WebAssembly Debugging with LLDB

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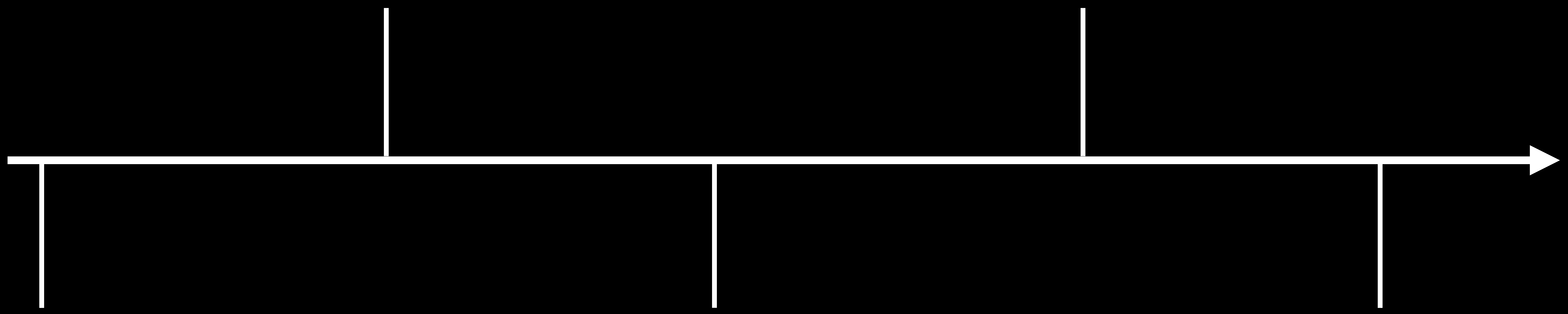
FOSDEM '26 LLVM Dev Room

History



2018
Akio Yasui
creates WasmKit
(WAKit)

Max Desiatov takes
over maintainership
2022

2023
Yuta Saito joins and
WasmKit achieves 100%
SpecTest coverage

WasmKit is used
in CI for Swift 6.0
2024

2025
WebAssembly is officially
supported in Swift 6.2 and
WasmKit ships with the toolchain

https://github.com/swiftlang

https://github.com/swiftwasm

https://swiftwasm.org

Goal

- First class debugging experience for Swift compiled to WebAssembly
  - Source-level debugging (breakpoints, stepping, variables)
  - Swift language support (e.g. *Reflection Metadata*)

