FORMAL REASONING OF VARIOUS CATEGORIES OF WIDELY EXPLOITED SECURITY VULNERABILITIES USING POINTER TAINTEDNESS SEMANTICS1

Shuo Chen, Karthik Pattabiraman, Zbigniew Kalbarczyk and Ravi K. Iyer *Center for Reliable and High-Performance Computing, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, 1308 W. Main Street, Urbana, IL 61801. {shuochen , pattabir, kalbar, iyer}@crhc.uiuc.edu*

- Abstract: This paper is motivated by a low level analysis of various categories of severe security vulnerabilities, which indicates that a common characteristic of many classes of vulnerabilities is pointer taintedness. A pointer is said to be tainted if a user input can directly or indirectly be used as a pointer value. In order to reason about pointer taintedness, a memory model is needed. The main contribution of this paper is the formal definition of a memory model using equational logic, which is used to reason about pointer taintedness. The reasoning is applied to several library functions to extract security preconditions, which must be satisfied to eliminate the possibility of pointer taintedness. The results show that pointer taintedness analysis can expose different classes of security vulnerabilities, such as format string, heap corruption and buffer overflow vulnerabilities, leading us to believe that pointer taintedness provides a unifying perspective for reasoning about security vulnerabilities.
- Key words: Security Vulnerability, Static Analysis, Program Semantics, Equational Logic, Pointer Taintedness

¹ This work is supported in part by a grant from Motorola Inc. as part of Motorola Center for Communications, in part by MURI Grant N00014-01-1-0576, and in part by NSF CCR 00-86096 ITR.

1. INTRODUCTION

Programming flaws that result in security vulnerabilities are constantly discovered and exploited in real applications. A significant number of vulnerabilities are caused by improper use of library functions in programs. For example, omitting buffer size checking before calling string manipulation functions, such as *strcpy* and *strcat*, causes many buffer overflow vulnerabilities. Passing user input string as the format string in *printf*-like functions causes format string vulnerabilities. Heap corruption vulnerabilities are the result of invoking the *free* function with a pointer pointing to an overflowed buffer or a buffer that has not been allocated by the heap manager. Library functions are usually secure only under certain conditions, and therefore, formally extracting security conditions from library code can be a valuable aid in implementing applications free of security vulnerabilities.

We introduce the notion of pointer taintedness as a basis for reasoning about security vulnerabilities. The notion of pointer taintedness is based on the observation that the root cause of many reported vulnerabilities is due to the fact that a pointer value (including return address) can be derived directly or indirectly from user input. Since pointers are internal to applications, their values should be transparent to users. Thus a taintable pointer is a potential security vulnerability. By analyzing the application source code, the potential for pointers to be tainted can be determined and hence possible vulnerabilities can be identified.

Existing compiler-based techniques, such as CQUAL [7] and SPLINT [1], perform taintedness analysis by associating an attribute or a type qualifier with program symbols, i.e., variables, constants, arguments and return values. Although these techniques allow reasoning about taintedness of symbols, they cannot analyze the taintedness of pointers unless C statements explicitly perform the tainting. As we will show, there are many situations (e.g., format string vulnerabilities, heap corruptions and stack buffer overflows) where pointers become tainted without explicit assignment statements in the code. Pointer taintedness that leads to well known vulnerabilities usually occurs as a consequence of low level memory writes, typically hidden from the high level code. Hence a memory model is necessary to reason about pointer taintedness. This paper proposes a formalization to define and analyze pointer taintedness so as to uncover potential security vulnerabilities. We focus on commonly used library functions because many widely exploited vulnerabilities are caused by pointer taintedness occurring in library functions.

Formal Reasoning of Various Categories of Widely Exploited Security Vulnerabilities Using Pointer Taintedness Semantics 3

A memory model is formally defined in this paper using equational logic², which forms the basis of the semantics of pointer taintedness. A mechanical reasoning technique is applied to several library functions to examine the possibility of a pointer being tainted. The analysis process for each library function yields a set of formally specified preconditions that must be satisfied to eliminate the possibility of pointer taintedness. These pre-conditions either correspond to already known vulnerability scenarios (e.g., format string vulnerability and heap corruption) or indicate the possibility of function invocation scenarios that may expose new vulnerabilities.

2. RELATED WORK

Security vulnerabilities have been reported in many applications. The *Bugtraq* vulnerability list and *CERT* advisories maintain information about reported vulnerabilities. Security vulnerabilities can be modeled using finite state machines, by breaking them into multiple simple operations, each of which may be associated with one or more logical predicates [10].

Many static detection techniques have been developed based on the recognition of existing categories of security vulnerabilities. Techniques such as [1] and [2] can check security properties if vulnerability analysts are able to specify them as annotations in the code. Domain-specific techniques require less human effort, but each technique only detects a specific type of vulnerability. Static detection techniques are proposed to detect to buffer overflow vulnerabilities, e.g. [6]. Runtime mechanisms against security attacks have been introduced in [8] and [9]. Xu et. al. [5] recently proposed efficient approaches to randomize memory layout and to encode control flow information, which aims at defeating various attacks in a generic manner.

The notion of taintedness was first proposed in Perl language as a security feature. Inspired by this, static detection tools like SPLINT [1] and CQUAL [7] also use taintedness analysis to guarantee that user input data is never used as the format string argument in *printf*-like functions. In both these tools, taintedness is an attribute associated with C program symbols. A symbol gets tainted only if an explicit C statement passes a tainted value to it by assignment, argument passing or function return. As shown in the next section, in many real attacks, pointers are tainted without explicit C statements tainting program symbols. Since these tools do not have a memory model, they cannot determine whether an address is tainted and

² An introduction to equational logic can be found in [11].

hence cannot reason about the underlying memory status. In [12], several examples are provided where data can be tainted without being detected by SPLINT and CQUAL. The inability to reason about taintedness at the memory level is an inherent limitation of existing taintedness analysis tools.

3. POINTER TAINTEDNESS EXAMPLES

Our study indicates that many known security vulnerabilities, such as format string, heap corruption, buffer overflow and *Glibc glob* vulnerabilities, arise due to pointer taintedness. In these examples, the pointers become tainted without explicit C assignment statements. Due to space limitations, only the example of the format string vulnerability is discussed in detail. Other examples are described in the extended version of this paper [12]. In this section, we first give a high level description (Table 1) of the format string vulnerability, and show how it can be exploited. We then show that a memory model (Figure 1) is necessary for reasoning about pointer taintedness.

Table 1: Format String Vulnerability Illustration

1 aprel 1. Fullmat String Vallici applie must allow			
int Vfprintf (FILE $*$ s, const char	//This is how to call <i>Printf</i> correctly		
*format, va list ap)	strcpy(buf,"hello");		
char $*$ p;	$i = 1234.$		
int count;	Printf("string=%s\ndata=%d\n%n",buf,i,&j); L3:		
$p = format; $	Printf("total output length=%d\n",j);		
*(int *) ap = count; L1:			
	//This is how format string vulnerability occurs		
ን	scanf("%s",buf);		
	L4: Printf(buf);		
$L5$: Printf("\ni=%d\n",i); int Printf (const char *format,)			
va list arg; Contractor			
Vfprintf (stdout, format, arg); L2 :			
	Program Output:		
	O1 : string=hello		
	O2: $data = 1234$		
int i,j;	O3: total output length=23		
int main()	O4: 134514747123413451916812345		
char buf $[100]$;	O5: $i = 31$		

 $\frac{1}{2}$ The format string vulnerability is caused by incorrect invocation of *printf*-like functions (e.g., *printf, sprintf, snprintf, fprintf* and *syslog*). Table 1 gives examples of correct and incorrect invocations of *Printf()* (a simplified version of LibC *printf()* that we developed). This sample program produces five lines of output (shown in Table 1). Output lines O1 and O2 result from executing line L3 of the code: the string *buf* hosting "*hello*", and the integer *i* has the value 1234. In addition, line L3 uses the format directive *%n* to write the character count (i.e., the number of characters printed up to that point) into the address of the corresponding integer variable. In this case, the length of "*string=hello¶data=1234*¶" is 23, so *Printf()* writes 23 to the integer *j*.

