Undefined Behavior in LLVM

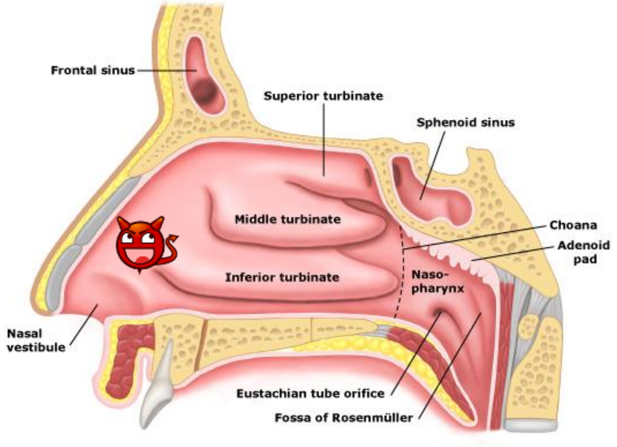
John Regehr

Trust-in-Soft / University of Utah

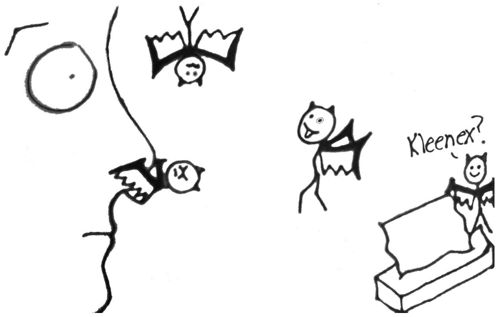
- sqrt(-1) = ?
  - i
  - NaN
  - Arbitrary value
  - Exception
  - Undefined behavior
- **Undefined behavior** (UB) is a design choice
  - System designers use UB when they don't feel like committing (or can't commit) to any particular semantics

Undefined behavior is undefined

- Technically, anything can happen next
  - “Permissible undefined behavior ranges from ignoring the situation completely with unpredictable results, to having demons fly out of your nose.”
- In practice, UB is implemented lazily: by assuming it will never happen



(image from @whitequark)

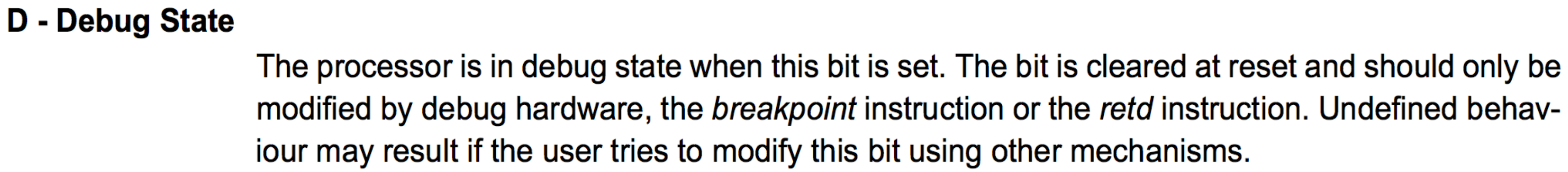


(image from EvilTeach on Stackoverflow)

Common consequences include…

- Predictable and useful result on one platform, different result on another platform
- Unpredictable or nonsensical result
- Memory corruption
- Remote code execution
- Trap or fault
- No consequences at all

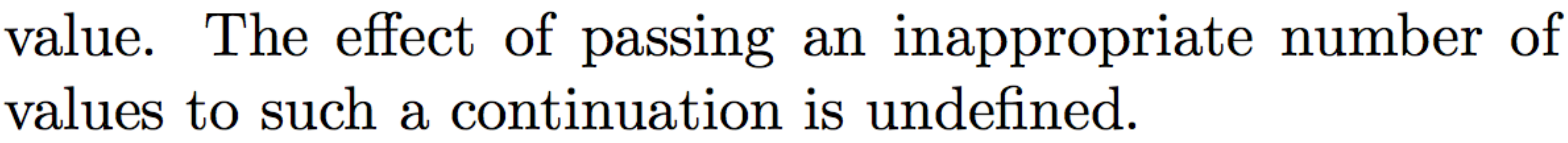
- AVR32 (embedded CPU):



D - Debug State

The processor is in debug state when this bit is set. The bit is cleared at reset and should only be modified by debug hardware, the *breakpoint* instruction or the *retd* instruction. Undefined behaviour may result if the user tries to modify this bit using other mechanisms.

- Scheme R6RS:



value. The effect of passing an inappropriate number of values to such a continuation is undefined.

