MICHIGAN STATE UNIVERSITY

Secure Bit: Buffer Overflow Protection

"Give me a (little) bit,
and I will solve buffer overflow."

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Overview

- Introduction
- Reviews
- Theory
- Secure Bit
- Design
- Implementation
- Evaluation
- Analysis
- Conclusion
- Demo

Simple Buffer Overflow

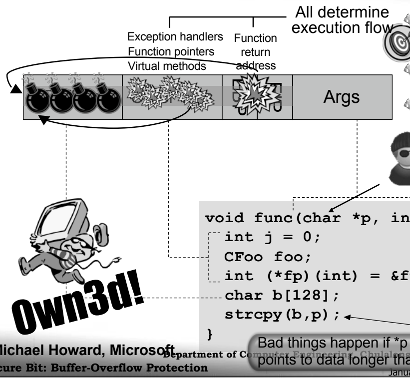
```
#include <stdio.h>
int main(char argc,char *argv[]) {
        int age;
        char name[8];
        char tmp[20];
        printf("Enter your age:");
        gets(tmp);
        age=atoi(tmp);
        printf("Enter your name:");
        gets(name);
        printf("-----------\n%s is %d
years old\n"
            ,name,age);
}
```

```
$./a.out
Enter your age:15
Enter your name: RichardJ1
-----------
RichardJ1 is 49 years old
```

What's wrong?

"RichardJ"	'1' '\0'
name	age

Stack Buffer Overflows at Work



- Return-address attacks (Stack smashing)
- Function-pointer attacks
- Frame-pointer attacks

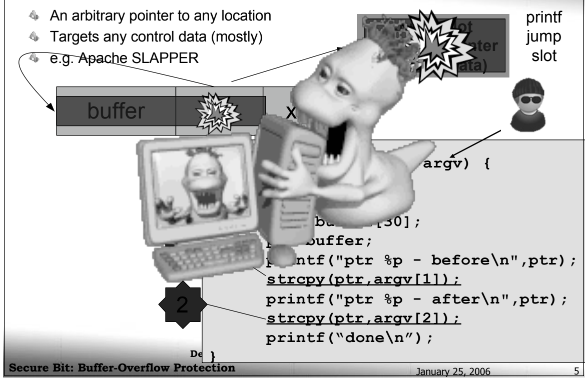
```
void func(char *p, int i) {
  int j = 0;
  CFoo foo;
  int (*fp)(int) = &func;
  char b[128];
  strcpy(b,p);
}
```

Bad things happen if *p points to data longer than b

Michael Howard, Microsoft

Sample Buffer-Overflow Attack

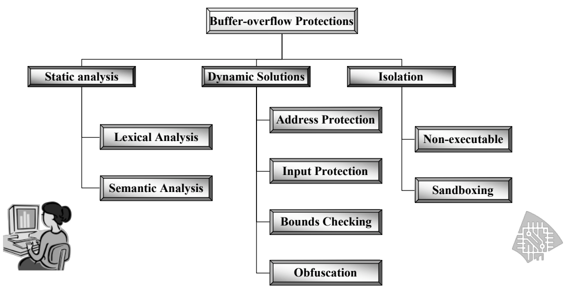
- An arbitrary pointer to any location
- Targets any control data (mostly)
- e.g. Apache SLAPPER



Observations

- Mandatory conditions:
  - Injecting malicious code/data ? or known address of shell code.
  - Redirect program to execute malicious code/data
- Similar Vulnerabilities
  - Integer Overflow (A subset of buffer-overflow)
  - “printf” vulnerability

Classification of Buffer Overflow Protection



Static Analysis

Prevent the problem before deploying the program.

- Only known problems are prevented.
- No run-time info
- False alarm ?

