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PIkit: A New Kernel-Independent Processor-Interconnect Rootkit

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Rootkit Background

- **Rootkit**: a malicious software running on compromised machines without being detected.

- Typical root attack scenario

Goal: **One time root permission**	**Goal:** Rootkit installation using **SW/HW vulnerabilities**	**Goal:** Malicious activity **using payloads**
Approaches: Vulnerability Exploitation Social Engineering	**Requirement:** Remove Traces of Intrusion Hiding its presence	**Example:** Sniff Passwords Steal Files

- Different types of rootkits by payloads and by vulnerabilities

Rootkit Classification

		Malicious Payloads	
		User-Level	Kernel-Level
Vulnerabilities	Software	T0rn (SANS '00), Lrk5 ('00), dica ('02), etc.	ROR (USESEC '09), DKOM (BLACK HAT '04), knark ('99), etc.
	Hardware	**This work (PIkit)**	Cloaker (S&P '08), Shadow Walker (BLACK HAT '05)

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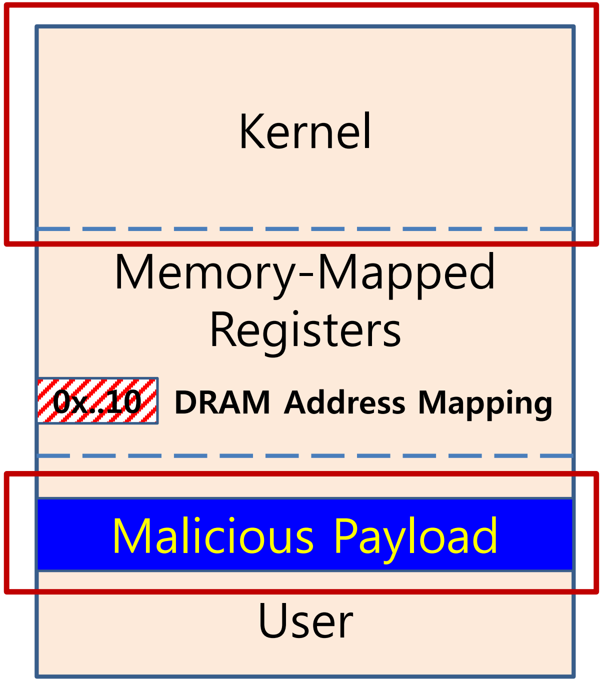
High-level overview of PIkit

Kernel-Independent
(No code modification or injection)

Vulnerable hardware feature
(Processor-interconnect in x86 multi-socket server)

A very stealthy rootkit
(only simple read/write memory operations)



Before/After PIkit installation

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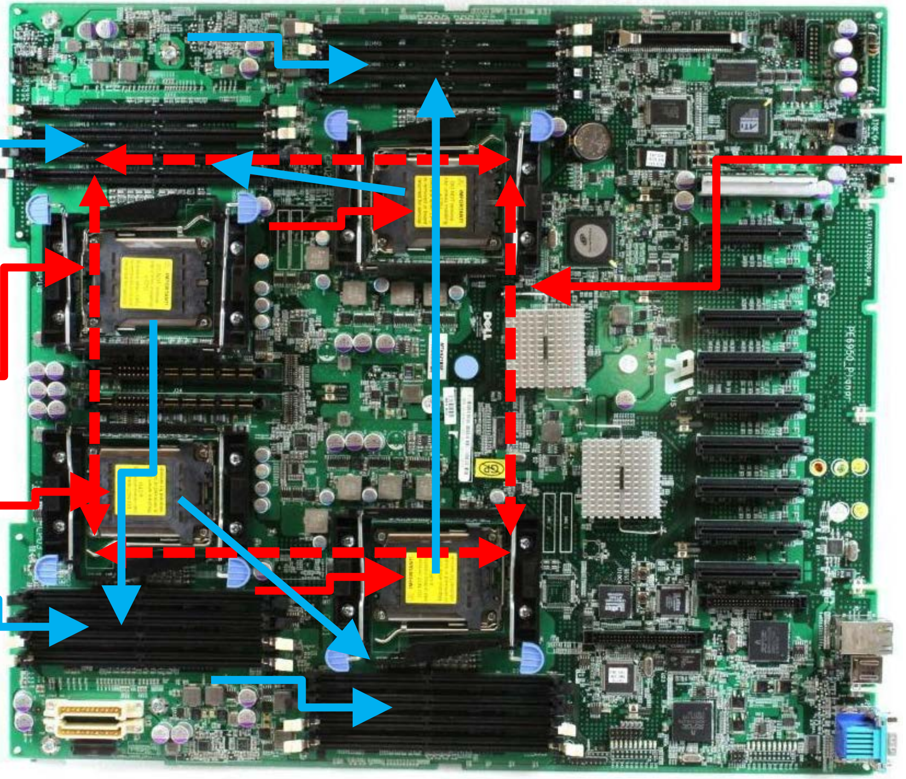
Analysis of Processor-Interconnect in Multi-Socket Servers