- How?
  - Teach WebAssembly tools about Swift
  - Teach LLDB about WebAssembly

Approaches to Wasm Debugging

Wasmtime

Code is JIT'ed in runtime
LLDB debugs the runtime

- ✓ Mature tooling can be used unmodified
- ! Mixed runtime and user code

Chrome Dev Tools

Fully browser based
Uses LLDB to parse DWARF

- ✓ Seamless experience with JavaScript
- ! Needs language support in Chrome

WAMR

Provides GDB remote stub
that LLDB can connect to

- ✓ Native LLDB experience
- ! Requires extensions in LLDB

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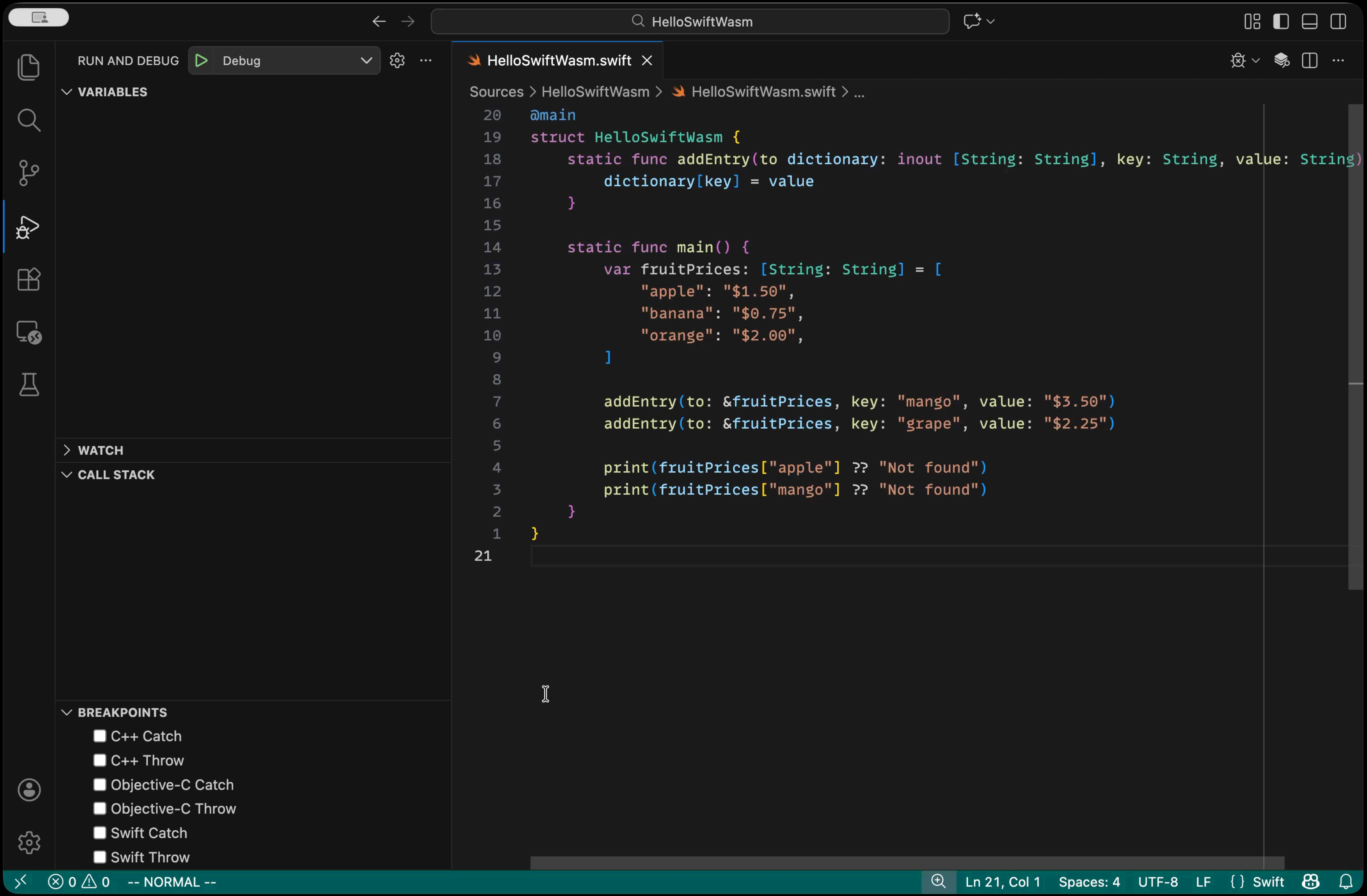
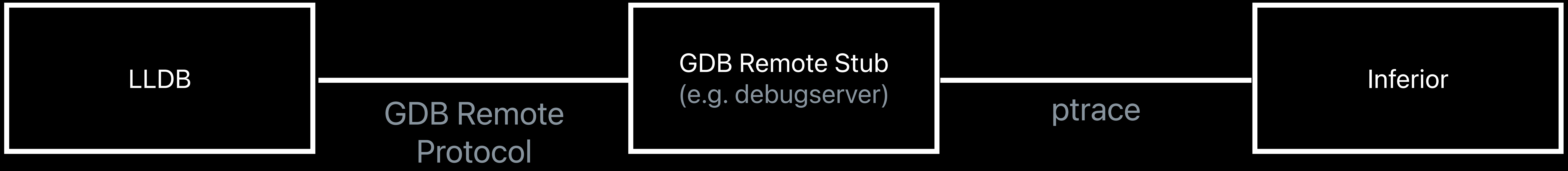


```swift
@main
struct HelloSwiftWasm {
    static func addEntry(to dictionary: inout [String: String], key: String, value: String)
        dictionary[key] = value
    }

    static func main() {
        var fruitPrices: [String: String] = [
            "apple": "$1.50",
            "banana": "$0.75",
            "orange": "$2.00",
        ]

        addEntry(to: &fruitPrices, key: "mango", value: "$3.50")
        addEntry(to: &fruitPrices, key: "grape", value: "$2.25")

        print(fruitPrices["apple"] ?? "Not found")
        print(fruitPrices["mango"] ?? "Not found")
    }
}

