Finding races and memory errors with compiler instrumentation.

AddressSanitizer, ThreadSanitizer.

Konstantin Serebryany, Dmitry Vyukov

GNU Tools Cauldron
10 July 2012

Agenda

- AddressSanitizer, a memory error detector
- ThreadSanitizer, a data race detector
- Status of GCC and LLVM implementations

AddressSanitizer

a memory error detector

Memory Bugs in C++

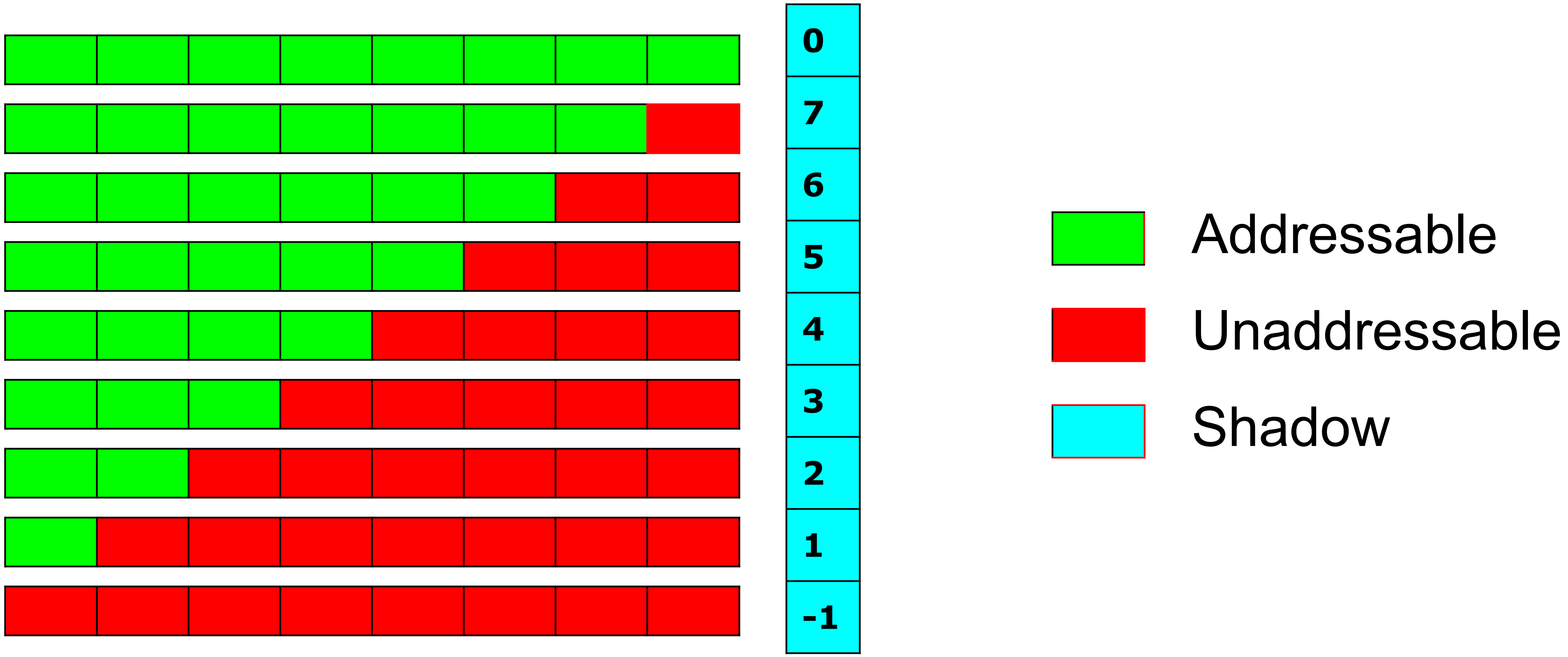
- Buffer overflow
  - Heap
  - Stack
  - Globals
- Use-after-free (dangling pointer)
- Uninitialized memory reads
- Leaks
- Double free
- Invalid free
- Overapping memcpy parameters
- ...

