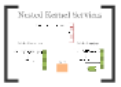
The Nested Kernel Architecture

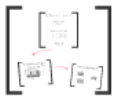
1) What's the problem?

2) Nested Kernel Approach

3) Intra-Kernel Isolation



4) Evaluation

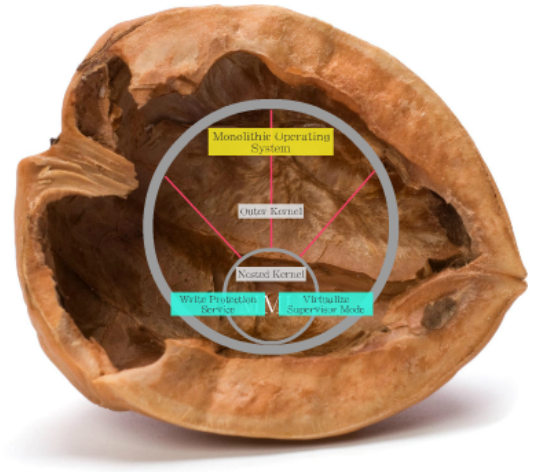


5) Future Work

Nested Kernel: An Operating System Architecture for Intra-Kernel Privilege Separation

*Nathan Dautenhahn	UIUC
Theodoros Kasampalis	UIUC
Will Dietz	UIUC
John Criswell	University of Rochester
Vikram Adve	UIUC

Nested Kernel



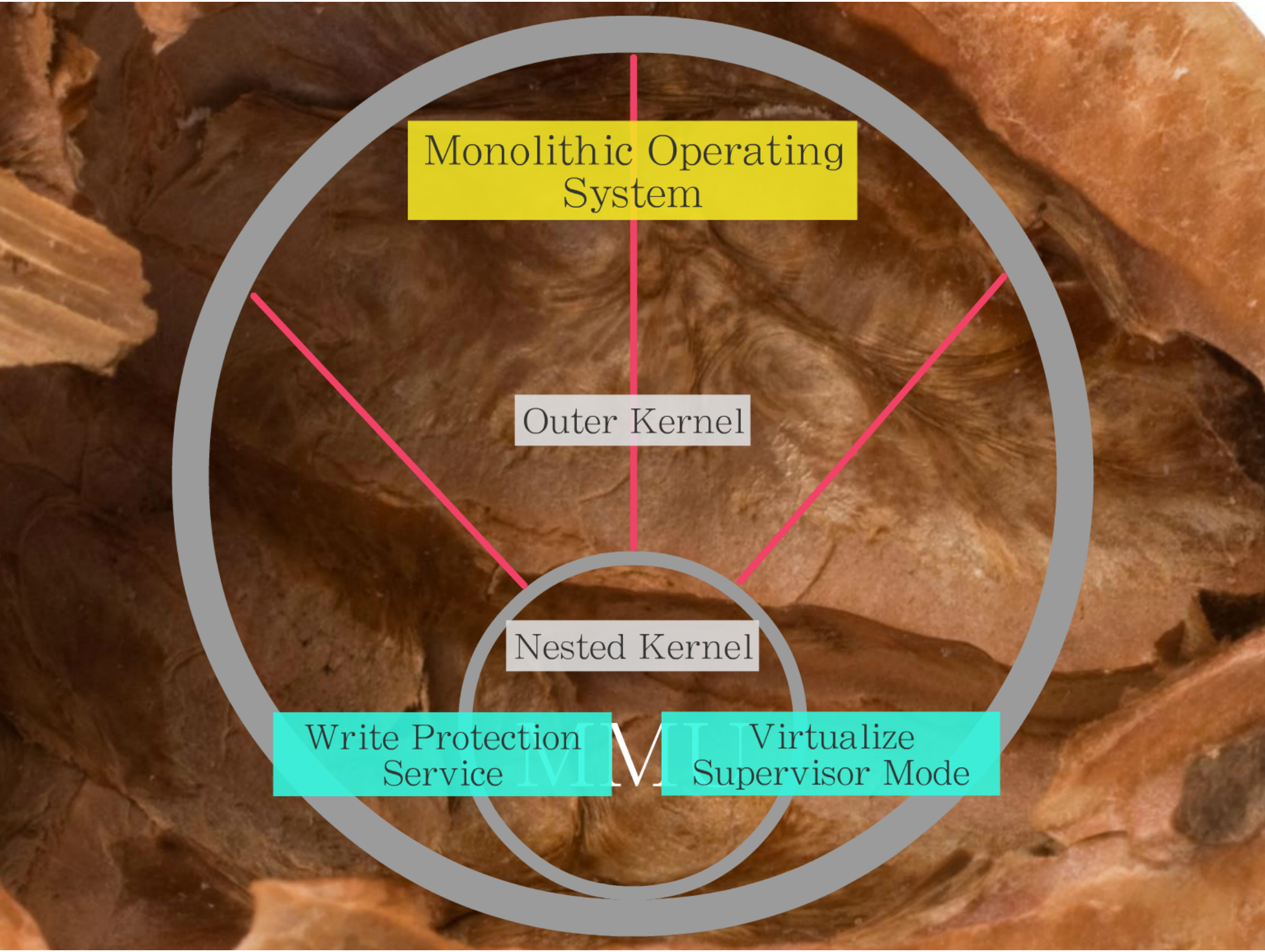
Key Takeaways

- Retrofit the nested kernel architecture in FreeBSD 9.0

FreeBSD

- Isolate MMU at a single hardware privilege level by virtualizing supervisor mode

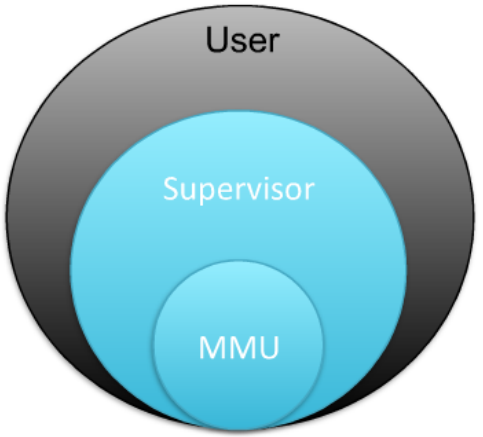
- Intra-kernel memory protection services
- Lifetime kernel code integrity in FreeBSD 9.0


Monolithic Operating System
Outer Kernel
Nested Kernel
Write Protection Service
MMU
Virtualize Supervisor Mode

Key Takeaways

- Retrofit the nested kernel architecture in FreeBSD 9.0

- Isolate MMU at a single hardware privilege level by virtualizing supervisor mode

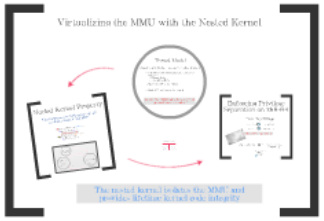


- Intra-kernel memory protection services
- Lifetime kernel code integrity in FreeBSD 9.0

The Nested Kernel Architecture

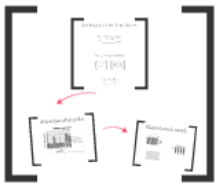
1) What's the problem?