```

☐ C++ Catch
☐ C++ Throw
☐ Objective-C Catch
☐ Objective-C Throw
☐ Swift Catch
☐ Swift Throw

Architecture



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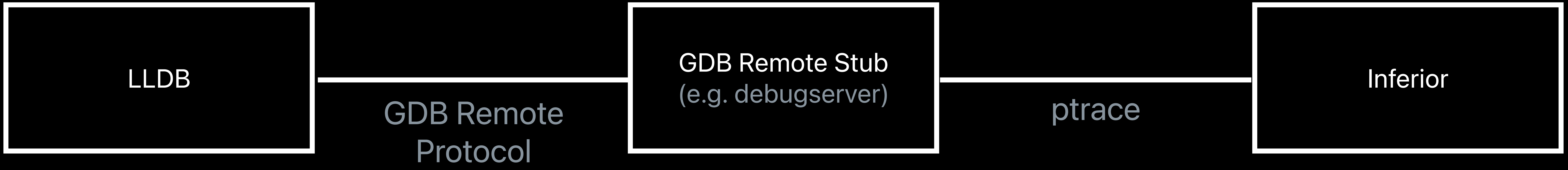
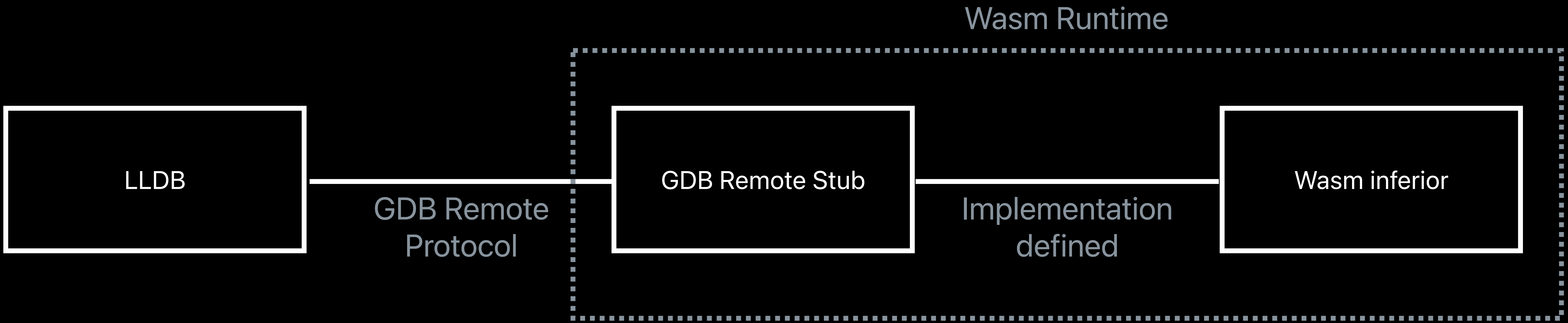




Existing WebAssembly Support

- Upstream
  - Loading binaries
  - Creating types from DWARF

- Downstream
  - Patches in the WAMR repository
  - Unmerged PRs from Paolo Severini