AddressSanitizer overview

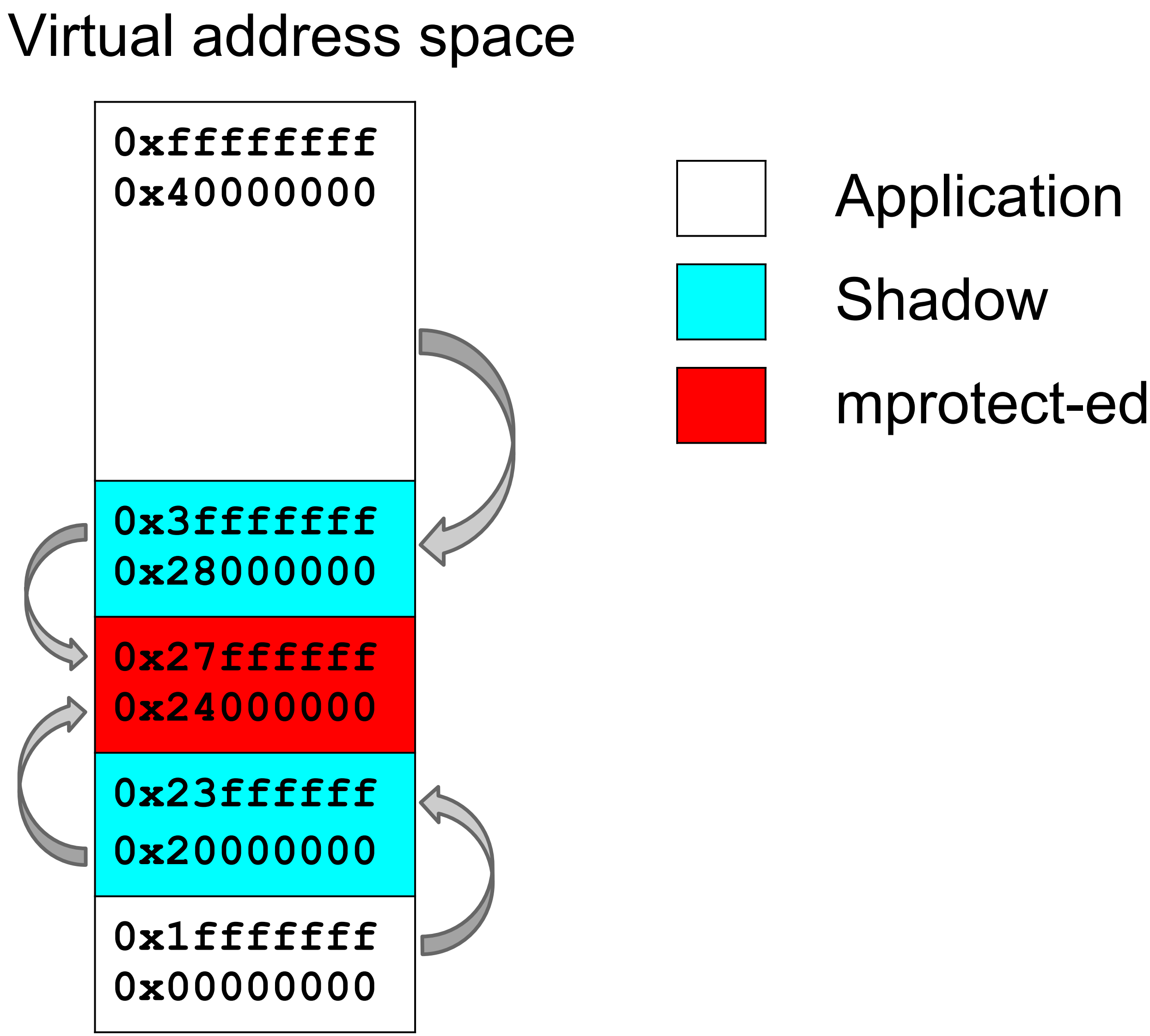
- Compile-time instrumentation module
  - Platform independent
- Run-time library
  - Supports Linux, MacOS, Android, Windows
- Released in May 2011
- Part of LLVM since November 2011

Shadow byte

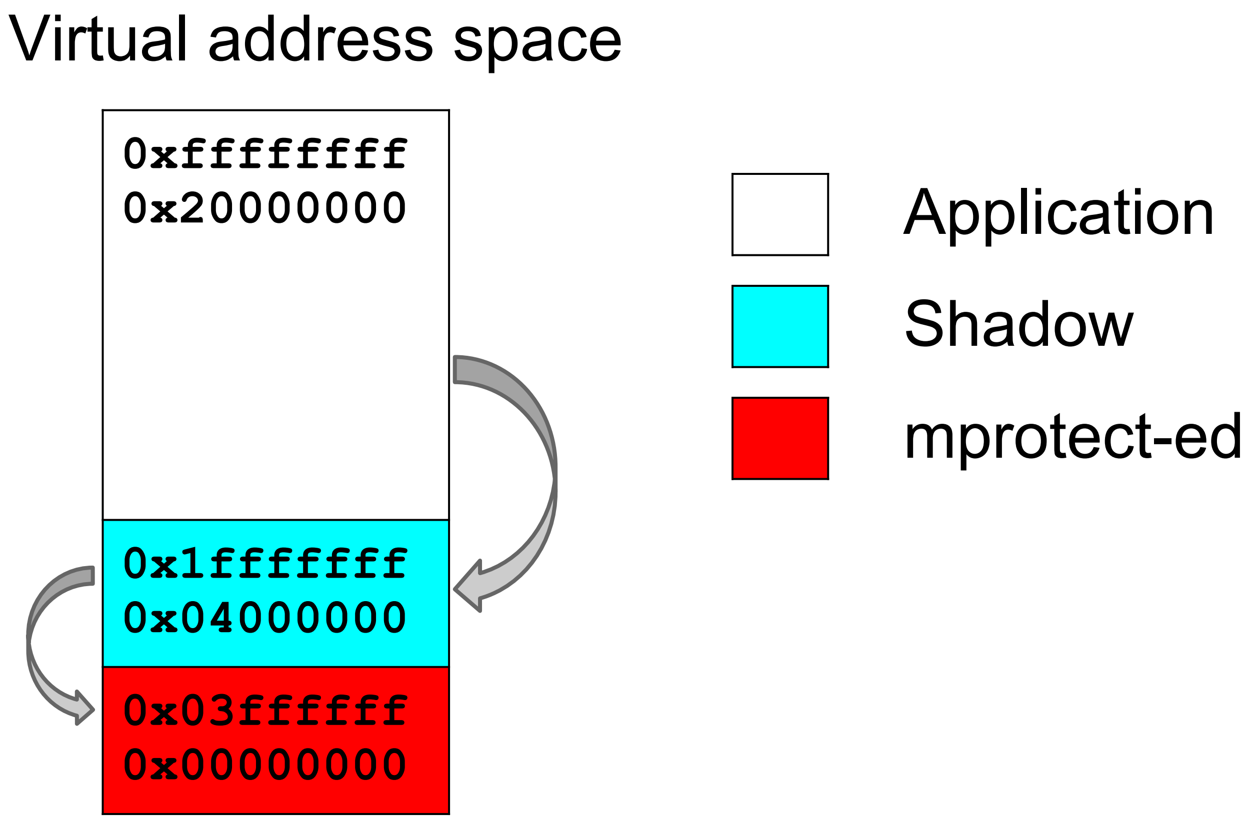
- Every aligned 8-byte word of memory has only 9 states
- First N bytes are addressable, the rest 8-N bytes are not
- Can encode in 1 byte (shadow byte)
- Extreme: 128 application bytes map to 1 shadow byte.



