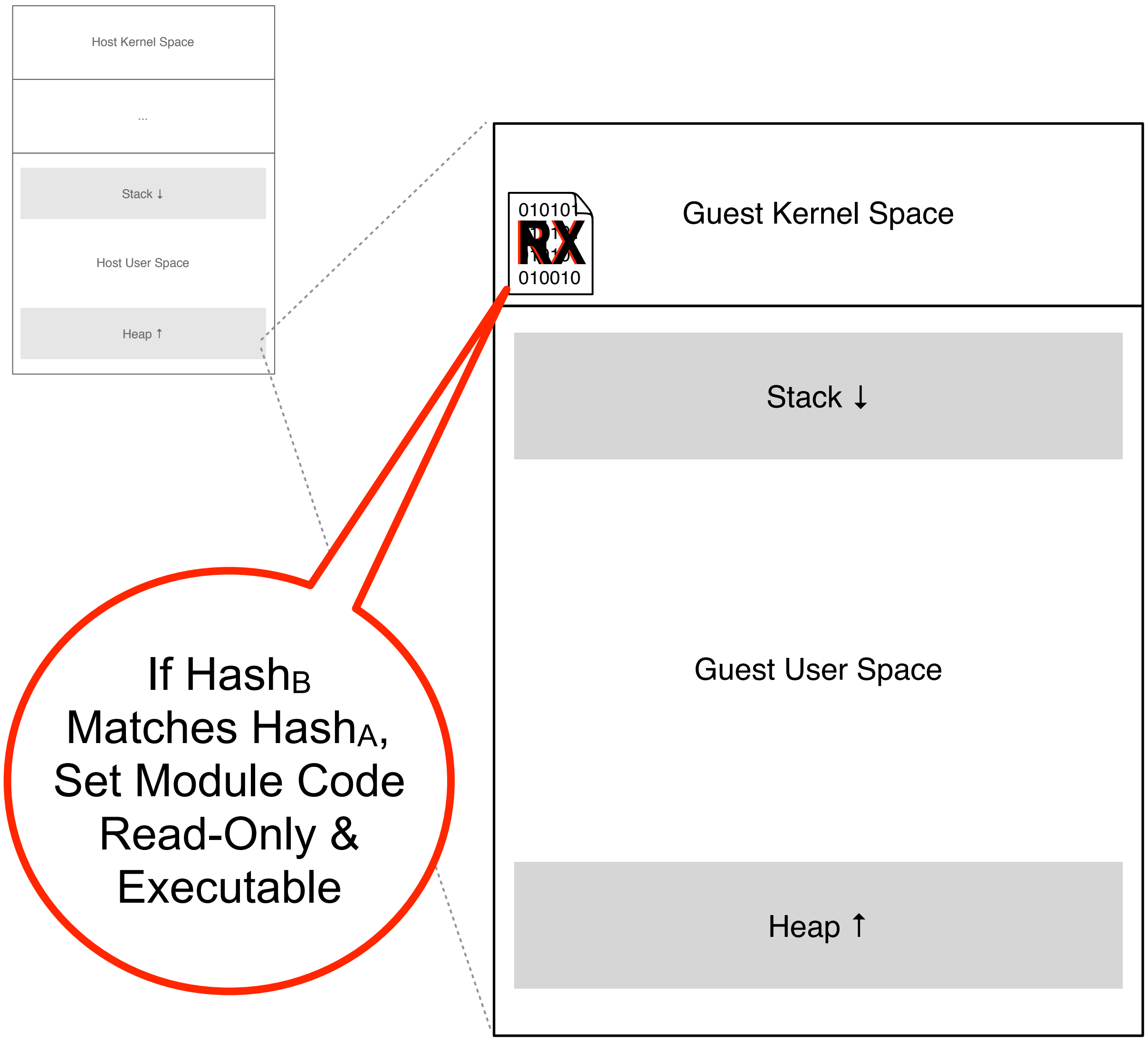