Examples
- ITS4 – string matching
- FlawFinder & RATS
- Splint, BOON – security enhanced lint, semantic analysis
- STOBO – profiling tool
- LibSafe – safe standard C lib

Dynamic Solutions

- Address Protection
- Input Protection
- Bounds Checking
- Obfuscation

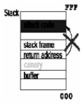
Issues

- Assumptions
- Creation of **metadata**
- Validation of **metadata**
- Handling of invalid data

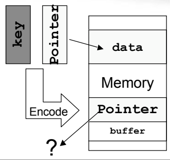
Address Protection: metadata

Canary Words

- Use canary for detecting the modification of addresses
- StackGuard, ProPolice

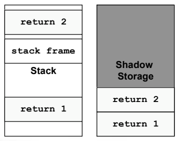


Address Encode



- Encode an address with a pre-defined key
- Decode on dereference
- PointGuard

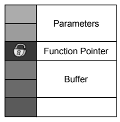
Copy of Address



- Use another copy for verification
- StackGhost, RAS, Split Stack, RAD, DISE, StackShield, SCACHE, LibVerify

Tags

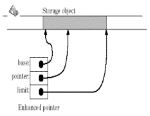
- Use a bit associated with each word for tagging return address, function pointers
- IBM system/38



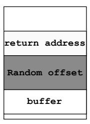
Other Dynamic Solutions

Bound Checking

- Symbol table/ Segment Descriptor Table
- Enhanced Pointers, Segmentation



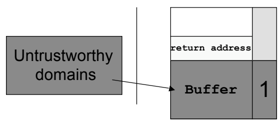
Obfuscation



- Permute the order of variables, routines, and structures
- Address Obfuscation, ASLR

Input Protection

- Input must not be used as control data
- Boundary
  - Minos: segmentation
  - Tainted pointer: SimpleScalar I/O functions
  - Dynamic Flow Tracking: SimpleScalar I/O functions
- Untaint
  - Minos: creation time
  - Tainted pointer: CMP, XOR
  - Dynamic Flow Tracking: XOR



Isolation

- **Limit** the execution of code that may result from buffer-overflow attacks. (NX, kernel NX)
- **Sandbox** the whole process from accessing certain system resources based on a predefined policy. (TCPA)
- **Secure** code **installation** and run-time environment (SPEF)

Additional Space & Interface (Ctd.)

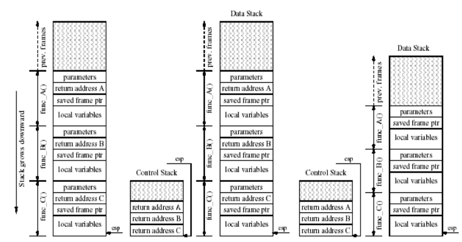
- Meta data is necessary.
- Segmentation:
  - IA-32 uses 64-bit descriptor, I-432 uses 128-bit descriptor.
  - 1 descriptor per variable
- StackGuard:
  - A canary word per call
- Secure Bit:
  - 1 bit (Minimum?)
  - 1 time cost

•Effectiveness?
•Run-time Penalty?

SimpleScalar

- A RISC architecture = Simple ISA
- Simple design
- Parallelism & Hazards
- Caches

Split Stack

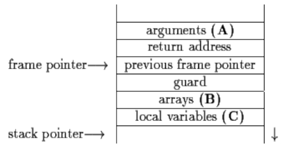


(a) Unified Stack (b) Compiler-based Split Stack (c) Architecture Supported Split Stack

- Separate Control and Data Stack

By UIUC

IBM ProPolice



- Guard Value (Similar to StackGuard)
- Declare pointers after buffer.
- Pointer in Structure ?

Original Code

```
int bar() {
   void (* funct2)();
   char buff[80];
```

Reorder Code

```
int bar() {
   char buff[80];
   void (* funct2)();
```

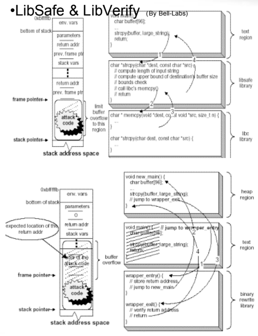
Figure from J. Etoh., "GCC extension for protecting applications from stack-smashing attacks," http://www.trl.ibm.com/projects/security/ssp/ , June 2000

By IBM Research, Japan

Others (software)

- Adddress Obfuscation: (By Stony Brook U., NY.)
  - Randomize the base address of the memory segment
  - Permute the order of variables/routines
  - Problem: Fragmentation, compatibility ?
- SPEF: (By Microsoft & UCLA)
  - Using encryption to securely install the software
  - Instruction is decoded and reordered in I-CACHE
- Instruction-Set Randomization (By Columbia U. & Draxel U)
  - XORing instruction with a per-process key
- Difficulty in injecting malicious code/data does not protect the system from buffer overflow attacks. Why ?