- C/C++ have tons and tons of undefined behaviors
  - divide by zero, use of dangling pointer, shift past bitwidth, signed integer overflow, …
- LLVM has undefined behavior too

```
int foo (int x) {
    return (x + 1) > x;
}
int main () {
    printf("%d\n", (INT_MAX + 1) > INT_MAX);
    printf("%d\n", foo(INT_MAX));
    return 0;
}
```

```
$ gcc -O2 intmax-overflow.c ; ./a.out
0
1
```

```
int main() {
    int *p = (int*)malloc(sizeof(int));
    int *q = (int*)realloc(p, sizeof(int));
    *p = 1;
    *q = 2;
    if (p == q)
        printf("%d %d\n", *p, *q);
}
$ clang -O realloc.c ; ./a.out
1 2
```

Without -DDEBUG

```
void foo(char *p) {
#ifdef DEBUG
  printf("%s\n", p);
#endif
  if (p != 0)
    bar(p);
}
```

```
_foo:
    testq   %rdi, %rdi
    je      L1
    jmp     _bar
L1: ret
```

With -DDEBUG

```
void foo(char *p) {
#ifdef DEBUG
  printf("%s\n", p);
#endif
  if (p != 0)
    bar(p);
}
```

```
_foo:
    pushq    %rbx
    movq     %rdi, %rbx
    call     _puts
    movq     %rbx, %rdi
    popq     %rbx
    jmp      _bar
```

As developers, what can do we about undefined behavior in C and C++?

- Only use these languages appropriately
- Use modern coding style
- Dynamic tools
  - UBSan, ASan, Valgrind
  - And test like crazy, use fuzzers, etc.
- Static analysis tools
  - Enable and heed compiler warnings
  - Lots more

Facts About UB in LLVM

- It exists to support generation of good code
- It is independent of undefined behavior in source or target languages
  - You can compile an UB-free language to LLVM
- It comes in several flavors
- Reasoning about optimizations in the presence of UB is very difficult

- Compilers transform source programs to target programs in a series of steps, e.g.
  - Swift ➔ SIL
  - SIL ➔ LLVM
  - LLVM ➔ ARMv8
- At each step
  - OK to remove UB
  - Must not add UB
  - This is **refinement**
- Example: Shift instructions are defined for shifts past bitwidth
  - But different processors define it differently

LLVM has three kinds of UB

1. Undef
   - Explicit value in the IR
   - Acts like a free-floating hardware register
     - Takes all possible bit patterns at the specified width
     - Can take a different value every time it is used
   - Comes from uninitialized variables
   - Further reading
     - http://sunfishcode.github.io/blog/2014/07/14/undef-introduction.html

- We want this optimization:

```
%add = add nsw i32 %a, %b
%cmp = icmp sgt i32 %add, %a
    =>
%cmp = icmp sgt i32 %b, 0
```

- But undef doesn’t let us do it:

```
%add = add nsw i32 %INT_MAX, %1
%cmp = icmp sgt i32 undef, %INT_MAX
```

- There’s no bit pattern we can substitute for the undef that makes %cmp = true

LLVM has three kinds of UB

2. Poison
   - Ephemeral effect of math instructions that violate
     - nsw – no signed wrap for add, sub, mul, shl
     - nuw – no unsigned wrap for add, sub, mul, shl
     - exact – no remainder for sdiv, udiv, lshr, ashr
   - Designed to support speculative execution of operations that might overflow
   - Poison propagates via instruction results
   - If poison reaches a side-effecting instruction, the result is true UB

LLVM has three kinds of UB

3. True undefined behavior
   - Triggered by
     - Divide by zero
     - Illegal memory accesses
   - Anything can happen as a result
     - Typically results in corrupted execution or a processor exception

- Which of these transformations is OK?

```
%result = add nsw i32 %a, %b
    =>
%result = add i32 %a, %b
```

I'm OK

```
%result = add i32 %a, %b
    =>
%result = add nsw i32 %a, %b
```

- Use Alive to do automated proofs about LLVM peephole optimizations:
  - https://github.com/nunoplopes/alive
  - Alive understands all three kinds of UB

```
$ ./alive.py add.opt
----------------------------------------
Optimization: 1
Precondition: true
  %result = add nsw i32 %a, %b
=>
  %result = add i32 %a, %b

Done: 1
Optimization is correct!
```

```
$ ./alive.py add-bad.opt
----------------------------------------
Optimization: 1
Precondition: true
  %result = add i32 %a, %b
=>
  %result = add nsw i32 %a, %b


ERROR: Domain of poisoness of Target is smaller
than Source's for i32 %result

Example:
%a i32 = 0x7FFFEFFF (2147479551)
%b i32 = 0x7FFFFBFF (2147482623)
Source value: 0xFFFFEBFE (4294962174, -5122)
Target value: poison
```

- We translated a bunch of InstCombine patterns into Alive
  - Found some wrong ones, reported bugs
  - Found some missed opportunities to preserve UB flags (nsw, nuw, exact)
- Details can be found in a paper
  - http://www.cs.utah.edu/~regehr/papers/pldi15.pdf
- Please try out Alive if you reason about peephole optimizations in LLVM

Conflicting design goals for LLVM UB

1. Enable all optimizations that we want to perform
2. Be internally consistent
3. Be consistent with the LLVM implementation

The current scheme generally works fine

- But it’s not clear that it actually meets any of these three goals

- Nuno Lopes is heading an effort to rework poison and undef
  - Currently they are (we think) unnecessarily complicated
  - Goal is to make undef a bit stronger and drop poison entirely
  - No change to "true UB"
- Other compilers (GCC, Microsoft) have similar UB-related concepts
  - Detailed specifications are hard to find
  - Same motivation: support efficient code gen

Thanks!