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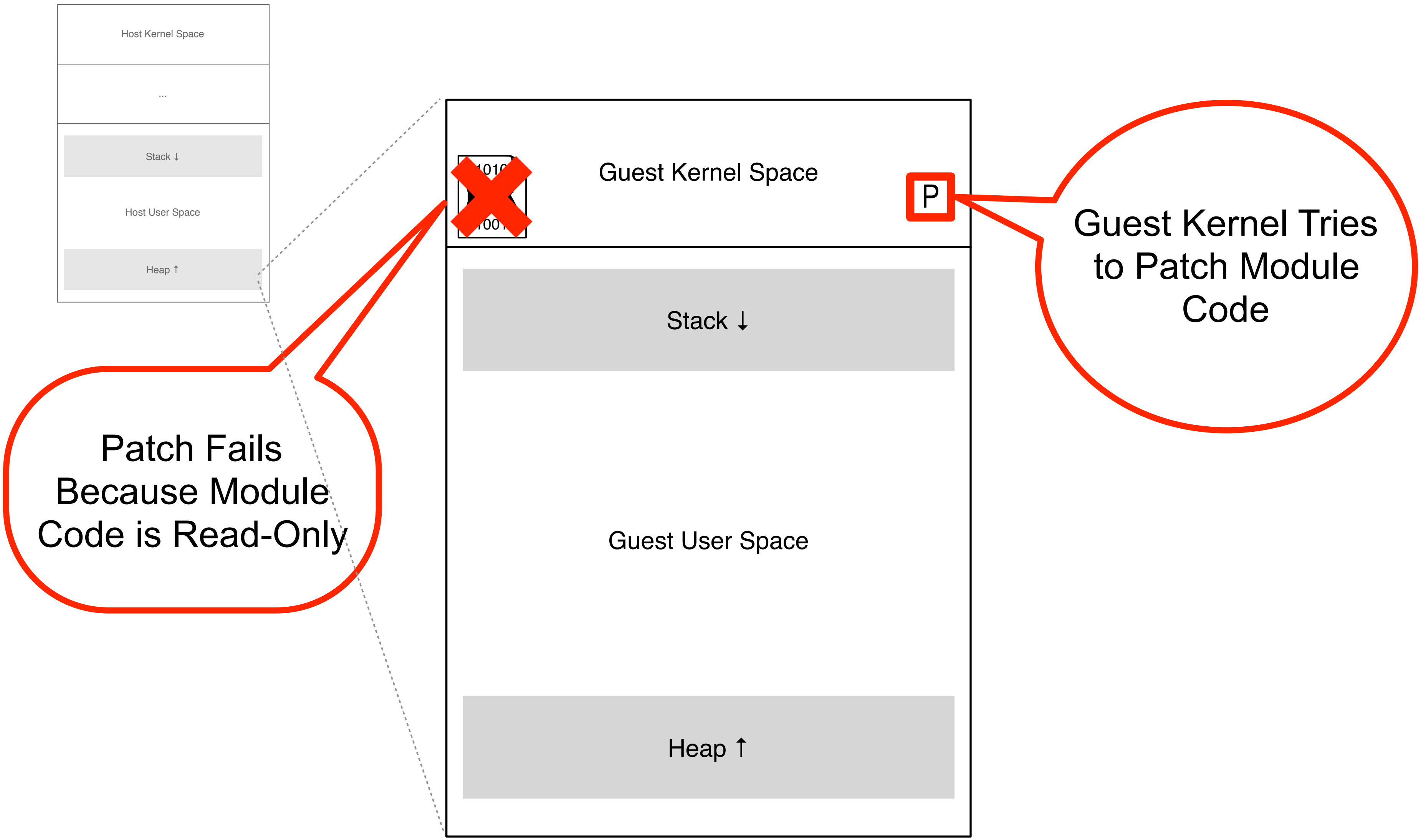

