cse504 class presentation

- LCLint (PLDI'96 paper)
- Splint (IEEE'02 paper)
- Prefix (Intrinsa SP&E'00 paper)

jaeyeon.jung@intel.com

04/07/2010

part I

static detection of dynamic memory errors

the problem

- memory errors are hard to detect at compile-time
- observations
  - many bugs result from *invalid assumptions* about the results of functions and the values of parameters and global variables.
  - these bugs are platform independent.

memory errors

- misuses of null pointers
- lack of memory allocation or deallocation
- uses of undefined storage
- unexpected aliasing

sample.c

```
extern char *gname;

void setName (char *pname) {
    gname = pname;
}
```

sample.c

```
extern char *gname;

void setName (char *pname) {
    gname = pname;
}
```

1. must not be a sole ref.

sample.c

```
extern char *gname;

void setName (char *pname) {
    gname = pname;
}
```

2. gname and pname are aliased.

sample.c

```
extern char *gname;

void setName (char *pname) {
    gname = pname;
}
```

3. gname may not be dereferenced if pname is a null pointer.

sample.c

```
extern char *gname;

void setName (char *pname) {
    gname = pname;
}
```

4. gname may not be dereferenced
as a rvalue unless pname pointed to defined storage.

the approach

- make assumptions explicit with annotations
  - function interfaces, variables, types
- extend LCLint to statically detect the errors
  - LCLint became secure programming Lint http://www.splint.org/

annotations

- syntactic comments
  - e.g., /* @null@ */
- used in
  - type declaration
  - function parameter or return value declarations
  - global and static variable declarations

annotations --- null pointers

```
1 extern char *gname;
2
3 void setName (/*@null@*/ char *pname) {
4     gname = pname;
5 }
```

sample.c:5: function returns with non-null global gname referencing null storage.

    sample.c:4: storage gname may become null.

annotations --- null pointers

```
extern char *gname;
extern /*@truenull@*/
  isNull (/*@null@*/ char *x);
void setName (/*@null@*/ char
  *pname) {
   If (!isNull(pname)) {
     gname = pname;
   }
}
```

annotations --- definition

- out: referenced storage need not be defined
- in/partial/undef: referenced storage is completely/partially/not defined
- reldef: value assumed to be defined when it is used, but need not be assigned to defined storage

annotations --- allocation

```
extern /*@only@*/ char *gname;

void setName (/*@temp@*/ char *pname) {
    gname = pname;
}
```

1. memory leak
2. gname will become a dead pointer if the caller deallocates the actual parameter

annotations --- aliasing

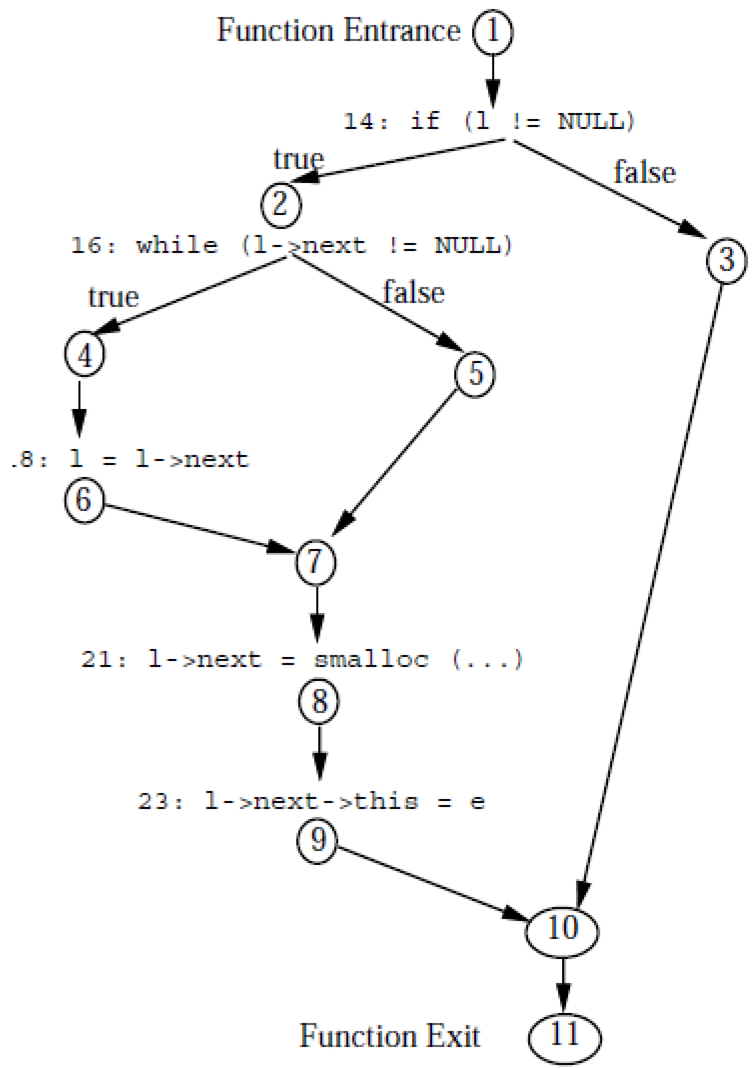
- unique: parameter aliasing
- returned: a reference to the parameter may be returned

