Bugs: Difference in Beliefs

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Sides from the authors of “Uncertainty to Belief: Inferring the Specification Within” and “Towards Optimization-Safe Systems Analyzing the Impact of Undefined Behavior”

What is a Bug?

a bug is -

a *contradiction* in beliefs

MUST - implied by the code

a deviation from *common behavior*

MAY - inferred from the code

probability of coincidence

Bugs Cost??

Patriot missile defense system

28 dead soldiers, 98 wounded

Therac-25 medical device

Several people dead, others wounded

General Electric XA/21

50 million people left without water, electricity.

What Bugs Means to You?

How to find bugs?

What is your belief set?

- MUST set
- MAY set

What is the implied sets?

Inconsistency means possible bugs!!

Trivial consistency: NULL pointers

*p implies MUST belief:

- p is not null

A check (p == NULL) implies two MUST beliefs:

- POST: p is null on true path, not null on false path
- PRE: p was unknown before check

```
/* 2.4.1: drivers/isdn/svmb1/capidrv.c */
if(!card)
  printk(KERN_ERR, "capidrv-%d: …", card->contrnr…)
```

```
/* drivers/net/wan/sdla_chdlc.c:3948 */
if (!card){
   lock_adapter_irq(&card->wandev.lock,&smp_flags);
   card->tty=NULL;
```

Null pointer fun

Use-then-check

```
/* 2.4.7: drivers/char/mxser.c */
struct mxser_struct *info = tty->driver_data;
unsigned flags;
if(!tty || !info->xmit_buf)
    return 0;
```

Contradiction/redundant checks

```
/* 2.4.7/drivers/video/tdfxfb.c */
fb_info.regbase_virt = ioremap_nocache(...);
if(!fb_info.regbase_virt)
    return -ENXIO;
fb_info.bufbase_virt = ioremap_nocache(...);

if(!fb_info.regbase_virt) {
    iounmap(fb_info.regbase_virt);
```

Internal Consistency: finding security holes

Applications are bad:

- Rule: “do not dereference user pointer <p>”
- One violation = security hole
- Big Problem: which are the user pointers???

Sol’n: forall pointers, cross-check two OS beliefs

- “*p” implies safe kernel pointer
- “copyin(p)/copyout(p)” implies dangerous user pointer
- Error: pointer p has both beliefs.

```
/*
 * Find a routing entry, we only return a FULL match
 */
static struct ipddp_route* ipddp_find_route(struct ipddp_route *rt)
{
        struct ipddp_route *f;

        for(f = ipddp_route_list; f != NULL; f = f->next)
        {
                if(f->ip == rt->ip
                        && f->at.s_net == rt->at.s_net
                        && f->at.s_node == rt->at.s_node)
                        return (f);
        }

        return (NULL);
}
```

- In linux 2.

```
/* drivers/n
case SIOCADD
      return
case SIOCDEL
      return ipddp_delete(rt);
case SIOFCINDIPDDPRT:
   if(copy_to_user(rt, ipddp_find_route(rt),
                        sizeof(struct ipddp_route)))
         return -EFAULT;
```

  – "rt" as a tainted pointer, checking warns that rt is passed to a routine that dereferences it

Statistical: Deriving deallocation routines

Use-after free errors are horrible.

- Problem: lots of undocumented sub-system free functions
- Soln: derive behaviorally: pointer “p” not used after call “foo(p)” implies MAY belief that “foo” is a free function

Conceptually: Assume all functions free all arguments

- (in reality: filter functions that have suggestive names)

A bad free error

```
/* drivers/block/cciss.c:cciss_ioctl  */
if (iocommand.Direction == XFER_WRITE){
   if (copy_to_user(...)) {
        cmd_free(buff, c);
        if (buff != NULL) kfree(buff);
        return(-EFAULT);
  }
}
if (iocommand.Direction == XFER_READ) {
     if (copy_to_user(...)) {
         cmd_free(buff, c);
         kfree(buff);
     }
}
cmd_free(buff, c);
if (buff != NULL) kfree(buff);
```

“A must be followed by B”

“a(); … b();” implies MAY belief that a() follows b()

- You might believe a-b paired, or might be a coincidence

Checking derived lock functions

Simplest:

```
/* fs/proc/inode.c:41:de_put: */
lock_kernel();
if (!de->count) {
        printk("de_put: entry already free!\n")
        return;
}
unlock_kernel();
```