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



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



- Requires **`-fPIE -pie`** (linux)
- Gives ~6% speedup on x86_64

Instrumentation: 8 byte access

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

```
char *shadow = (a>>3)+Offset;
if (*shadow)

    ReportError(a);
*a = ...
```

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

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

```
char *shadow = (a>>3)+Offset;
if (*shadow &&
    *shadow <= ((a&7)+N-1))
   ReportError(a);
*a = ...
```

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>
ud2a                         # generate SIGILL*

movq $0x1234,(%rdi) # original store
```

*** May use call instead of UD2**

Instrumenting stack

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



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

Instrumenting stack

```
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 globals

```
int a;
```

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

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 **`memset`**
- Prints error messages

Report example: use-after-free

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

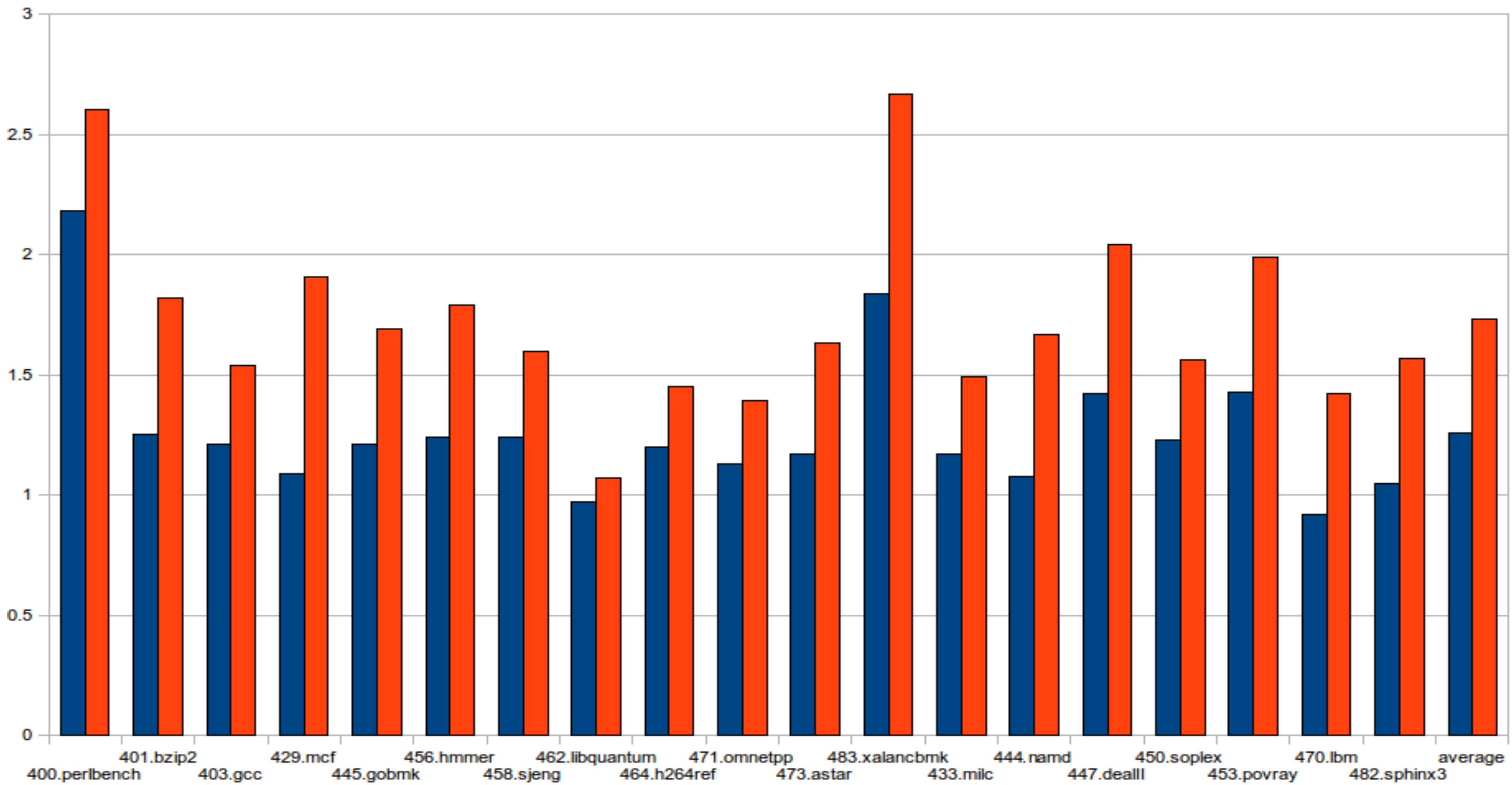
Report example: stack-buffer-overflow

ERROR: AddressSanitizer **stack-buffer-overflow**
  on address 0x7f5620d981b4
  at pc 0x4024e8 bp 0x7fff101cbc90 sp 0x7fff101cbc88