2) Nested Kernel Approach



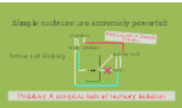
3) Intra-Kernel Isolation

4) Evaluation



5) Future Work


Monolithic Operating System Architecture
MacBook Air



Drivers

Monolithic Operating System Architecture

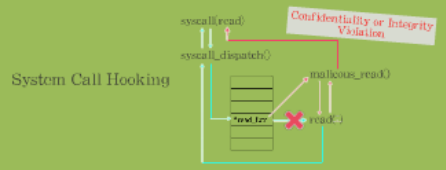
File System

Virtual Memory

CPU Virtualization

Networking

Simple malware are extremely powerful:



Problem: A complete lack of memory isolation

Drivers

Monolithic Operating System Architecture

File System

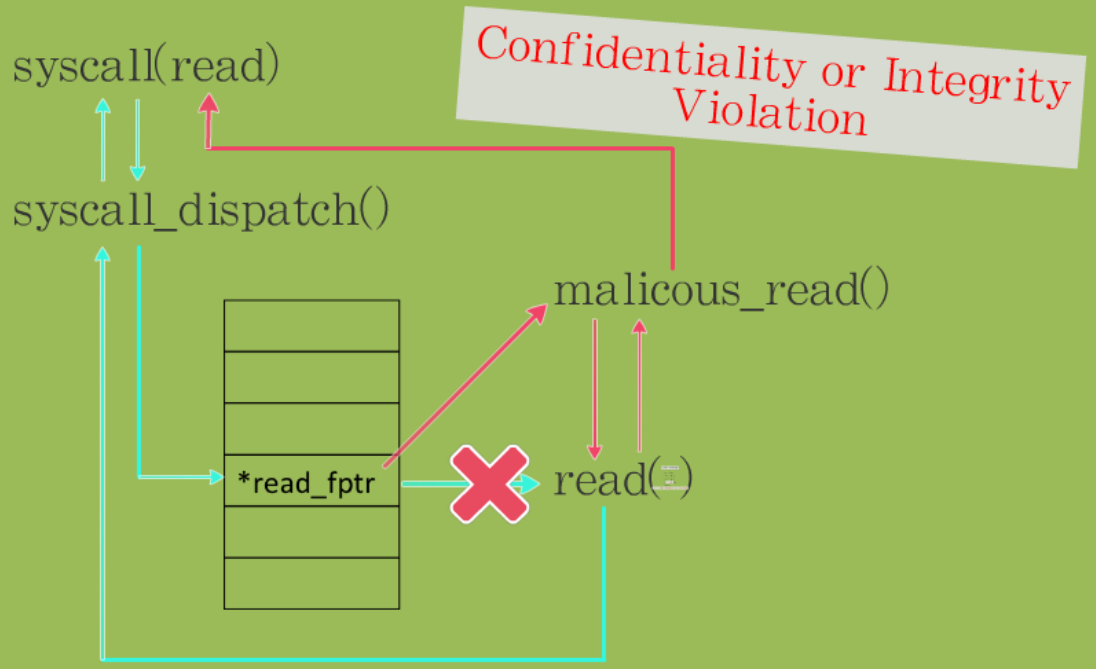
Virtual Memory

CPU Virtualization

Networking

Simple malware are extremely powerful:

System Call Hooking



Problem: A complete lack of memory isolation

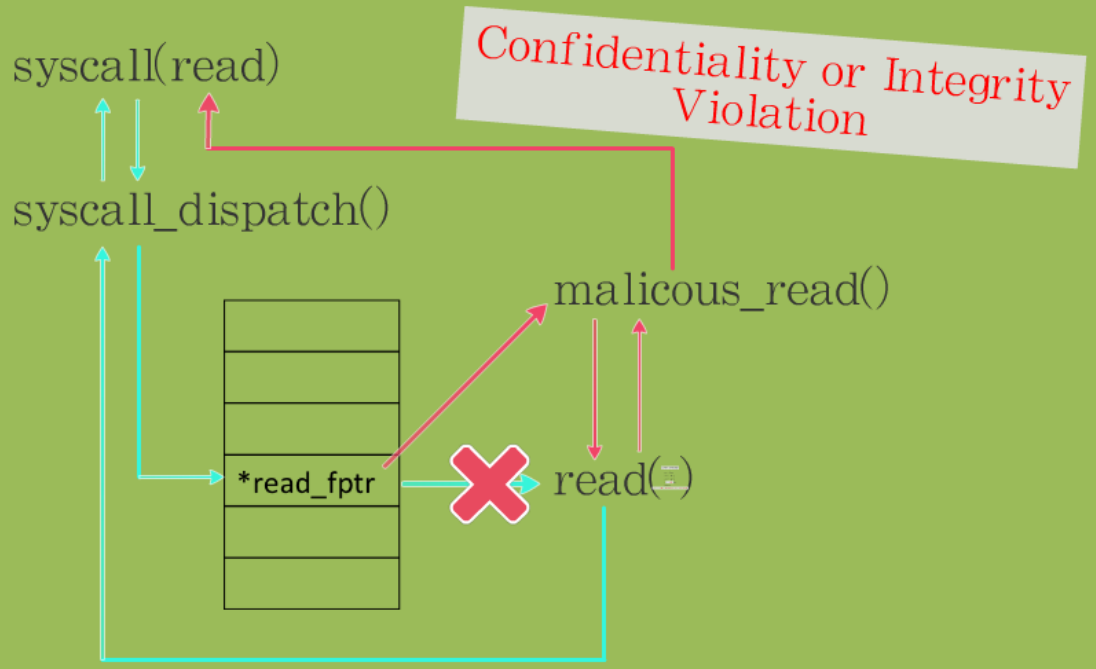
Code Injection

```
operation;
operation;
operation;
a NOOP d();
return;
```

Violates the integrity of audit recording

Simple malware are extremely powerful:

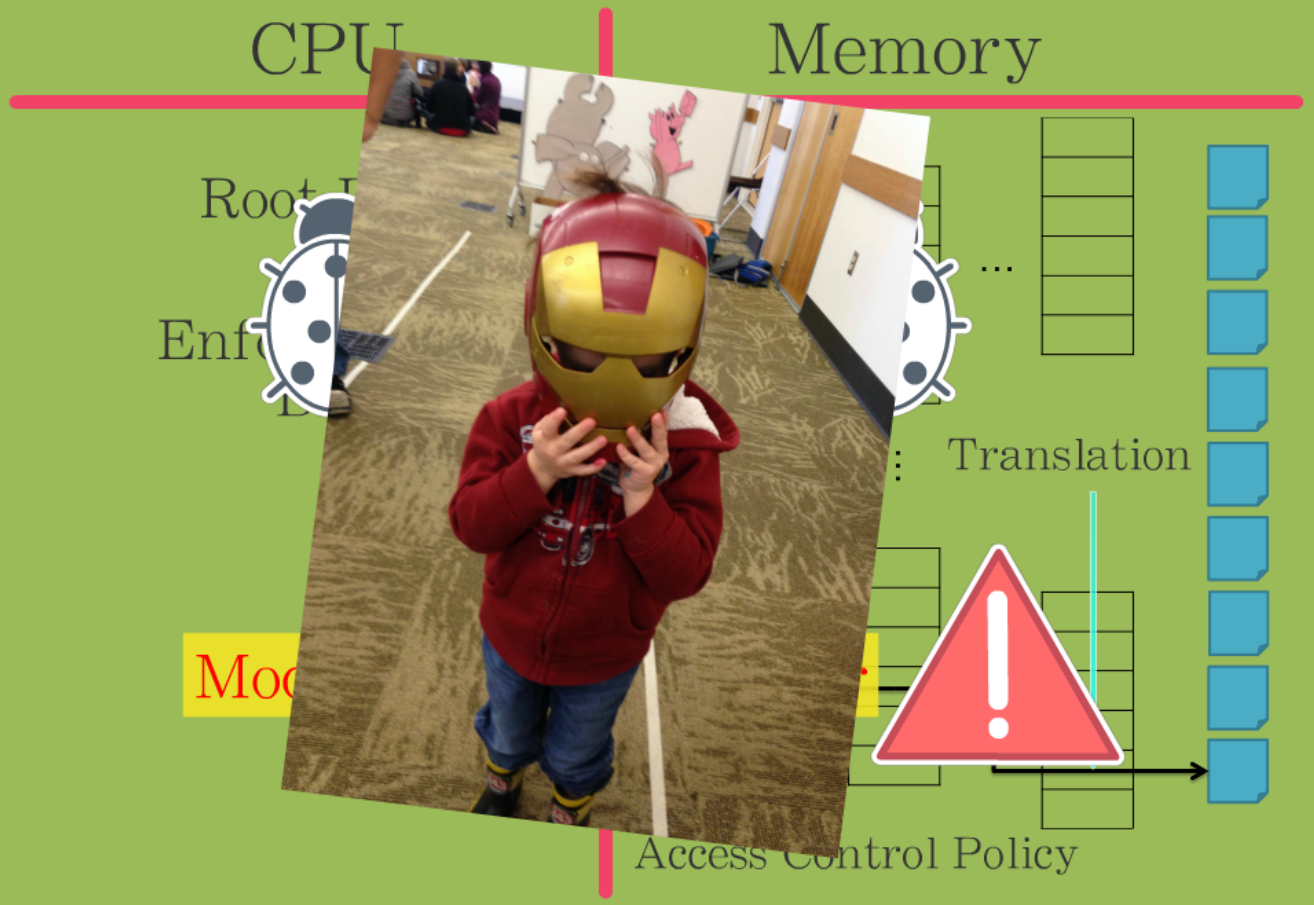
System Call Hooking



Problem: A complete lack of memory isolation

Observation: If we can Restrict Access to the Page Tables then Enable Memory Isolation

