MemorySanitizer

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Agenda

- How it works
- What are the challenges
- Random notes

MSan report example

```
int main(int argc, char **argv) {
  int x[10];
  x[0] = 1;
  if (x[argc]) return 1;
  ...
% clang ... stack_umr.c && ./a.out

WARNING: Use of uninitialized value
    #0 0x7f1c31f16d10 in main stack_umr.c:4
Uninitialized value was created by an
allocation of 'x' in the stack frame of
function 'main'
```

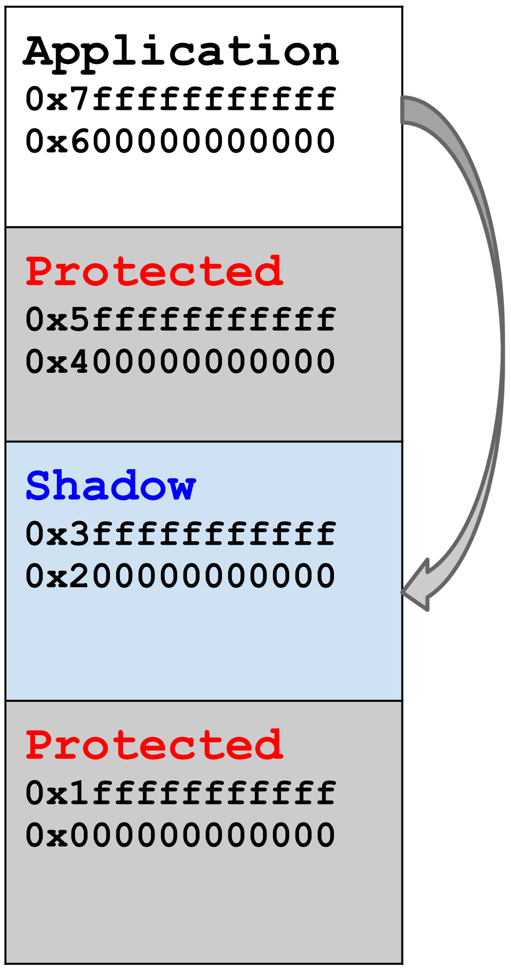
Shadow memory

- 1 application bit => 1 shadow bit
    - 1 = poisoned (uninitialized)
    - 0 = clean (initialized)

- Alternative: 8 bits => 2 bits (Valgrind)
    - 0 = all ok; 1 = all poisoned; 2 = not addressable
    - 3 = partially poisoned (use secondary 1:1 shadow)
    - Slower to extract (VG is slow anyway)
    - Racy updates (VG is single-threaded)
    - More important if combined with redzones
        - VG, but not MSan

Direct 1:1 shadow mapping

```
Shadow = Addr - 0x400000000000;
```



Shadow propagation

Reporting every load of uninitialized data is too noisy.

```
struct {
  char x;
  // 3-byte padding
  int y;
}
```

It's OK to copy uninitialized data around.

Uninit calculations are OK, too, as long as the result is discarded. People do it.

Shadow propagation

- Assign shadow temps to app IR temps.
- Propagate shadow values through expressions
  - A = op B, C => A' = op' B, C, B', C'
- Propagate shadow through function calls: arguments & return values.
- Report UMR only on some uses (branch, syscall, etc)
  - PC is poisoned (a conditional branch)
  - Syscall argument is poisoned (a side-effect)

Shadow propagation

- A = const: A' = 0
- A = load B: A' = load B & ShadowMask
- store B, A: store B & ShadowMask, A'
- A = B << C: A' = B' << C
- A = B & C: A' = (B' & C') | (B & C') | (B' & C)
- A = (B == C):
  - D = B ^ C;   D' = B' | C'; now A = (D == 0)
  - A' = !(D & ~D') && D'
  - Exact.
- Vector types: easy!

Approximate propagation

$$A = B + C: \quad A' = B' \mid C'$$

Exact propagation logic is way too complex.
This is faster than test-and-report.

Bitwise OR is common propagation logic.

- Never makes a value "less poisoned".
- Never makes a poisoned value clean.

