Sanitizers: Instrumentation for Efficient Debugging

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HIC for FAIR
Helmholtz International Center

FIAS Frankfurt Institute for Advanced Studies

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Outline

you know valgrind, right?

Think valgrind, but ...

- faster
- more precise
- detects more/different issues
- switched on at compile time:
  - instrumentation added at compile time
  - not at run time as valgrid does

Existing sanitizers:

Address	memory (stack & heap & globals) error detector
Thread	data race detector
Memory	detector of uninitialized reads
Undefined	undefined behavior checker
...	more (`http://clang.llvm.org/docs/UsersManual.html#controlling-code-generation`)

Experimental but interesting (asan):

use-after-return	accessing local variable after the function exit
use-after-scope	accesing local variable after it went out of scope

- sanitzers developed for clang
- ports to GCC ongoing:
  - 4.8 Address & Thread Sanitizer
  - 4.9 Undefined Behavior Sanitizer

Address Sanitizer

fast memory error detector

- Out-of-bounds accesses to heap, stack and globals
- Use-after-free
- Use-after-return (to some extent)
- Double-free, invalid free
- Memory leaks (experimental)
- slowdown: $2\times$

Thread Sanitizer

- detects data races
- slowdown is about $5\times$–$15\times$
- memory overhead is about $5\times$–$10\times$

Memory Sanitizer

- detector of uninitialized reads
- slowdown is $3\times$

Undefined Behavior Sanitizer

- undefined behavior checker
- small runtime cost and no impact on address space layout or ABI
- finds:
  - misaligned pointer or creation of a misaligned reference
  - **`bool`** value which is neither `true` nor `false`
  - out of bounds array indexing (statically)
  - value of an enumerated type which is not in range
  - conversion to, from, or between floating-point types which would overflow the destination
  - floating point division by zero
  - indirect call of a function through a function pointer of the wrong type
  - integer division by zero
  - use of a null pointer or creation of a null reference
  - ...

Address Sanitizer

```
1  int main(int argc, char **argv)
2  {
3    int *array = new int[100];
4    delete[] array;
5    return array[argc];
6  }
```

```
clang++ -O2 -g -fno-omit-frame-pointer -std=c++11
-fsanitize=address -o asan asan.cpp
```

Address Sanitizer

```
1  ==================================================================
2  ==31582==ERROR: AddressSanitizer: heap-use-after-free on address 0x61400000fe44 at pc 0
       x462f52 bp 0x7fff080b22d0 sp 0x7fff080b22c8
3  READ of size 4 at 0x61400000fe44 thread T0
4      #0 0x462f51 in main /home/mkretz/src/sanitize_examples/asan.cpp:5
5      #1 0x2b6a8bdedec4 in __libc_start_main /build/buildd/eglibc-2.19/csu/libc-start.c:287
6      #2 0x462e35 in _start (/home/mkretz/src/sanitize_examples/asan+0x462e35)
7
8  0x61400000fe44 is located 4 bytes inside of 400-byte region [0x61400000fe40,0x61400000ffd0)
9  freed by thread T0 here:
10     #0 0x44d81e in operator delete[](void*) /home/mkretz/src/llvm/projects/compiler-rt/lib/
           asan/asan_new_delete.cc:85
11     #1 0x462f1e in main /home/mkretz/src/sanitize_examples/asan.cpp:4
12     #2 0x2b6a8bdedec4 in __libc_start_main /build/buildd/eglibc-2.19/csu/libc-start.c:287
13
14 previously allocated by thread T0 here:
15     #0 0x44d51e in operator new[](unsigned long) /home/mkretz/src/llvm/projects/compiler-rt
           /lib/asan/asan_new_delete.cc:54
16     #1 0x462f13 in main /home/mkretz/src/sanitize_examples/asan.cpp:3
17     #2 0x2b6a8bdedec4 in __libc_start_main /build/buildd/eglibc-2.19/csu/libc-start.c:287
18
19 SUMMARY: AddressSanitizer: heap-use-after-free /home/mkretz/src/sanitize_examples/asan.cpp
       :5 main
20 Shadow bytes around the buggy address:
21   0x0c287fff9f70: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
22   0x0c287fff9f80: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
23   0x0c287fff9f90: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
24   0x0c287fff9fa0: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
25   0x0c287fff9fb0: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
26 =>0x0c287fff9fc0: fa fa fa fa fa fa fa fa[fd]fd fd fd fd fd fd fd
27   0x0c287fff9fd0: fd fd fd fd fd fd fd fd fd fd fd fd fd fd fd fd
```

