Finding races and memory errors with LLVM instrumentation

AddressSanitizer, ThreadSanitizer

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LLVM Dev Meeting
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Agenda

- AddressSanitizer (memory error detector)
- ThreadSantizer (race detector)
- Challenges

Memory bugs in C++

- Out-of-bounds accesses (OOB, buffer overflow/underflow)
  - Heap
  - Stack
  - Globals
- Use-after-free (UAF, dangling pointer)
- Use-after-return (UAR)
- Uninitialized memory reads (UMR)
- Leaks
- Double free
- Invalid free
- Overapping memcpy parameters
- ...

AddressSanitizer vs Valgrind (Memcheck)

	Valgrind	AddressSanitizer
Heap out-of-bounds	YES	YES
Stack out-of-bounds	NO	YES
Global out-of-bounds	NO	YES
Use-after-free	YES	YES
Use-after-return	NO	Sometimes/YES
Uninitialized reads	YES	NO
Overhead	10x-30x	1.5x-3x
Platforms	Linux, Mac	Same as GCC/LLVM *

AddressSanitizer overview

- Compile-time instrumentation
  - Currently uses LLVM, 1 KLOC
  - GCC variant is in progress
- Run-time library (~5 KLOC)
- Supports {x86,x86_64} x {Linux,Mac}
  - ARM/Linux almost works (in progress)
- Found hundreds bugs since May 2011
  - Chromium (WebKit, ffmpeg)
  - Server-side apps
  - Even one in clang
- Soon to be in LLVM mainline
  - Instrumentation module is already committed

Shadow bytes

Every aligned 8-byte word of memory have only 9 states:
first k (0<=k<=8) bytes are addressable, the rest are not.

State of every 8-byte word can be encoded in 1 byte
(shadow byte)

(Extreme: up to 128 application bytes per 1 shadow byte)

Instrumentation: 8 byte access

```
*a = ...
```

→

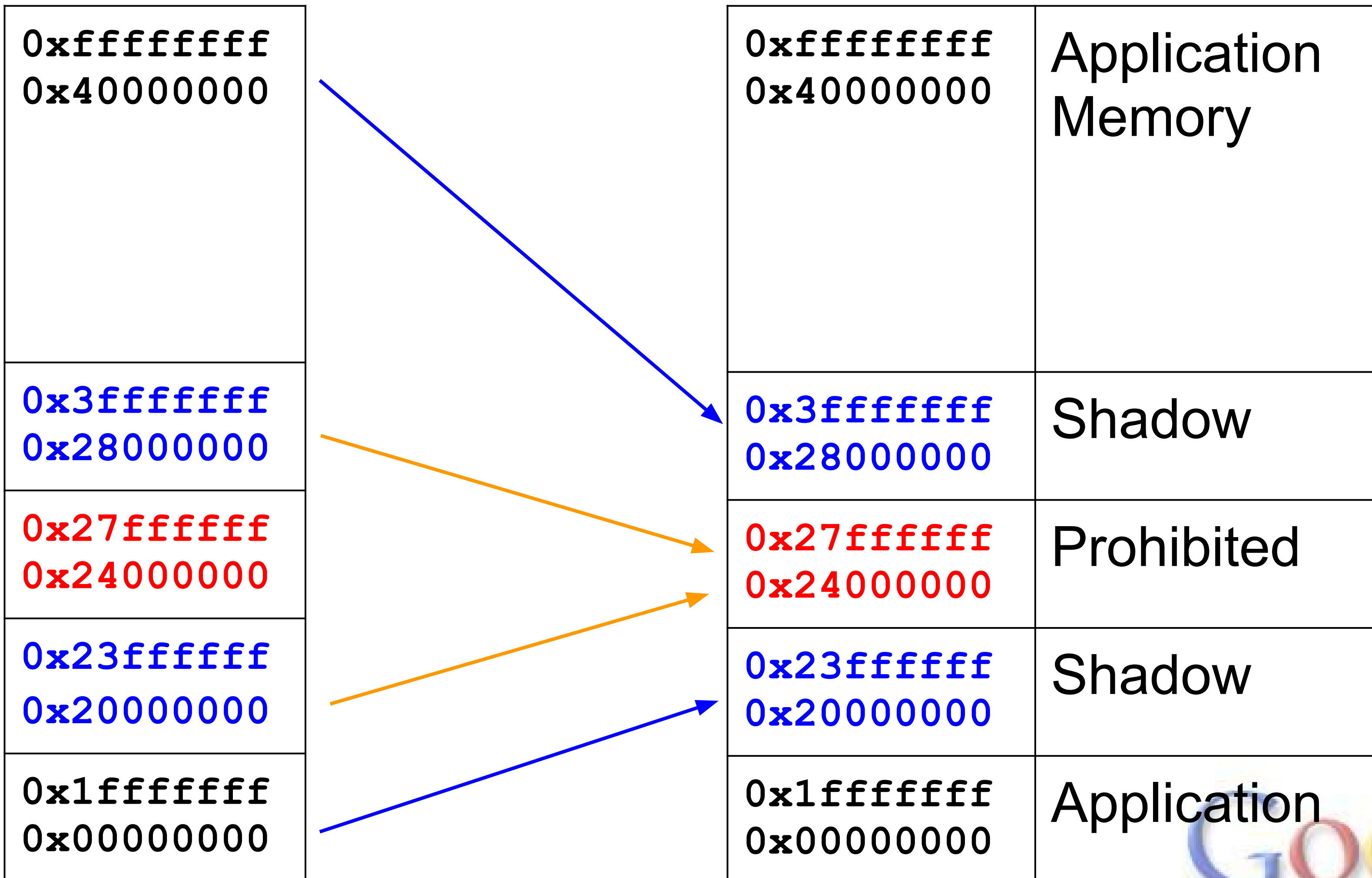
```
char *shadow = MemToShadow(a);
if (*shadow)
   ReportError(a);
*a = ...
```