Relational comparison

A = (B > C) : A' = (B' | C' != 0)

```
struct S { int a : 3;  int b : 5; };
bool f(S *s) { return s->b; }

%tobool = icmp ugt i16 %bf.load, 7
```

False positive when `a` is uninitialized.

Relational comparison

A = (B > C) : A' = ?

b	a

B = `xxxxx???`

C = `00000111`

Is B > C?

1. **Yes**
2. **No**
3. ~~Maybe~~

Relational comparison

A = (B > C) : A' = ?

- Bmin = MinValue(B, B'); Bmax = MaxValue(B, B')
- Cmin = MinValue(C, C'); Cmax = MaxValue(C, C')
- A' = ((Bmax > Cmin) != (Cmax > Bmin))
- Slow! Up to 50% performance degradation on specs.

Current solution:

- Exact propagation if B or C is a constant.
- A' = B' | C' otherwise.

Tracking origins

- Where was the poisoned memory allocated?

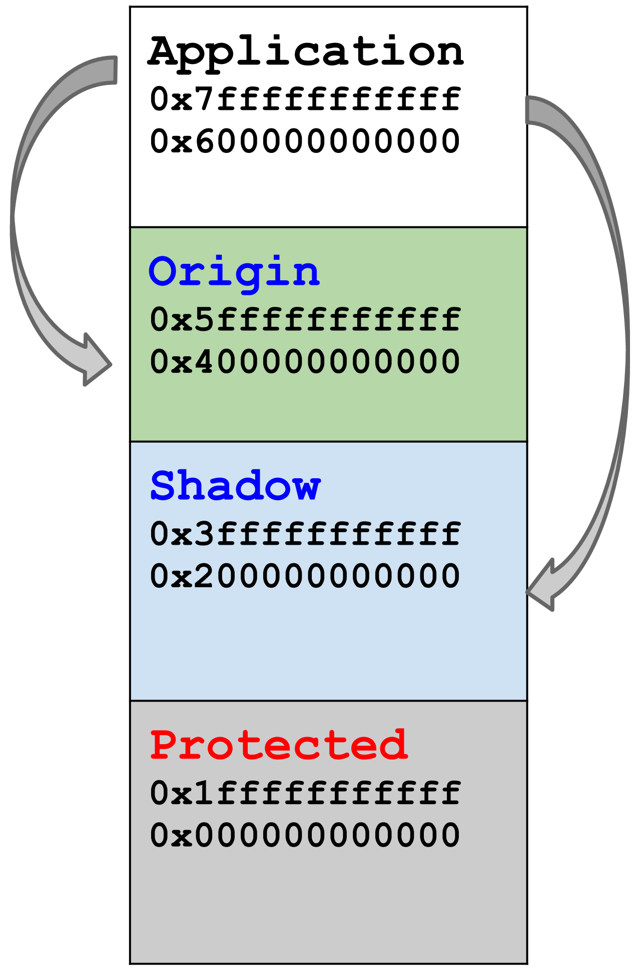
```
a = malloc() ...
b = malloc() ...
c = *a + *b  ...
if (c) ...   // UMR. Is 'a' guilty or 'b'?
```

- Valgrind `--track-origins`: propagate the origin of the poisoned memory alongside the shadow

- MSan: secondary shadow
  - Origin-ID is 4 bytes, 1:1 mapping
  - 2x additional slowdown

Secondary shadow (origin)

```
Origin = Addr - 0x200000000000;
```



Tracking origins

- Origin propagation

```
B = op D, E          B" = select E', E", D"
A = op B, C          A" = select C', C", B"
```

Call instrumentation

```
call void @f(i64 %a, i64 %b)
```

```
store i64 %Sa, ... @__msan_param_tls ...
store i64 %Sb, ... @__msan_param_tls ...
call void @f(i64 %a, i64 %b)
```

```
__msan_param_tls:
```