READ of size 4 at 0x7f5620d981b4 thread T0
    #0 0x4024e8 in main example_StackOutOfBounds.cc:4
    #1 0x7f5621db6c4d in __libc_start_main ??:0
    #2 0x402349 in _start ??:0

Address 0x7f5620d981b4 **is located at offset 436 in frame <main>** of T0's stack:
  This frame has 1 object(s):
    [32, 432) 'stack_array'

1.26x slowdown (writes only)
1.73x slowdown (reads & writes)



Real-life performance

- Almost no slowdown for GUI programs
  - Chrome, FireFox
  - They don't consume all of CPU anyway
- 1.5x - 4x slowdown for server side apps with -O2
  - The larger the slower (instruction cache)

Memory overhead

- Heap redzones: 16-31 bytes per allocation (minimal)
  - default: 128-255 bytes per allocation
- Stack redzones: 32-63 bytes per addr-taken local var
- Global redzones: 32-63 bytes per global
- Fixed size Quarantine (256M)
- Shadow:
  - (Heap + Globals + Stack + Quarantine) / 8
- **Typical overall memory overhead is 2x - 4x**
- Stack size increase up to 3x
- `mmap MAP_NORESERVE` 1/8-th of all address space
  - 16T on 64-bit
  - 0.5G on 32-bit

Trophies

- Chromium (including WebKit); in first 10 months
  - heap-use-after-free: 201
  - heap-buffer-overflow: 73
  - global-buffer-overflow: 8
  - stack-buffer-overflow: 7
- Mozilla
- FreeType
- FFmepeg
- libjpeg-turbo
- Perl
- Vim
- LLVM
- GCC (Bug 52629)
- WebRTC
- ...

Future work

- Avoid redundant checks (static analysis)
- Instrument or recompile libraries
- Instrument inline assembler
- Adapt to use in a kernel
- Port to Windows
    - Mostly, frontend work
    - Plain C and simple C++ already works
    - Help is welcome!

C++ is suddenly
a much safer language

Challenge

Implement AddressSanitizer in Hardware

ThreadSanitizer

a data race detector

ThreadSanitizer v1

- Based on Valgrind
- Used since 2009
- Slow (20x-300x slowdown)
  - Still, found thousands races
  - Also, faster than others
- Other race detectors for C/C++:
  - Helgrind (Valgrind)
  - Intel Parallel Inspector (PIN)

ThreadSanitizer v2 overview

- Simple compile-time instrumentation
- Redesigned run-time library
  - Fully parallel
  - No expensive atomics/locks on fast path
  - Scales to huge apps
  - Predictable memory footprint
  - Informative reports

Slowdown

Application	Tsan1	Tsan2	Tsan1/Tsan2
RPC benchmark	283x	8.5x	33x
Server app test	28x	2x	14x
String util test	30x	2.4x	13x

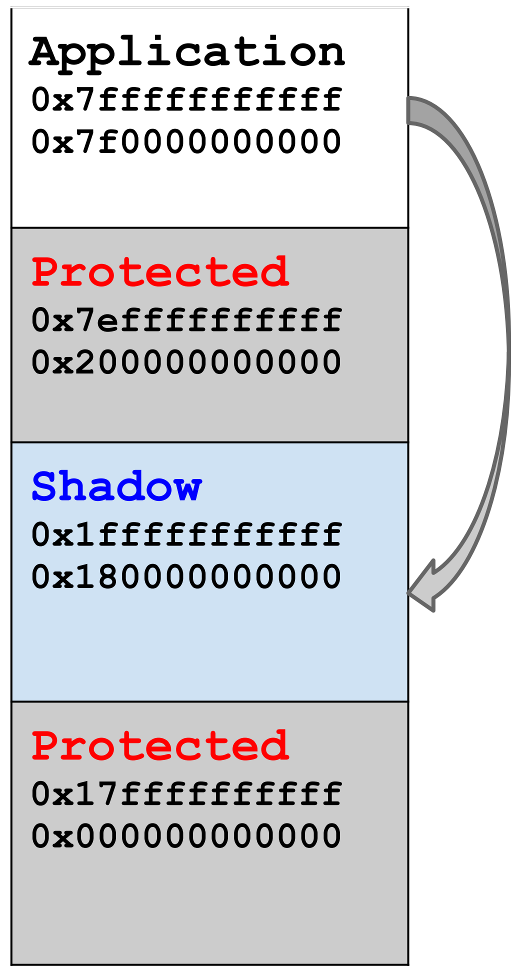
Compiler instrumentation

```
void foo(int *p) {
  *p = 42;
}
```

```
void foo(int *p) {
  __tsan_func_entry(__builtin_return_address(0));
  __tsan_write4(p);
  *p = 42;
  __tsan_func_exit()
}
```

Direct mapping (64-bit Linux)