Address Sanitizer

```
21     0x0c287fff9f70: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
22     0x0c287fff9f80: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
23     0x0c287fff9f90: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
24     0x0c287fff9fa0: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
25     0x0c287fff9fb0: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
26   =>0x0c287fff9fc0: fa fa fa fa fa fa fa fa[fd]fd fd fd fd fd fd fd
27     0x0c287fff9fd0: fd fd fd fd fd fd fd fd fd fd fd fd fd fd fd fd
28     0x0c287fff9fe0: fd fd fd fd fd fd fd fd fd fd fd fd fd fd fd fd
29     0x0c287fff9ff0: fd fd fd fd fd fd fd fd fd fd fa fa fa fa fa fa
30     0x0c287fffa000: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
31     0x0c287fffa010: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
32   Shadow byte legend (one shadow byte represents 8 application bytes):
33     Addressable:           00
34     Partially addressable: 01 02 03 04 05 06 07
35     Heap left redzone:     fa
36     Heap right redzone:    fb
37     Freed heap region:     fd
38     Stack left redzone:    f1
39     Stack mid redzone:     f2
40     Stack right redzone:   f3
41     Stack partial redzone: f4
42     Stack after return:    f5
43     Stack use after scope: f8
44     Global redzone:        f9
45     Global init order:     f6
46     Poisoned by user:      f7
47     ASan internal:         fe
48   ==31582==ABORTING
```

Thread Sanitizer

```
1  #include <thread>
2  int Global;
3  int main()
4  {
5    std::thread t([]() {
6      Global = 42;
7    });
8    Global = 43;
9    t.join();
10   return Global;
11 }
```

```
clang++ -O2 -g -fno-omit-frame-pointer -std=c++11
-fsanitize=thread -o tsan tsan.cpp
```

Thread Sanitizer

```
1  ==31585==Re-execing with stack size limited to 33554432 bytes.
2  ==================
3  WARNING: ThreadSanitizer: data race (pid=31585)
4    Write of size 4 at 0x7f8ef22ffca4 by thread T1:
5      #0 operator() /home/mkretz/src/sanitize_examples/tsan.cpp:6 (tsan+0x00000008533d)
6      #1 void std::_Bind_simple<main::$_0 ()>::_M_invoke<>(std::_Index_tuple<>) /usr/lib/gcc/
           x86_64-linux-gnu/4.8/../../../../include/c++/4.8/functional:1731 (tsan+0
           x00000008533d)
7      #2 std::_Bind_simple<main::$_0 ()>::operator()() /usr/lib/gcc/x86_64-linux-gnu
           /4.8/../../../../include/c++/4.8/functional:1720 (tsan+0x00000008533d)
8      #3 std::thread::_Impl<std::_Bind_simple<main::$_0 ()> >::_M_run() /usr/lib/gcc/x86_64-
           linux-gnu/4.8/../../../../include/c++/4.8/thread:115 (tsan+0x00000008533d)
9      #4 <null> <null>:0 (libstdc++.so.6+0x0000000b1bef)
10
11   Previous write of size 4 at 0x7f8ef22ffca4 by main thread:
12     #0 main /home/mkretz/src/sanitize_examples/tsan.cpp:8 (tsan+0x000000084f18)
13
14   Location is global 'Global' of size 4 at 0x7f8ef22ffca4 (tsan+0x0000016caca4)
15
16   Thread T1 (tid=31589, running) created by main thread at:
17     #0 pthread_create /home/mkretz/src/llvm/projects/compiler-rt/lib/tsan/rtl/
           tsan_interceptors.cc:877 (tsan+0x00000001e91b)
18     #1 <null> <null>:0 (libstdc++.so.6+0x0000000b1e3e)
19     #2 __libc_start_main /build/buildd/eglibc-2.19/csu/libc-start.c:287 (libc.so.6+0
           x000000021ec4)
20
21 SUMMARY: ThreadSanitizer: data race /home/mkretz/src/sanitize_examples/tsan.cpp:6 operator
       ()
22 ==================
23 ThreadSanitizer: reported 1 warnings
```


Memory Sanitizer

```
1  #include <cstdio>
2  int main(int argc, char** argv)
3  {
4    int* a = new int[10];
5    a[5] = 0;
6    if (a[argc]) {
7      printf("xx\n");
8    }
9    return 0;
10 }
```

```
clang++ -O2 -g -fno-omit-frame-pointer -std=c++11
-fsanitize=memory -o msan msan.cpp
```

Memory Sanitizer

```
1  ==31590== WARNING: MemorySanitizer: use-of-uninitialized-value
2      #0 0x7f5a7b6b7916 in main /home/mkretz/src/sanitize_examples/msan.cpp:6
3      #1 0x7f5a7a247ec4 in __libc_start_main /build/buildd/eglibc-2.19/csu/libc-start.c:287
4      #2 0x7f5a7b6b775a in _start (/home/mkretz/src/sanitize_examples/msan+0x5c75a)
5
6  SUMMARY: MemorySanitizer: use-of-uninitialized-value /home/mkretz/src/sanitize_examples/
         msan.cpp:6 main
7  Exiting
```