Multi-socket (NUMA) Server

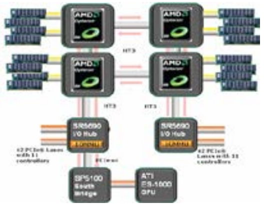
DRAM Memory x 4

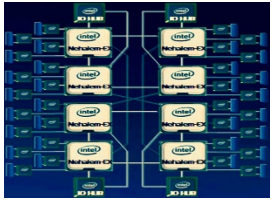
Processor x 4



Processor-Interconnect

AMD HyperTransport (HT)





Intel Quick-Path Interconnect (QPI)

* DELL PowerEdge 6950

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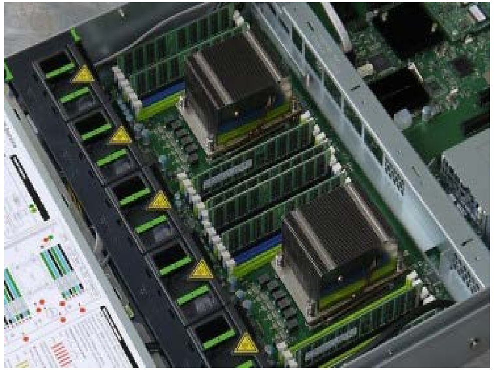
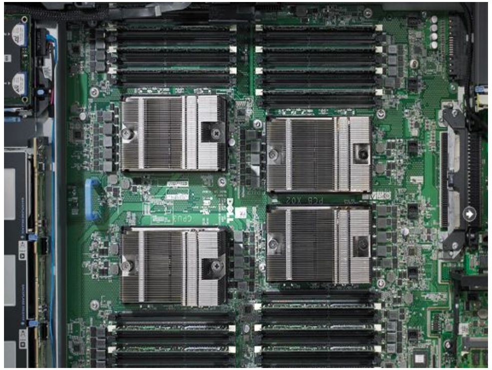
Multi-socket Server Market Share



2-ways Intel multi-sockets
(Fujitsu RX2540)

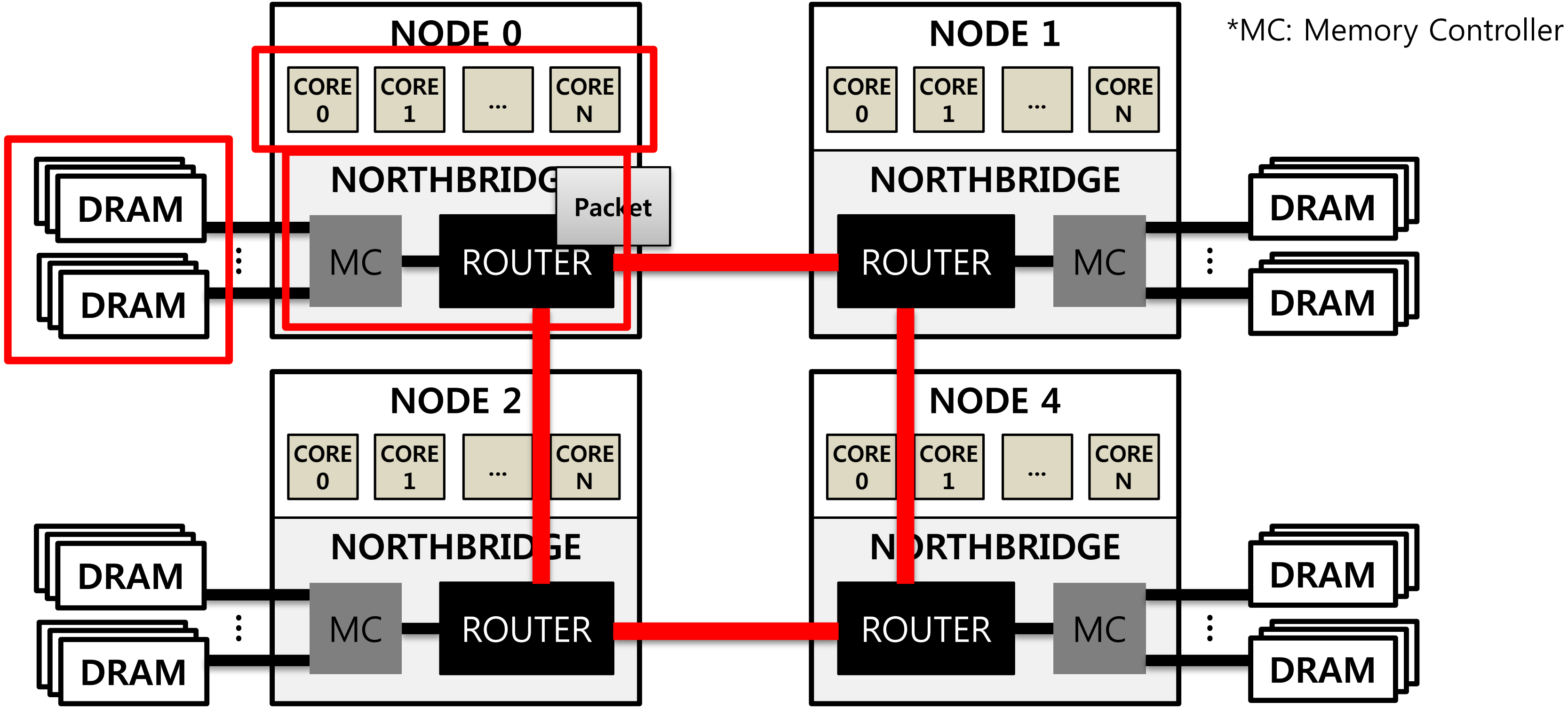
8-ways Intel multi-sockets
(DELL PowerEdge C6100)