Page Tables in Typical Systems



Super-Duper-Ooper-Schmooper Big Idea:

Isolate the MMU using the MMU

- Single Privilege Level
- Efficient Privilege Switch
- Apply to Monolithic OS
- No Control Flow Integrity

Virtualizing the MMU with the Nested Kernel

Threat Model

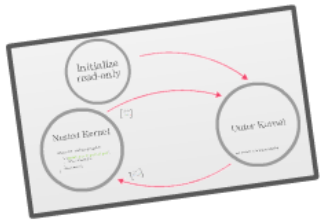
Goal: restrict MMU access to nested kernel

- Outer Kernel Under Complete Control of Attacker
  - Source Code
  - Execution State
- No Control Flow Integrity
- Nested Kernel source is trusted

Isolate the MMU not defend against general kernel attacks

Nested Kernel Property

The nested kernel interposes on all modifications of the MMU



Enforcing Privilege Separation on x86-64

Code Deprivilege

Static Code Privilege Separation

Code Verification ✚ Lifetime Kernel Code Integrity

The nested kernel isolates the MMU and provides lifetime kernel code integrity

Threat Model

Goal: restrict MMU access to nested kernel

- Outer Kernel Under Complete Control of Attacker
  - Source Code
  - Execution State
- No Control Flow Integrity
- Nested Kernel source is trusted

Isolate the MMU not defend against general kernel attacks

Nested Kernel Property

The nested kernel interposes on all modifications of the MMU

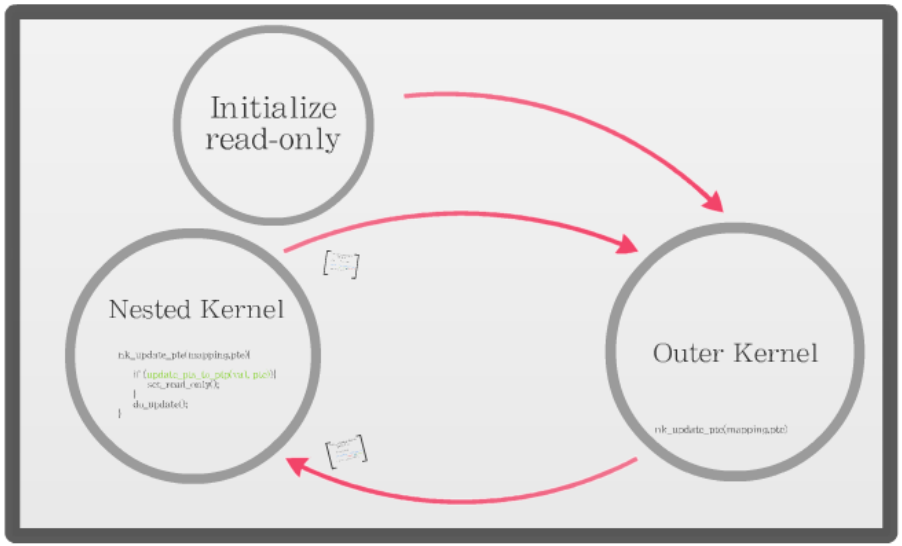
1. Access to Page Tables is configured read-only

   CPU: Base PTR -> CR3 ✚ Memory: PTs

   Nested Kernel key assumption: can enforce read-only on supervisor code

2. Read-only permissions enforced while the outer kernel executes

   CPU: CR0 write-protect enable flag



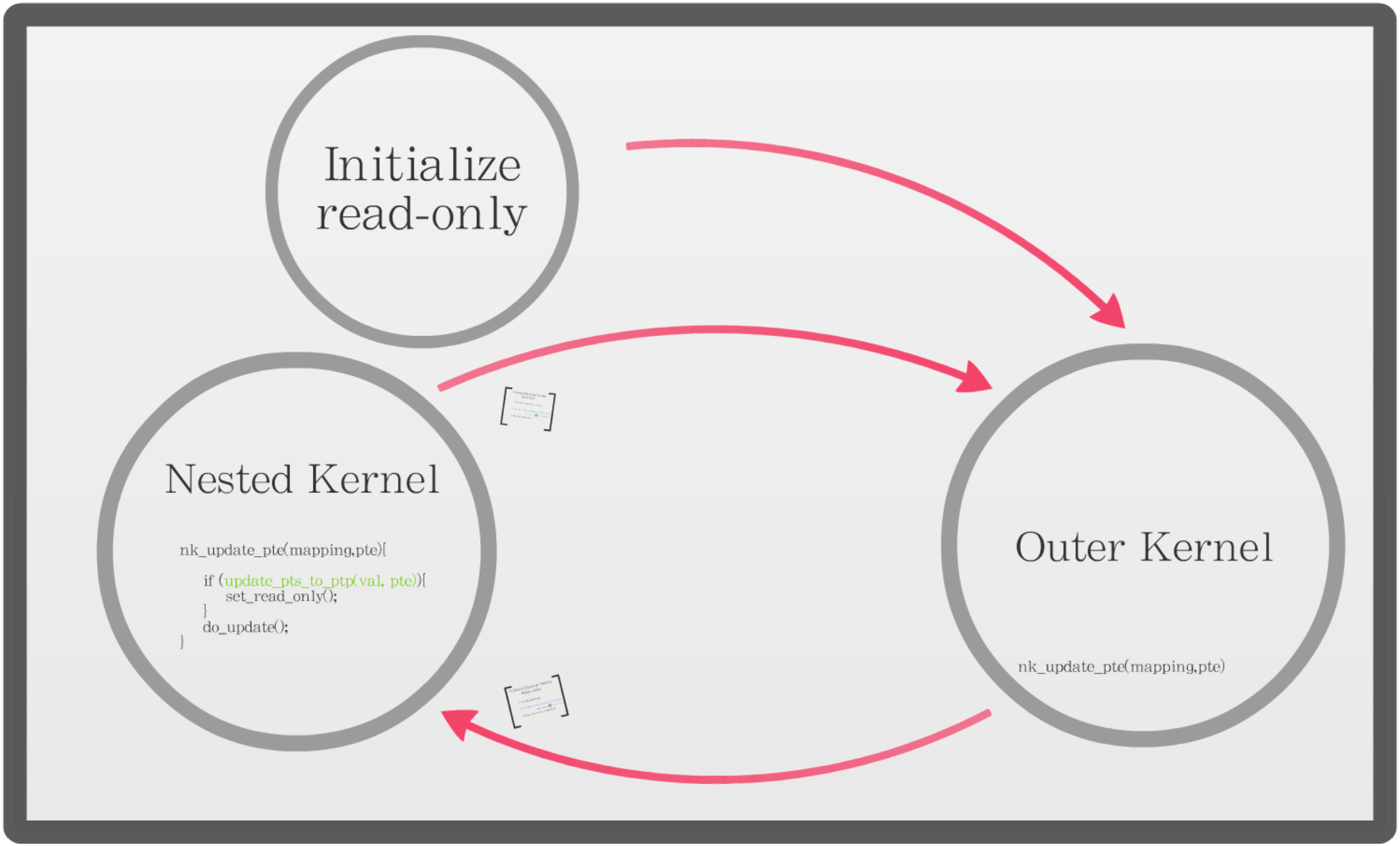
Access to Page Tables is configured read-only