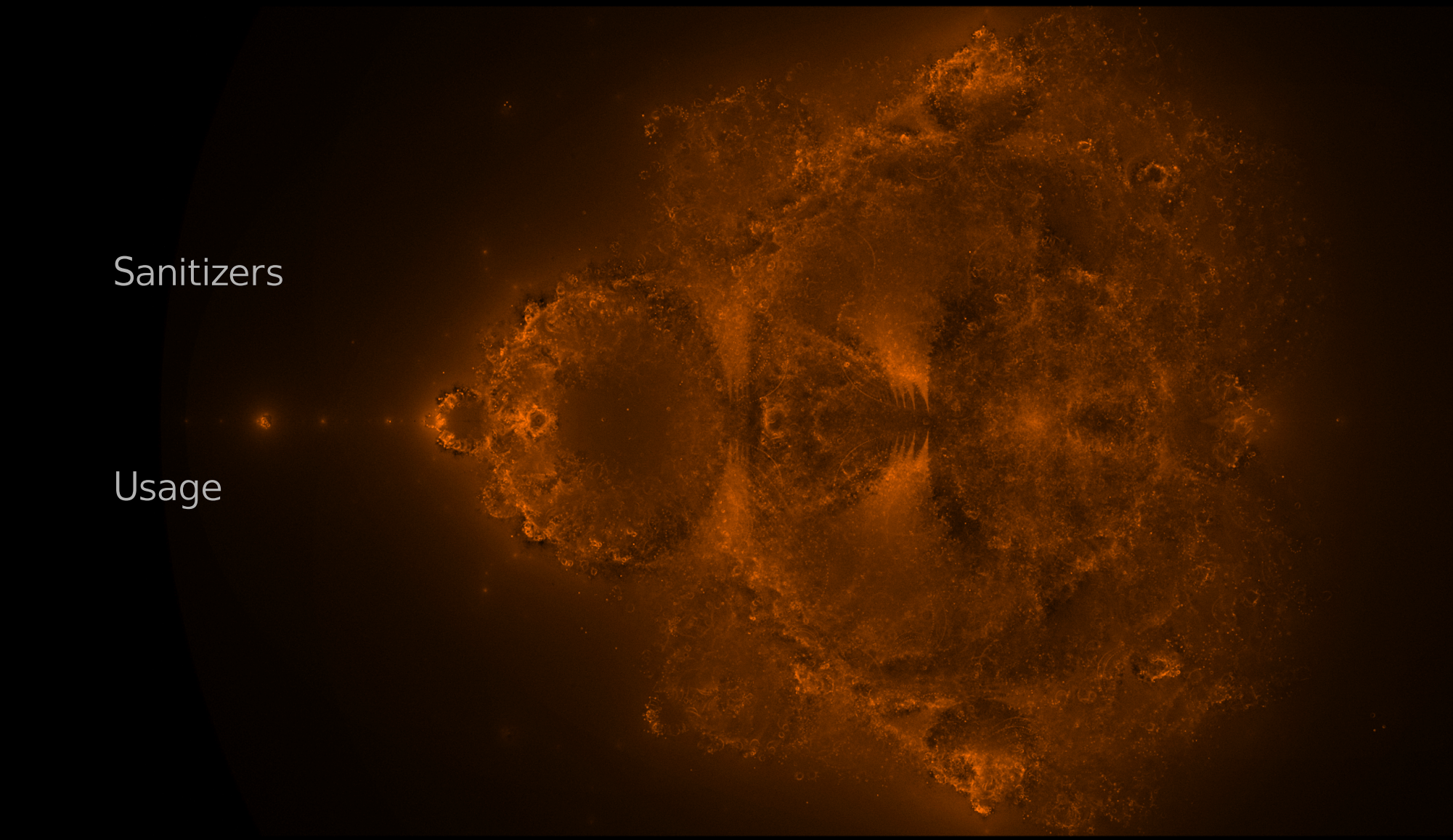
Undefined Behavior Sanitizer

```
1  int main()
2  {
3    float x = 1;
4    float y = 0;
5    x /= y;
6    return x;
7  }
```

```
clang++ -O2 -g -fno-omit-frame-pointer -std=c++11
-fsanitize=undefined -o usan usan.cpp
```

Undefined Behavior Sanitizer

```
1   usan.cpp:5:5: runtime error: division by zero
2   /home/mkretz/src/sanitize_examples/usan.cpp:6: runtime error: value inf is outside the
        range of representable values of type 'int'
```


Sanitizers
Usage