4-ways AMD multi-sockets
(DELL PowerEdge R815)

In datacenters and high-performance computing,
over 80% of the x86 server are multi-socket servers (from IDC)

Processor-Interconnect Overview



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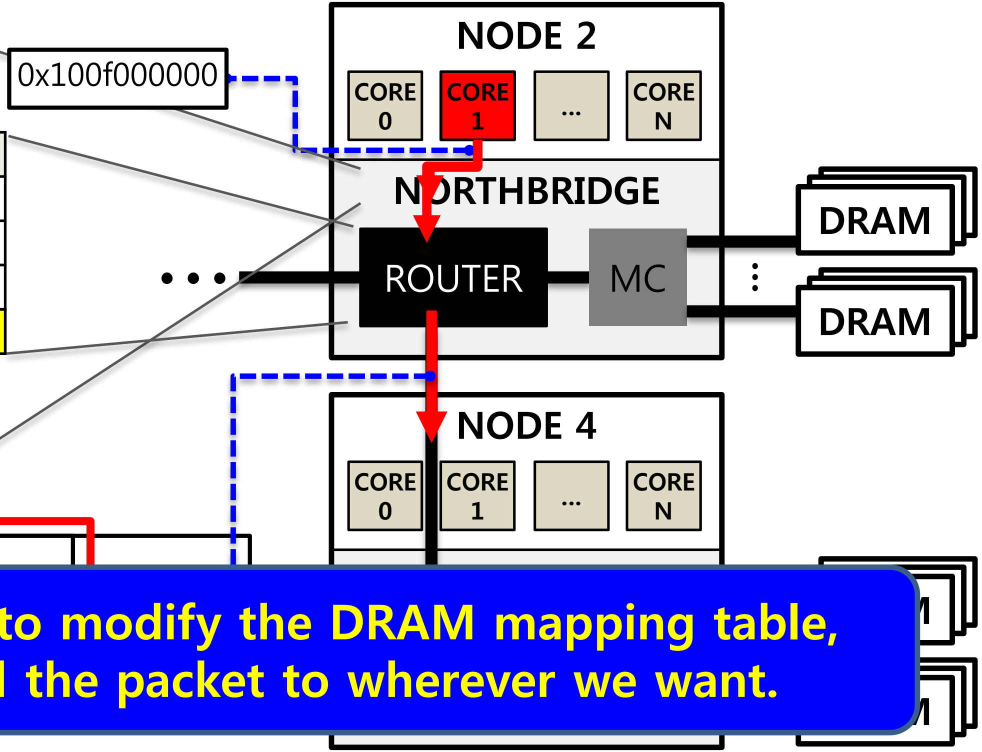
Memory access in Processor-Interconnect