evaluation --- toy program

- employee database program (1K LoC)
- adding annotations is an iterative process
  - 13 only, 1 out, 1 null
- found three bugs
  - null pointers, allocation, aliasing

evaluation --- toy program

```
1  typedef /*@null@*/ struct _list
2  {
3    /*@only@*/ char *this;
4    /*@null@*//*@only@*/ struct _list *next;
5  } *list;
6
7  extern /*@out@*//*@only@*/ void *
8    smalloc (size_t);
9
10 void
11 list_addh (/*@temp@*/ list l,
12            /*@only@*/ char *e)
13 {
14   if (l != NULL)
15     {
16       while (l->next != NULL)
17         {
18           l = l->next;
19         }
20
21       l->next = (list)
22         smalloc (sizeof (*l->next));
23       l->next->this = e;
24     }
25 }
```



evaluation --- LCLint

- 100K lines of code
- < 4 minutes to check
- adding all annotations required a few days over the course of a few weeks by one person
- revealed limitations of strict annotations
  - e.g., handling an error condition

summary

- the annotations improve
  - static checking
  - maintaining and developing code
- a combination of static checking and run-time checking is promising to producing reliable code.

part II

Improving security using extensible lightweight static analysis

the problem

- the techniques for avoiding security vulnerabilities are not codified into the software development process
- C is difficult to secure
  - unsafe functions
  - confusing APIs

the solution

- Splint: a lightweight static analysis tool for ANSI C
  - detects stack and heap-based buffer overflow vulnerabilities
  - support user-defined checks
    - constrain the values of attributes at interface points
    - specify how attributes change

the challenges

- false positive & false negatives
- tradeoff between precision and scalability
  – limited to data flow analysis within procedure bodies
  – merges possible paths at branch points
  – use heuristics to analyze loop

example --- buffer overflow analysis

- requires, ensures
- maxSet
  - highest index that can be safely written to
- maxRead
  - highest index that can be safely read
- char buffer[100];
  - ensures maxSet(buffer) == 99

SecurityFocus.com Example

```
char *strncat (char *s1, char *s2, size_t n)
  /*@requires maxSet(s1)
              >=maxRead(s1) + n@*/

  void func(char *str){
     char buffer[256];
     strncat(buffer, str, sizeof(buffer) - 1);
     return;
  }
```

uninitialized array

Source: Secure Programming working document, SecurityFocus.com

http://www.cs.virginia.edu/evans/talks/usenix.ppt

Warning Reported

```
char *  strncat (char *s1, char *s2, size_t n)
/*@requires maxSet(s1) >= maxRead(s1) + n @*/
```

```
char buffer[256];
strncat(buffer, str, sizeof(buffer) - 1);
```

```
strncat.c:4:21: Possible out-of-bounds store:
    strncat(buffer, str, sizeof((buffer)) - 1);
  Unable to resolve constraint:
    requires maxRead (buffer @ strncat.c:4:29)  <= 0
  needed to satisfy precondition:
    requires maxSet (buffer @ strncat.c:4:29)
             >= maxRead (buffer @ strncat.c:4:29) + 255
  derived from strncat precondition:
    requires maxSet (<parameter 1>)
             >=  maxRead (<parameter1>) + <parameter 3>
```


http://www.cs.virginia.edu/evans/talks/usenix.ppt

example --- taint analysis

```
attribute taintedness
  context reference char *
  oneof untainted, tainted
  annotations
    tainted reference ==> tainted
    untainted reference ==> untainted
  transfers
    tainted as untainted ==> error "Possibly tainted storage used as untainted."
  merge
    tainted + untainted ==> tainted
  defaults
    reference ==> tainted
    literal ==> untainted
    null ==> untainted
end
```

http://www.cs.virginia.edu/~evans/pubs/ieeesoftware.pdf

example --- taint analysis

```
char *strcat
  (/*@returned@*/ char *s1,
    char *s2)
  /*@ensures s1:taintedness =
     s1:taintedness | s2.taintedness@*/
```

annotated declarations define taint propagation at the interface for standard library functions

evaluation --- wu-ftpd

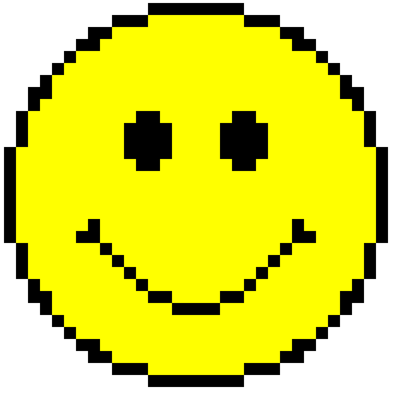
- 20K LoC
- < 4 seconds to check the code on a slow (1.2GHz) machine
- found a few known bugs using the taint analysis
- 101 warnings after adding 66 annotations
  - 76 false positives
    - external assumptions, arithmetic limitations, alias analysis, flow control, loop heuristics