Evilest:

```
/* 2.4.1: drivers/sound/trident.c:trident_release:
  lock_kernel();
  card = state->card;
  dmabuf = &state->dmabuf;
  VALIDATE_STATE(state);
```

```
#define VALIDATE_MAGIC(FOO,MAG)                                 \
({                                                              \
        if (!(FOO) || (FOO)->magic != MAG) {                    \
                printk(invalid_magic,__FUNCTION__);             \
                return -ENXIO;                                  \
        }                                                       \
})

#define VALIDATE_STATE(a) VALIDATE_MAGIC(a,TRIDENT_STATE_MAGIC)
```

Towards Optimization-Safe Systems Analyzing the Impact of Undefined Behavior

Xi Wang, Nickolai Zeldovich, M. Frans Kaashoek, Armando Solar-Lezama
MIT CSAIL

Slides converted from the authors' own version

Belief: compiler == faithful translator

C

```c
int main()
{
    ...
    return 0;
}
```

GCC

X86

```
...
movq %rsp, %rbp
xorl %eax, %eax
popq %rbp
ret
```

Not true if your code invokes undefined behavior

- Security implications

Example: compiler discards sanity check

```
char *buf         = ...;
char *buf_end     = ...;
unsigned int off = /* read from untrusted input */;
if (buf + off >= buf_end)
  return;           /* validate off: buf+off too large*/
if (buf + off < buf)
  return;           /* validate off: overflow, buf+off wrapped around */
/* access buf[0..off-1] */
```

- C spec: pointer overflow is undefined behavior
  - gcc: buf + off cannot overflow, different from hardware!
  - gcc: if (buf + off < buf) => if (false)
- Attack: craft a large off to trigger buffer overflow

Undefined behavior allows such optimizations

Undefined behavior: the spec “imposes no requirements”

- Original goal: emit efficient code
- Compilers assume a program never invokes undefined behavior
- Example: no bounds checks emitted; assume no buffer overflow

```
*p = 42;          /* store 42 to p */
   ↓
mov $42, (%rdi)  /* no bounds checks */
```

Examples of undefined behavior in C

Meaningless checks from real code: pointer p; signed integer x

Pointer overflow:	`if (p + 100 < p)`
Signed integer overflow:	`if (x + 100 < x)`
Oversized shift:	`if (!(1 << x))`
Null pointer dereference:	`*p; if (p)`
Absolute value overflow:	`if (abs(x) < 0)`

Problem: unstable code confuses programmers

Unstable code: compilers discard code due to undefined behavior

C

```c
...
if (p + 100 < p)
  return;
```

GCC

X86

```
...
nop
nop
```

- Security checks discarded
- Weakness amplified
- Unpredictable system behavior

Contributions

- A case study of unstable code in real world
- An algorithm for identifying unstable code
- A static checker STACK
  - 160 previously unknown bugs confirmed and fixed
  - Users: Intel, several open-source projects,...

Example: broken check in Postgres

Implement 64-bit signed division x/y in SQL

```
if (y == -1 && x < 0 && (x / y < 0))   /* -2^63/-1 < 0? */
  error();
```

- Some compilers optimize away the check
- x86-64's idivq traps on overflow: DoS attack

```sql
SELECT ((-9223372036854775808)::int8) / (-1);
```

Example: fix check in Postgres

Our proposal:

```
if (y == -1 && x == INT64_MIN) /* INT64_MIN is -2^63*/
```

Developer's fix:

```
if (y == -1 && ((-x < 0) == (x < 0)))
```

- Still unstable code: time bomb for future compilers
  - "it's an overflow check so it should check for overflow"
  - "we don't want the constant INT64_MIN;it's less portable"

“This will create MAJOR SECURITY ISSUES in ALL MANNER OF CODE. I don’t care if your language lawyers tell you gcc is right. . . . **FIX THIS! NOW!**”

a gcc user

bug #30475 - assert(int+100 > int) optimized away

“I am sorry that you wrote broken code to begin with . . . **GCC is not going to change**. ”

a gcc developer

bug #30475 - assert(int+100 > int) optimized away

Test existing compilers

12 C/C++ compilers

- gcc
- aCC (HP)
- Icc (Intel)
- open64 (AMD)
- suncc (Oracle)
- ti (TI’s TMS320C6000)
- clang
- armcc (ARM)
- msvc (Microsoft)
- pathcc (PathScale)
- xlc(IBM)
- windriver (Wind River’s Diab)

Examples of unstable code

Meaningless checks from real code: pointer p; signed integer x

Pointer overflow:	if (p + 100 < p)	=> if (false)
Signed integer overflow:	if (x + 100 < x)	=> if (false)
Oversized shift:	if (!(1 << x))	=> if (false)
Null pointer dereference:	*p; if (p)	=> if (false)
Absolute value overflow:	if (abs(x) < 0)	=> if (false)