•LibSafe & LibVerify (By Bell-Labs)



StackGuard

- Random canary
- Terminator canary
- Terminator with diversity canary
- MemGuard Protection
- Similar tool from IBM ProPolice
- Alignment?

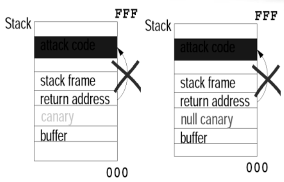
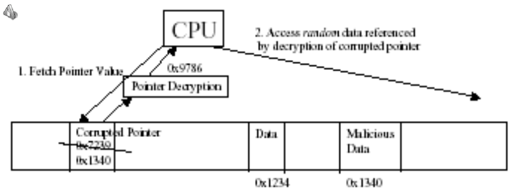


Figure from "StackGuard: Defending Programs Against Stack Smashing Attacks," Poster Presentation from http://www.cse.ogi.edu/DISC/projects/immunix/StackGuard/

By Oregon Graduate Institute (Immunix)

PointGuard

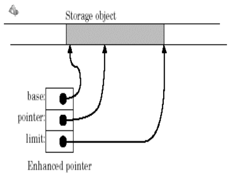


- Encrypt the pointer for storing, decrypt for dereferring
- Compatibility ?
- Initialization ?
- Performance ?
- Encryption Algorithm ?

By Oregon Graduate Institute (Immunix)

Array Bounds Checking/Segmentation

- Symbol table/ Segment Descriptor Table
- Explicitly declare and refer every buffer with base and boundary (including integer, float,.. Why ?)



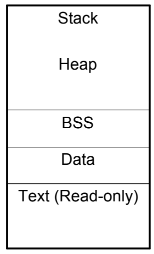
- Example: Intel IA-32, I-432
- More than 30 times slowdown

```
char *a;
char b[10];
*a = &b;
b[11]=10;

for (a=b;a<&b[10];a++)
        *a='0';
```


Address Obfuscation

- Randomize the base address of the memory segment
- Permute the order of variables/routines
- Random gaps between object
- Problem: Fragmentation, compatibility ?
- Similar method: PAX’s ASLR (Address Space Layout Randomization)



By Stony Brook U., NY.

SPEF

- Secure Program Execution Framework
- Using encryption to securely install the software
- Instruction is decoded and reordered in I-CACHE
- Difficult to inject malicious code
- Performance ?
- Data ?

By Microsoft & UCLA

Others (software)

- StackGhost: (by Purdue)
  - Use register window
- Split Stack: (by UIUC)
  - Separate control and data stack
- SRAS: (by UIUC)
  - Use RAS as a validation copy the address
- Overflow?, Speculative update (non-LIFO)?

- RAD: (By State U. of New York at Stony Brook)
  - Use mprotect to protect Return Address Repository (RAR)
  - MineZone RAR, Read-only RAR
  - Performance ?
- StackShield: (by Vendicator)
  - Save redundant copy of return address
  - Copy the return address from the redundant copy back to original stack
  - Check the return address with the redundant copy
  - Force the code to be in text section
  - Legal use of executing code in heap : LISP, OOP

Hardware: Non-Executable Stack/Memory

- Software/Hardware “NX” (currently in the news)
- Heap-based attacks
- Legal use of executable stack ?
- Attacks that do not injecting the malicious code/data?