Instrumentation: N byte access (N=1, 2, 4)

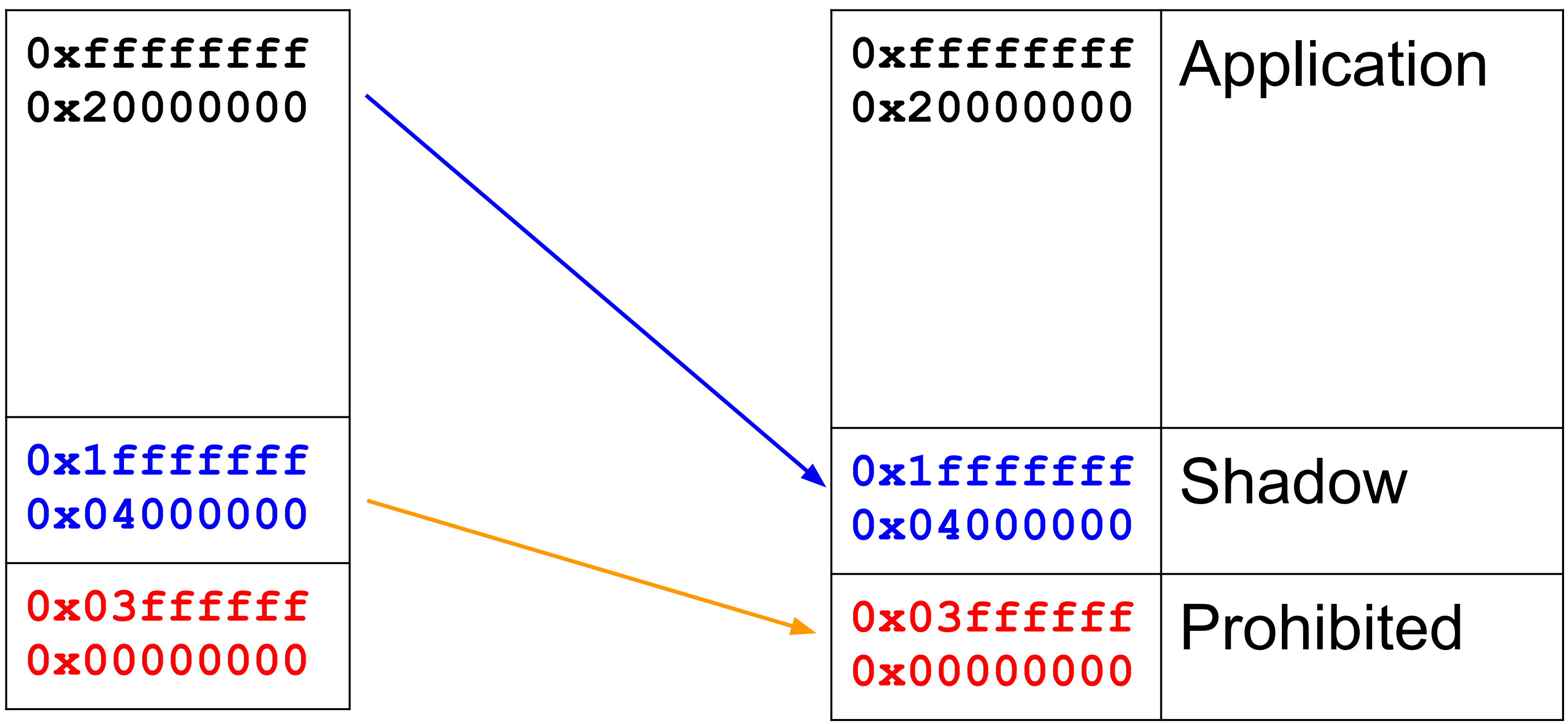
```
*a = ...
```

```
char *shadow = MemToShadow(a);
if (*shadow &&
     *shadow <= ((a&7)+N-1)) {
   ReportError(a);
}
*a = ...
```