This value is printed out in line O3 of the program output. The format string vulnerability is caused by incorrect invocation of *Printf* in line L4, which directly uses *buf* as the format string (the proper usage should be *Printf("%s", buf)*).

We now show how an attacker can exploit this vulnerability. Let's assume that the attacker wants to corrupt an arbitrary memory location (e.g., the global integer *i*). In order to do this, he/she constructs an input string *buf* as given below (observe that the beginning of the input string corresponds to the address of global integer *i*):

Figure 1. In *Vfprintf()*, there are two pointers: p is the pointer to sweep over The string is read by *scanf()* and passed to *Printf()*, which in turn, calls *Vfprintf()*. Just before Line L1 is executed, the stack layout is like the one in The string is read by *scanf()* and passed to *Printf()*, which in turn, calls the format string *buf* (from "\x78" to"%n"), and *ap* is the pointer to sweep over the arguments (starting from the 12-byte gap). The attacker deliberately embeds three "%d" directives in *buf* so that *ap* can consume the 12-byte gap and get to the word 0x08049978. A padding string "12345" follows the "%d" directives in order to adjust the character count. As we see in the program output line O4, the words in the 12-byte gap are printed as three integers followed by a padding string "12345". Eventually, when *p* arrives at the position of "%n" (i.e., the code line L1 is about to be executed), *ap* happens to arrive at the position of 0x08049978. Line L1 writes the character count *count* to the location pointed by **ap*. In this case, since the content in the location pointed by $*ap$ is the address of the integer i , the character count 31 is written to *i*. Note that this attack can overwrite any memory location, including locations containing return addresses or the global offset table of an application, which can result in the execution of the attacker's code.

6 *Shuo Chen, Karthik Pattabiraman, Zbigniew Kalbarczyk and Ravi K. Iyer*

We can view the above vulnerability as a consequence of pointer taintedness. In the above code (Table 1), the string *buf* is obtained from user input and is hence tainted (as indicated in Figure 1 as a grey area). When the pointer *ap* sweeps over the stack and points to *buf*, **ap* becomes tainted. *ap* is then dereferenced in Line L1, and the tainted value of **ap* is the target address of the write operation. This can lead to the corruption of an arbitrary memory location. Thus we see that pointer taintedness is the root cause of this vulnerability. Note that the pointer **ap* gets tainted because *ap* moves into the tainted memory locations, and there is no explicit assignment of a tainted value to **ap* in the C code. Hence a memory model is necessary to reason about the taintedness of **ap*. The next section defines the formal semantics of pointer taintedness using a memory model, and Section 5 shows how the semantics can be used to reason about security vulnerabilities in library functions.

4. SEMANTICS FOR POINTER TAINTEDNESS

Starting with the programming semantics of Goguen and Malcolm [3], this section proposes a formal semantics to reason about pointer taintedness in programs. The semantics proposed in [3] defines instructions, variables and expressions. We extend this semantics to include memory locations and addresses. Using the memory model, the notion of taintedness is incorporated into the semantics.

We define tainted data as: (1) data coming from input devices (e.g., by *scanf(), fscanf(), recv(), recvfrom()*), or (2) data copied or arithmetically calculated from tainted data. A tainted pointer is a pointer whose value (semantically equivalent to "data") is tainted. This definition can be formalized in equational logic using the Maude tool [4], which we used to reason about pointer taintedness.

In the semantics defined in [3], a *Store* represents the current state of all program variables. We extend this definition of a *Store* to be a snapshot of the entire memory state at a point in the program execution. The execution of a program instruction is defined as a function taking two arguments, a *Store* and an instruction, and producing another *Store*. There are two attributes associated with every memory location of a *Store*: *content* and *taintedness*. Accordingly, two operations, *fetch* and *location-taintedness*, are formally defined. The *fetch* operation Ftch(S,I) gives the content of the Ftch(S,I) gives the content of the *dness* operation $LocT(S,I)$ returns a content of the specified address is address I in store S; the *location-taintedness* operation $LocT(S,I)$ returns a value indicating whether the content of the specified address is Boolean value indicating whether the content of the specified address is tainted.

Formal Reasoning of Various Categories of Widely Exploited Security Vulnerabilities Using Pointer Taintedness Semantics 7

There is no notion of "variable" in this semantics. Any variable in a C program is mapped to a memory location addressed by the integer with the same name as the program variable. For example, the C program variable foo is mapped as a memory location addressed by the integer foo. We define
the \land operator to dereference an integer, i.e., to fetch the location addressed
by the integer. Note that the address (a.k.a., the left value) the \land operator to dereference an integer, i.e., to fetch the location addressed \sim operator to dereference an integer, i.e., to fetch the location addressed
he integer. Note that the address (a.k.a., the left value) of the C program
able foo is represented by the integer foo in the semantics; and t by the integer. Note that the address (a.k.a., the left value) of the C program variable foo is represented by the integer foo in the semantics; and the foo is represented by the integer foo in the semantics; and the a.k.a., the right value) of the C program variable foo is represented
b). The expressions in the semantics are arithmetic operators (e.g., \star) consetenting content (a.k.a., the right value) of the C program variable foo is represented
ic operators (e.g.,
ces. For example, by by (\land foo). The expressions in the semantics are arithmetic operators (e.g., +, - and \star) concatenating integers and integer dereferences. For example, expression 200+(\land foo) represents "200 plus the content of the +, - and *) concatenating integers and integer dereferences. For example, variable foo". Expression 200+foo represents "200 plus the address of the C
program variable foo".
We define two operations – *evaluation* and *expression-taintedness* – for
gyreggiang, head on the fatch and legation taint program variable foo".

foo".
5 oper
d on: We define two operations – *evaluation* and *expression-taintedness* – for expressions, based on the *fetch* and *location-taintedness* operations. The *evaluation* operation Eval(S,E) gives the result of evaluating the expression E
under store S; the *expression-taintedness* operation ExpT(S,E) indicates
whether expression E contains any data from a tainted location, e.g under store S; the *expression-taintedness* operation ExpT(S,E) indicates S; the *expression-taintedness* operation $ExpT(S,E)$ indicates ression E contains any data from a tainted location, e.g., $)+2$) indicates whether the expression (\sim foo $)+2$ contains any tainted location, which is equivalent whether expression E contains any data from a tainted location, e.g., licates whether the expression $(\uparrow$ foo $)$ +2 contains any ocation, which is equivalent to checking whether the located by foo is tainted. Thus neinten taintedness is !-*defined as a dereference of a tainted expression.* $pT(S, (\triangle foo)+2)$ indicates whether the expression $(\triangle foo)+2$ contains any
ta from a tainted location, which is equivalent to checking whether the
emory location addressed by foo is tainted. Thus *pointer taintedness is* data from a tainted location, which is equivalent to checking whether the memory location addressed by foo is tainted. Thus pointer taintedness is mory location addressed by foo is tainted. *Thus pointer taintedness is* ined as a dereference of a tainted expression.
Table 2 lists a set of axioms for the *evaluation* and *expression-*

taintedness operations, and gives examples of applying the equations.

Table 2: Axioms of *Evaluation* **and** *Expression-Taintedness* **Operations**

Lines 1-6 define how to evaluate an expression under store S. For S. For
er store example, line 1 indicates that the evaluation result of a constant I under store S is the constant I. Line 2 indicates that $Eval(S, \triangle E1)$ can be computed by first evaluating E1 under S, then applying *fetch* operation on the evaluation result.
The semantics of arithmetic operations are defined in Lines 3-6.
Lines 7-C define the *expression-taintedness* operator. Note that the
relati The semantics of arithmetic operations are defined in Lines 3-6.