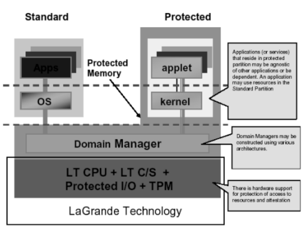
Instruction Set Randomization

- XORing instruction with key
- Per process key
- Difficult to inject malicious code
- Library ?
- Data ?

By Columbia U. & Draxel U.

Complement to Intel’s LaGrande & Microsoft’s NGSCB

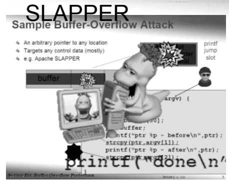
- NGSCB
  - Strong process isolation
  - Sealed storage
  - Secure user interface
  - Attestation
- Hardware support sandboxing
  - Domain separation

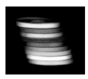


Trusted = Secure ?

Analysis

- Pitfalls
  - Insufficient assumptions
  - Insufficient protection of metadata
- Performance
- Compatibility and Transparency (e.g. non-LIFO control flows)
- Deployment and Cost





Compatibility: Non-LIFO Control Flow

```
NEAR_ENTRY:
   POP AX      ; POP instruction pointer (IP)
               ; from the top of stack into
               ; accumulator (AX)
   PUSHCS      ; PUSH CS
   PUSHAX      ; PUSH IP back onto stack
FAR_ENTRY:

   RETF        ; POP IP and CS off stack
```

•FAR & NEAR Call Optimization (for size)
•RET for JMP
•More..

IP	CS
Canary	IP
…	…

Current approaches?
•Ignore
•Cannot handle

From articles

- Microprogramming, April, 1972
  "I believe that
  the average computer of the year 2000 will: ….
  – Have word by word protection and data description, …"
- ACM SIGARCH, July, 2003
  "Is anyone up for a discussion of capabilities, segments, 2-dimensional memory? Techniques which, among other things, render buffer overrun impossible."

Facts

- Buffer overflow can occur in Java, Perl or any type-safe languages.
- No protection mechanism is perfect, but the reimplementation of all code: BIOS, Kernel, Library (Static & Dynamic), Drivers, applications, etc…

Why?

Really?

- How about the Secure Bit?

Theory

- ***Definition 1:***The condition wherein the data transferred to a buffer exceeds the storage capacity of the buffer and some of the data "overflows" into another buffer, one that the data was not intended to go into.
- ***Definition 2:*** A **buffer-overflow attack on control data** is an attack that (possibly implicitly) uses memory-manipulating operations to overflow a buffer which results in the modification of an address to point to malicious or unexpected code.
- ***Observation:*** An analysis of buffer-overflow attacks indicates that a buffer of a process is always overflowed with a buffer passed from another domain (machine, process)—hence its malicious nature.
- ***Definition 3:*** Maintaining the integrity of an address means that the address has not been modified by overflowing with a buffer passed from another domain.

Theory

Postulate 1: In buffer-overflow attacks on control data, the generic buffer/memory-manipulating operations are used by the vulnerable routine to overflow the address (e.g. a return address or a function pointer).

Theorem 1: Modifying an address by replacing ("overflowing") it using a buffer passed from another domain is a necessary condition for buffer-overflow attack on control data.

Restatement: If there is to be a buffer-overflow attack on control data, an address must be modified using a buffer passed from another domain.

Proof:
Theorem 1 follows directly from Definition 1, and Definition 2.

QED

Corollary 1.1: Preserving the integrity of an address is a sufficient condition for preventing a buffer-overflow attack.

Restatement: If the integrity of an address is preserved, that is a sufficient condition for preventing a buffer-overflow attack.

Proof: From Theorem 1, "If there is to be a buffer-overflow attack, an address must be modified by manipulating a buffer from another domain." The contrapositive of that statement is "If an address cannot be modified (or such modification can be detected), then a buffer-overflow attack is not possible." We know that the contrapositive of a true statement is true.

QED

Secure Bit

Give me a little Bit and I will solve buffer-overflow attacks.

Protocol 1:
Passing a buffer across domains (devices, machines, and processes) always sets the Secure Bit.