Mapping: Shadow = (Addr>>3) + Offset



Mapping: **Shadow** `= (Addr>>3) + 0`



- Requires **`-fPIE -pie`**
- Gives ~6% speedup
- Can this be made default for everyone?

Instrumentation example (x86_64)

```
shr $0x3,%rax                # shift by 3
mov $0x100000000000,%rcx
or %rax,%rcx                 # add offset
cmpb $0x0,(%rcx)             # load shadow
je 1f <foo+0x1f>
mov %rdi,%rax                # failing address in %rax
ud2a                         # generate SIGILL*
movq $0x1234,(%rdi)          # original store
```

*Can use call instead of UD2

Instrumenting stack

- Fast protocol
    - Poison redzones at function entry
    - Unpoison redzones at function exit (must happen)
    - Assume the rest of the stack frame is unpoisoned
    - + Fast: O(number of locals) instructions
    - - Tricky when exceptions or longjmp are present
    - - Small probability of finding use-after-return
- Slow protocol
    - Poison redzones and unpoison locals at function entry
    - Poison the entire frame at function exit (optional)
    - + Friendly to exceptions and longjmp
    - + Better for use-after-return
    - - Slower: O(size of the stack frame) instructions

Instrumenting stack

```
void foo() {
  char a[328];



  <------------- CODE ------------->
}
```

Instrumenting stack (fast protocol)

```
void foo() {
  char rz1[32];  // 32-byte aligned
  char a[328];
  char rz2[24];
  char rz3[32];
  int  *shadow = (&rz1 >> 3) + kOffset;
  shadow[0] = 0xffffffff;    // poison rz1

  shadow[11] = 0xffffff00;  // poison rz2
  shadow[12] = 0xffffffff;  // poison rz3
  <------------- CODE ------------->
  shadow[0] = shadow[11] = shadow[12] = 0;
}
```

Instrumenting stack (slow protocol)

```
void foo() {
  char rz1[32];  // 32-byte aligned
  char a[328];
  char rz2[24];
  char rz3[32];
  int  *shadow = (&rz1 >> 3) + kOffset;
  shadow[0] = 0xffffffff;     // poison rz1
  shadow[1:10] = 0;           // unpoison a
  shadow[11] = 0xffffff00;    // poison rz2
  shadow[12] = 0xffffffff;    // poison rz3
  <------------- CODE ------------->
  shadow[0:13] = 0xffffffff;
}
```

Instrumenting globals

```
int a;
```

→

```
struct {
  int original;
  char redzone[60];
} a;  // 32-aligned
```

```
double b;
```