Lines 7-C define the *expression-taintedness* operator. Note that the relationship between the *expression-taintedness* and *location-taintedness* operators is similar to the relationship between the *evaluation* and *fetch* operators. Line 7 indicates that an integer constant is not a tainted expression. Line 8 indicates that determining whether the expression \triangle E1 is AE1 is
by the
E1+E2
het the tainted is equivalent to checking whether the location addressed by the evaluation result of $E1$ is tainted. Line B indicates that the expression $E1+E2$ E1 is tainted. Line B indicates that the expression $E1+E2$
1 or E2 is tainted. The example of Line C shows that the
2 is tainted if and only if the location pointed to by foc is tainted if either E1 or E2 is tainted. The example of Line C shows that the E1 or E2 is tainted. The example of Line C shows that the $+$ 2 is tainted if and only if the location pointed to by foo
g to the equation in Lines 7 and 8. expression $(^{6}$ foo) + 2 is tainted if and only if the location pointed to by foot is tainted, according to the equation in Lines 7 and 8.

Table 3: Semantics of Statements

Statement Semantics is tainted, according to the equation in Lines 7 and 8.

Table 3: Semantics of Statements

- 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 2008 - 200 $\frac{\text{se } P2 \text{ H}}{\text{hile } T \text{ do } P}$
Table 3
atements.
atements.
atements.
in anguage atements.
at cannot
assemble 4
Figure 3
Figure 4
Figure 4
Figure 4
Figure 4
Figure 4
Figure 4
Figure 5
Figure 5
Figure 5
Figure 5
Figure 5
Fi of If the condition T is true, execute P, repeat until T is false

B gives the informal semantics of a subset of the sup

Their formal semantics are similar to the specifications gives sufficient to analyze a wide variety pove in all in rn ics ent she divided and all the set of $\frac{E1}{1}$ and $\frac{1}{1}$ dhence are a set of $\frac{1}{1}$ and $\frac{1}{1}$ denotes a set of $\frac{1}{1}$ and $\frac{1}{1}$ If the condition T is true, Execute P1

otherwise execute P2

If the condition T is true, Execute P1

If the condition T is true, execute P₁ repeat until T is false

the informal semantics of a subset of the supported
 else P2 fi

while T do F

Table

statements

[3], and ar

C languag

statements

semantics.

exit canno

these also.

Formal

fairly strain

fairly strain

in Table 4

(LocT) oper

1

Tech((LocT) complex

1

Tech((LocT) Co
otherwise execute P2

If the condition T is true, execute P,

the informal semantics of a

formal semantics are similar to tl

ent to analyze a wide variety of

ever, they are not sufficient to

cample, the program counte If the condition T is the

the informal sem

formal semantics and

the informal semantics and

tever, they are not

cample, the prograr

in C statements, su

deled, but it is rela

cations of stateme

ard. Axioms definin
 Table 3 gives the informal semantics of a subset of the supprest
atements. Their formal semantics are similar to the specifications given

[3], and are sufficient to analyze a wide variety of program constructs

C languag Table 3 gives the informal semantics of a subset of the supported statements. Their formal semantics are similar to the specifications given in [3], and are sufficient to analyze a wide variety of program constructs in the C language. However, they are not sufficient to faithfully model all C statements. For example, the program counter has not been defined in the semantics. So certain C statements, such as goto, break, continue, return and exit cannot be modeled, but it is relatively easy to extend the semantics for these also. these also.

)-fairly straightforward. Axioms defining it cannot be modeled, but it is relatively easy to extend the semantics for ese also.
Formal specifications of statements other than the mov statement are enrify straightforward. Axioms defining mov statement semantics are mov statement semantics are shown
 etch (Ftch) and *location-taintedness*

nstruction on store S. in Table 4. The goal is to define the *fetch* (Ftch) and *location-taintedness*

 $\frac{1}{2}$ 3 4 $\frac{1}{2}$ in (, in figure 34 in ('in fide de $\frac{4}{\text{ln}}$ in (C $\frac{1}{\text{ln}}$ for $\frac{1}{\text{ln}}$ e $\frac{1}{2}$ in (; in f(; in f(; in t) Ftch((S ; m
Ftch((S ; m
LocT((S ; m
LocT((S ; n
he semico
netion on pv[E1]<-E
ates that i:
ing the loc
valuation
ssion E1 $\frac{\log |E_1|}{\log |E_2|}$
a store,
2) is the s
f the expration X1
result of
does not E2),X1) = Eval(S,E2) if (Eval(S,E1) is X1) .

E2),X1) = Ftch(S,X1) if not (Eval(S,E1) is X1) .

E2),X1) = ExpT(S,E2) if (Eval(S,E1) is X1)

E2),X1) = LocT(S,X1) if not (Eval(S,E1) is X1)

tor in our notation represents th Ftch((S; m
LocT((S; n
LocT((S; n
he semico
nction on
ov[E1]<-E
ates that i:
ing the loc
valuation
ssion E1 lon opera

a store,

2) is the s

2) is the expr

the expr

ation X1

result of

does not E2),X1) = Ftch(S,X1) if not (Eval(S,E1) is X1).

F2),X1) = ExpT(S,E2) if (Eval(S,E1) is X1).

F2),X1) = LocT(S,X1) if not (Eval(S,E1) is X1).

tor in our notation represents the execution which results in a new store. For LocT((S ; m

LocT((S ; m

he semicol

iction on
 $\text{ov}[E1] < E$

ates that if

ing the loc

valuation

ssion E1 a store,

2) is the s

the expression X1 a

result of

does not E2),X1) = ExpT(S,E2) if (Eval(S,E1) is X1) .
E2),X1) = LocT(S,X1) if not (Eval(S,E1) is X1) .
E2),X1) = LocT(S,X1) if not (Eval(S,E1) is X
tor in our notation represents the execution of results in a new store. For
ore af LocT((S ; m
he semicol
iction on
 ∞ [E1]<-E2
ates that if
ing the loc
valuation
ssion E1 2) is the s
the expression X1 a
result of
does not E2),X1) = LocT(S,X1) if not (Eval(S,E1) is X1).

tor in our notation represents the executio

which results in a new store. For (

fore after executing mov[E1]<-E2 on store s

ession E1 evaluates to X1 under store S, the
 The semicolon operator in our notation represents the execution of an instruction on a store, which results in a new store. For example, $(S; mov[E1] < -E2)$ is the store after executing $mov[E1] < -E2$ on store S. Line 1 indicates that if the expression E1 evaluates to X1 under store S, then when E1 evaluates to X1 under store S, then when
recuting the instruction $\text{mov}[E1] < E2$, we get
nder store S. Line 2 indicates that if the fetching the location X1 after executing the instruction $\text{mov}[E1] < -E2$, we get
t of E2 under store S. Line 2 indicates that if the
not evaluate to X1 under S, then when fetching the the evaluation result of E2 under store S. Line 2 indicates that if the evaluate to $X1$ under S, then when fetching the expression E1 does not evaluate to X1 under S, then when fetching the
 location X1 after executing the instruction mov[E1]<-E2, we still get the X1 after executing the instruction $\text{mov}[E1] < -E2$, we still get the
n the location X1 under S (i.e., before executing the instruction
 \lt -E2). Similarly, the LocT operation is defined for mov statement in content in the location X1 under S (i.e., before executing the instruction X1 under S (i.e., before executing the instruction y , the LocT operation is defined for mov statement in mov[E1] \le -E2). Similarly, the LocT operation is defined for mov statement in Lines 3 and 4. Lines 3 and 4.

5. FORMAL REASONING ON POINTER TAINTEDNESS VIOLATIONS

This section presents pointer taintedness analysis for three common library functions based on the defined semantics, and extracts their associated security preconditions. The analysis identifies several known vulnerabilities, such as format string, buffer overflow and heap corruption vulnerabilities, thereby showing that pointer taintedness based reasoning is able to unify different kinds of vulnerabilities.