Restatement: All input will have the Secure Bit set.

Hardware Enforcement: (Protocol 2)
Data from another domain (with Secure Bit set) must not be used as jump target.

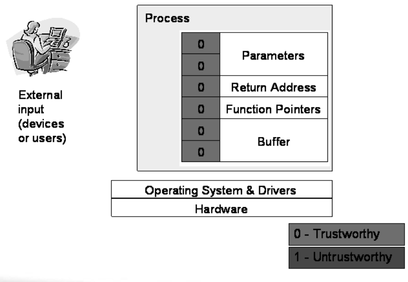
Secure Bit (Cont.)

Similar Concepts

- **"All input is evil until proven otherwise"** [Howard and LeBlanc]
- **"Data must be validated as it crosses the boundary between untrusted and trusted environments."** [Howard and LeBlanc]

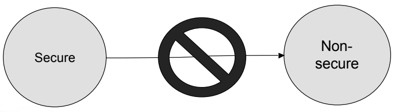
Concept

Data passing from another domain must not be used as a return address or a function pointer



Secure System

- ***Definition 4:*** A **security policy** is a statement that partitions the states of the system into a set of authorized, or secure, states and a set of unauthorized or nonsecure, states. [Bishop]
- ***Definition 5:*** A **secure system** is a system that starts in an authorized state and cannot enter an unauthorized state. [Bishop]



Formalization

Lemma 2: A **system which preserves the integrity** of an address (e.g. a return addresses or a function pointer) is **a secure system** with respect to buffer-overflow attacks.

Restatement: A system that does not use input as a control data is a secure system with respect to buffer-overflow attacks on control data.

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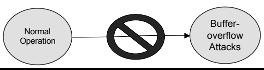


Proof:
Assume that a system is partitioned into two states:
normal operation and **buffer-overflow attack**.

Only overwriting the address (e.g. a return address or a function pointer) with an address passed as a buffer (input) to vulnerable programs will result in the state of buffer-overflow attack.
By the definition of buffer-overflow attacks (Definition 2)

If such overflowing can be recognized and prevented, the system will not result in the state of buffer-overflow attacks.
By the definition of preservation of the address (Definition 3)

With respect to Definition 5, our system cannot enter an unauthorized state and is considered to be a secure system
QED

Formalization (Cont.)

Lemma 3: Secure Bit and Protocol 1 can preserve the integrity of an address, and result in a secure system with respect to buffer-overflow attacks.

Proof:
With Secure Bit and Protocol 1, we can detect that an address (e.g. a return address or a function pointer) is overflowed by a buffer passed from another domain (including input).

If we can detect that an address is modified by a buffer from another domain, we can preserve the integrity of the address.
This follows directly from Definition 3.

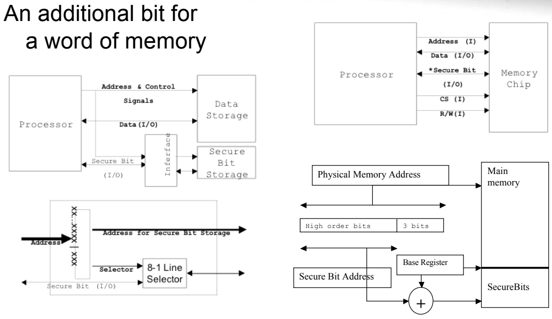
Thus Secure Bit preserves the integrity of the address and is a secure system with respect to buffer-overflow attacks.
This follows directly from Lemma 2.
QED

Protocol Enforcement

- "Threat surface" is defined as all possible input crossing from the software interface.
- A domain is a boundary with respect to the current process
- ***sbit_write*** mode is added to a processor for passing data across domain (set Secure Bit)
- The ***kernel*** will use this mode to move data across domains.
- ***Call, Jump, and Return instructions*** are modified.