`Shadow = N * (Addr & Mask);` // Requires -pie

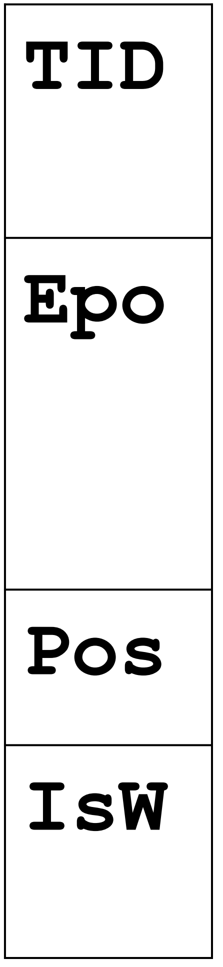


Shadow cell

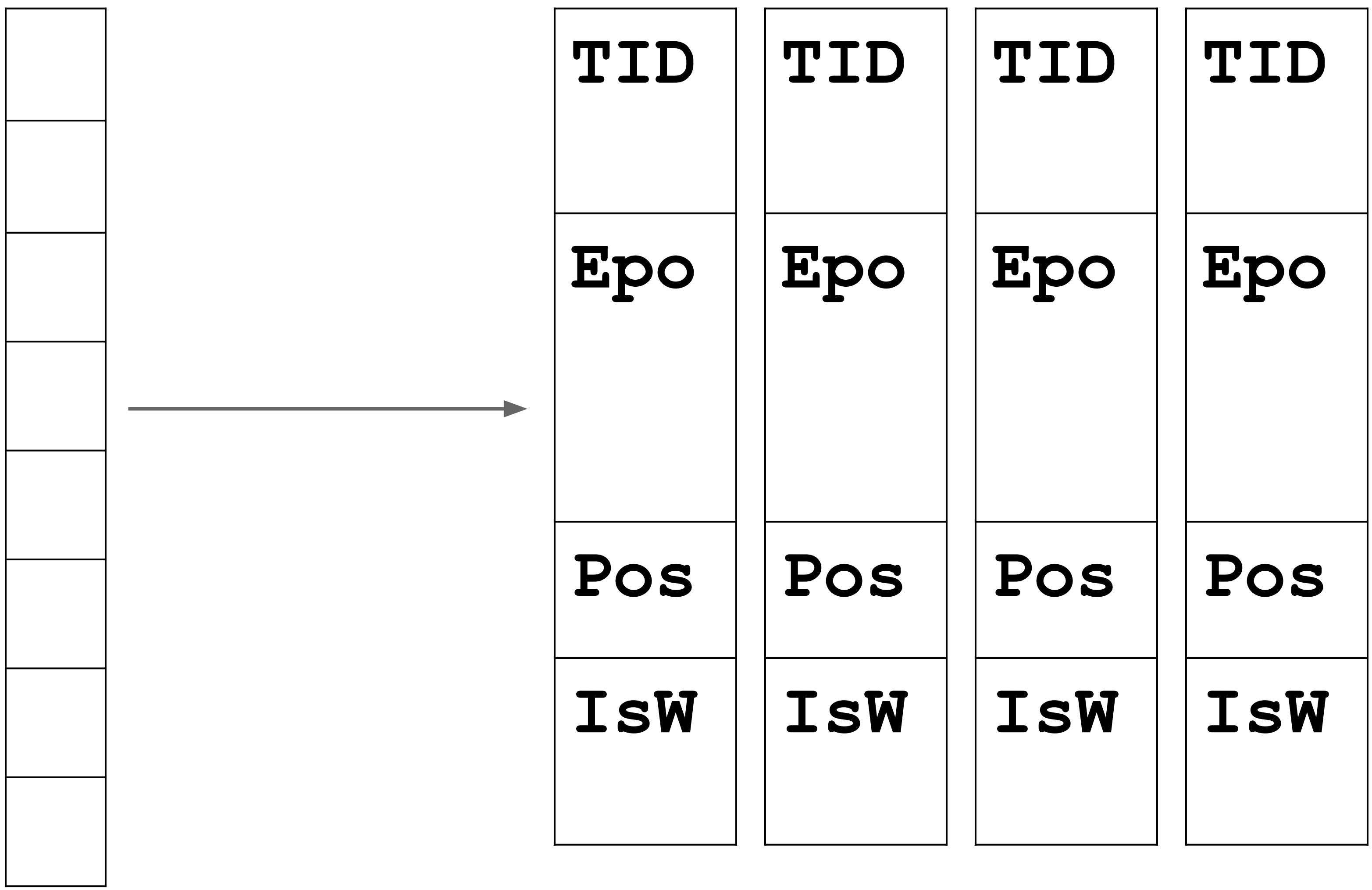
An 8-byte shadow cell represents one memory access:

- ~16 bits: TID (thread ID)
- ~42 bits: Epoch (scalar clock)
- 5 bits: position/size in 8-byte word
- 1 bit: IsWrite