Our experience suggests that statements needing critical examination for pointer taintedness are typically indirect writes, where a pointer points to a target address to be written, e.g., the pointer p in $\ast p =$ foo and p in * p = foo and
ts is important because
itedness violations. For memcpy(p,foo,10). Checking indirect write statements is important because
these statements can result in two types of pointer taintedness violations. For
example, in the statement *p = foo, (1) if the value of p is tainte these statements can result in two types of pointer taintedness violations. For example, in the statement *p = foo, (1) if the value of p is tainted, then data *p = foo, (1) if the value of p is tainted, then data
nemory location; (2) if p is a pointer to a buffer but
e the buffer, then the statement *p = foo can taint foo can be written to any memory location; (2) if p is a pointer to a buffer but
points to a location outside the buffer, then the statement $*p = foo$ can taint
the memory location p points to, which may be a location of points to a location outside the buffer, then the statement $*p = foo can taint$
cation of a return the memory location p points to, which may be a location of a return address, a function frame pointer or another pointer. address, a function frame pointer or another pointer.

5.1 Analysis of *strcpy()*

A simple but interesting example is *strcpy(),* which copies a NULLterminated source string to a destination buffer. The string manipulation functions, including *strcpy()*, *strcat()* and *sprintf()*, are known to cause a significant number of buffer overflow vulnerabilities. Our formal reasoning extracts security preconditions from the implementation of *strcpy()*. The source code of *strcpy()* and its formal representation are given in Table 5.

As the only indirect write operations in the source code are in Line 1 and Line 2, it is enough to prove the three theorems listed in Table 6. We assume that the NULL-terminator (i.e., the character \Im) of the source string src is src is
size
dst is
...ffor at the location at the location ($src + srclen$), and that the size of the buffer dst is dstsize.
Theorem NV1 ensures that before Line L1, the content of the variable dst is
not tainted; Theorem NV2 ensures that for any address A outside the buf Theorem NV1 ensures that before Line L1, the content of the variable dst is dst is
puffer
L1 is A outside the buffer

1 A after Line L1 is st (from dst to dst+dstsize), the taintedness of location A after Line L1 is
 $\frac{1}{2}$

same as the taintedness of location A before Line L0. NV3 is similar to NV1,
but proves the property for the memory state before Line L2 is executed.
Table 5: Source Code and Formal Semantics of *strepy()*
char * strepy (but proves the property for the memory state before Line L2 is executed.

 $*$ dst=0;
 $*$ dst=0;
 $*$ dst=0;
 $*$ orem NV1:
 α orem NV2:
 $A \in INT \bullet$
orem NV3:
 $Table 7 g$
 \rangle ving the tl
ause of the manipu
 N page α
and dst are manipu
and dst are y occur wing the f
 α rable 7: S
initially, the $\frac{40}{100}$
 Theorem NV1:

Theorem NV2:
 $\forall A \in INT$

Theorem NV3:

Table 7 g

Table 7 g

proving the 1

because of t

string manip

MAN page c

src and dst a

may occur v

causing the discussed in

Table 7: 9

1. Initially, the

2. The For Sovem NV1: If S

or MV2: If S

or MV2: If S
 $A \in INT \bullet A$

Loo

or MV3: If S
 \Box

Table 7 gives

ving the theor

ause of the l

ng manipulati

N page of *str*

and dst and is

y occur wher

sing the func

y occur wher
 $\frac{1}{2}$: mov

1.2: mov

1, then

1, then

1, then

1, then

1, then

1, then

2, dst+

2, then

mditions

recondit

overflow

tes the section 6.

tes the section 6.

tes the cobe

cobe [$^{\wedge}$ dst] < - 0

tion *strepy()*

is the store a

dstsize) ≤ A

extracted in

extracted in

extracted in

vulnerabil

vulnerabil

2. Violation

location of c

2. Violation of wered by th L2: mov

if or Fund

1, then

0, and S2

30, ^dst-

2, then

mditions

recondit

overflow

tes the section 6.

tes the section 6.

tes the validity

overflow

tes the section 6.

tes the validity $\begin{bmatrix} \wedge & \text{dst} \end{bmatrix}$
 \therefore is the stor-
 \therefore is the stor-
 \therefore is the stor-
 \therefore dstsize) \leq
 \therefore extracted

ions, Con
 \vee vulneral

been docu

cenario of

2. Violati-

location of

vered by

y of Theore e for Fund
1, then
0, and S2
50, ^dst+
2, then
multions
reconditions
reconditions
already
tes the section 6.
tes the section 6.
tes the validitions $\frac{1}{2}$
 $\frac{1}{2}$ is the stort
 $\frac{1}{2}$
 $\begin{array}{c}\n 0. \\
 \hline\n 0. \\
 \hline\n \end{array}$
 $\begin{array}{c}\n 2 \text{ of the right,} \\
 4 \text{ of the right,} \\
 3 \text{ of the right,} \\
 4 \text{ of the right,} \\
 5 \text{ of the right,} \\
 6 \text{ of the right,} \\
 7 \text{ of the right,} \\
 8 \text{ of the right,} \\
 1 \$ L2: mov
 $\frac{1}{2}$ for Fun
 $\frac{1}{2}$, then
 $\frac{1}{2}$
 $\frac{1}{2}$, then
 $\frac{1}{2}$
 $\frac{1}{2}$, then
 $\frac{1}{2}$
 $\frac{1}{2}$
 $\frac{1}{2}$
 $\$ 1, ther
0, and
50, ^d:
2, ther
mditio
recon
overflalread
tes the ction
tes the Vali
such
such S2 is the stol

st+dstsize) \leq

ns extracted

ms extracted

ditions, Con

ow vulnera

y been docu

e scenario o

6.2. Violati

e location

covered by

dity of Theore

a way that the e a

a

e a

in diti

bili ume

f o on

the

<u>e b</u>

the $\forall A \in$
Theorem
Tabl proving
because string n
MAN p
src and may oc
causing
discusse
Table 1.
Initial
2. The b
3. The b
locati
4. srclen NV1: If S1 is the store before Line L1, then

LocT(S1,dst) = false

NV2: If S0 is the store before Line L0, and

INT • A < Eval(S0, ^dst) or Eval(S0, ^ds

LocT(S2,A) = LocT(S0, A)

NV3: If S3 is the store before Line L2, LocT(S1,dst) = false

0 is the store before
 \lt Eval(S0, \land dst) or
 $cT(S2,A) = LocT(S0,$
 3 is the store before
 $LocT(S3,dst) = false$

s a set of security

rems. Among the 1

large number of b

ion. This condition 2 i

is examined Theorem

Tabl

proving

because string n

MAN p

src and

may oc

causing

discusse

Tabl

1. Initial

1. Initial

3. The b

locati

4. srclen

5. NV2: If S0 is the store before Line L0, and S2 is the store after Line L1,
 $A \le Eval(SO, \text{ ^3dS})$ or Eval(S0, ^dst+dstsize) $\le A \le$

LocT(S2,A) = LocT(S0, A)

NV3: If S3 is the store before Line L2, then

LocT(S2,As) = LocT(\forall A \in INT • A \le Eval(S0, \land dst) or Eval(S0, \land dst+dstsize) \le A =>

Ineorem NV3: If S3 is the store before Line L2, then
 $\text{LocT(S3,dst)} = \text{I} \cdot \text{B}$ and $\text{LocT(S3,dst)} = \text{false}$

Table 7 gives a set of security pr LocT(S2,A) = LocT(S0, A)
Theorem NV3: If S3 is the store before Lin
LocT(S3,dst) = false
Table 7 gives a set of security pre-
proving the theorems. Among the fou-
because of the large number of buffi
string manipulation. proving
because
string n
MAN p
src and
may oc
causing
discusse
Table 1
1. Initial
2. The b
locati
4. srclen
5.2
We NV3: If S3 is the store before Line L2, then
 $\text{LocT(S3,dst)} = \text{false}$
 $\text{C} \neq \text{C}$ is executive precondition

the theorems. Among the four precond

of the large number of buffer overfluanipulation. This condition has alrea LocT(S3, dst) = false

s a set of security

rems. Among the

large number of t

ion. This condition
 rcpy. Condition 2

is examined furthe

n a program miss

tion frame of *str*

tion 6.1.

attion of dst is not ta

and Table 7 gives a set of security preconditions extracted in the process of proving the theorems. Among the four preconditions, Condition 4 is known because of the large number of buffer overflow vulnerabilities caused by string manipulation. This condition has already been documented on Linux MAN page of *strcpy*. Condition 2 indicates the scenario of overlap between src and dst and is examined further in Section 6.2. Violation of Condition 3 may occur when a program miscalculates the location of a stack buffer, causing the function frame of *strcpy()* to be covered by the buffer and may occur when a program miscalculates the location of a stack buffer, causing the function frame of *strcpy()* to be covered by the buffer and is discussed in Section 6.1.