Design: Memory Architecture

An additional bit for a word of memory



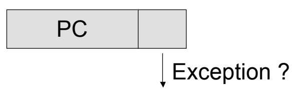
Design: Instruction Set Architecture

- sbit_write flag
- The semantics of the ***CALL and JUMP instruction*** are modified to validate the Secure Bit
- Other ***instructions that access memory*** are modified to carry the Secure Bit along with the memory word when the sbit_write mode is cleared, and to set the Secure Bit at the destination when the sbit_write mode is set.
- ***Operations*** (e.g. shift, arithmetic, or logical) with an insecure operand have an insecure result (Secure Bit is set). An immediate operand is considered to be secure (Secure Bit is cleared).

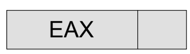
Design (Cont.)

- ALU

- Program Counter

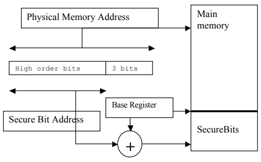


- Registers



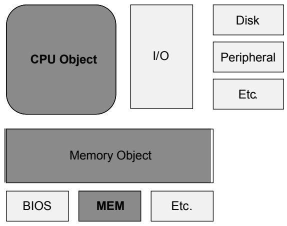
Design: Operating System

- Domains and Buffer Manipulation
  - Moving data between Kernel and Process in sbit_write mode
- Virtual Memory
  - Firmware
  - Software Management
  - Regular Paging on top of modified Hardware



Implementation

- BOCHS C++ Objects
- Memory Boundary
- Multiple Instances
- Instructions Set
- More than 5304 routines (3600 routines in CPU Object)



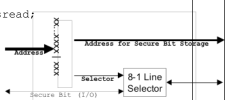
BOCHS: Secure Bit interface

Set/Clear Secure Bit	Read Secure Bit

```
// Set/Clear Secure Bit by KPR
   Bit32u a20addr_s;
   Bit8u sbyte;
   for (int i=0;i<len ;i++ )
   {
        a20addr_s=(a20addr+i)>>3;
        sbyte=(a20addr+i) &
   0x00000007;
        sbyte=1 << sbyte;
        if (*sbit==1)
        { // set

   vector_s[a20addr_s]|=(sbyte&0xff)
   ;
        }
        else
        { // clear

   vector_s[a20addr_s]&=~(sbyte&0xff
   );
        }
        sbyte=sbyte<<1;
   }
```

Set/Clear Secure Bit

```
// Read Secure Bit by KPR
   Bit32u a20addr_s;
   Bit8u sbyte;
   Bit8u sread;
   sread=0x00;
   for (int i=0;i<len ;i++ )
   {
        a20addr_s=(a20addr+i)>>3;
        sbyte=(a20addr+i) &
   0x00000007;
        sbyte=1 << sbyte;

   sread|=(vector_s[a20addr_s]&sbyte)
   ;
        sbyte=sbyte<<1;
   }
   *sbit=sread;
```



Read Secure Bit

BOCHS: Memory Interfaces

Avoid modifying 3000+ routines

```
/// Overload Functions
/// For Secure Bit (KPR)
///
/// Read Data and Secure Bit
BX_MEM_SMF void    readPhysicalPage(BX_CPU_C *cpu, Bit32u addr,
   unsigned len, void *data, int *sbit) BX_CPP_AttrRegparmN(3);
/// Write Data and Secure Bit
BX_MEM_SMF void    writePhysicalPage(BX_CPU_C *cpu, Bit32u addr,
   unsigned len, void *data, int *sbit) BX_CPP_AttrRegparmN(3);
/// Write Data (with optional Secure Bit)
/// if ignore=0, leave the Secure Bit unmodified
BX_MEM_SMF void    writePhysicalPage(BX_CPU_C *cpu, Bit32u addr,
   unsigned len, void *data, int *sbit,int ignore) BX_CPP_AttrRegparmN(3);
///
/// End (KPR)
///
/// Read Data, ignore Secure Bit
BX_MEM_SMF void    readPhysicalPage(BX_CPU_C *cpu, Bit32u addr,
   unsigned len, void *data) BX_CPP_AttrRegparmN(3);
/// Write Data, ignore Secure Bit
BX_MEM_SMF void    writePhysicalPage(BX_CPU_C *cpu, Bit32u addr,
   unsigned len, void *data) BX_CPP_AttrRegparmN(3);
```