DRAM Address Mapping Table

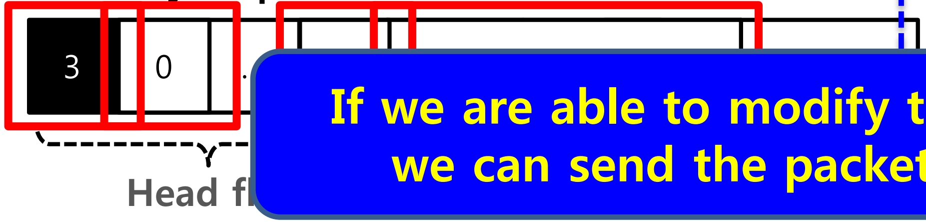
	Base Address	Limit Address	Destination ID
0	0x0000000000	0x041F000000	0
1	0x0420000000	[illegible]	[illegible]
2	0x0820000000	0x0C1F000000	2
3	0x0C20000000	0x101F000000	3
4	RE[illegible]	[illegible]	[illegible]ED
5	RE[illegible]	[illegible]	[illegible]
6	RESERVED	RESERVED	RESERVED
7	RESERVED	RESERVED	RESERVED

Dest Node ID	Output Port
	North
	Local
	[illegible]h

Reserved for scalability



Memory Request Packet



If we are able to modify the DRAM mapping table, we can send the packet to wherever we want.

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DRAM Address Mapping Table

	Base Address	Limit Address	Destination ID
0	0x0000000000		0
1	0x0420000000		1
3	RESERVED		RESERVED
4	0x0C20000000		2
4	RESERVED		RESERVED
5	RESERVED		RESERVED
6	RESERVED		RESERVED
7	RESERVED		RESERVED

Configurability

Discrepancy

Extra entries

No integrity checking

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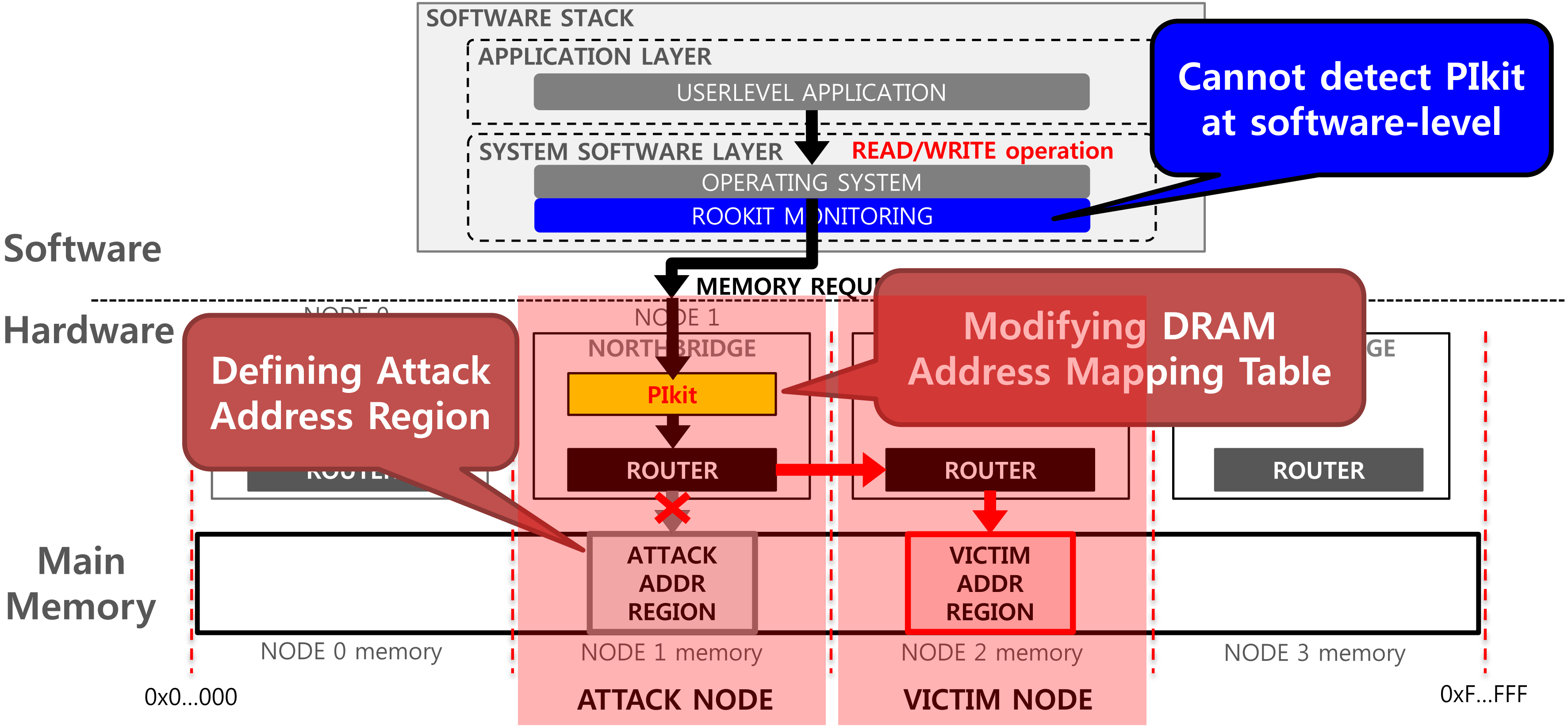
PIkit Design & Implementation