→

```
struct {
  double original;
  char redzone[56];
} b;  // 32-aligned
```

Use-after-return

- Default mode
  - Will report UAR only occasionally as "strange" stack buffer overflow
- Special mode (slower, in progress)
  - Put all stack objects on heap
  - Delay reuse

```
int LocalPtr() {
  int local;
  return &local;
}

void Bad() {
  int *p = LocalPtr();
  Access(p);
}
```

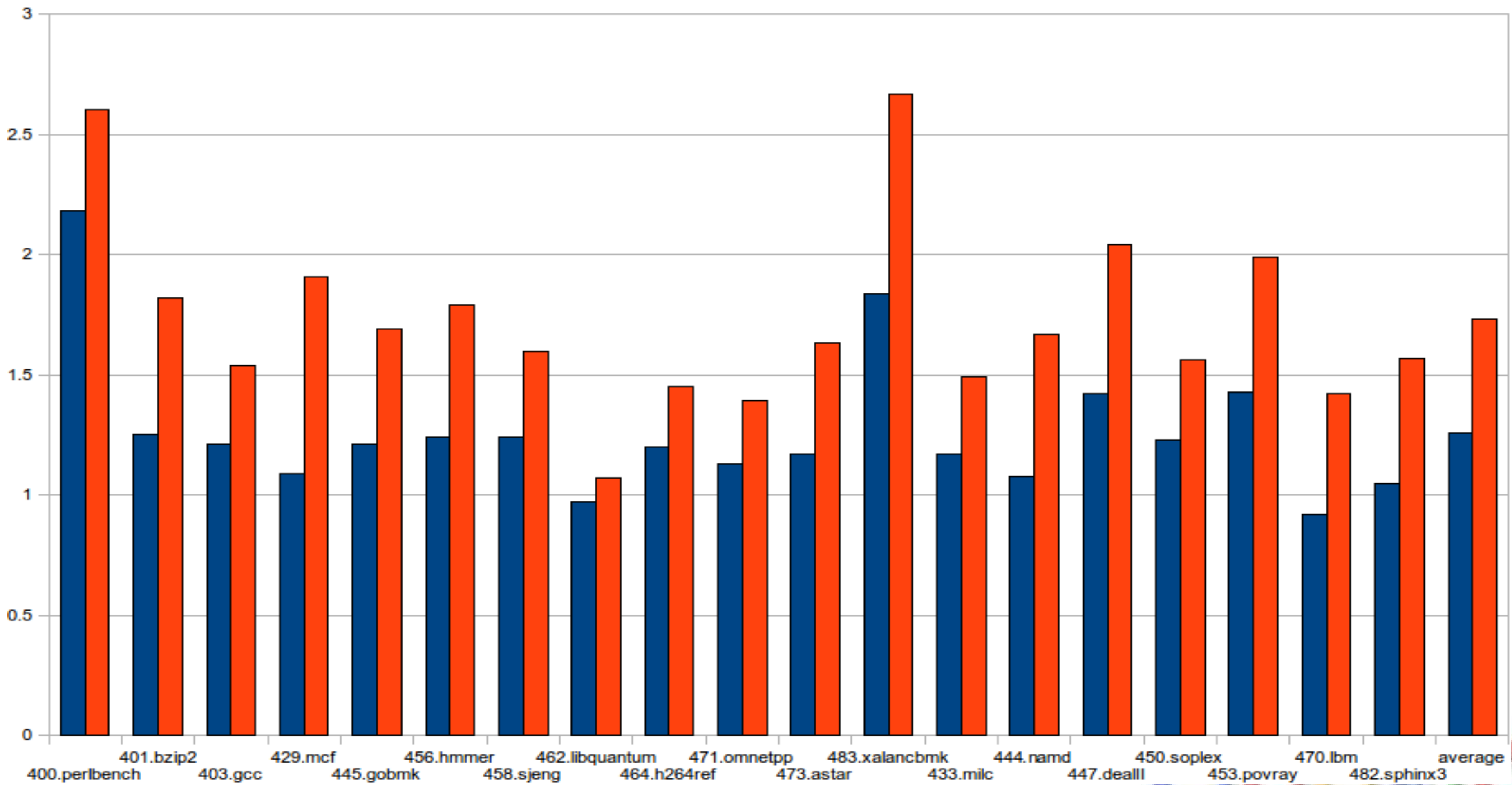
Run-time library

- Initializes shadow memory at startup
- Provides full **`malloc`** replacement
  - Insert poisoned redzones around allocated memory
  - Quarantine for **`free`**-ed memory
  - Collect stack traces for every **`malloc/free`**
- Provides interceptors for functions like **`strlen`**
- Prints error messages