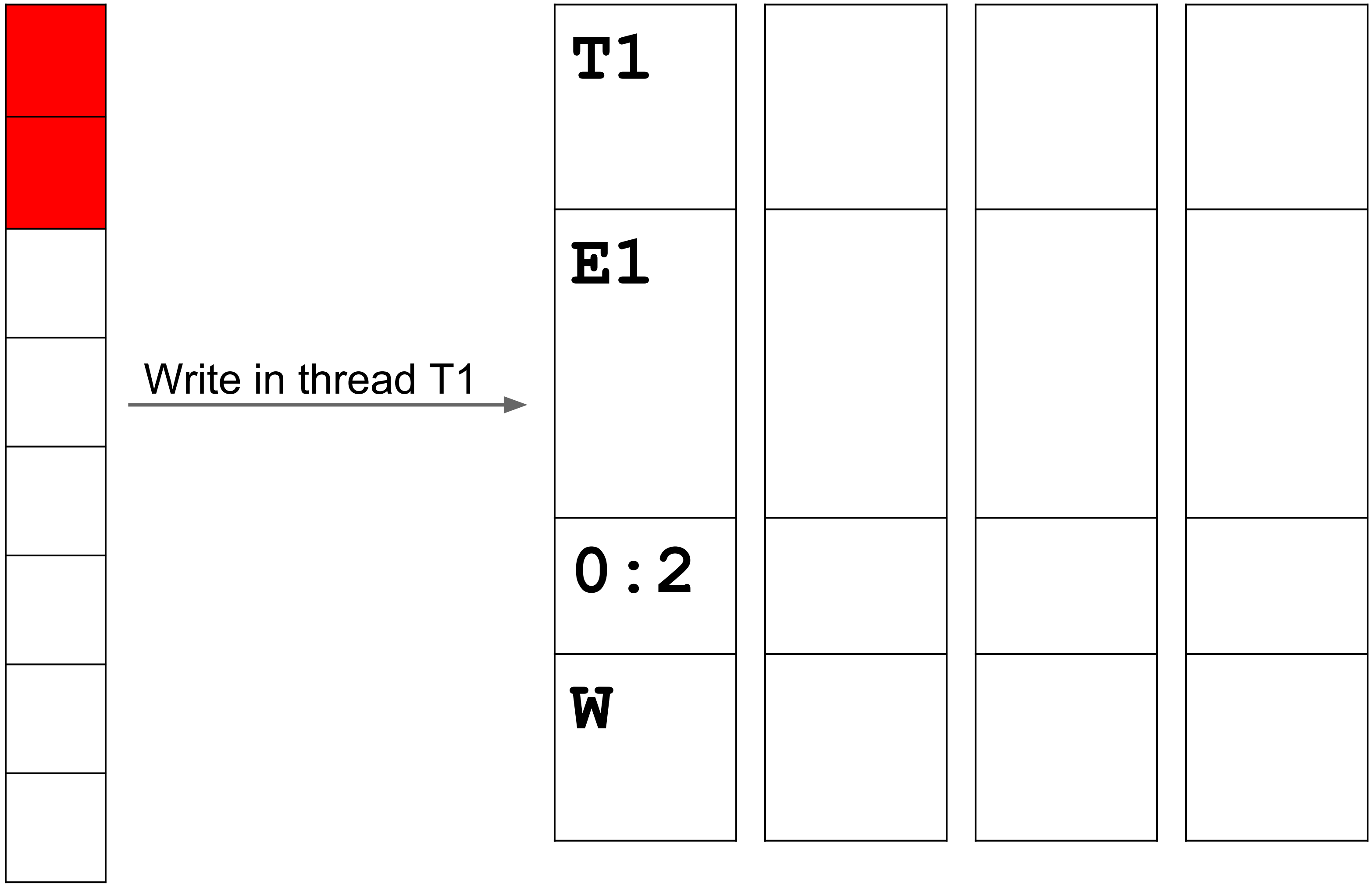
Full information (no more dereferences)