Table 7: Sufficient Conditions to Ensure the Validity of Theorems NV1 – NV3

4. srclen < dstsize

5.2 Analysis of *Free()*

2. The buffers src and dst do not overlap in
the NULL-terminator of the src string.
3. The buffer dst does not cover the functior
locations &dst, &src and &res.
4. srclen < dstsize
5.2 Analysis of $Free()$
We implemented a bi the NULL-terminator of the src string.

3. The buffer dst does not cover the function frame of *strcpy()*, which consists of the

1. srclen < dstsize

4. srclen < dstsize

5.2 **Analysis of** *Free()*

We implemented a bina F
 P
 $\text{P$ does not cover the func

&src and &res.

 ysis of *Free()*

ented a binary buddy

() and *Free()*. The me

ock. The binary buddy

memory block Free

ddy block is also free

eedBlock and BuddyBl 5.2 **Analysis of** *Free()*
We implemented a binary buddy heap
function $Malloc()$ and $Free()$. The memory bl
pointer FreedBlock. The binary buddy heap 1
the deallocated memory block FreedBlock
block if the buddy block is also fre managed to be distributed to be on the struct: Example 1

Seprement system including

b be freed is pointed to by

ement algorithm requires

emerged with its buddy

BuddyBlock points to the

s of type HEAP_BLOCK as Solved the Subset of Stream Contracts Street

2. **Analysis of Free**

2. **Analysis of Free**

2. **Analysis of Free**

2. The interpret of the binary

deallocated memory block

ck if the buddy block is alsuldy block. FreedBloc **EXECUTE:**
2 **Anal**
We impleme
notion *Malloci*
inter FreedBlo
ek if the bud
ddy block. Free We implemented a binary buddy heap management system including function *Malloc()* and *Free()*. The memory block to be freed is pointed to by pointer FreedBlock. The binary buddy heap management algorithm requires $\frac{\text{mod}}{\text{mod}}$ Block. The binary buddy heap management algorithm requires
ed memory block FreedBlock to be merged with its buddy
puddy block is also free. The pointer BuddyBlock points to the
FreedBlock and BuddyBlock are structs of time the deallocated memory block FreedBlock to be merged with its buddy $($ Block to be merged with its buddy
The pointer BuddyBlock points to the
ock are structs of type HEAP_BLOCK as block if the buddy block is also free. The pointer BuddyBlock points to the buddy block. FreedBlock and BuddyBlock are structs of type HEAP_BLOCK as buddy block. FreedBlock and BuddyBlock are structs of type HEAP_BLOCK as buddy block.

Formal Reasoning of Various Categories of Widely Exploited Security Vulnerabilities Using Pointer Taintedness Semantics 11

shown in Table 8. The Size field indicates the size of the memory chunk. The Size field indicates the size of the memory chunk. The nether the memory chunk is free. Fields Fwd and Bak a doubly-link list of free memory chunks. busy field indicates whether the memory chunk is free. Fields Fwd
are pointers to maintain a doubly-link list of free memory chunks.
Table 8: Indirect Write Statements in Free() Source Code
typedef struct. HEAP BLOCK { and :#* are pointers to maintain a doubly-link list of free memory chunks.

Table 8: Indirect Write Statements in *Free()* **Source Code**

Form int Size; $\frac{1}{\pi}$ int Busy; $\frac{1}{\pi}$ int Busy; $\frac{1}{\pi}$ int Busy; $\frac{1}{\pi}$ HEAP_BLOCK * Fwd, $\frac{1}{2}$ HEAP_BLOCK;
There are three lines in rations are performed. Si:
luding FreedBlock, Buddyl
ldyBlock->Fwd int Size; // The size of the block.

int Busy; // Is this block busy?

struct_HEAP_BLOCK * Fwd,* Bak; // List to the

<u>}</u> HEAP_BLOCK;

There are three lines in the *Free()* func

rations are performed. Six pointers are ir struct_HEAP_BLOCK * Fwd,* Bak; // List to tleater_BLOCK;

There are three lines in the *Free()* functions are performed. Six pointers are

uuding FreedBlock, BuddyBlock, FreedBld

ldyBlock->Fwd and BuddyBlock->Bak. Table
 rations are performed. Six pointers are involved in the ope

uding FreedBlock, BuddyBlock, FreedBlock->Fwd, FreedBlock

ddyBlock->Fwd and BuddyBlock->Bak. Table 9 states the theorer

ved for conditions guaranteeing that p t writer
t writer
t and to l. It
is none
the secifier of the second
the secifier of the call
and the call
and the call
and the call There are the
There are thermations are pluding FreedHdyBlock->Fwd
IdyBlock->Fwd
wed for cond umed that the offse six pointers is
six pointers is
TICS, (^FreedB
DTCS, ^((^FreedB
DTCS, ^((^FreedB
DTCS, ^((^FreedB
DTCS, ^((^ There are three lines in the *Free()* function where indirect write operations are performed. Six pointers are involved in the operations, including FreedBlock, BuddyBlock, FreedBlock->Fwd, FreedBlock->Bak assumed that the offset of the Fwd field in the HEAP_BLOCK structure is 2, and that the offset of the Bak field is 3. Theorem NV1 ensures that none of the six pointers is tainted before executing any indirect writes. Block, BuddyBlock, FreedBlock->Fwd, FreedBlock->Bak, d and BuddyBlock->Bak. Table 9 states the theorem to be ditions guaranteeing that pointers are not tainted. It is BuddyBlock->Fwd and BuddyBlock->Bak. Table 9 states the theorem to be
proved for conditions guaranteeing that pointers are not tainted. It is
assumed that the offset of the Pak field in the HEAP_BLOCK structure is 2,
and assumed that the offset of the 'Wall field in the 'Hall's $\frac{1}{2}$ and that the offset of the Bak field is 3. Theorem NV1 ensures that none of the six pointers is tainted before executing any indirect writes.
Table 9: Th BuddyBlock->Fwd and BuddyBlock->Bak. Table 9 states the theorem to be proved for conditions guaranteeing that pointers are not tainted. It is the six pointers is tainted before executing any indirect writes.