Compilers often discard unstable code

	`if(p+100<p)`	`if(x+100<x)`	`if(!(1<<x))`	`*p; if(!p)`	`if(abs(x)<0)`
gcc-4.8.1	O2	O2		O2	O2
clang-3.3	O1	O1	O1		
aCC-6.25					O3
armcc-5.02		O2			
icc-14.0.0		O1		O2	
msvc-14.0.0				O1	
open64-14.0.0	O1	O2			O2
pathcc-1.0.0	O1	O2			O2
suncc-5.12				O3	
ti-7.4.2	O0	O0			
windriver-5.9.2		O0			
xlc-12.1	O3				

Compilers become more aggressive over time

	`if(p+100<p)`	`if(x+100<x)`	`if(!(1<<x))`	`*p; if(!p)`	`if(abs(x)<0)`
(1992) gcc-1.42					
(2001) gcc-2.95.3		O1			
(2006) gcc-3.4.6		O1		O2	
(2007) gcc-4.2.1	O0	O2			O2
(2013) gcc-4.8.1	O2	O2		O2	O2
(2009) clang-1.0	O1				
(2010) clang-2.8	O1	O1			
(2013) clang-3.3	O1	O1	O1		

Observation

- Compilers silently remove unstable code
- Different compilers behave in different ways
  - Change/upgrade compiler => broken system
- Need a systematic approach

Our approach: precisely flag unstable code

C/C++ source → LLVM IR → STACK → warnings

```
% ./configure
% stack-build make        # intercept cc & generate LLVM IR
% poptck                  # run STACK in parallel
```

STACK provides informative warnings

```
1. res = x / y;
2. if (y == -1 && x < 0 && res < 0)
3.   return;
```

The check at line 2 is simplified into false, due to division at line 1

```
model: |                              # possible optimization
  %cmp3 = icmp slt i64 %res, 0
  -->  false
stack:                                # location of unstable code
  - div.c:2
core:                                 # why optimized away
  - div.c:1
    - signed division overflow
```

Design overview of STACK

- What's the difference, compilers vs most programmers?
  - Assumption Δ: programs don't invoke undefined behavior
- What can compilers do only with assumption Δ?
  - Optimize away unstable code
- STACK: mimic a compiler that selectively enables Δ
  - Phase I: optimize w/o Δ
  - Phase II: optimize w/ Δ
  - Unstable code: difference between the two phases

Example of identifying unstable code

```
res = x / y;
if (y == -1 && x < 0 && res < 0)
  return;
```

- Assumption Δ:
  - No division by zero: y ≠ 0
  - No division overflow: y ≠ -1 OR x ≠ INT_MIN
- STACK can optimize "res < 0" to "false" only with Δ
  - Phase I: is "res < 0" equivalent to "false" in general? No.
  - Phase II: is "res < 0" equivalent to "false" with Δ? Yes!
- Report "res < 0" as unstable code

Compute assumption Δ

One must not trigger undefined behavior at any code fragment

- Reach(e): when to reach and execute code fragment e
- Undef(e): when to trigger undefined behavior at e