VarArg handling

Problem: va_arg is lowered in the frontend.

```
%ap = alloca [1 x %struct.__va_list_tag], align 16
%arraydecay1 = bitcast [1 x %struct.__va_list_tag]* %ap to i8*
call void @llvm.va_start(i8* %arraydecay1)
%gp_offset_p = getelementptr inbounds [1 x %struct.__va_list_tag]* %ap, i64 0, i64 0, i32 0
%gp_offset = load i32* %gp_offset_p, align 16
%fits_in_gp = icmp ult i32 %gp_offset, 41
br i1 %fits_in_gp, label %vaarg.in_reg, label %vaarg.in_mem
```

```
vaarg.in_reg:                                ; preds = %entry
```

```
%0 = getelementptr inbounds [1 x %struct.__va_list_tag]* %ap, i64 0, i64 0, i32 3
%reg_save_area = load i8** %0, align 16
%1 = sext i32 %gp_offset to i64
%2 = getelementptr i8* %reg_save_area, i64 %1
%3 = add i32 %gp_offset, 8
store i32 %3, i32* %gp_offset_p, align 16
br label %vaarg.end
```

```
vaarg.in_mem:                                ; preds = %entry
```

```
%overflow_arg_area_p = getelementptr inbounds [1 x %struct.__va_list_tag]* %ap, i64 0, i64 0, i32 2
%overflow_arg_area = load i8** %overflow_arg_area_p, align 8
%overflow_arg_area.next = getelementptr i8* %overflow_arg_area, i64 8
store i8* %overflow_arg_area.next, i8** %overflow_arg_area_p, align 8
br label %vaarg.end
```

```
vaarg.end:                                   ; preds = %vaarg.in_mem, %vaarg.in_reg
```

```
%vaarg.addr.in = phi i8* [ %2, %vaarg.in_reg ], [ %overflow_arg_area, %vaarg.in_mem ]
%vaarg.addr = bitcast i8* %vaarg.addr.in to i32*
```

```
%4 = load i32* %vaarg.addr, align 4
```

What is %4's shadow?

VarArg handling

Solution (bad): Fill va_list shadow in va_start.

- Platform-dependent.
- Complex and error-prone.
- Works.

Solution (good):

- Emit va_arg in the frontend.

Ret instrumentation

```
%a = call i64 @f()
```

```
%a = call i64 @f()
%Sa = load i64 @__msan_retval_tls

f():
...
store i64 %Sa, @__msan_retval_tls
ret i64 %a

__msan_retval_tls:  A'
```

SIMD intrinsics

Guessing memory effects based on signature and mod/ref behaviour:

- vector store
- vector load
- arithmetic, logic, etc
- special handling for mem*, va_* and bswap.

MSan overhead

- Without origins:
  - CPU: 3x
  - RAM: 2x
- With origins:
  - CPU: 5x
  - RAM: 3x + malloc stack traces

Optimization

- MemorySanitizer instrumentation inhibits inlining.
  - Must be done late.
- Lots of redundant instrumentation.
  - Re-run some generic optimization passes.
    - 13% perf improvement.

Future ideas.

- App, shadow and origin locations never alias.
- Fast pass origin tracking.

Tricky part :(

- Missing any write instruction causes false reports
- Must monitor ALL stores in the program
  - libc, libstdc++, syscalls, inline asm, JITs, etc

Solution #1: partial

- Use instrumented libc++ or libstdc++
- Wrappers for libc (more than 140 functions)
- Handlers for raw system calls (in-progress)
- Instrument everything else
  - Or isolate uninstrumented parts (ex.: zlib has ~2 interface functions with clear memory effects)
- Works for some real apps:
  - Can bootstrap Clang
- FAST

Solution #2: static + dynamic

- Simple DynamoRIO tool (MSanDr)
  - Instrument stores by cleaning target shadow.
  - Instrument RET and every indirect branch by cleaning function argument shadow.
  - Avoids false positives.

- SLOW, unclear speedup potential
  - Very slow startup
  - Still much faster than Valgrind

- Applicable to all apps
  - Chrome (DumpRenderTree)

MSan summary

- Finds uses of uninitialized memory
- 10x faster than Valgrind
- Provides better warning messages
- Has deployment challenges

Q&A

Why not combine ASan and MSan?

- Slowdowns will add up
  - Bad for interactive or network apps
- Memory overheads will multiply
  - ASan's redzones * MSan's rich shadow
- Not trivial to implement