High-Level Overview of PIkit installation



Defining Attack Address Region

- Only the attacker should have access to **a particular memory region.**
  - To prevent any unknown system behaviors (system crash)

- The memory range of the attack address region needs to be equal to **resolution** of the memory mapping table.
  - ex) AMD Opteron 6128: 16 MB
  - Can take advantage of huge pages (malloc for 1 GB huge page)

- The process that received the memory allocation is **continuously running**.

Modifying DRAM Address Mapping Table

- Need to translate **VA (virtual address)** to **PA (physical address)**
  - Attack Address Region: VA, DRAM Address Mapping: PA
  - e.g. /proc/(pid)/pagemap
- **Memory-mapped register** (AMD: 8 set of DRAM Base/Limit Registers)
  - DRAM Base Address Register

DramBase (RW)	...	IntlvEn (RW)	...	WE (RW)	RE (RW)
48–24			2	1	0

  - DRAM Limit Address Register

DramLimit (RW)	...	IntlvSel (RW)	...	**DstNode (RW)**
48–24			2	0

With root permission, the registers can be modified by using system read/write commands (eg. setpci)

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How to modify DRAM Address Mapping Table

0x07C0000000~0x07C1000000 : 2

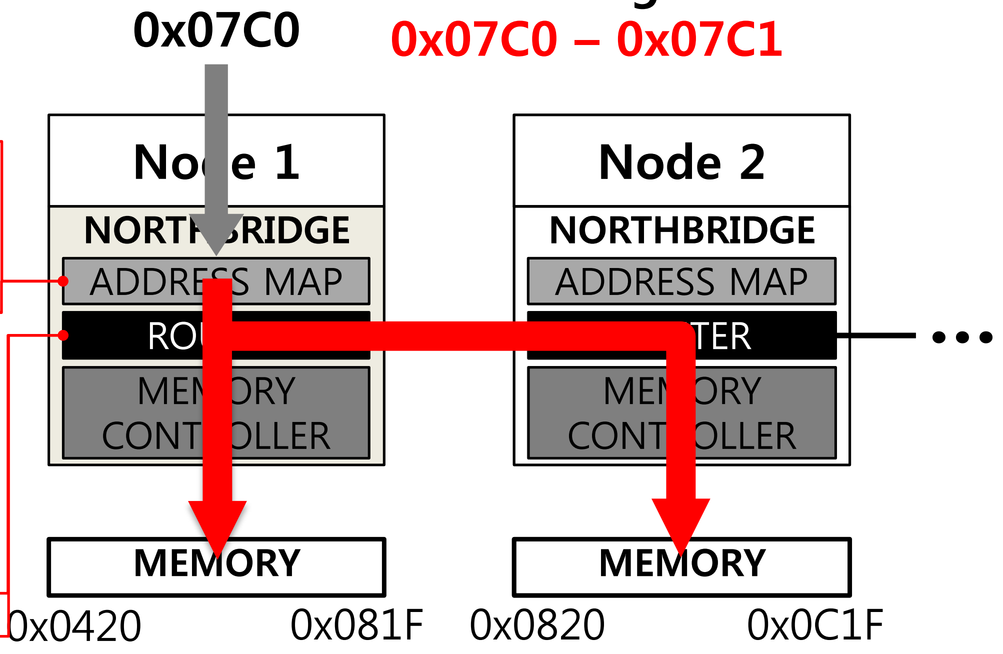
		nit Address	Dest ID
0	0x0000000000	0x041F000000	0
1	RESERVED	RESERVED	RESERVED
2	0x0820000000	0x0C1F000000	2
3	0x0C20000000	0x101F000000	3
4	0x0420000000	0x07BF000000	1
5	0x07C0000000	0x07C1000000	2
6	0x07C2000000	0x081F000000	1
7	RESERVED	RESERVED	RESERVED

Example – AMD Opteron 6128 server

DRAM Address Mapping Table

Base Addr	Limit Addr	Dest Node ID
0x0000	0x041F	0
RESERVED	RESERVED	RESERVED
0x0820	0x0C1F	2
0x0C20	0x101F	3
0x0420	0x07BF	1
0x07C0	0x07C1	2
0x07C2	0x081F	1
Reserved	Reserved	Reserved