Object Files

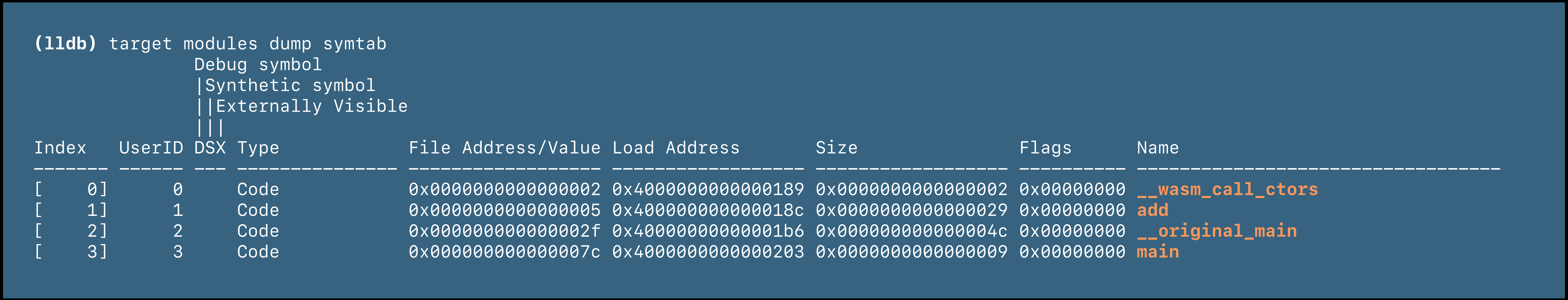
- Replace ad-hoc section parsing in `ObjectFileWasm`
  - Support standard (code, data) and custom sections (DWARF, Swift)
  - Mini Wasm interpreter for *init expression*

```
(lldb) target modules dump sections
SectID             Type          Load Address                             Perm File Off.  File Size  Flags      Section Name
------------------ ------------- ---------------------------------------  ---- ---------- ---------- ---------- ----------------------------
0x0000000000000001 code          [0x4000000000000187-0x400000000000020c)  ---  0x00000187 0x00000085 0x00000000 simple.wasm.code
0x000000000000000f dwarf-abbrev  [0x4000000000000239-0x40000000000002e2)  ---  0x00000239 0x000000a9 0x00000000 simple.wasm..debug_abbrev
0x0000000000000014 dwarf-info    [0x40000000000002f1-0x40000000000003c6)  ---  0x000002f1 0x000000d5 0x00000000 simple.wasm..debug_info
0x000000000000001b dwarf-ranges  [0x40000000000003d6-0x40000000000003ee)  ---  0x000003d6 0x00000018 0x00000000 simple.wasm..debug_ranges
0x000000000000001c dwarf-str     [0x40000000000003fc-0x40000000000004e3)  ---  0x000003fc 0x000000e7 0x00000000 simple.wasm..debug_str
0x0000000000000015 dwarf-line    [0x40000000000004f1-0x4000000000000557)  ---  0x000004f1 0x00000066 0x00000000 simple.wasm..debug_line
0x0000000000000040 wasm-name     [0x400000000000055e-0x40000000000005c5)  ---  0x0000055e 0x00000067 0x00000000 simple.wasm.name
0x0000000000000100 data          [0x4000000000000215-0x400000000000021e)  ---  0x00000215 0x00000009 0x00000000 simple.wasm..rodata
0x0000000000000200 data          [0x4000000000000224-0x4000000000000228)  ---  0x00000224 0x00000004 0x00000000 simple.wasm..data
```

https://github.com/llvm/llvm-project/pull/153634

Symbol Table

- Symbolication and breakpoints
  - Function offset and size are stored in **function section**
  - Function names encoded in the **names section**



```
(lldb) target modules dump symtab
               Debug symbol
               |Synthetic symbol
               ||Externally Visible
               |||
Index   UserID DSX Type            File Address/Value Load Address       Size               Flags      Name
------- ------ --- --------------- ------------------ ------------------ ------------------ ---------- ----------------------------------
[    0]      0     Code            0x0000000000000002 0x4000000000000189 0x0000000000000002 0x00000000 __wasm_call_ctors
[    1]      1     Code            0x0000000000000005 0x400000000000018c 0x0000000000000029 0x00000000 add
[    2]      2     Code            0x000000000000002f 0x40000000000001b6 0x000000000000004c 0x00000000 __original_main
[    3]      3     Code            0x000000000000007c 0x4000000000000203 0x0000000000000009 0x00000000 main
```