BOCHS: Instruction Set

- Macros for operations on Secure Bit

```
// Secure Bit operation for each type of ALU instruction
#define SBIT_SHX(sbit1)   (sbit1 ==0)?0:1
#define SBIT_ROX(sbit1)   (sbit1 ==0)?0:1
#define SBIT_XOR(sbit1,sbit2)      (sbit1|sbit2)==0?0:1
#define SBIT_AND(sbit1,sbit2)      (sbit1|sbit2)==0?0:1
#define SBIT_OR(sbit1,sbit2)       (sbit1|sbit2)==0?0:1
#define SBIT_NOT(sbit1)   (sbit1 ==0)?0:1
#define SBIT_ADD(sbit1,sbit2)      (sbit1|sbit2)==0?0:1
#define SBIT_SUB(sbit1,sbit2)      (sbit1|sbit2)==0?0:1
#define SBIT_MUL(sbit1,sbit2)      (sbit1|sbit2)==0?0:1      // and DIV
```

- Set Secure Bit

```
sbit=(sbit_mode)? 1:sbit;
```

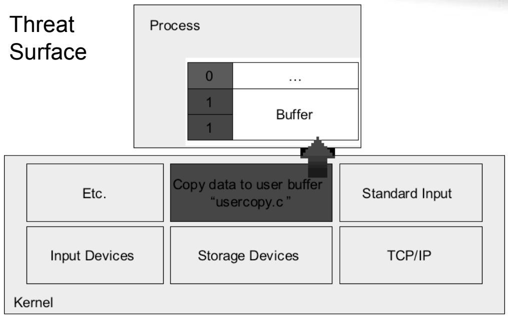
- Validate Control data

```
 // Validate call target
  if (sbit != 0) {
        BX_INFO(("call_ew: sbit of target is not secure"));
#ifdef HAS_SBIT_EXCEPTION
                exception(BX_GP_EXCEPTION, 0, 0);
#endif
  }
```

About 2410 lines of code in 607 routines affected

Linux Kernel

Threat Surface



Linux Kernel (Sample Code)

Sbit_write mode

```
// For Secure Bit 2
#define SET_SBITMODE() \
    asm volatile( \
        "    pushl    %eax\n" \
        "    lahf\n" \
        "    orb    $0x20, %ah\n" \
        "    sahf\n" \
        "    popl    %eax" )
#define CLR_SBITMODE() \
    asm volatile( \
        "    pushl    %eax\n" \
        "    lahf\n"    \
        "    andb    $0xdf, %ah\n" \
        "    sahf\n" \
        "    popl    %eax" )
```

```
unsigned long
__generic_copy_to_user(void *to,
   const void *from, unsigned
   long n)
{
   SET_SBITMODE();
   if (access_ok(VERIFY_WRITE,
   to, n))
        __copy_user(to,from,n);
   CLR_SBITMODE();
   return n;
}
```


Evaluation

- Booting Linux: complex test of **compatibility** of Secure Bit from an operating system point of view
- Running existing application: Test of backward compatibility and **transparency** to a legacy application
- Hacking Test: Test protection against buffer overflow, i.e. test the **effectiveness** of Secure Bit
- Modified Instructions: the **impact** of Secure Bit on instruction set architecture

Tested Applications

- **gzip** (SPEC CPU2000): Lempel-Ziv coding (LZ77) compression algorithm
- **bzip2** (SPEC CPU2000): Burrows-Wheeler block-sorting text compression algorithm, and Huffman coding.
- **gcc** (SPEC CPU2000): Compiler. Exercises a wide variety of data structures
- **Perl** and Shell scripts: Popular scripting languages.
- **OpenSSL**: cryptography library
- **Apache** with mod_ssl: Apache version 1.3.12 and mod_ssl. Vulnerable to SLAPPER worm. multithreaded server application (including SSL).
- **Telnetd** and WUFTPD: legacy network applications (and protocols).
- **OpenSSH**: Encrypted client-server applications.
- **Java** Virtual Machine: Sun JVM and Kaffe. Garbage collector, Virtual Machine and lightweight processes (threads).