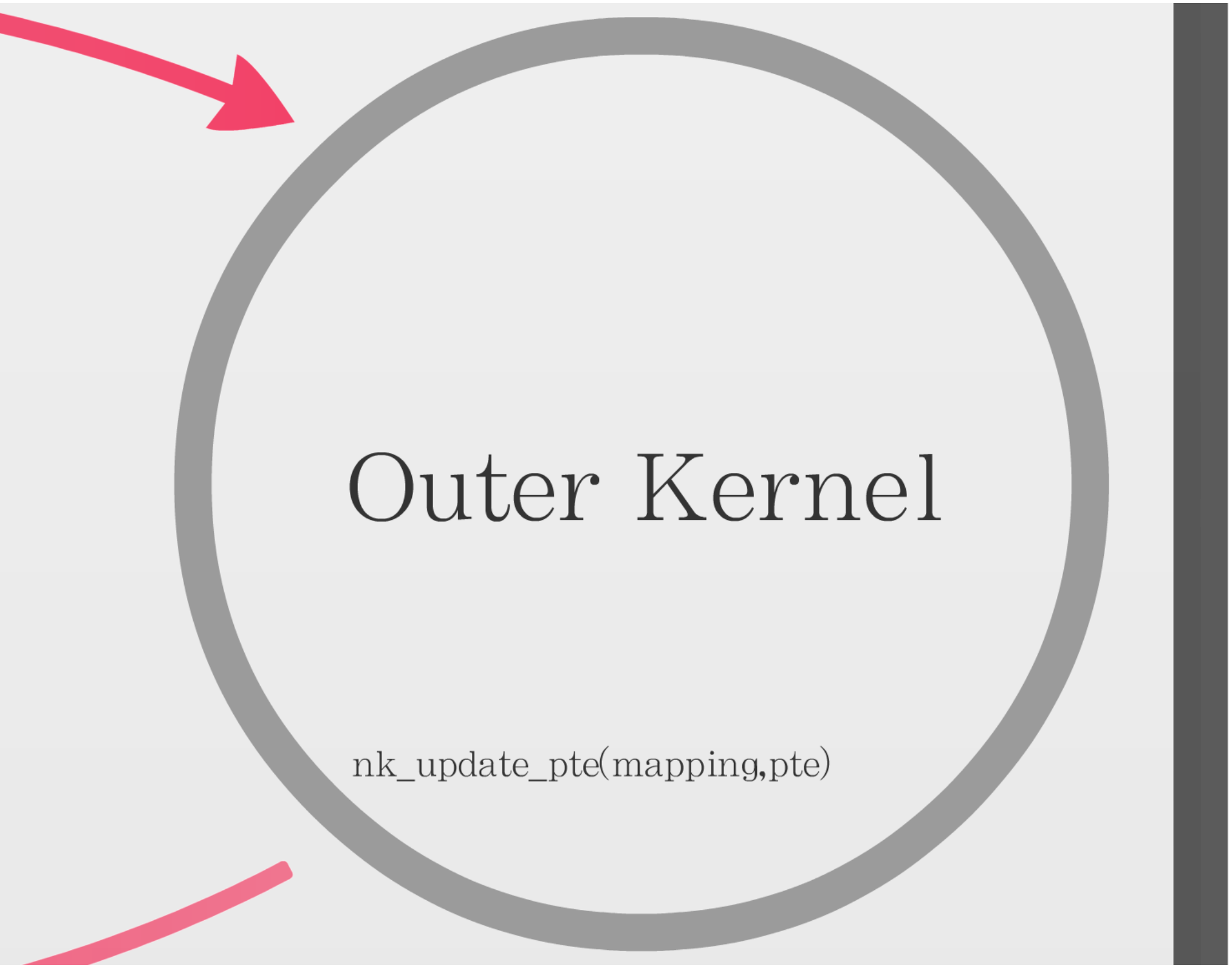
CPU: Base PTR -> CR3 ✚ Memory: PTs

Nested Kernel key assumption: can enforce read-only on supervisor code

Read-only permissions enforced while the outer kernel executes

CPU: CR0 write-protect enable flag


Initialize
read-only
Nested Kernel
nk_update_pte(mapping,pte){
if (update_pts_to_ptp(val, pte)){
set_read_only();
}
do_update();
}
Outer Kernel
nk_update_pte(mapping,pte)


Outer Kernel
nk_update_pte(mapping,pte)

Virtual Privilege Switch Entry Gate

1. Disable interrupts
2. Disable write-protection enforcement

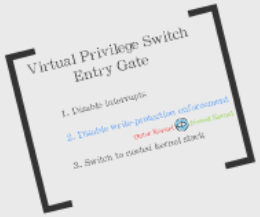
Outer Kernel  Nested Kernel

3. Switch to nested kernel stack

Nested Kernel

```
nk_update_pte(mapping,pte){

    if (update_pts_to_ptp(val, pte)){
        set_read_only();
    }
    do_update();
}
```



Virtual Privilege Switch Exit Gate

1. Switch to outer kernel stack

2. Enable write-protection enforcement

Nested Kernel  Outer Kernel

3. Enable interrupts

Nested Kernel Property

The nested kernel interposes on all modifications of the MMU

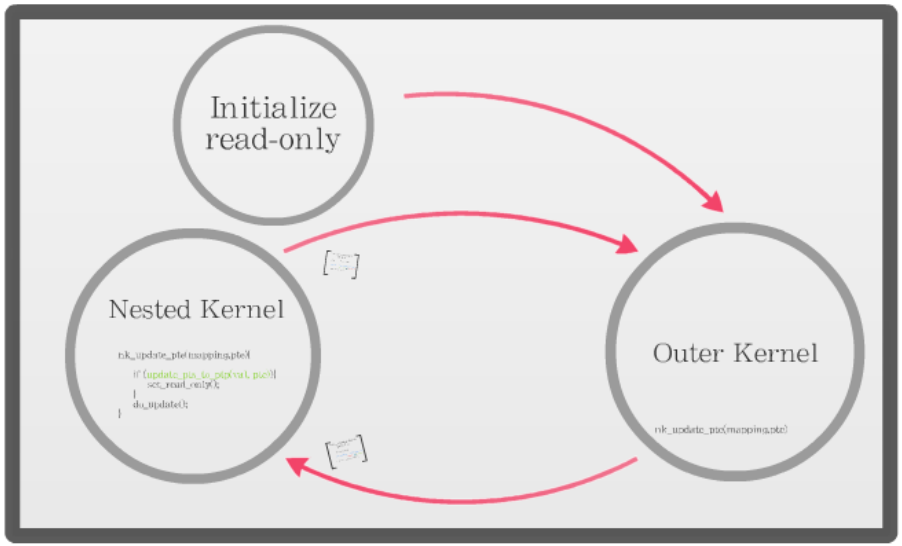
1. Access to Page Tables is configured read-only

   CPU: Base PTR -> CR3 ✚ Memory: PTs

   Nested Kernel key assumption: can enforce read-only on supervisor code

2. Read-only permissions enforced while the outer kernel executes

   CPU: CR0 write-protect enable flag

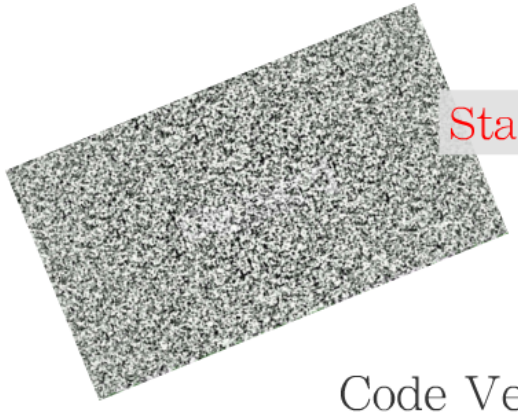


Enforcing Privilege Separation on x86-64

Code Deprivilege

mov cr3, val  nk_wr_cr3(val)

mov cr0, val  nk_wr_cr0(val)