Attack Region:
0x07C0 – 0x07C1



Routing Table

Dest Node ID	Link
0	North
1	Local
2	East
3	South

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Extending PIkit to Intel Architecture

	AMD Opteron 6128	Intel 7500 series
Memory-mapped Registers	DRAM Base/Limit registers	Source Address Decoder (SAD), Target Address Decoder (TAD)
Lookup Location	Source node	Source node, Destination node
Structure	BASE : LIMIT : DEST	SAD – LIMIT : DEST : VALID TAD – LIMIT : OFFSET
Granularity	16MB	64MB
# of entries	8	20

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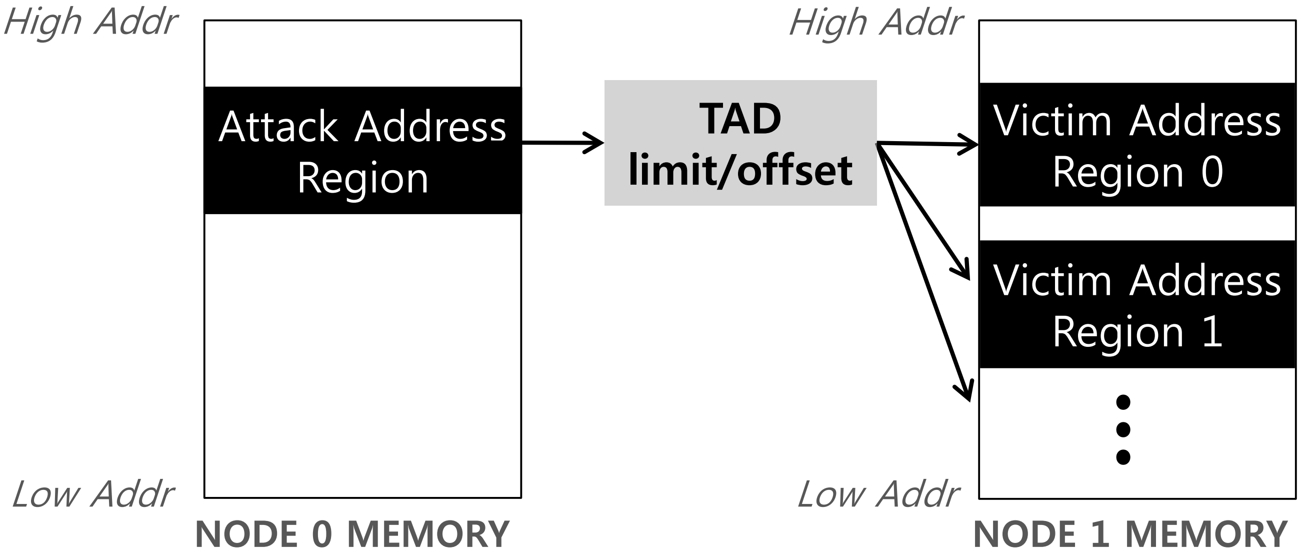
Modifying TAD



Based on the offset value, a fine-grained attack possible.

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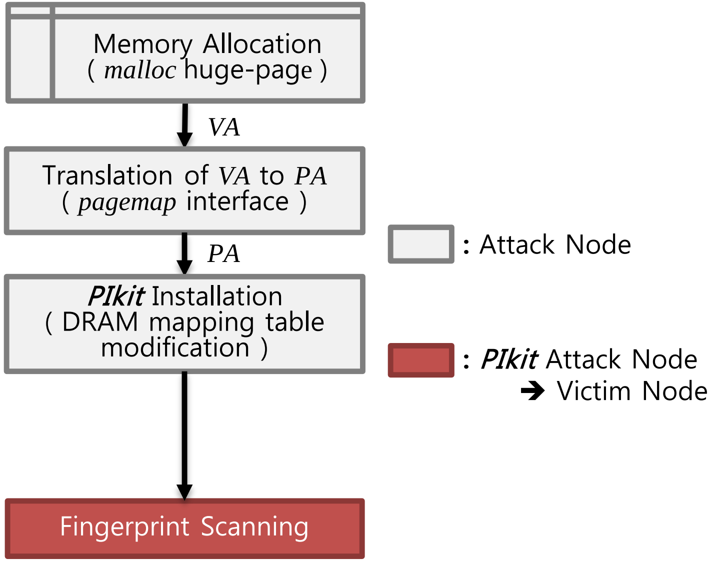
Malicious User-Level Payloads