wu-ftpd vulnerablity

```
int access_ok( int msgcode) {
   char class[1024], msgfile[200];
   int limit;

    ...

   limit = acl_getlimit(class, msgfile);
```



l

http://www.cs.virginia.edu/evans/talks/usenix.ppt

summary

- static analysis is promising but
  - limited to finding problems that manifest as inconsistencies between the code and assumptions documented in annotations
  - annotating legacy code is laborious
- static analysis helps codifying knowledge into tools not to avoid making same mistakes

part III

A static analyzer for finding dynamic programming errors

the problem

- many bugs are caused by the interaction of multiple functions and may be revealed only in unusual cases
  - compilers, Lint are limited to intra-procedural checks
  - annotation checkers require too much work
  - debugging tools incur performance overhead

the design goals

- practical
  - effectively check C/C++ programs
  - leverage information automatically derived from the program text
- analysis limited to achievable paths
- actionable
  - automatic characterization of defects

PREfix’s key concept

- simulate functions using VM
  - achievable paths
- automatically generate a function’s model
- bottom-up analysis

PREfix

- parse the source code into abstract syntax tree
- run topological sort for simulating functions from the leaf
- load existing models for relevant functions
- simulate functions
  - simulate achievable paths
  - per-path simulation

per-path simulation

- memory: exact values and predicates
  - known exact value, initialized but unknown value, uninitialized value
  - dereference
- operations on memory
  - setting, testing, assuming
- conditions, assumptions and choice points
- end-of-path analysis
  - leak analysis

model -- deref

```
int deref(int *p)
{
    if (p==NULL)
        return NULL;
    return *p;
}
```

model -- deref

```
int deref(int *p)
{
    if (p==NULL)
        return NULL;
    return *p;
}
```

```
(deref
        (param p)
    (alternate return_0
        (guard peq p NULL)
        (constraint memory_initialized p)
        (result peq return NULL)
        )
    (alternate return_X
        (guard pne p NULL)
        (constraint memory_initialized p)
        (constraint memory_valid_pointer p)
        (constraint memory_initialized *p)
        (result peq return *p)
        )
    )
```

model generation

- record all the per-path memory state
  - tests -> constraints
- save externally visible states
  - parameters, return values and globals
- merge states
  - for performance
  - equivalent merging (e.g., one assumes x>0 and the other assumes x<=0)
  - no aggressive merging (e.g., [merge *p=5 and *p=8 -> *p is initialized] caused accuracy issues

evaluation

Table I. Performance on sample public domain software.

Program	Language	Number of files	Number of lines	PREfix parse time	PREfix simulation time
Mozilla	C++	603	540 613	2 h 28 min	8 h 27 min
Apache	C	69	48 393	6 min	9 min
GDI Demo	C	9	2655	1 s	15 s

OK performance on a slow machine

evaluation

Table II. Warnings reported in sample public domain software.

Warning	Mozilla	Apache	GDI
Using uninitialized memory	26.14%	45%	69%
Dereferencing uninitialized pointer	1.73%	0	0
Dereferencing NULL pointer	58.93%	50%	15%
Dereferencing invalid pointer	0	5%	0
Dereferencing pointer to freed memory	1.98%	0	0
Leaking memory	9.75%	0	0
Leaking a resource (such as a file)	0.09%	0	8%
Returning pointer to local stack variable	0.52%	0	0
Returning pointer to freed memory	0.09%	0	0
Resource in invalid state	0	0	8%
Illegal value passed to function	0.43%	0	0
Divide by zero	0.35%	0	0
Total number of warnings	1159	20	13

false +s: 10% - 25% (Apache)

evaluation

Table III. Relationships between available Models, coverage, execution time and defects reported.

Model set	Execution time (minutes)	Statement coverage	Branch coverage	Predicate coverage	Total warning count	Using uninit memory	NULL pointer deref	Memory leak
None	12	90.1%	87.8%	83.9%	15	2	11	0
System	13	88.9%	86.3%	82.1%	25	6	12	7
System & auto	23	73.1%	73.1%	68.6%	248	110	24	124

the decrease in coverage as more models are introduced

summary

- PREfix is a dynamic checker with
  - adjustable thresholds on path coverage
  - heuristics to manage paths to check
  - efficient function models
- bugs found by PREfix
  - caused by multi-function interactions
  - off main code paths
  - more found in yonger code

take-away

- LCLint (PLDI paper) & Splint (IEEE paper)
  - static analysis with annotations
  - manual, iterative process but improves maintaining and developing code
- Prefix (Intrinsa SP&E paper)
  - dynamic checker with models and heuristics
  - automatic, inter-procedural analysis, but may produce lots of false positives