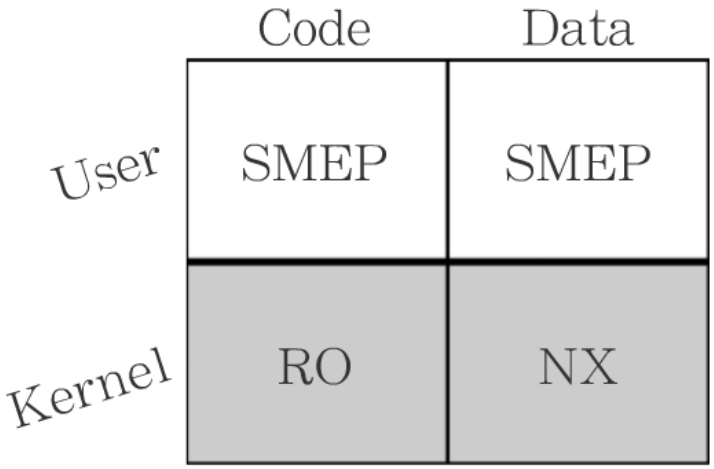
Static Code Privilege Separation

Code Verification ✚ Lifetime Kernel Code Integrity 

Outer Kernel Execution Integrity

- Guaranteed Mediation
- Return Integrity
- Special Operating Modes

Lifetime Kernel Code Integrity



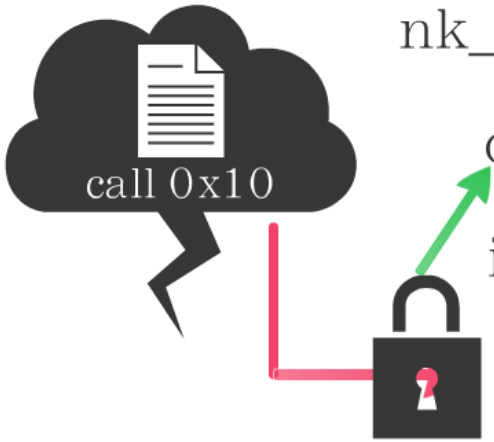
0 All kernel mappings non-executable

1 If code:
- verify with scanner
- configure as executable and read-only

2 User mode code and data: supervisor mode execution prevention

Outer Kernel Execution Integrity

- Guaranteed Mediation
- Return Integrity
- Special Operating Modes




```
nk_update_pte:
    disable write-protection
    if valid_update(newvalue, pte):
        *pte = newvalue;            // 0x10
    enable write-protection
    return;
```

Mediation

Nested Kernel Protections

CPU Protections	Memory Protections
Page Table Base: mov cr3, val	Page Tables --- read-only
Write-protect Enable: mov cr0, val	Kernel Code --- read-only
Non-exececutable: mov cr4, val	Kernel Data --- NoExecute
SMEP: wrmsr(EFER, val)	User Code + Data --- user-priv

Virtualizing the MMU with the Nested Kernel

Threat Model

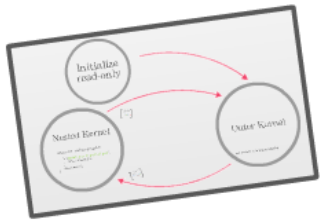
Goal: restrict MMU access to nested kernel

- Outer Kernel Under Complete Control of Attacker
  - Source Code
  - Execution State
- No Control Flow Integrity
- Nested Kernel source is trusted

Isolate the MMU not defend against general kernel attacks

Nested Kernel Property

The nested kernel interposes on all modifications of the MMU



Enforcing Privilege Separation on x86-64

Code Deprivilege

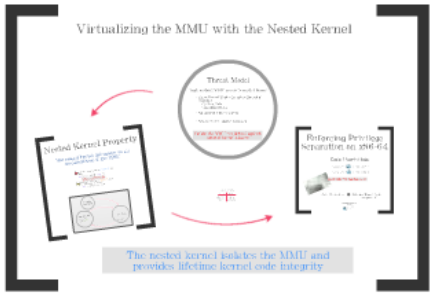
Static Code Privilege Separation

Code Verification ✚ Lifetime Kernel Code Integrity

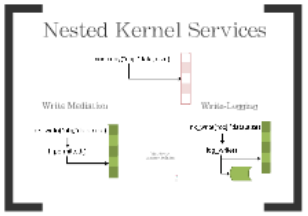
The nested kernel isolates the MMU and provides lifetime kernel code integrity

1) What's the problem?

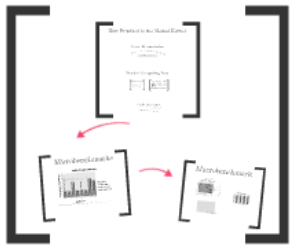
2) Nested Kernel Approach



3) Intra-Kernel Isolation

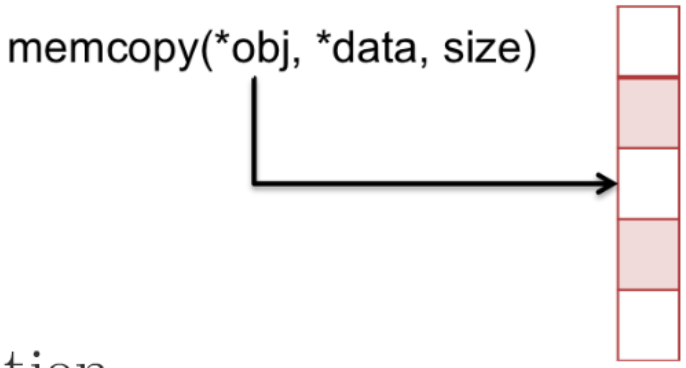


4) Evaluation

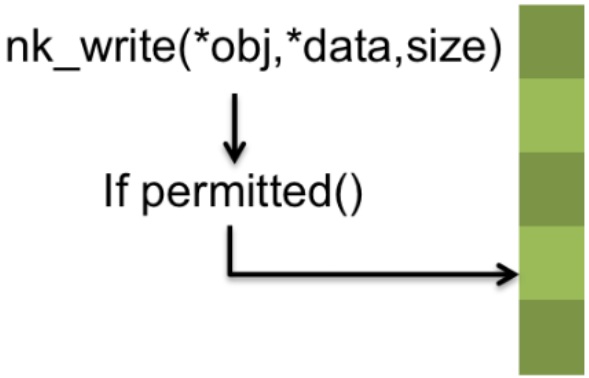


5) Future Work

Nested Kernel Services

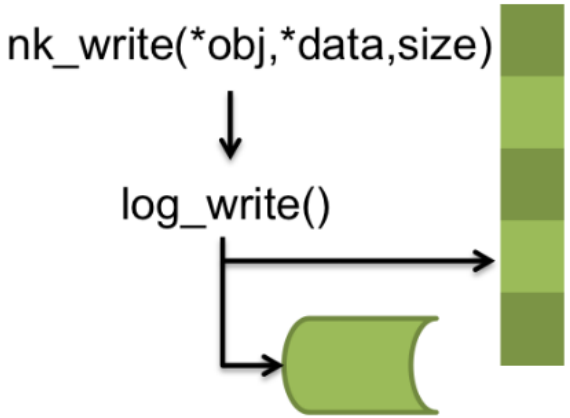


Write Mediation



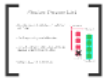
Intra-kernel memory isolation

Write-Logging



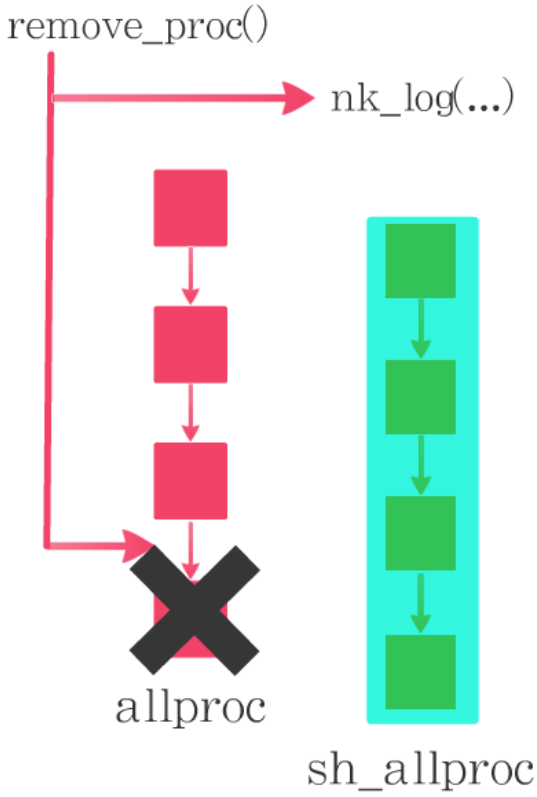
Intra-kernel memory isolation

Use Case	Mitigation	Policy
Code Injection	Kernel Code Integrity	Read-only
Function Call Hooking	Syscall Vector Table	Write-Once
Forensics	Shadow Process List	Log-Write
Security Monitor	Syscall Recording	Append-Only