https://github.com/llvm/llvm-project/pull/153093

Backtraces

- New ProcessWasm plugin
  - No stack memory, registers or ABI (prior to Wasm EH)
  - LLDB has to rely on the runtime for unwinding
  - GDB remote extension: qWasmCallStack

```
(lldb) bt
* thread #1, name = 'nobody', stop reason = breakpoint 2.1
  * #0: 0x40000000000001a8 simple.wasm`add(a=1, b=2) + 28 at /path/to/simple.c:4
    #1: 0x40000000000001f1 simple.wasm`main + 59 at /path/to/simple.c:10
    #2: 0x400000000000020a simple.wasm`main + 7
```

https://github.com/llvm/llvm-project/pull/150143

Variables

- **Location descriptions** in DWARF
  - Empty: location unavailable
  - Implicit: location unavailable but value is known (value)
  - Memory: location in memory (address)
  - Register: location in memory (register name)

```
0x00000062:     DW_TAG_formal_parameter
                  DW_AT_location          (DW_OP_reg7)
                  DW_AT_name              ("a")      └► DWARF register 7
                  DW_AT_decl_file         ("/tmp/simple.c")
                  DW_AT_decl_line         (3)
                  DW_AT_type              (0x0000009f "int")
```

Register Locations

- Wasm uses virtual registers in DWARF
  - Globals (qWasmGlobal)
  - Locals (qWasmLocal)
  - Operand stack (qWasmStackValue)

```
0x00000062:     DW_TAG_formal_parameter
                  DW_AT_location        (DW_OP_WASM_location 0x0 0x2, DW_OP_stack_value)
                  DW_AT_name            ("a")                  │   └► argument: 2 (index)
                  DW_AT_decl_file       ("/tmp/simple.c")      └────► location: local (qWasmLocal)
                  DW_AT_decl_line       (3)
                  DW_AT_type            (0x0000009f "int")
```

https://github.com/llvm/llvm-project/pull/151010

Memory Locations

- Separate address spaces for *code* and *memory*
  - wasm32: encoded in the top 32 bits of a 64-bit address
  - wasm64: unsupported (until we have address space support)

```
struct wasm_addr_t {
  uint64_t offset    : 32;
  uint64_t module_id : 30;
  uint64_t type      : 2;

  wasm_addr_t(lldb::addr_t addr)
      : offset(addr & 0x00000000ffffffff),
        module_id((addr & 0x00ffffff00000000) >> 32), type(addr >> 62) {}
}
```

https://github.com/llvm/llvm-project/pull/150143

Swift Support

- Teach `libSwiftReflection` about Wasm
  - Reflection metadata is generated by the compiler
  - Consumed by the runtime & the debugger
  - Stored in custom section: reimplement section parsing

```
(lldb) v dictionary
([String : String]) dictionary = 4 key/value pairs {
  [0] = (key = "apple", value = "$1.50")
  [1] = (key = "banana", value = "$0.75")
  [2] = (key = "mango", value = "$3.50")
}
```

https://github.com/swiftlang/swift/pull/83923

Platform Plugin

- New `PlatformWasm`
  - Automatically selected for targets with a WebAssembly triple
  - Launches binaries under the runtime and connects to GDB stub
  - Your choice of runtime, configurable in `~/.lldbinit`

https://github.com/llvm/llvm-project/pull/171507

First Class Debugging for WebAssembly

- Any **language** supported by LLDB
  - Swift (swiftc)
  - C, C++ (clang, emscripten)

- Any **runtime** implementing the protocol
  - WebAssembly Micro Runtime (WAMR)
  - WasmKit
  - JavaScriptCore (WebKit)

https://lldb.llvm.org/resources/lldbgdbremote.html#wasm-packets

What's next

- Extend the **LLDB test suite**
  - Compile test binaries to WebAssembly
  - Run and debug them under WasmKit
  - Uncover bugs LLDB and GDB stubs
- Support more Swift language features
- Support address spaces for Wasm64