A **Table 9: Theorems to Prove for Function** *Free()*

 $ExpT(S)$
ExpT(S
ExpT(S
ExpT(S
Conditi
the condition
the conditional dilustra
and 4
illustra
2. Immerical dilustra
3. Immerical dilustra
4. All freed NV1: If S is the store before executing the indirect writes, then $(\wedge$ FreedBlock) = false and $|/|F{\text{read}}|00\kappa|s$ is not tain $(\wedge$ FreedBlock) + 2)) = false and $|/|F{\text{read}}|00\kappa|s$ is not tain $(\wedge$ FreedBlock) + 2)) = ExpT(S, (\land FreedBlock)) = false and

ExpT(S, (\land BuddyBlock)) = false and

ExpT(S, \land ((\land FreedBlock) + 2)) = false

ExpT(S, \land ((\land FreedBlock) + 3)) = fals

ExpT(S, \land ((\land BuddyBlock) + 2)) = fals

ExpT(S ExpT(S, (\wedge BuddyBlock)) = false and

ExpT(S, \wedge ((\wedge FreedBlock) + 2)) = false

ExpT(S, \wedge ((\wedge FreedBlock) + 3)) = false

ExpT(S, \wedge ((\wedge BuddyBlock) + 2)) = false

ExpT(S, \wedge ((\wedge BuddyBlock) + 3) ExpT(S, $\land ((\land$ FreedBlock) + 2)) = false and

ExpT(S, $\land ((\land$ FreedBlock) + 3)) = false and

ExpT(S, $\land ((\land$ BuddyBlock) + 2)) = false and

ExpT(S, $\land ((\land$ BuddyBlock) + 3)) = false

The process of proving the theorems
 ExpT(S, $\land ((\land$ FreedBlock) + 3)) = false and

ExpT(S, $\land ((\land$ BuddyBlock) + 2)) = false and

ExpT(S, $\land ((\land$ BuddyBlock) + 3)) = false

The process of proving the theorems

conditions that guarantee the validity of

the ExpT(S, $\land ((\land$ BuddyBlock) + 2)) = false and

ExpT(S, $\land ((\land$ BuddyBlock) + 3)) = false

The process of proving the theorems of

conditions that guarantee the validity of

the conditions. The function *Free()* is

functi ExpT(S, $\wedge ((\wedge$ BuddyBlock) + 3)) = false

The process of proving the theorer

conditions that guarantee the validity

the conditions. The function *Free()*

function can guarantee these condi

unlikely to occur, and th The The Unit of the heap range, i.e., no Fwd ble-linked Julin Heap range of the block in the Vio The The Search is not tain

The Mandal Search is not tain

Tracted a set of formally spectrum

Tracted a set of formally spectrum ThuadyBlock
Tracted a set
racted a set
fe to be ca
Violations
for conditions
for conditions
for conditions
for conditions
the Validity of
mory range
k points to a l
and Bak
he heap range
ble-linked list
in any free-ch
d in >Bak is not tainted

>>Fwd is not tainted

>>Fwd is not tainted

of formally specii

.. Table 10 descri

lled when the ca

of condition 1

on 7. Violations

lations of conditic

rability. An exam

on 6.3.

f Theorem NV1

o racted a set

neorem NV

fe to be ca

Violations

for conditions

for conditions

for conditions

for conditions

for the Validity

of the Validity

mory range

k points to a l

wd and Bak

he heap rang

ble-linked list

i ->Fwd is not tainte
->Bak is not tainted
->Bak is not tainted
of formally speci
1. Table 10 descr
lled when the case
of condition 1
on 7. Violations
lations of condition
rability. An example 1.
5.3.
<u>f Theorem NV1</u>
of the neorem NV1
fe to be cal
Violations
for conditions, and viol
rflow vulner
ted in Sectic
the Validity of
mory range of
k points to a k
wd and Bak
he heap rang
ble-linked list
in any free-ch
d in a free-ch! >Bak is not tainted
of formally specif
of formally specif
and the cal of condition 1
on 7. Violations
ations of condition
ability. An exam
on 6.3.
Theorem NV1
of the current funct
ocation on the heap
links of the block
e, fe to be cal
Violations
for conditions, and viol
rflow vulner
ted in Sections
the Validity of
mory range of
k points to a k
wd and Bak
he heap rang
ble-linked list
in any free-ch
d in a free-ch! of formally specif

. Table 10 descri

led when the ca

of condition 1

on 7. Violations

ations of condition

rability. An exam

on 6.3.

<u>Theorem NV1</u>

of the current func

pocation on the heap

links of the block

e, i. The process of proving the theorems extracted a set of formally specified conditions that guarantee the validity of Theorem NV1. Table 10 describes the conditions. The function *Free()* is safe to be called when the caller function can guarantee these conditions. Violations of condition 1 are unlikely to occur, and the same is true for condition 7. Violations of condition 6 cause the classic double-free errors, and violations of condition 3 and 4 lead to the popular heap buffer overflow vulnerability. An example illustrating violation of condition 2 is presented in Section 6.3.

Table 10: Sufficient Conditions to Ensure the Validity of Theorem NV1

-
- 2. Immediately before *Free()* is called, FreedBlock points to a location on the heap.
3. Immediately before *Free()* is called, the Fwd and Bak links of the block of
- FreedBlock are not tainted.
- 3. Immed
FreedE
4. All free
5. No Fw
5. No Fw
6. Before
7. If Bude natioc
Pointing
Dinting *Fri*
Aly<u>B</u> ely berore *rree()* is called, the l
k are not tainted.
So the set of tainted.
So the set of the bear within
the star of the bear of the bear.
FBak pointers in any free-chunk doined
bee() is called, FreedBlock is not linke
points to a location on the heap.

I and Bak links of the block of

I heap range, i.e., no Fwd or Bak

a-linked list are tainted.

In any free-chunk list.

in a free-chunk double-linked list. ediately before Frediately before Frediately before Frediately before
dBlock are not taine-chunk double
points to any loc
wd or Bak pointe
re Free() is called
ddyBlock is free, 4. All lin
5. Nc
5. Nc
6. Be
7. If r
ks
fo
<u>Bu</u> ediately before *Free*
ediately before *Free*
dBlock are not taint
ree-chunk double-li
points to any locat
wd or Bak pointers
re *Free()* is called,
ddyBlock is free, the by scalicy, receivours forms to a botation in the heap $P(\theta)$ is called, the Fwd and Bak links of the block
head lists are within the heap range, i.e., no Fwd or B
and.
and.
may free-chunk double-linked list are tainted.
 dBlock are not taintere-chunk double-lin
points to any locatic
wd or Bak pointers is
re *Free()* is called, Fi
ddyBlock is free, the The lists are within the heap range, i.e., no Fwd or Bak

al. any free-chunk double-linked list are tainted.

any free-chunk double-linked list are tainted.

BuddyBlock is inked in any free-chunk list.

BuddyBlock is linke All free-chunk double-linke
All free-chunk double-linke
links points to any location
No Fwd or Bak pointers in a
Before *Free()* is called, Free
If BuddyBlock is free, then tion outside the heap.

is in any free-chunk double-linked list are tainted.

FreedBlock is not linked in any free-chunk list.

hen BuddyBlock is linked in a free-chunk double-linked list.

hen BuddyBlock is linked in a fr
- # , ks
| F
BL
BL No Fwd or Bak pointers in any free-chunk do
No Fwd or Bak pointers in any free-chunk do
Before *Free()* is called, FreedBlock is not link
If BuddyBlock is free, then BuddyBlock is link
-
- 6. Before /
7. If Buddy *ree()* is called,
Block is free, t any free-chunk list.

any free-chunk list.

a free-chunk double- I , I , o. Berore *Tree*
7. If BuddyBlo α is called, in the linked in any receiver is not imide in any receiver is not imide in a free-check is free, then BuddyBlock is linked in a free-check is free. F ,

5.3 Analysis of *Printf()*

We implemented a function *Printf()*, similar to the LibC function *printf()*, except that *Printf()* calls its child function *Vfprintf()*, which is a simplified version of LibC function *vfprintf()*. *Vfprintf()* implements the format directives *%%*, *%d*, *%s* and *%n*. The total length of *Vfprintf()* is 55 lines. Pointer p is used to sweep over the format string format. The argument list is p is used to sweep over the format string format. The argument list is
ver by pointer ap.
c are only two lines of indirect write operations in the function
 (11) . Line L1 is to get the lest digit of data and gave it in t swept over by pointer ap.