Shadow Process List

- Rootkit removes evidence of malicious activities
- Challenge: policy and allocation
- Created a shadow allproc list and force updates to go through nk_log()
- Ensure attacker is observed

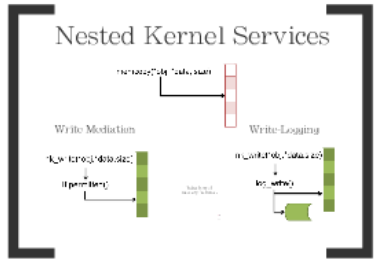


Security Monitor

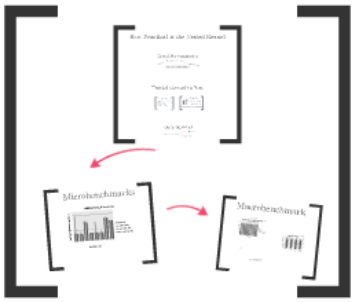
- Attacker cannot remove events
- Guaranteed invocation and isolation of security monitor
- No Virtual Machine Introspection

2) Nested Kernel Approach

3) Intra-Kernel Isolation



4) Evaluation



5) Future Work

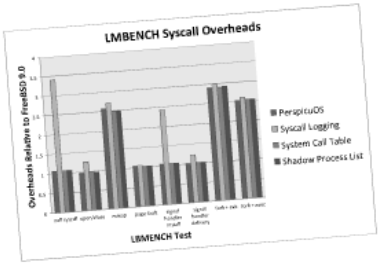
How Practical is the Nested Kernel

Kernel Reorganization

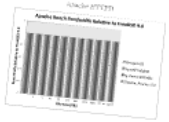
Trusted Computing Base

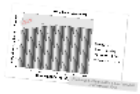
Code Scanner

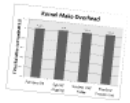
Microbenchmarks



Macrobenchmark







How Practical is the Nested Kernel

Kernel Reorganization

~1900 LOC Modified

52 Files

~100 Deleted

IOMMU + SMP + NX Configuration support needed

Trusted Computing Base

Nested Kernel Lines of Code

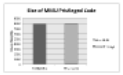
4000 C

800 Assembly

248 Python Scanner

SLOCCOUNT

TCB for Nested Kernel and MMU Isolation



FreeBSD 9.0: 7.9 MB

PerspicuOS: 34 KB