Report example (use-after-free)

```
==10613== ERROR: AddressSanitizer heap-use-after-free
  on address 0x7fe8740a6214
  at pc 0x40246f bp 0x7fffe5e463e0 sp 0x7fffe5e463d8

READ of size 4 at 0x7fe8740a6214 thread T0
    #0 0x40246f in main example_UseAfterFree.cc:4
    #1 0x7fe8740e4c4d in __libc_start_main ??:0

0x7fe8740a6214 is located 4 bytes inside of 400-byte region

freed by thread T0 here:
    #0 0x4028f4 in operator delete[](void*) _asan_rtl_
    #1 0x402433 in main example_UseAfterFree.cc:4

previously allocated by thread T0 here:
    #0 0x402c36 in operator new[](unsigned long) _asan_rtl_
    #1 0x402423 in main example_UseAfterFree.cc:2
```

Performance: 1.73x slowdown on cpu2006



Real-life performance

- Almost no slowdown for GUI programs
  - They don't consume all of CPU anyway
- 1.5x - 4x slowdown for server side apps
  - The larger the slower (instruction cache?)
  - Up to 8x with -O1 (inlining? instruction cache?)

Memory overhead

- Heap redzones
  - default is 128-255 bytes per allocation
  - minimal is 32-63 bytes per allocation
- Stack redzones: 32-63 bytes per address-taken local variable
- Global redzones: 32-63 bytes per global
- Fixed size Quarantine (250M)
- (Heap + Globals + Stack + Quarantine) / 8 for shadow

- Typical overal memory overhead is 2x - 4x
  - Seen between 1.1x and 20x
- Stack size increase
  - Seen up to 3x
- Maps (but not reserves) 1/8-th of all address space
  - 16T on 64-bit
  - 0.5G on 32-bit

ThreadSanitizer

- Dynamic detector of data races
  - Uses both lock-set and happens-before
  - Algorithm: [WBIA'09]
  - Similar tools: Helgrind, DRD, Intel Parallel Inspector
- Based on run-time instrumentation
  - Valgrind for Linux and Mac
  - PIN for Windows
- Found 1000+ races in Google code since 2008
- VERY slow (30x is not unusual)
- Decided to use compiler instrumentation
  - A bit similar to LiteRace and Sun Studio (both proprietary)
  - AddressSanitizer is a by-product

ThreadSanitizer + compiler instrumentation

- High level: very similar to AddressSanitizer
- Compiler:
  - Instrument every memory access (call run-time)
  - Instrument function call/entry/exit
    - Unwind is slow, need shadow call stack
- The rest happens in run-time
  - Same state machine as used with Valgrind
  - Intercept various libc/pthread functions
- ~4x faster than with Valgrind (3x-10x)
  - Also parallel
- Status: can build and run Chrome (GCC and LLVM)
- State machine under redesign, expect to be even faster

Challenge: detect UMRs

- Uninitialized Memory Read? Use Valgrind :(
- False positives if some stores are not instrumented
- Need to instrument every store instruction in libraries
- Hybrid tool?
  - Compiler instrumentation for user code
  - Dynamic instrumentation (DynamoRIO?) for libraries

Challenge: statically avoid redundant checks

```
// Instrument only the first access
*a = …
if (…) *a = …

// Instrument only the second access (?)
if (…) … = *a
*a = …

// Instrument only a[0] and a[n-1]
for (int i = 0; i < n; i++) a[i] = i;

// Combine two accesses into one
struct { double align; int a, b; } x; …
x.a = …; x.b = …
```

Q&A

http://code.google.com/p/address-sanitizer/

http://code.google.com/p/data-race-test/