ap.
70 l
.buf There are only two lines of indirect write operations in the function (Table 11). Line L1 is to get the last digit of data and save it in the nth argument list pointer pointing to the current argument. ata and save it in the nth
the character count to the
ent. Note that ap is the position of the buffer buf. Line L2 is to assign the character count to the memory location pointed by the current argument. Note that ap is the argument list pointer pointing to the current argument. memory location pointed by the current argument. Note that mory location pointed by the current argument. Note that ap is the ument list pointer pointing to the current argument.
Corresponding to the two indirect write operations, we need to prove the

theorems given in Table 12. Theorem NV1A ensures that before executing code in Line L1, the memory location containing the variable n is not tainted. Theorem NV1B ensures that after Line L1, the memory location buf+10 is not tainted. Theorem NV1A and NV1B can be easily proved by
the theorem prover. Theorem NV2 ensures that before Line L2, the
expression ($\land \land$ ap) is not tainted, i.e., the memory location pointed by $(\land$
and is the theorem prover. Theorem NV2 ensures that before Line L2, the expression ($\land \land$ ap) is not tainted, i.e., the memory location pointed by (\land ap) is not tainted, i.e., the memory location pointed by the content of ap) is not tainted, i.e., the memory location pointed by the content of variable ap is not tainted. The preconditions extracted in the process of proving Theorem NV2 are given in Table 13.
Table 11: Indicate Write Statemen variable ap is not tainted. The preconditions extracted in the process of
proving Theorem NV2 are given in Table 13.
Table 11: Indirect Write Statements in *Vfprintf()* Source Code proving Theorem NV2 are given in Table 13.

Table 11: Indirect Write Statements in *Vfprintf()* **Source Code**

Table 12: Theorems Need to Prove for *Vfprintf()*

Table 13: Sufficient Conditions to Ensure the Validity of Theorem NV2

-
- 3. Suppose the memory segment that ap sweeps over is called ap activitiv range,
- no locations within ap_activitiy_range are tainted before Vfprintf() is called. 4. *ap never points to any location within

Theorem

Table 13

ver poin

iever poin

iever poin

iever poin

four co

ee that

of *Vfpr*

13). As

in the a ExpT(S1,(\land n)) = false
is the store after executocT(S2,(buf + 10)) =
ite store after executocT(S2,(buf + 10)) =
ite store before executoc
ExpT(S3, ($\land \land$ ap)) = f
on multions to Ensure the burnel burnel and the curren Table 13
ever poin
ever poin
ose the
ocations
four compared that
of *Vfpr*
13). As
in the a NV1B: If S2 is the store after executing Line L1, then

LocT(S2,(buf + 10)) = false

NV2: If S3 is the store before executing Line L2, then

ExpT(S3, (^ ^ ap)) = false

Sufficient Conditions to Ensure the Validity of Theo LocT(S2,(buf + 10)) = false
the store before executing l
ExpT(S3, (^ ^ ap)) = false
multions to Ensure the Validition
within the current functiation of variable ap, i.e., *ap
nent that ap sweeps over is
tivitiy_range are ever poin
hever poin
ose the
ocations
hever point
four compared to the *Vfpr*
13). As
in the a NV2: If S3 is the store before executing Line L2, then

ExpT(S3, (^ ^ ap)) = false
 $\text{Sufficient Conditions to Ensure the Validity of Theorem}$
 $\text{F. Sufficient Conditions to Ensure the Validity of Theorem}$
 $\text{F. Sufficient Conditions to the location of variable ap, i.e., } \pi ap != \& ap.$
 $\text{memory segment that ap sweeps over is called } ap_a$
 $\text{with in } ap_a \text{zityity, range are tained before } \text{Wiprintf()}$
 $\text{in this } ap_a \$ ExpT(S3, ($\land \land$ ap)) = false

onditions to Ensure the Vali

tion within the current fund

ation of variable ap, i.e., *a

ment that ap sweeps over

tivitiy_range are tainted be

cation within ap_activitiy_ra

m a set of The big and the same points to any location within ap_activity_range at $\frac{4}{1}$. *ap never points to any location within ap_activity_range.
The four conditions form a set of sufficient conditions, guarantee that there i *ant* white
white intitiaties 3. Suppose the memory segment that ap sweeps over is called . no locations within $ap_activity_range$ are tainted before *Vfprin*, 4 , $*ap$ never points to any location within $ap_activity_range$. The four conditions form a set of sufficient co 3. Suppose the m
no locations w
 $\frac{4}{1}$. *ap never point
The four con
guarantee that
version of *Vfpri*
(Table 13). As il
located in the ac dit
he
utf(lus
tiv ions form
re is nc
). Forma
strated in
ity range Example are tainted before *Viprintf()* is
 Witiy_range are tainted before *Viprintf()* is

1 a set of sufficient conditions, which is

pointer taintedness situation in the

t string vulnerabilities do not satisfy of

F ! The beatiens when $\frac{dP}{dP}$ and $\frac{dP}{dP}$ are ap never points to any locations form antee that there is not ion of *Vfprintf()*. Formal point 13). As illustrated in the activity range ap activity range.
ap activity range.
sufficient conditions, which
taintedness situation is
the tainted data (word
e., ap points to this dat
, The four conditions form a set of sufficient and the four conditions form a set of sufficient and there is no pointer tainted assignment and the set of *Vfprintf()*. Format string vulnerable 13). As illustrated in Figure The four conditions form a set of sufficient conditions, which if satisfied, ,
,
,
,
,
,
, guarantee that there is no pointer taintedness situation in the analyzed version of *Vfprintf()*. Format string vulnerabilities do not satisfy condition 3 (Table 13). As illustrated in Figure 1, the tainted data (word 0x08049978) is located in the activity range of ap, i.e., ap points to this data. For the other $\frac{d}{dt}$ three conditions, we are currently unaware of any existing applications violating them.

6. EXAMPLES ILLUSTRATING VIOLATIONS OF LIBRARY FUNCTIONS' PRECONDITIONS

In the previous section, we have given a significant number of preconditions for common library functions. Not all of them are likely to occur in real application code. In this section, we give possible scenarios (constructed examples) in which some of the preconditions detailed in the previous section are violated, and explain how an attacker can exploit them. To the best of our knowledge, these vulnerabilities have not been reported in any real application or described in the literature.

6.1 Example of *strcpy()* **violation – condition 3**

Condition 3 in Table 7 for *strcpy()* states that the buffer *dst* does not cover the function frame of *strcpy()*, which consists of *dst, src* and *res.* Otherwise it is possible to overwrite the stack frame of *strcpy()* and modify the address of the *dst* string. Since *strcpy()* can write to the location *(*dst),* this can be used to write to any memory location, including function pointers, and hence transfer control to malicious code.

Consider the code sample in Table 14a, in which *buf* and *input* are allocated on the stack in the function frame of *foo()*. The string *input* is obtained from the user and passed as the *src* argument of *strcpy().* The *dst* argument of *strcpy()* is *buf + index*, where *index* is computed by subtracting the length of *input* from the end of the buffer *buf*. After *strcpy()* is called, the stack frame looks as shown in Table 14b. Assume that the attacker enters an input string longer than 20 bytes as input. Since the input buffer has a size of 100 bytes, this may not cause buffer overflow. However, this makes the value of *index* computed to become negative, which in turn makes *dst* point to a stack location before *buf* and in the function frame of *strcpy()* (thereby violating the pre-condition). In the above example, setting the *index* to (-16) makes *dst* point to the location of itself on the stack. The *strcpy()* code then writes to the location of *(*dst)*, thereby overwriting *dst* itself. Subsequent writes to $(^*dst)$ can then modify the contents of the location pointed to by this new value of *dst*. This allows the attacker to write any value to any memory location, including sensitive locations such as function pointers.

The functionality of the code shown in Table 14a is to push data to the end of a buffer. We believe it is possible that applications require such a

14 *Shuo Chen, Karthik Pattabiraman, Zbigniew Kalbarczyk and Ravi K. Iyer*

functionality. For example, a program may need to copy data at the end of a buffer and prefix headers in front the data. The pointer arithmetic shown in Table 14a is an efficient means of implementing such an operation, so we argue that the sample code demonstrates a possible scenario in real applications.