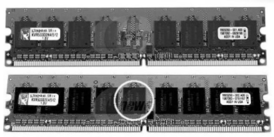
Hacking Test

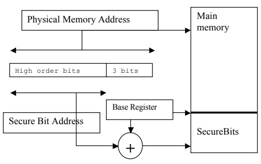
- Stack smashing and return-address attacks
- Function-pointer attacks
- Global Offset Table attacks
- Apache SLAPPER worm

- See DEMO

Analysis

- Space & Memory Interface
  - Trivial modifications
  - Covered in 3 days of MOORE's LAW
  - Minimal (comparing to Segmentation)
- Backward Compatibility
  - 100% to legacy user binaries
- Deployment
  - Processor only solution
- Performance
  - No significant penalty





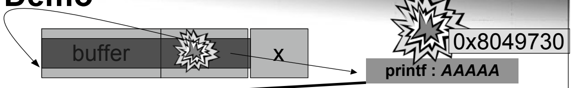
Conclusion

- Compatibility & Transparency
  - Compatibility with legacy user binary
  - Working with threads, non-LIFO control flows, and process communication
- Effectiveness
  - Catch all buffer-overflow attacks on control data
- Simple
  - Trivial hardware modifications

Publications

- Patent Pending (October, 2005)
- Piromsopa, K. and Enbody, R. Secure Bit : Transparent, Hardware Buffer-Overflow Protection, *IEEE Transaction on Dependability and Secure Computing* (Major revision)
- Piromsopa, K. and Enbody, R. Survey of Buffer-Overflow Protection, *ACM Computer Survey* (submitted)
- Piromsopa, K. and Enbody, R. Buffer-Overflow Protection: The Theory, EIT2006 (submitted)
- Piromsopa, K. and Enbody, R. Arbitrary Copy: Bypassing Buffer-Overflow Protections, EIT2006 (submitted)
- More.. (IEEE Micro, WDDD at ISCA)

Demo




```
int residentcode() {
  /* We are in trouble */
  execl("/bin/sh","/bin/sh",0x00);
}
int vulnerable(char **argv) {
  int x;
  char *ptr;
  char buffer[30];
  ptr=buffer;
  printf("ptr %p - before\n",ptr);
  strcpy(ptr,argv[1]);  /* overflow ptr */
  printf("ptr %p - after\n",ptr);
  strcpy(ptr,argv[2]);  /* overflow the
    target */
}
int main (int argc,char *argv[]) {
  printf("Sample program.\n");
  vulnerable(argv);
  printf("Program exits normally\n");
}
```

0x8048454

```
int main(int argc,char **argv) {
  int *iptr;
  char *buf1 = (char
    *)malloc(sizeof(char)*46);
  char buf2[5]="Addr";
  char **arr = (char **)malloc(sizeof(char
    *)*4);
  memset(buf1,'x',0x20);
  iptr=(int *) buf1;
  iptr+=(0x20 / sizeof(int));
/* printf entry in the GOT */
  *iptr=0x08049730;
  buf1[0x24]='\0';
/* address of residentcode() */
  iptr=(int *)buf2;
  *iptr=0x08048454;
/* arguments for execv() */
  arr[0]="./vul";  arr[1]=buf1;
    r[2]=buf2;  arr[3]='\0';
    :v(arr[0],arr);
```

Demo

- Mount a multi-stage buffer-overflow attacks in the emulator

Without Secure Bit2

```
$ ./wrapper
Sample program.
ptr 0xbffff960 - before
ptr 0x8049730 - after
sh-2.05b#
```

With Secure Bit2

```
$ ./wrapper
Sample program.
ptr 0xbffff960 - before
ptr 0x8049730 - after
Segmentation fault
```

Emulator Console

Questions?

- Thank you
- http://www.cp.eng.chula.ac.th/~krerk/sbit2/