Debugging With LLVM

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Our Background

- Compiler engineers at Arm
  - Arm Compiler For Linux
  - Downstream and upstream LLVM
  - Based in Manchester, UK
- Scalable Vector Extension (SVE) for AArch64
- OpenMP Committee Member (Graham)
- LLDB developer in previous life (Andrzej)

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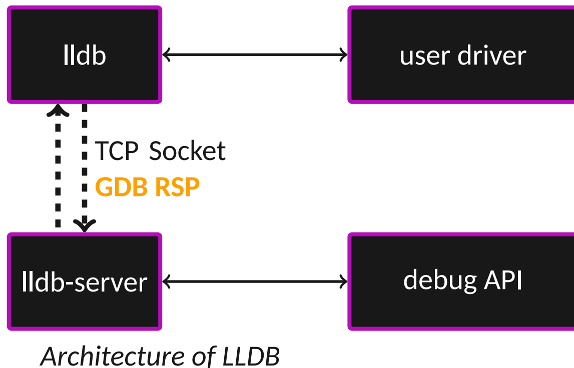
Part 1

LLDB

LLDB - Architecture



Architecture of LLDB

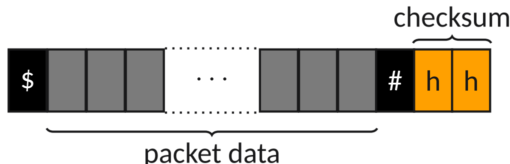
LLDB offers multiple options:

- **user drivers:** command line, lldb-mi, Python
- **debug API:** ptrace/simulator/runtime/actual drivers

GDB Remote Serial Protocol

- Simple, ASCII message based protocol
- Designed for debugging remote targets
- Extended for LLDB, see **lldb-gdb-remote.txt**

GDB RSP packet structure:



Debugging:

```
(lldb) log enable gdb-remote packets
(lldb) log list
```

LLDB command structure

- lldb command syntax is fairly structured:

```
(lldb)  <noun> <verb> [-options [option-value]] [argument [argument...]]
```

- For example:

```
(lldb)  breakpoint set --file foo.c --line 12
(lldb)  process launch --stop-at-entry -- -program_arg value
```

- When in doubt:

```
(lldb)  apropos <keyword>
```

GDB to LLDB command map

gdb	lldb
% gdb –args a.out 1 2 3	% lldb – a.out 1 2 3
(gdb) run (gdb) r	(lldb) process launch – <args> (lldb) run <args> (lldb) r <args>
(gdb) step (gdb) s	(lldb) thread step-in (lldb) step (lldb) s
(gdb) next (gdb) n	(lldb) thread step-over (lldb) next (lldb) n
(gdb) break main	(lldb) breakpoint set –name main (lldb) br s -n main (lldb) b main

GDB to LLDB command map

gdb	lldb
(gdb) break test.c:12	(lldb) breakpoint set –file test.c –line 12 (lldb) br s -f test.c -l 12 (lldb) b test.c:12
(gdb) info break	(lldb) breakpoint list (lldb) br l
(gdb) set env DEBUG 1	(lldb) settings set target.env-vargs DEBUG=1 (lldb) set se target.env-vargs DEBUG=1 (lldb) env DEBUG=1
(gdb) show args	(lldb) settings show target.run-args

- More at: https://lldb.llvm.org/use/map.html

Beyond basic usage

- Evaluating expressions:

```
(lldb)  expr (int) printf ("Print nine: %d.", 4 + 5)
```

- Python interpreter:

```
(lldb)  script
>>> import os
>>> print("I am running on pid ".format(os.getpid()))
```

- Custom commands:

```
(lldb)  command script add -f my_commands.printworld hello
```

LLDB links

- LLDB Tutorial: https://lldb.llvm.org/use/tutorial.html
- GDB RSP: https://www.embecosm.com/appnotes/ean4/embecosm-howto-rsp-server-ean4-issue-2.html
- llvm-tutor: https://github.com/banach-space/llvm-tutor/

Part 2

LLVM Sanitizers

Binary Instrumentation to aid Debugging

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```
clang -g -O1 -fsanitize=address my_prog.c -o my_prog
```

- Several sanitizers available to target different possible bugs, e.g. address (ASAN), thread (TSAN), memory (MSAN)
- Wraps various operations in your code (e.g. memory traffic)

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- Tunable behavior on encountering a problem

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- Can be combined

```
-fsanitize=signed-integer-overflow -fno-sanitize-recover=address
```

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```

- ASAN, MSAN, and TSAN are **mutually exclusive!**

Address Sanitizer (ASAN)

main.c