Problem: Ex: Altinstructions

- Example from the Linux kernel
  – Alternative Instructions (altinstructions)
- Altinstructions enable the kernel to optimize code at run-time based on the capabilities of the CPU
  – At compile time, a list of alternative instructions may be stored in special ELF headers
  – At run-time, if an altinstruction is defined for the current CPU, the alternative replaces the default instruction
- Why do this?
  – Linux distributors can ship just one binary that will be optimized for multiple CPUs

Problem: Ex: Altinstructions

- Altinstructions Example: "run-time memory barrier patching" (RTMBP)
  - Default Linux memory barrier instruction sequence:
    - `lock; addl $0,0(%%esp)`
  - Memory barrier instruction sequence for Pentium 4:
    - `lfence`

Problem: Ex: AltInstructions

- RTMBP in the context of NICKLE-like system
  - Offline a hash would be calculated over the unoptimized code
  - Two options for online authentication:
    - Unoptimized code would pass authentication and guest would run without the RTMBP optimization
    - Optimized code would fail authentication

OUR APPROACH:

Verify each patch at run-time.

Approach: Definitions

- Patch: Each valid replacement instruction sequence
- Patch Definition:
  - patch-location: where the patch may get applied
  - patch-length: size of the replacement instruction
  - patch-data: holds the replacement instruction
- Patch Set: whitelist of valid patch definitions
- Patch Site: location in code which may or may not be patched at run time

Approach: Patch Example

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Source Code → x86 Assembly → Raw Hex Dump

```
rcu_idle_enter();
while (!need_resched()) {

  check_pgt_cache();
  rmb();

  if (cpu_is_offline(cpu))
    play_dead();

  local_touch_nmi();
```

```
call    0xc04bb940
lea     0x0(%esi),%esi
mov     %esp,%eax
and     $0xffffe000,%eax
mov     0x8(%eax),%eax
test    $0x8,%al
jne     0xc0402366
lock addl $0x0,(%esp)
bt      %ebx,(%esi)
sbb     %eax,%eax
test    %eax,%eax
je      0xc0402377
call    0xc04063b0
```

```
e8 26 96 0b 00 8d b6 00
00 00 00 89 e0 25 00 e0
ff ff 8b 40 08 a8 08 75
38 f0 83 04 24 00 0f a3
1e 19 c0 85 c0 74 3b e8
6f 40 00 00
```

example patch site in memory

	location	length	data
lock addl $0x0,(%esp)	0xc040232e	6	f0 83 04 24 00 0f
lfence	0xc040232e	6	0f ae e8 90 90 90

Approach: Patch Verification

- Offline:
  - Generate cryptographic hashes, as before
    - Except: skip patch sites for hash calculation
  - Generate a whitelist of patch definitions
    - At least one definition for each patch site
- Online
  - At code load-time:
    - Verify code hashes, again skipping patch sites
    - Verify contents of each patch site using whitelist
  - At write-fault (caused by W⊕KX protection):
    - If writing to patch site, allow patch site to be overwritten by valid patch