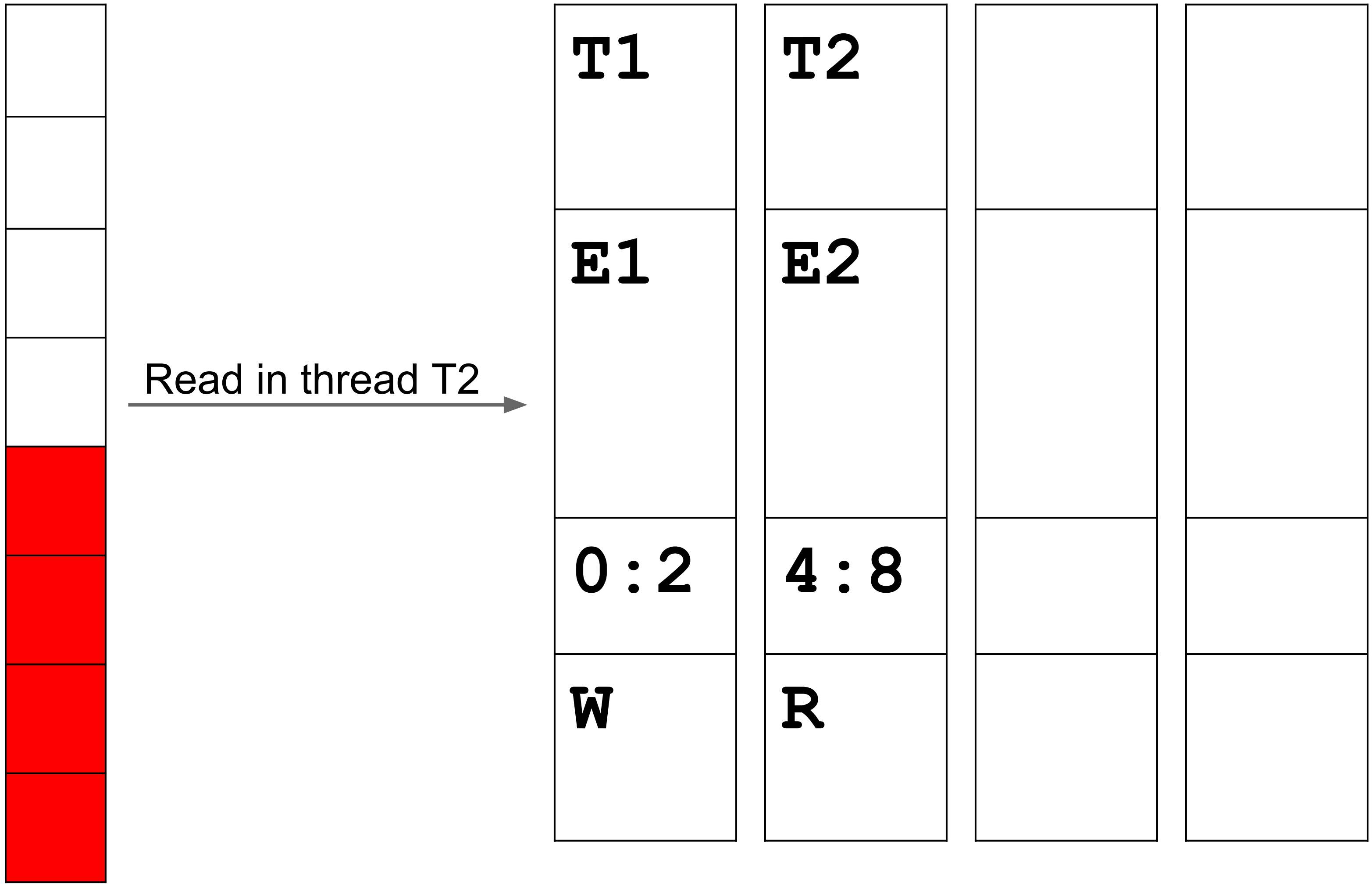
N shadow cells per 8 application bytes



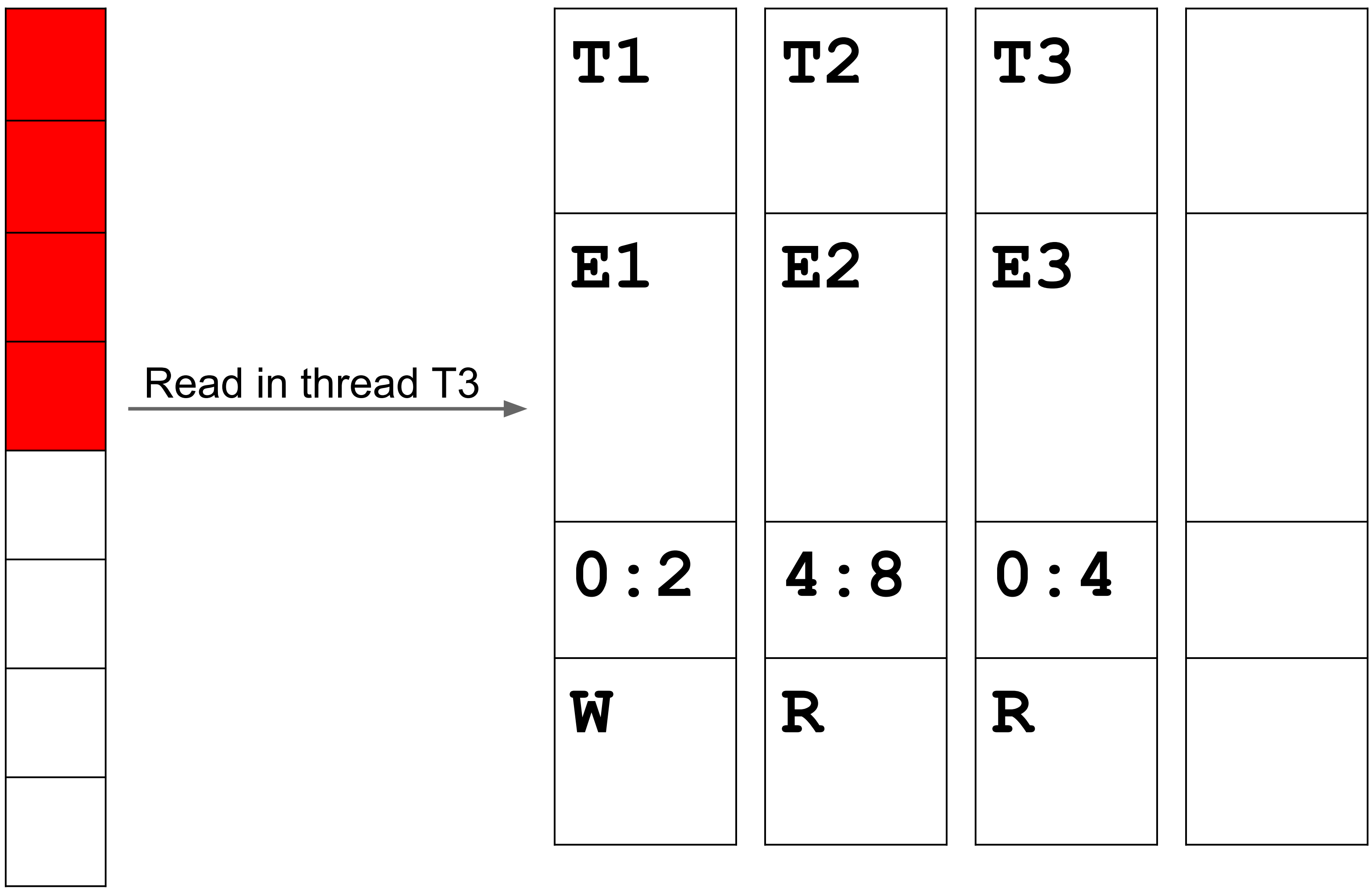
Example: first access



Example: second access



Example: third access



Example: race?