MMU TCB FreeBSD 9.0 / PerspicuOS: 232x

Code Scanner

40 implicit instructions

2 writes to cr0

38 wrmsr

Kernel Reorganization

~1900 LOC Modified

52 Files

~100 Deleted

IOMMU + SMP + NX Configuration support needed

Trusted Computing Base

Nested Kernel Lines of Code

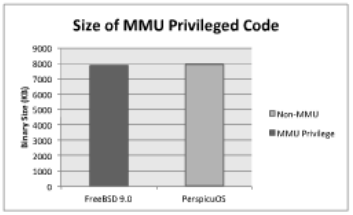
SLOCCOUNT

4000 C

800 Assembly

248 Python Scanner

TCB for Nested Kernel and MMU Isolation



FreeBSD 9.0: 7.9 MB

PerspicuOS: 34 KB

MMU TCB FreeBSD 9.0 / PerspicuOS: 232x

Nested Kernel Lines of Code

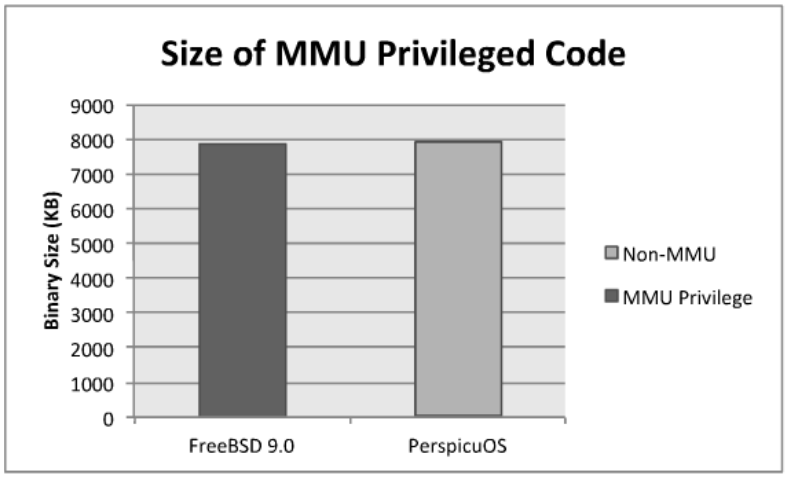
SLOCCOUNT

4000 C

800 Assembly

248 Python Scanner

TCB for Nested Kernel and MMU Isolation



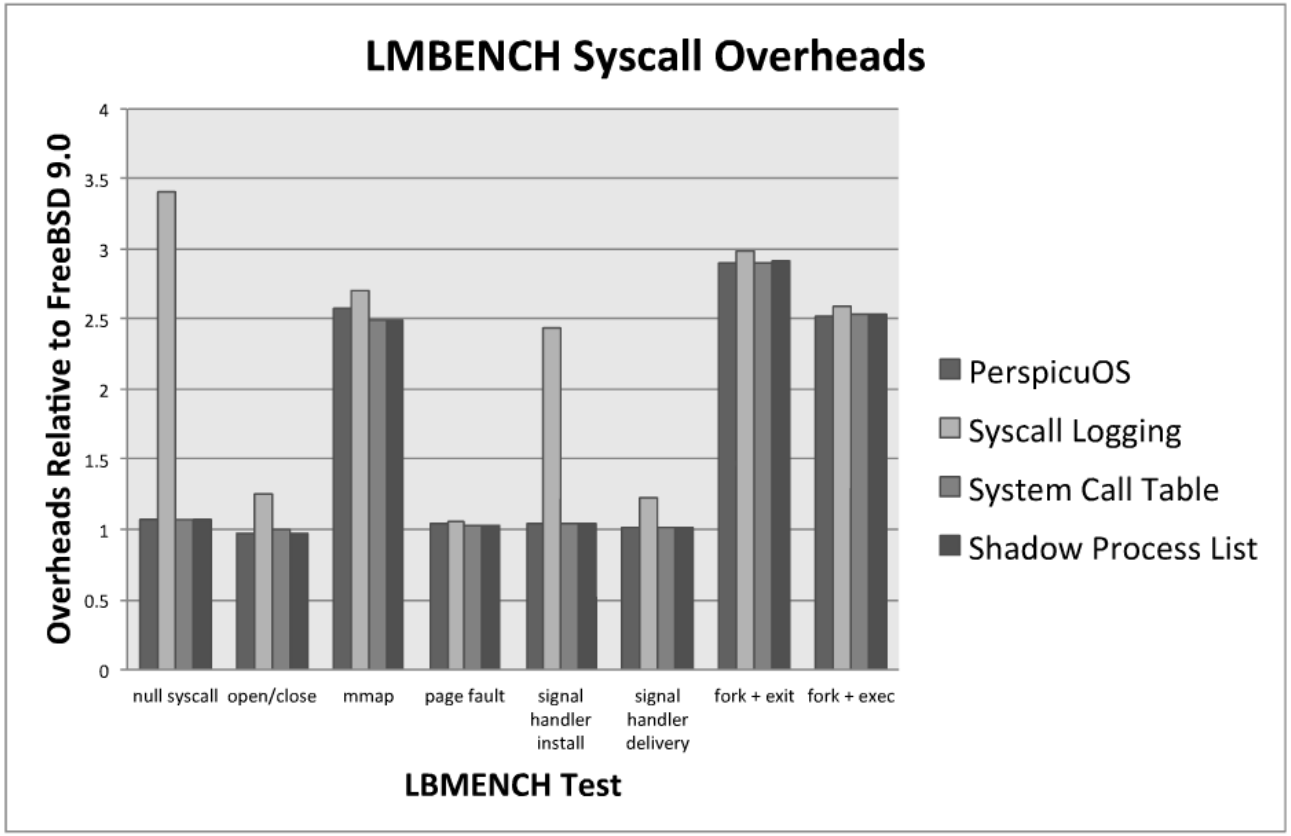
FreeBSD 9.0: 7.9 MB

PerspicuOS: 34 KB

MMU TCB FreeBSD 9.0 / PerspicuOS: 232x

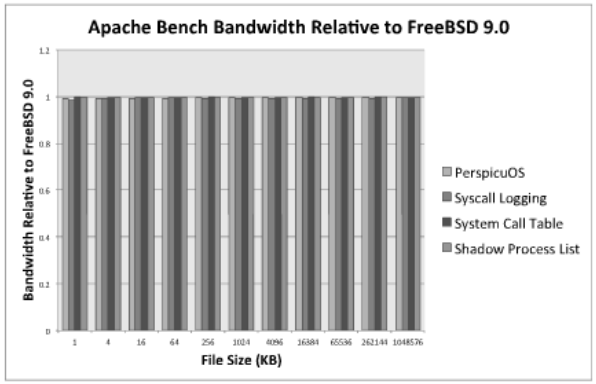
Code Scanner

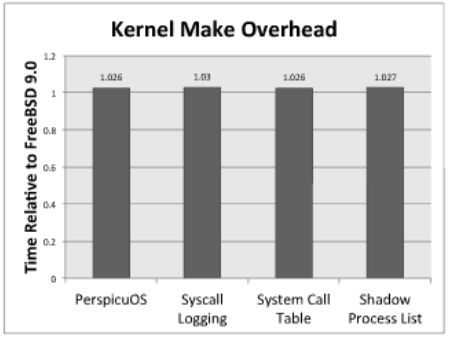
Microbenchmarks

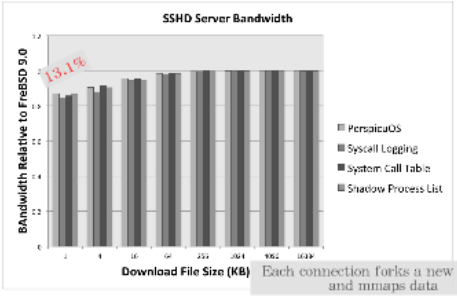


Macrobenchmark

Apache HTTPD

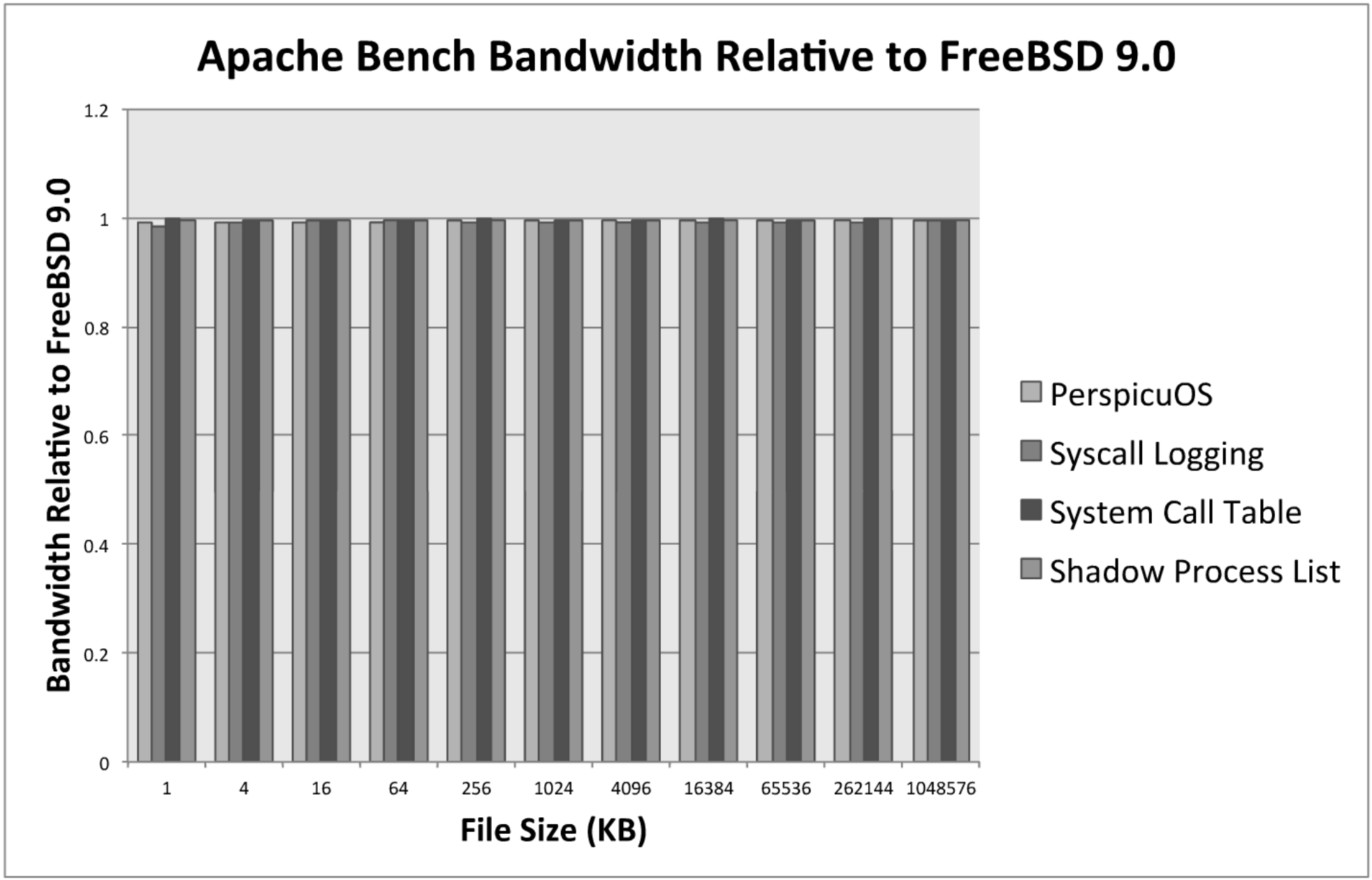


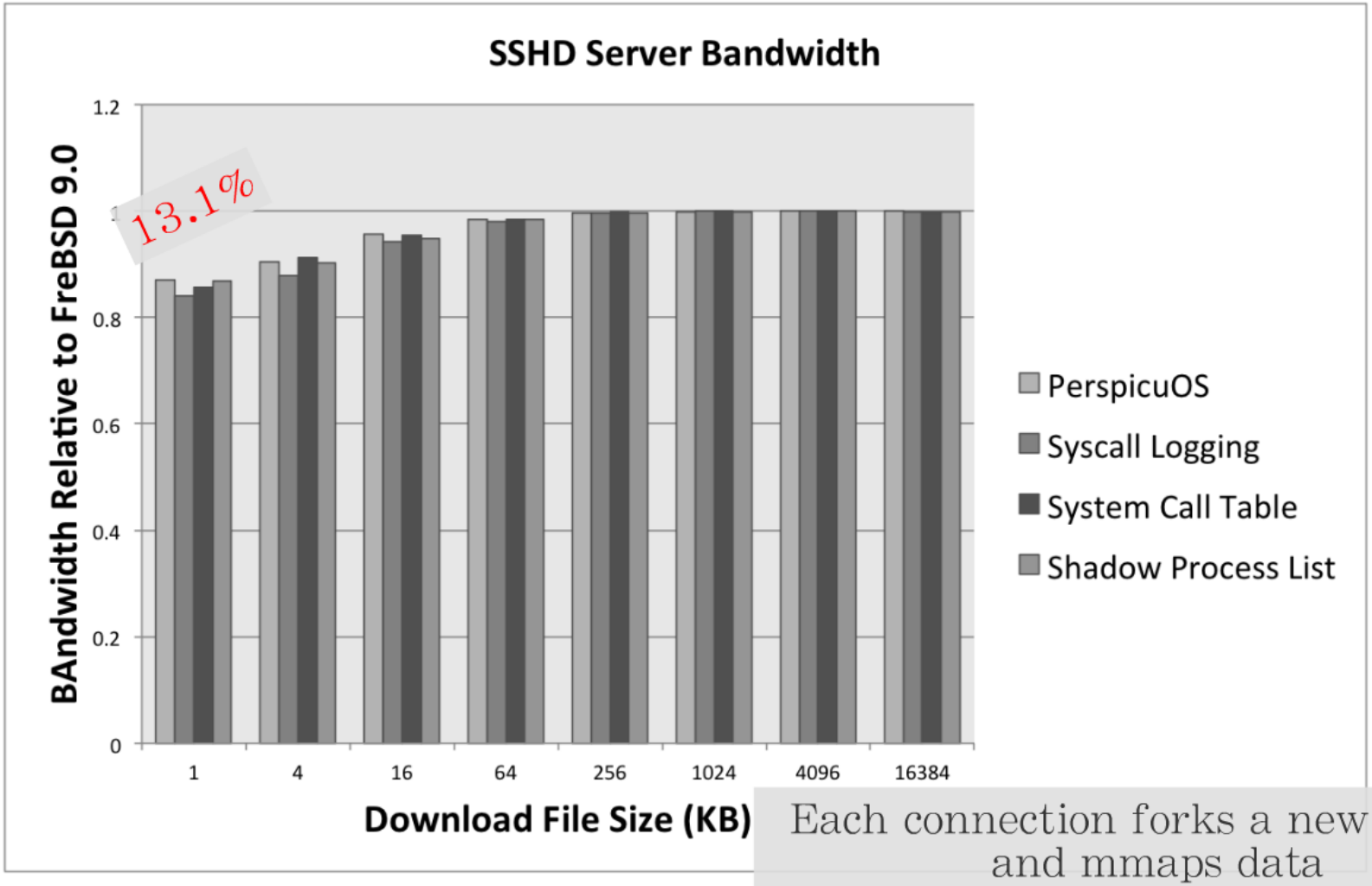




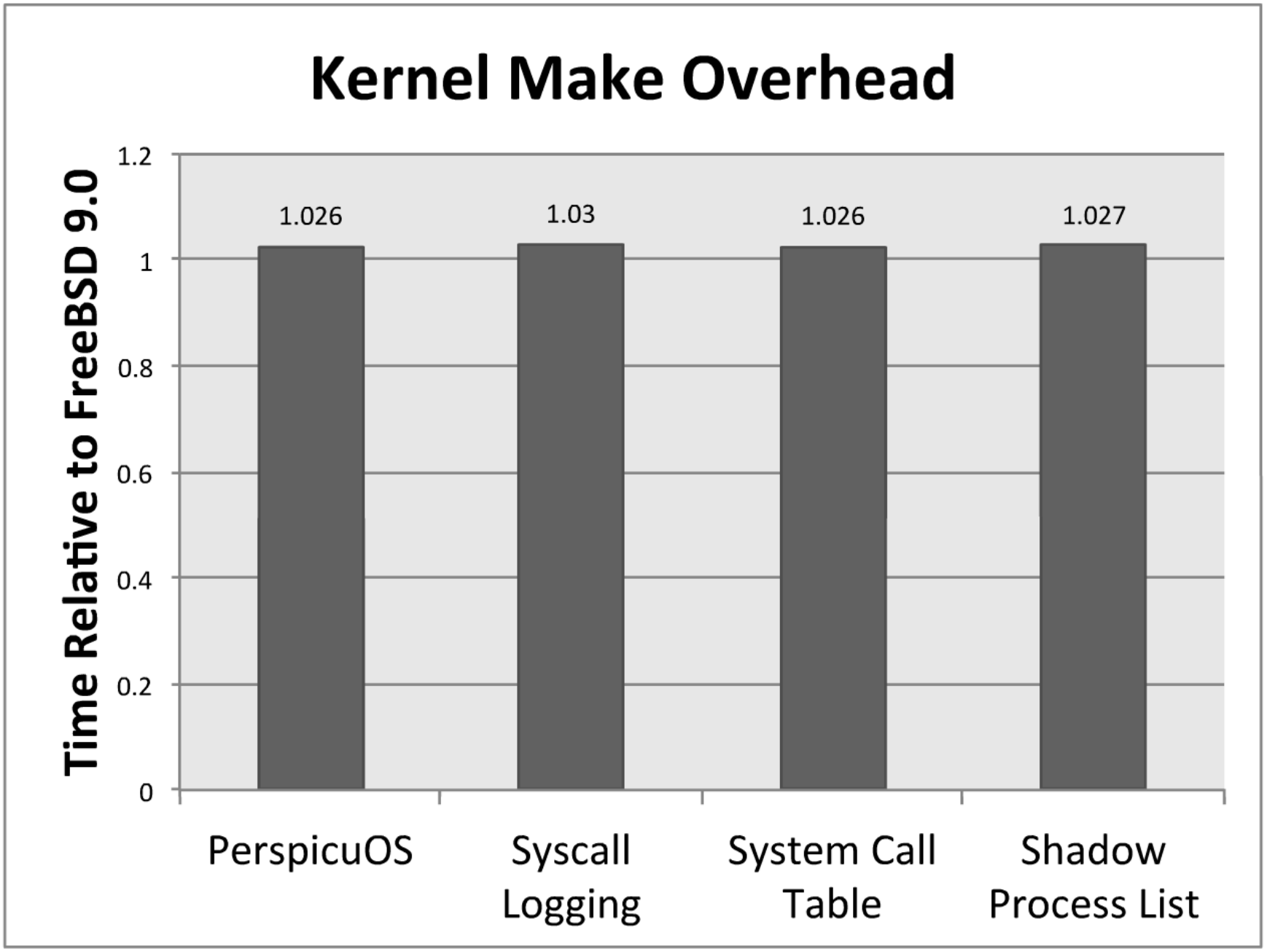
Each connection forks a new process and mmaps data

Apache HTTPD

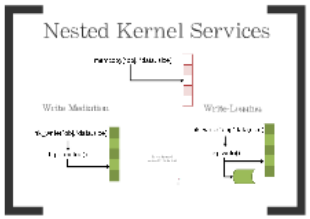