$$\Delta = \forall e:\ \mathrm{Reach}(e) \rightarrow \neg \mathrm{Undef}(e)$$

Example: compute assumption Δ

One must not trigger undefined behavior at any code fragment

$$\Delta = \forall e{:}\mathrm{Reach}(e) \rightarrow \neg \mathrm{Undef}(e)$$

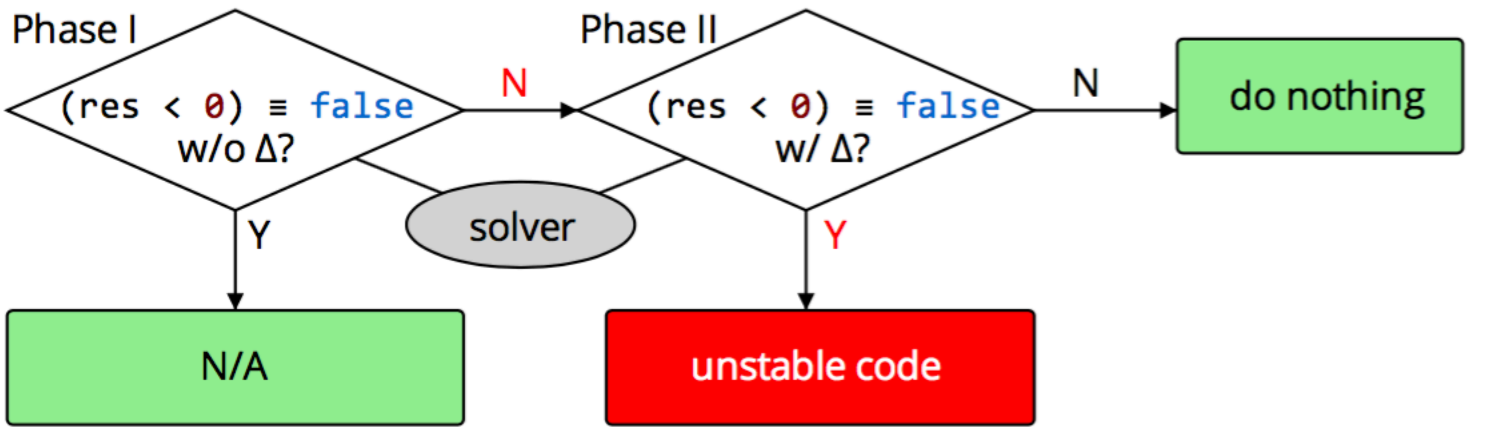
```
1. res = x / y;
2. if (y == -1 && x < 0 && res < 0)
3.   return;
```

```
Δ = true → ¬((y == 0) ∨ (x == -1 ∧ y == INT_MIN)) # line 1
  ∧ true → ¬false                                 # line 2
  ∧ ((y == -1) ∧ (x < 0) ∧ (x/y < 0)) → ¬false    # line 3

Δ = ¬((y == 0) ∨ (x == -1 ∧ y == INT_MIN))
```

Find unstable code by selectively enabling Δ

```
1.  res = x / y;
2.  if (y == -1 && x < 0 && res < 0)
3.    return;
```



Summary of STACK

- Compute assumption Δ: no undefined behavior
- Two-phase framework: w/o and w/ Δ
  - Report unstable code from difference
- Limitations
  - Missing unstable code: Phase II not powerful enough
  - False warnings: Phase I not powerful enough

Implementation of STACK

- LLVM
- Boolector solver
- ~4,000 lines of C++ code
- Per-function for better scalability
  - Could miss bugs

Evaluation

- Is STACK useful for finding unstable code?
- How precise are STACK's warnings?
- How prevalent is unstable code?
- How much time to analyze a large code base?

STACK finds new bugs

- Applied STACK to many popular systems
- Inspected warnings and submitted patches to developers
  - Binutils,Bionic,Dune,e2fsprogs,FFmpeg+Libav,file,FreeType, GMP, GRUB, HiStar, Kerberos, libX11, libarchive, libgcrypt, Linux kernel, Mosh, Mozilla, OpenAFS, OpenSSH, OpenSSL, PHP, plan9port, Postgres, Python, QEMU, Ruby+Rubinius, Sane, uClibc, VLC, Wireshark, Xen, Xpdf
- Developers accepted most of our patches
  - 160 new bugs

STACK warnings are precise

- Kerberos: STACK produced 11 warnings
  - Developers accepted every patch
  - No warnings for fixed code
  - Low false warning rate: 0/11

- Postgres: STACK produced 68 warnings
  - 9 patches accepted: server crash
  - 29 patches in discussion: developers blamed compilers
  - 26 time bombs: can be optimized away by future compilers
  - 4 false warnings: benign redundant code
  - Low false warning rate: 4/68

Unstable code is prevalent

- Applied STACK to all Debian Wheezy packages
  - 8,575 C/C++ packages
  - ~150 days of CPU time to build and analyze
- STACK warns in ~40% of C/C++ packages

STACK scales to large code bases

Intel Core i7-980 3.3 GHz, 6 cores

	build time	analysis time	# files
Kerberos	1 min	2 min	705
Postgres	1 min	11 min	770
Linux kernel	33 min	62 min	14,136

How to avoid unstable code

- Programmers
  - Fix bugs
  - Work around: disable certain optimizations
- Compilers & checkers
  - Many bug-finding tools fail to model C spec correctly
  - Use our ideas to generate better warnings
- Language designers: revise the spec
  - Eliminate undefined behavior? Perf impact?

Other application

Reflections on trusting trust [Thompson8

- Hide backdoors
  - Submit a new feature with unstable code
  - Could easily slip through code review

Summary

- Compilers optimize away unstable code
  - Subtle bugs
  - Significant security implications
- Compiler writers: use our techniques to generate better warnings
- Language designers: trade-off between performance & security
- Programmers: check your C/C++ code using STACK

http://css.csail.mit.edu/stack/