Race if **`E1`** not "happens-before" **`E3`**

T1	**T2**	**T3**	
E1	**E2**	**E3**	
0:2	**4:8**	**0:4**	
W	**R**	**R**	

Fast happens-before

- Constant-time operation
  - Get TID and Epoch from the shadow cell
  - 1 load from TLS
  - 1 compare
- Similar to FastTrack (PLDI'09)

Shadow word eviction

- When all shadow words are filled, one random is replaced

Informative reports

- Need to report two stack traces:
  - current (easy)
  - previous (hard)
- TSan1:
  - Stores fixed number of frames (default: 10)
  - Information is never lost
  - Reference-counting and garbage collection

Previous stack traces in TSan2

- Per-thread cyclic buffer of events
  - 64 bits per event (type + pc)
  - Events: memory access, function entry/exit
  - Information will be lost after some time
- Replay the event buffer on report
  - Unlimited number of frames

Function interceptors

- 100+ interceptors
  - malloc, free, ...
  - pthread_mutex_lock, ...
  - strlen, memcmp, ...
  - read, write, ...

Limitations

- Only 64-bit Linux
- Heavily relies on TLS
  - Slow TLS on some platforms
- Hard to port to 32-bits :(
  - Too small address space
  - Expensive atomic 64-bit load/store
- Does not instrument:
  - pre-built libraries
  - inline assembler

Status of GCC and LLVM implementations

Disclaimer:
we are not experienced
GCC hackers

Implementation details

- AddressSanitizer
  - Common run-time library + tests: 12 KLOC
  - LLVM: 1 KLOC, in trunk, fully functional
  - GCC: 400 LOC
    - in google/main branch
    - finds only heap bugs, no stack and globals
    - some problems (next slide)
- ThreadSanitizer
  - Common run-time library + tests: 14 KLOC
  - Supports C/C++ and Go
  - LLVM: 400 LOC, in trunk, fully functional
  - GCC: 400 LOC, separate plugin
    - does not instrument atomic operations

Problems with GCC (AddressSanitizer)

- Compile time: SLOW!
  - clang < clang+asan < gcc < gcc+asan (all with -O2)
  - 483.xalancbmk (seconds): 170 < 212 < 338 < 446
- Run-time: 10%-15% slower than LLVM (-O2 vs -O2)
  - Still, not apples-to-apples
- How to get the address of a memory access?
  - Copied some code from mudflap, ugly
- Has to run before loop optimizations
  - Otherwise can’t use build_addr
- Can't deal with bitfield loads
- Adding redzones to stack and global objects:
  - GCC: not clear how to implement in IR (GIMPLE)
  - LLVM: single IR-only transformation pass

GCC from newcomer's point of view

```
Call->setDoesNotReturn();  // LLVM
```

```
TREE_THIS_VOLATILE (call) = 1;  // GCC
```

GCC from newcomer's point of view (2)

```
Value *B =
    IRB.CreateLoad(IRB.CreateIntToPtr(A, Ty));
```

```
t = build1 (INDIRECT_REF, shadow_type,
            build1 (VIEW_CONVERT_EXPR, shadow_ptr_type, t));
t = force_gimple_operand (t, &stmts, false, NULL_TREE);
gimple_seq_add_seq (&seq, stmts);
shadow_value = make_rename_temp (shadow_type,"");
g = gimple_build_assign (shadow_value, t);
```

GCC from newcomer's point of view (3)

```
if (isa<LoadInst>(I) || isa<StoreInst>(I)) ...
```

```
base = get_base_address (expr);
if (base == NULL_TREE
    || TREE_CODE (base) == SSA_NAME
    || TREE_CODE (base) == STRING_CST)
  return;

tcode = TREE_CODE (expr);

/* Below are things we do not instrument
   (no possibility of races or not implemented yet).  */
if (/* Compiler-emitted artificial variables.  */
    (DECL_P (expr) && DECL_ARTIFICIAL (expr))
    /* The var does not live in memory -> no possibility of races.  */
    || (tcode == VAR_DECL
        && TREE_ADDRESSABLE (expr) == 0
        && TREE_STATIC (expr) == 0)
    /* Not implemented.  */
    || TREE_CODE (TREE_TYPE (expr)) == RECORD_TYPE
    /* Not implemented.  */
    || tcode == CONSTRUCTOR
    /* Not implemented.  */
    || tcode == PARM_DECL
    /* Load of a const variable/parameter/field.  */
    || is_load_of_const (expr, is_write))
  return;
```

```
if (tcode == COMPONENT_REF)
  {
    tree field = TREE_OPERAND (expr, 1);
    if (TREE_CODE (field) == FIELD_DECL)
      {
        fld_off = TREE_INT_CST_LOW (DECL_FIELD_BIT_OFFSET (field));
        fld_size = TREE_INT_CST_LOW (DECL_SIZE (field));
        if (((fld_off % BITS_PER_UNIT) != 0)
            || ((fld_size % BITS_PER_UNIT) != 0))
          {
            /* As of now it crashes compilation.
               TODO: handle bit-fields as if touching the whole field.  */
            return;
          }
      }
  }

/* TODO: handle other cases
   (FIELD_DECL, MEM_REF, ARRAY_RANGE_REF, TARGET_MEM_REF, ADDR_EXPR).  */
if (tcode != ARRAY_REF
    && tcode != VAR_DECL
    && tcode != COMPONENT_REF
    && tcode != INDIRECT_REF
    && tcode != MEM_REF)
  return;
```

Summary

- We encourage the GCC community to implement AddressSanitizer and/or ThreadSanitizer compiler module in gcc trunk
- 90% of work is done (the run-time library, tests)

Q&A

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

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

Backup

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-300x	1.5x-3x
Platforms	Linux, Mac	Same as LLVM *

AddressSanitizer vs Mudflap

- Mudflap doesn't work (or is very slow) on any large app
- Otherwise, the functionality is similar