Possible Attacks

Attack Name	Memory Access	Attack Type	Experiment Setup
System corruption attack	-	Denial of service	-
Bash keyboard buffer attack	Read-Only	Key stroke sniffing	- Dell PE R815 - AMD Opteron 6128 - 4 nodes - Linux kernel 3.6.0
Bash shell credential object attack	Read-Write	Privilege escalation	
Shared library attack	Read-Write	Hidden function (Backdoor)	- Dell PE R620 - Intel Xeon E5-2650 - 2 nodes - Linux kernel 3.6.0

Overview of Bash Shell Credential Object Attack



Scanning the Fingerprint:
To find the credential object in the VICTIM REGION, an attacker needs to find the fingerprint by READ operation at ATTACK REGION

Scanning the Fingerprint

Process Table

PID	PCB
1	
2	
⋮	⋮
n	•

Process Control Block

⋮
Task state
Process credentials
Priority
Open files
⋮
Other flags

task_struct (sched.h)

Credential Management (include/linux/cred.h)

```
struct cred {
    uid_t         uid;         /* real UID of the task */
    gid_t         gid;         /* real GID of the task */
    uid_t         suid;        /* saved UID of the task */
    gid_t         sgid;        /* saved GID of the task */
    uid_t         euid;        /* effective UID of the task */
    gid_t         egid;        /* effective GID of the task */
    uid_t         fsuid;       /* UID for VFS ops */
    gid_t         fsgid;       /* GID for VFS ops */
    ...
    struct key    *thread_keyring; /* keyring private to this thread */
    struct key    *request_key_auth; /* assumed request_key authority */
    struct thread_group_cred *tgcred; /* thread-group shared credentials */
    ...
    struct user_namespace *user_ns; /* cached user->user_ns */
    ...
};
```

①

②

③

① **are known to the attacker (UID & GID)**

② **should be within 0xffff880000000000 – 0xffffc7ffffffffff**

③ **can be found in Symbol Lookup Table (/boot/System.map)**

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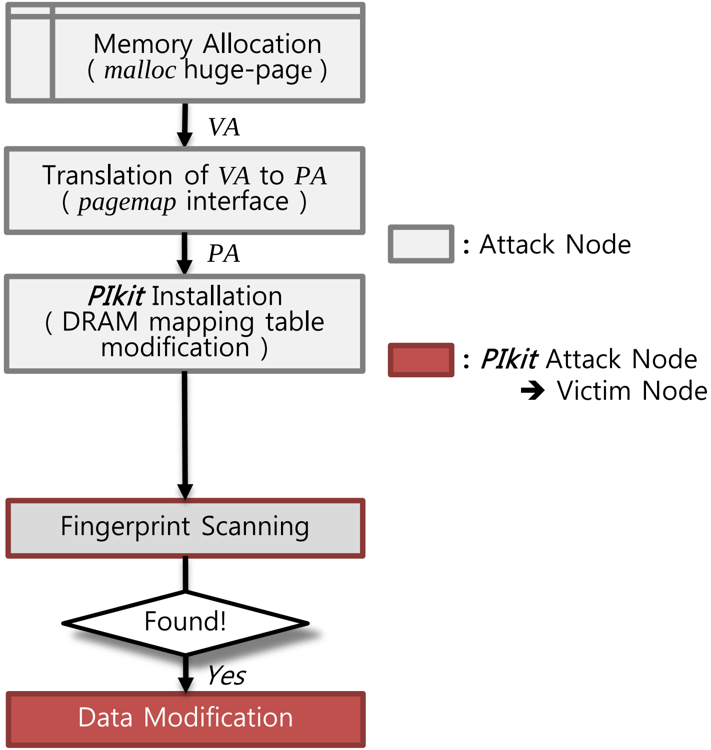
Overview of Bash Shell Credential Object Attack



Scanning the Fingerprint:
To find the credential object in the VICTIM REGION, an attacker needs to find the fingerprint by READ operation at ATTACK REGION

Modifying the Data:
If the fingerprint is found, an attacker can over write the EUID (or UID) to 0