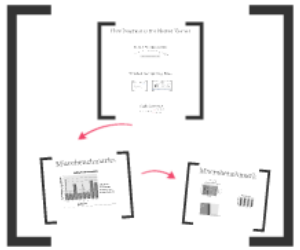
Each connection forks a new process and mmaps data


Kernel Make Overhead
Time Relative to FreeBSD 9.0
1.2
1
0.8
0.6
0.4
0.2
0
1.026
1.03
1.026
1.027
PerspicuOS
Syscall Logging
System Call Table
Shadow Process List

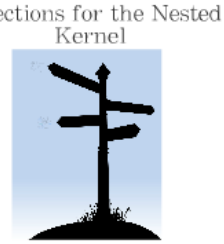
3) Intra-Kernel Isolation



4) Evaluation



5) Future Work



Directions for the Nested Kernel

Completing the Implementation

To Finish:

- NX Policies
- SMP
- Special operating modes (e.g., SMM)
- IOMMU Support
- MMU Operation Batching
- Port to FreeBSD Current and Refactor

To Add:

- Hardware-assisted virtualization (e.g. VT-x)
- Dynamic rewriting for maintenance

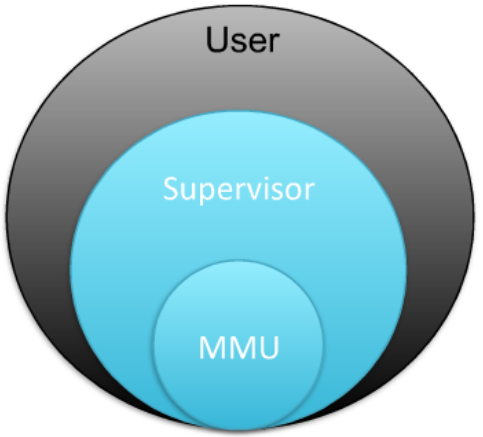
Future Research

- End-to-end intra-kernel security solutions
- Compelling memory isolation use cases (e.g., device drivers, file system, crypto)
- De-privileging to virtualize other hardware (e.g., EFLAGS)
- Nested Kernel VMMs
- Formal verification of Nested Kernel

Key Takeaways

- Retrofit the nested kernel architecture in FreeBSD 9.0

- Isolate MMU at a single hardware privilege level by virtualizing supervisor mode



- Intra-kernel memory protection services
- Lifetime kernel code integrity in FreeBSD 9.0