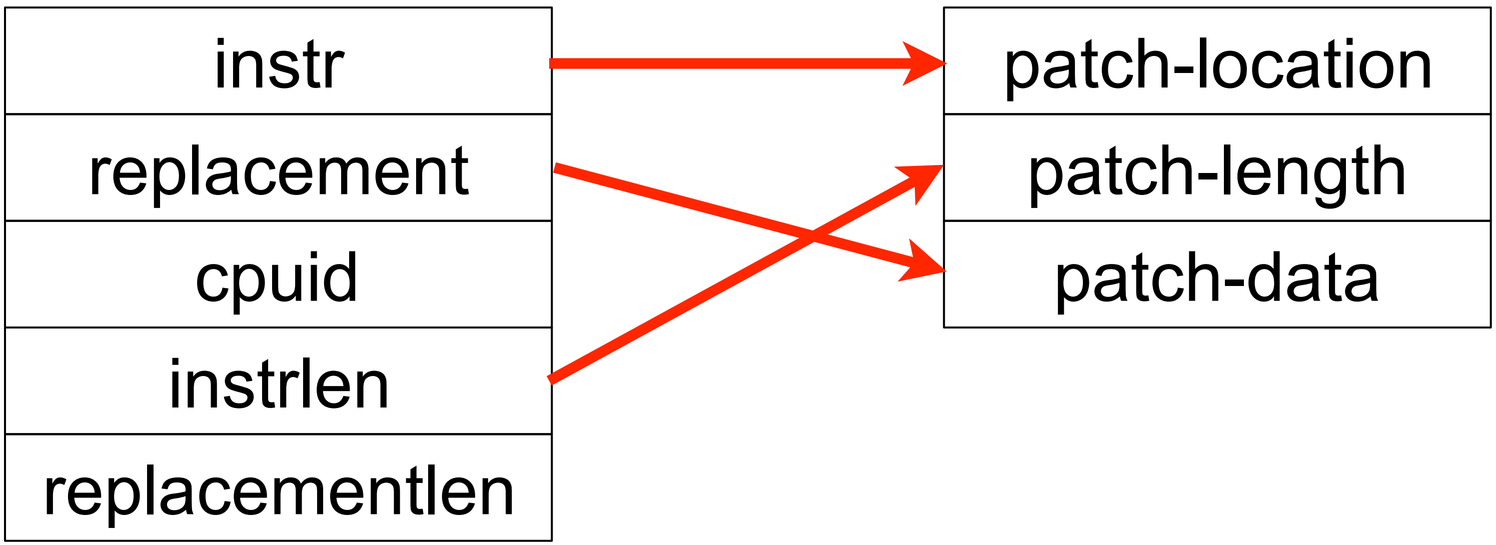
Approach: Patch Set Creation

- Patch set creation is challenging!
  – Requires deep knowledge of guest kernel (or kernel vendor participation)
- Example: Linux Kernel (v 2.6) has six[1] different mechanisms that may patch the kernel at runtime:
  – Alternative Instructions
  – SMP Locks
  – Jump Labels
  – Mcounts[1]
  – Paravirtual Instructions
  – Kprobes

[1] We identified a sixth mechanism after paper submission.

Approach: Ex. Altinstructions

- Generating a patch definition for an altinstruction



struct alt_instr
(from ELF headers)

patch definition

OUR EVALUATION:
Add patch verification to a NICKLE-like system.

Evaluation: NICKLE-KVM

- Our patch-level verification procedure is implemented as a subsystem of NICKLE-KVM
- NICKLE-KVM: NICKLE-like system based on KVM
  - KVM is a Linux-based VMM that takes advantage of hardware-assisted virtualization
  - Uses the page-level redirection technique introduced by hvmHarvard (rather than instruction-level technique used by NICKLE)
- Generated patch set for four of the six Linux kernel patching facilities (two weren't used by our guest)
- We implemented the load-time patch verification procedure for NICKLE-KVM

Evaluation: Patch Set Creation

- To evaluate our system we generated patch sets for the Linux kernel[2] (vmlinux) and 3308 kernel modules
  - The kernel contained 31,643 patch sites
  - The 11 modules needed by our guest contained 639 patch sites
- After adding patch-level verification, NICKLE-KVM correctly verified the integrity of all 32282 patch sites

[2] After paper submission we added kernel patch-site verification

Evaluation: Attacks

- Crafted synthetic attacks to test robustness:
  - Attacker modifies code outside of patch-site
    - Load fails due to cryptographic hash mistmatch
  - Attacker modifies code within patch site
    - Load fails if patch site does not receive valid patch
    - Load succeeds if patch site receives valid patch
  - Attacker modifies candidate patch code (ex. altinstructions ELF header)
    - Load fails if the spurious patch is selected