6.2 Example of *strcpy()* **violation – condition 2**

scanf("%s", i

index = 20 –

strcpy(buf +

}
 6.2 Ex

In Table 7

such a way

terminator of

infinite loop.

an inadverte

respectively.
 a) Buffer Ove

char* src = ma

char* src = ma

sprintf(src,"str index = 20 – strlen
strcpy(buf + index
strcpy(buf + index
}
6.2 Examp
In Table 7, conc
such a way that *d*.
terminator of *src* is
infinite loop. This can inadvertent free
respectively.
a) Buffer Overflow $\frac{1}{2}$
 In Table 7, condition 2 of *strcpy()* states that *src* and *dst* do not overlap in such a way that *dst* covers the null-terminator of *src,* otherwise the nullterminator of *src* string gets overwritten and the program can go into an infinite loop. This can happen in two ways: by a buffer overflow error or by an inadvertent free error, as illustrated in Table 15a and Table 15b, respectively.

Table 15: Examples of *strcpy()* **condition 2 violations**

strcpy(buf + index, input); ን	Stac	strcp src dst	
	Low	res	
6.2 Example of $\text{strcpy}()$ violation – condition 2			
In Table 7, condition 2 of $\text{strcpy}()$ states that src and dst do not overlap in such a way that <i>dst</i> covers the null-terminator of <i>src</i> , otherwise the null- terminator of <i>src</i> string gets overwritten and the program can go into an infinite loop. This can happen in two ways: by a buffer overflow error or by an inadvertent free error, as illustrated in Table 15a and Table 15b, respectively.			
Table 15: Examples of strcpy() condition 2 violations			
a) Buffer Overflow Error		b) Inadverent Free Error	
char* $src = \text{malloc}(20)$;		$src = \text{malloc}(40);$	
char* dst = malloc(20);		snprintf(src, 30, "some string of 30 or	
sprintf(src,"string with $>$ 20 characters");		more characters");	
stropy(dst, src);		free(src);	
		foo = malloc (10) ;	
		$dst = \text{malloc}(20);$	
		strepy $($ dst, src $)$;	

In the first piece of code (Table 15a), two buffers are allocated on the heap and one of them is overflowed. This buffer is then passed as the *src* argument to *strcpy()*, and the other one as the *dst* argument. Upon running this code multiple times³, we found that the memory manager consistently allocated nearly consecutive, successive memory addresses to *src* and *dst* respectively. As a result, when the *src* buffer is overflowed, its contents spill

³ We tried it with glibc on x86-linux and Sun Solaris platforms. Our results indicate that this is not an OS or platform specific phenomenon, but a feature of glibc.

into the *dst* buffer, causing it to overlap with the *src* string and cover the null-terminator, leading to a violation of the pre-condition.

The *src* and *dst* arguments can also overlap if the destination buffer is allocated from some portion of the source buffer. This situation is illustrated in Table 15b. Here *src* is first allocated on the heap and then freed, which returns the *src* buffer to the free pool. When *malloc()* requests are made subsequently for *foo* and *dst*, the memory manager reuses the block most recently returned to it, namely the *src* buffer, for allocating the buffers *foo* and *dst*. When *strcpy()* is called, *src* and *dst* overlap in such a way that *dst* covers the null terminator of *src*, which is a violation of the pre-condition. In real codes, this can happen as a result of using a buffer that is freed on an infrequently executed path and may not be uncovered during testing.

6.3 Example of *free()* **violation – condition 2**

Condition 2 of the *free()* function in Table 10 states that the pointer passed to *free()* must be within the heap range. This arises from the fact that the *free()* function itself does not perform this check. When a block is freed, the *free()* function checks for an integer value at the beginning of the block, which represents the size of the block to be freed. If it finds such an integer, it does the free*,* irrespective of whether the block is on the heap or not.

Consider what happens when a local buffer on the stack is passed to the *free()* function in Table 16. In this code, the local array *buf* of function *foo()* is passed to the function *print_str(),* which checks if the length of the string passed to it is more than the value *n* specified by the user, and if so, frees the buffer. The pointer **p** which is freed by *print str()* is aliased to *buf,* which is allocated on the stack in the function frame of *foo()*, leading to a violation of the pre-condition. Since this happens only when the user enters a string of more than 50 characters, it may not be uncovered while testing. In this example, the integer *i*, which is a local variable of *foo()* is present on the stack at the beginning of the block *buf*. The *free()* function assumes that this is the size of the buffer *buf* and attempts to deallocate a block of that size. Since the user also supplies this value, it is possible to free a block of any arbitrary size on the stack, and overwrite the contents of any memory location.

7. CONCLUSIONS AND FUTURE DIRECTIONS

This paper is motivated by a low level analysis of various security vulnerabilities, which indicates that the common cause of the vulnerabilities is pointer taintedness. To reason about pointer taintedness, a memory model is needed. The main contribution of this paper is the equational definition of a memory model, which associates the *taintedness* attribute with memory locations rather than with program symbols. Pointer taintedness analysis is applied on several C library functions to extract security preconditions. The results show that pointer taintedness analysis can expose different classes of security vulnerabilities, leading us to believe that pointer taintedness provides a unifying perspective for reasoning about security vulnerabilities. We plan to extend this work in a number of ways: (1) Reduce the amount of human intervention in the theorem proving tasks; (2) Define semantics for other C statements, such as goto, break and continue to make the technique goto, break and continue to make the technique
Incorporate this technique into compiler-based
ad to large applications. more widely applicable; (3) Incorporate this technique into compiler-based static checking tools to extend to large applications.

Acknowledgments:

We thank Jose Meseguer for his insightful suggestions on the project, and Tammi O'Neill for her careful reading of an early draft of this manuscript.

References:

- [1] D. Evans and D. Larochelle. Improving Security Using Extensible Lightweight Static Analysis. In IEEE Software, Jan/Feb 2002
- [2] B. Chess. Improving Computer Security Using Extended Static Checking. IEEE Symposium on Security and Privacy 2002
- [3] J. A. Goguen and G. Malcolm. Algebraic Semantics of Imperative Programs. MIT Press, 1996, ISBN 0-262-07172-X
- [4] M. Clavel, F. Durán, S. Eker, P. Lincoln, N. Martí-Oliet, J. Meseguer and C. Talcott *The Maude 2.0 System.* In Proc. Rewriting Techniques and Applications, 2003, 2003.
- [5] J. Xu, Z. Kalbarczyk and R. K. Iyer. Transparent Runtime Randomization for Security. To appear in Proc. Symposium on Reliable and Distributed Systems, 2003.
- [6] D. Wagner, J. Foster, E. Brewer, and A. Aiken. A First Step Towards Automated Detection of Buffer Overrun Vulnerabilities. Network and Distributed System Security Symposium (NDSS2000).
- [7] U. Shankar, K. Talwar, J. Foster, and D. Wagner. Detecting Format String Vulnerabilities With Type Qualifiers. 10th USENIX Security Symposium, 2001.
- [8] C. Cowan, C. Pu, D. Maier, et al. Automatic Detection and Prevention of Buffer-Overflow Attacks. 7th USENIX Security Symposium, San Antonio, TX, January 1998.
- [9] A. Baratloo, T. Tsai, N. Singh, Transparent Run-Time Defense Against Stack Smashing Attacks, Proc. USENIX Annual Technical Conference, June 2000.
- [10] S. Chen, Z. Kalbarczyk, J. Xu, R. K. Iyer. "A Data-Driven Finite State Machine Model for Analyzing Security Vulnerabilities". in IEEE International Conf. on Dependable Systems and Networks, 2003.
- [11] Introduction to equational logic. http://www.cs.cornell.edu/Info/People/gries/Logic/ Equational.html
- [12] S. Chen, K. Pattabiraman, Z. Kalbarczyk, R. K. Iyer. Formal Reasoning of Various Categories of Widely Exploited Security Vulnerabilities By Pointer Taintedness Semantics (Full Version). http://www.crhc.uiuc.edu/~shuochen/pointer_taintedness