```c
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

#define ARRAY_ELTS (10)
#define ARRAY_SIZE (sizeof(int) * ARRAY_ELTS)

extern int my_loop(int*, int);

int main(int argc, char **argv) {
  int *array = (int*)malloc(ARRAY_SIZE);
  memset(array, 0, ARRAY_SIZE);
  int result = my_loop(array, ARRAY_SIZE);

  printf("Result was: %d\n", result);

  return 0;
}
```

main.c

loop.c

```c
int my_loop(int *array, int num_elems) {
  int result = 0;

  for (int i = 0; i < num_elems; i++) {
    // Some expensive calculation not shown
    // here
    result += array[i];
  }
  return result;
}
```

loop.c

Address Sanitizer (ASAN)

- Detects out-of-bounds accesses, use-after-free/scope, double free
- Option to detect leaks (on by default on Linux)

```
ASAN_OPTIONS=detect_leaks=1 ./my_instrumented_binary
```

- Option to detect initialization order problem (Linux only)

```
ASAN_OPTIONS=check_initialization_order=1 ./my_instrumented_binary
```

Undefined Behavior Sanitizer

- Catches several cases of UB in C and C++
- Can also catch similar cases that are not technically UB but may still be undesirable

Undefined Behavior Sanitizer

Unsigned integer wrapping

```
#include <stdio.h>
#include <stdint.h>

unsigned getSizeOfA() {
  return 8;
}

unsigned getSizeOfB() {
  return 32;
}

int main(int argc, char **argv) {
  int64_t Offset = 0;

  Offset = (getSizeOfA() - getSizeOfB()) / 8 - Offset;

  printf("Offset %lld, Offset in Bits: %lld\n", Offset, Offset * 8);

  return 0;
}
```

Thread Sanitizer (TSAN)

```c
#include <pthread.h>
#include <stdio.h>

int *item = NULL;
int someval = 5;
int ready = 0;

void *thread1(void *x) {
  item = &someval;
  ready = 1;
  return NULL;
}

void *thread2(void *x) {
  if (!ready)
    return NULL;

  int val = *item;
  // Process item here.
  return NULL;
}
```

```c
int main() {
  int val = 0;
  pthread_t t0, t1;

  pthread_create(&t0, NULL, thread1, NULL);
  pthread_create(&t1, NULL, thread2, NULL);

  pthread_join(t0, NULL);
  pthread_join(t1, NULL);

  return 0;
}
```

Thread Sanitizer (TSAN)

- Detects data races, including on mutexes themselves (lock in one thread before init in another)
- Catches destruction of a mutex while still locked
- Catches signal handlers overwriting errno
- Can annotate the source to indicate correctness (ANNOTATE_HAPPENS_BEFORE, etc)
- Can report more history if required (2 is the default, 7 the max)

```
TSAN_OPTIONS="history_size=4" ./my_instrumented_binary
```

Memory Sanitizer (MSAN)

```
int main(int argc, char **argv) {
  int opt = atoi(argv[1]);
  int foo;

  switch (opt) {
  case 0:
    foo = 3;
    break;
  case 1:
    foo = 8;
  break;
  }

  printf("Foo is: %d\n", foo);
  return 0;
}
```

Memory Sanitizer (MSAN)

- Catches reads of uninitialized memory
- Only supports Linux/FreeBSD/NetBSD at present
- Can track origins of memory

```
-fsanitize=memory -fsanitize-memory-track-origins=2
```

More Precise Configuration

- May be too much overhead to instrument entire program, want to exclude hot code
- Can suppress in the source

```
__attribute__((no_sanitize(“address”)))
```

- May need a more centralized option

Sanitizer Special Case List

List of exclusions provided at compile time

```
clang -fsanitize=address -fsanitize-blacklist=exclusions.txt ...
```

```
#comments
#suppress for any sanitizer by default
src:/path/to/myfile.c
fun:func1
#cpp names mangled
#can suppress for specific sanitizer only with [sections]
src:/path/to/myotherfile.cpp
[address]
fun:_Z9OtherFuncv
#shell wildcard '*' allowed for file and function name matching
```

exclusions.txt

More info

- Haven't covered all of them
  - pointer-compare, pointer-subtract – detect UB on pointer comparisons for different objects
  - control-flow integrity (cfi) – catches corruption of branch addresses
  - dfsan – manual annotation of data flow
  - More being written – TySan under review for catching strict aliasing problems
- https://clang.llvm.org/docs/index.html
  - Links to documentation for several sanitizers and other built-in analysis and instrumentation tools
- https://github.com/google/sanitizers/wiki
  - Google's sanitizer wiki; old, but still contains some useful info
- Has been used in public CI instances (e.g. Travis)

Final thoughts

- LLDB is a very mature debugger
  - It is very likely already available on your platform
- LLVM’s sanitizers are very powerful, yet straightforward to use
  - No extra tools required - just add -fsanitize= when building
- You can use sanitisers from inside LLDB:

```
(lldb) memory history <address>
```

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