Dude, where's my code?

# Towards Optimization-Safe Systems

## Analyzing the Impact of Undefined Behavior

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

# Belief: compiler == faithful translator

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

```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 $\Rightarrow$ 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

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

# Example: compute assumption Δ

One must not trigger undefined behavior at any code fragment

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

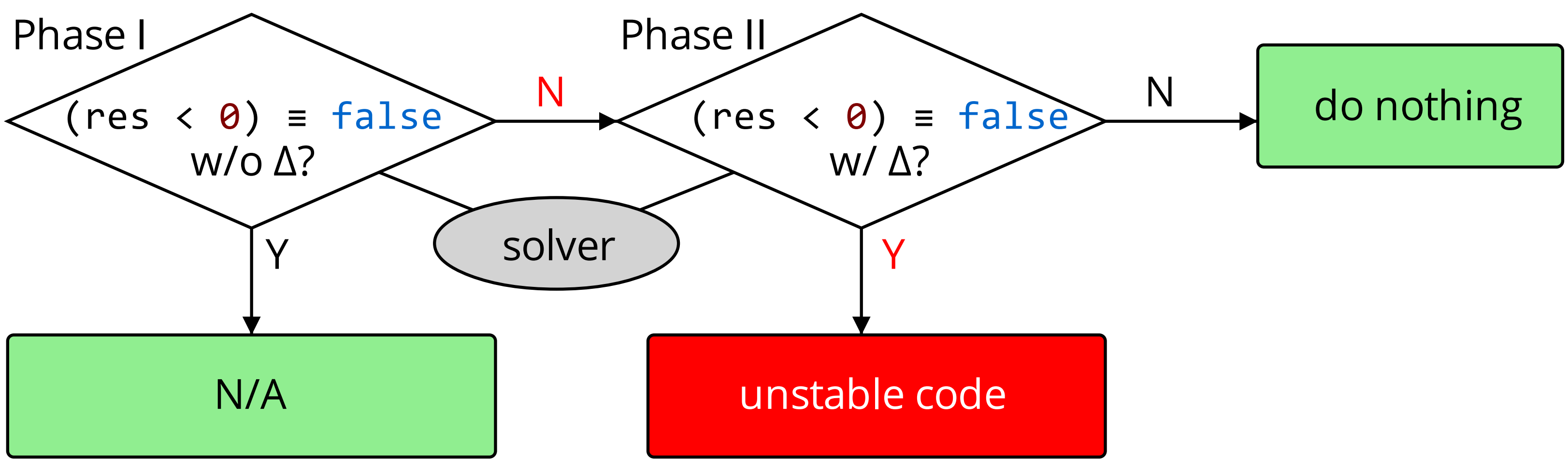
```
1. res = x / y;
2. if (y == -1 && x < 0 && res < 0)
3.   return;
```

```
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 |

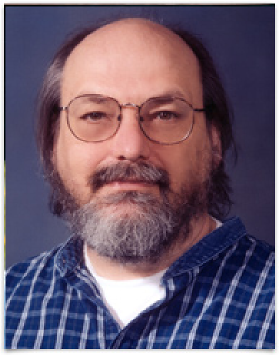
# How to avoid unstable code

- Programmers
  - Fix bugs
  - Workaround: 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* [Thompson84]

- 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/

# Q: CPU emulator

16-bit multiplication, from a well-known company

```
uint64_t mul(uint16_t a, uint16_t b)
{
    uint32_t c = a * b;
    return c;
}
```

What's the result of `mul(0xffff, 0xffff)`?

a) `1`

b) `0xfffe0001`

c) `0xfffffffffffe0001`