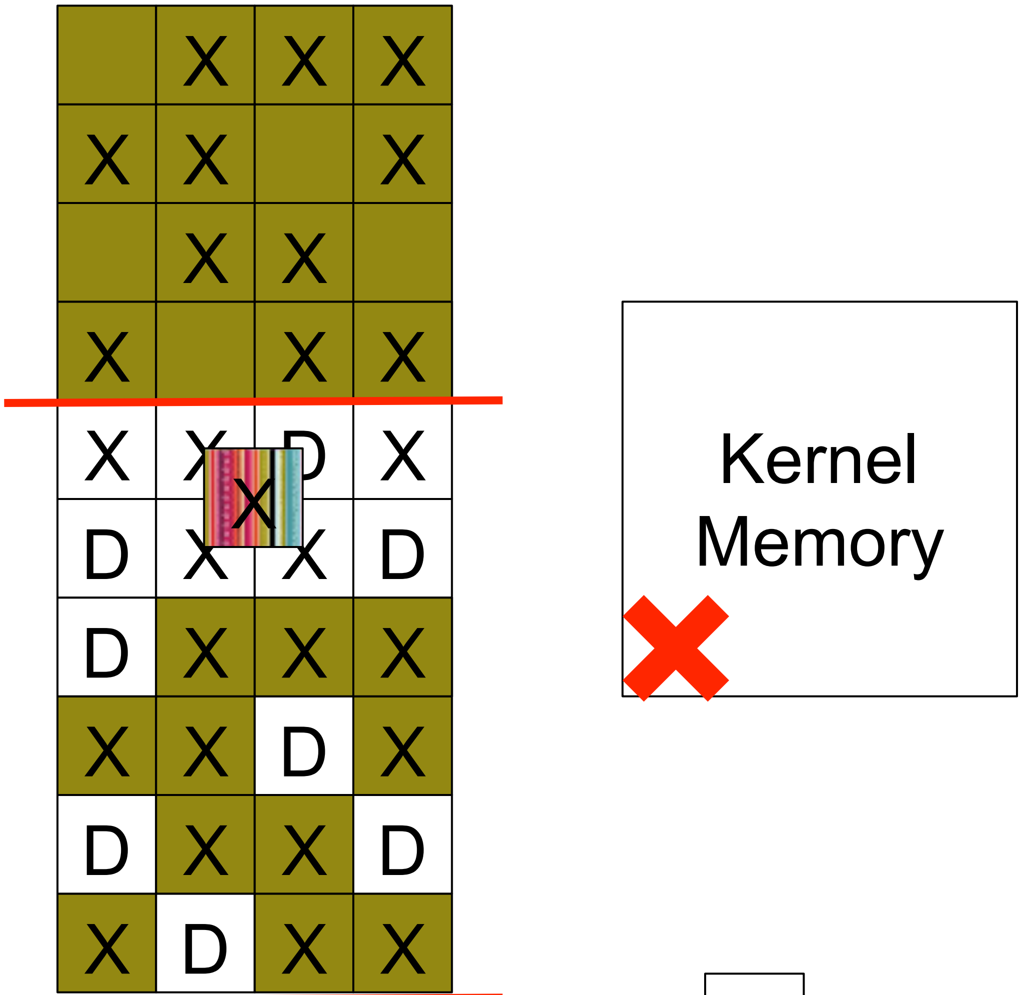
Evaluation: Performance

- Our load-time patch verification procedure incurs no additional NICKLE-KVM VM exits for patch-verification
  - Adds time for patch verification (lookup and string compare) proportional to the number of patches
- A write-fault-triggered patch verification procedure (not implemented) would incur one additional VM exit per patch that triggers a write-fault
  - Additional VM exit required for restoring read-only permission

Summary

- Previous NICKLE-like systems were not able to authenticate code introduced by self-patching kernels
- Our kernel code authentication procedure accommodates self-patching kernels by verifying each patch
- Our implementation is able to authenticate a self-patching guest Linux kernel and its modules (32,282 patch sites)

THANK YOU!



- At load-time, verify kernel code and set to read-only
- Run-time patch will fail due to read-only permissions

D Data Page   X Code Page

Problem: Self-Patching Kernels