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Modifying the Data

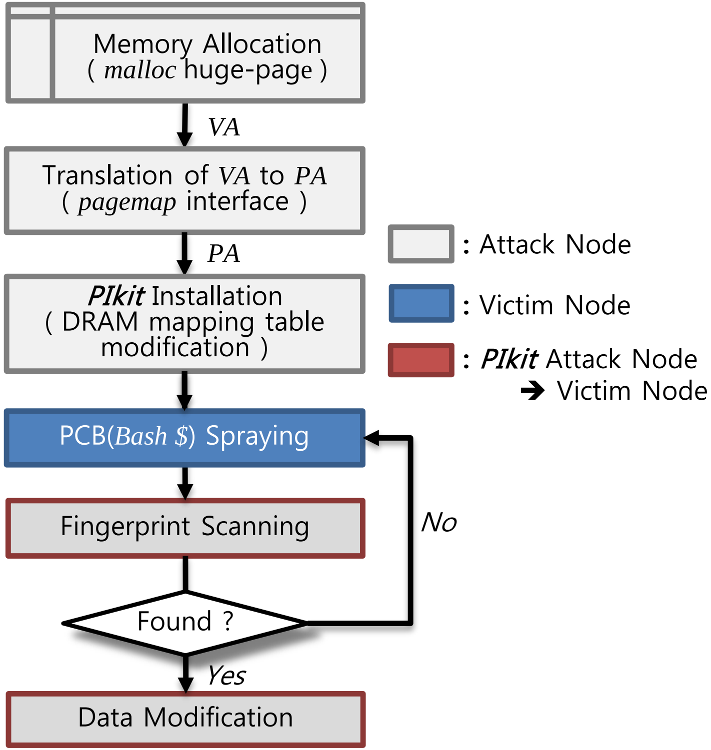
- Once the corresponding address of the credential data structure is determined from the scanning, the attacker can get a root shell by modifying either the ***euid*** or the ***uid*** field.

movnti $0, (Virtual Address)

- Result

```
[smith@server ~]$ id
uid=500(smith) gid=500(smith) groups=500(smith) context=unconfined_u:u
[smith@server ~]$ id
uid=500(smith) gid=500(smith) euid=0(root) egid=0(root) groups=0(root)
ined_t:s0-s0:c0.c1023
```

Overview of Bash Shell Credential Object Attack



Scanning the Fingerprint:
To find the credential object in the VICTIM REGION, an attacker needs to find the fingerprint by READ operation at ATTACK REGION

Modifying the Data:
If the fingerprint is found, an attacker can over write the EUID (or UID) to 0

Spraying the Process Control Block:
An attacker can increase the possibility that the credential data structure is placed in the VICTIM REGION

Overview of Shared Library Attack

□ : Attack Node ■ : Victim Node ◩ : Any Nodes ■ : *Pikit* Attack Node ➔ Victim Node

```
// dummy.c
void main(void){
    struct passwd *ret;
    int pid = getpid();
    int uid = getuid();
    ret = getpwuid(uid);
    printf("pid : %d₩n",pid);
    sleep (600);
}
```

```
$ ./dummy &
pid : 7145

$ gdb dummy 7145
(gdb) p getpwuid
$1 = {<text variable>}
0x3ade699570
```

Determine *VA* for a libc function

↓ *VA*

Translation of *VA* to *PA* (*pagemap* interface)

↓ *PA*

PIkit installation (SAD & TAD modification)

↓

Re-write malicious binary code for the libc function

↓

SUID program execution linked with the libc function → Privilege Escalation

↓

Restore original binary code for The libc function

0xc03100000001be55
0x8318ec8348fb8953
0x107400002bd9aa3d
0x002bb36835b10ff0
0x0deb00000103850f
0x0f002bb35935b10f

```
getpwuid()
{
    size_t buffersize;
    malloc(buffersize);
    ......
}
```

Original Binaries

Modified

0x48050f69b0ff3148
0x69622fffbb48d231
0x08ebc14868732f6e
0x50c03148e7894853
0x050f3bb0e6894857
0x050f583c6a5f016a

```
getpwuid()
{
    setuid(0);
    system("/bin/sh");
    ......
}
```

Malicious Binaries

```
[mike@server ~]$ passwd
# id
uid=702(mike) gid=702(mike) euid=0(root)
```

Discussions – Possible Solutions

Possible Solutions

- **Using Existing Features**
  - Enable AMD's LockDramCfg feature (included in "C6 State Management")
    - In old BIOS, it is disabled by default
  - Similar LockDramCfg feature is not readily available in Intel x86 CPUs.
- **Software-based Solution**
  - DRAM address mapping table monitor
    - Should be protected with a secure platform such as TrustZone, Intel SGX
- **Hardware-based Solutions**
  - Restrict # of entries used to equal # of nodes in the system
    - Does not completely remove the possibility of the PIkit
  - Design the DRAM address mapping table entries as write-once memory-mapped registers
    - Flexibility issues for CPU Hotplug or memory Hotplug

Conclusion

- **PIkit – a kernel-independent processor-interconnect rootkit**
  - Exploits vulnerable hardware features in Processor-Interconnect
  - Kernel Independent (No code injection or code modification to the kernel)
    - Enables malicious activities to be carried out with only user-level code
- **Four different attack scenarios**
  - Bash shell credential object attack, Bash keyboard buffer attack, Shared library attack
- **PIkit is a very stealthy rootkit**
  - Payloads consist of only read/write memory operations

Thank you! Questions?

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