LLVM MCJIT and debugging JIT-ited code

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Intel OpenCL* Team

- Responsible for the Intel SDK for OpenCL* applications.
- Develops LLVM-based OpenCL* compilers and tools.
- Enables future Intel® Architectures based on LLVM.
- The group is centered in Haifa, Israel:
  - With teams in California and Russia.
  - The MCJIT work is done in collaboration with a team in Waterloo, Canada.
Our OpenCL* compiler – high-level flow

OpenCL* source

Modified Clang-based front-end

LLVM IR

LLVM-generics and Intel-specific optimizations

LLVM IR

x86 code in memory

Codegen & JIT

OCL library

Execution
Our motivation – debugging JIT-ted code

• A JIT interface has been added to GDB in version 7.0:
  – Runtime registration of JIT-ted objects for debugging.
• In LLVM, the JIT only emits frame information.
  – Function names in JIT-ted code when examining core dumps.
• The (old) JIT path does not support emitting full DWARF information.
  – Adding this is a lot of effort.
Debugging JIT-ted code – a solution

• Why not reuse the existing DWARF emitter in MC?
  – MCJIT!
MCJIT

- MCJIT is: MC + Runtime Dynamic Loading
- No separate emitter (JIT) is needed.
- The MC-generated object is dynamically loaded into memory and executed.
Motivation for MCJIT

• Avoid duplicate encoding paths (JIT & MC).
• Need to handle inline assembly.
• Debugging.
MCJIT – how it works

- Implements the `ExecutionEngine` interface.
- Accepts a custom memory manager (`JITMemoryManager` interface), target information, and a module to JIT.
- Runs passes from `TargetMachine::addPassesToEmitMC`:
  - `addPassesToGenerateCode` – common CodeGen passes.
  - `createMCObjectStreamer` – emit object code.
  - This creates an object file in a memory buffer.
- Uses the runtime dynamic loader (`RuntimeDyld`) to load the object and perform relocations necessary for execution.
MCJIT – Runtime Dynamic Loader

• The problem:
  – MC emits an object file (.o)
  – Object files are not executable – need to be linked and loaded:
    – Linked: resolve relocations between call sites and symbols.
    – Loaded: resolve absolute addresses, allocate BSS sections and COMMON symbols, resolve calls to other shared objects, etc.
MCJIT – Runtime Dynamic Loader

• Solution: Runtime Dynamic Loader:
  – A “linking loader”.
  – Do just enough linking and loading to make the object file executable in JIT.

• **RuntimeDyld** – a generic object:
  – Loads appropriate implementation (**RuntimeDyldImpl** interface), depending on object file identification (in the **loadObject** method).
  – For MachO – **RuntimeDyldMachO**
  – For ELF – **RuntimeDyldELF**
Runtime dynamic loading of ELF objects

• Sections that require allocation (SHF_ALLOC) are allocated using the memory manager.
• The absolute addresses of symbols are recorded:
  – At this point we know the “load address” of the sections symbols belong to, so absolute addresses are available.
• COMMON symbols are collected and allocated in a single chunk of data.
• Relocations are fixed up accordingly.
Debugging with MCJIT

- **JITRegistrar** – a singleton object responsible for registering JIT-ted objects with GDB.
  - Implements the GDB JIT interface.
- **RuntimeDyldImpl**, after performing relocations:
  - Calls `jitdebugging::registerObjectWithDebugger` → `JITRegistrar::registerObject` → `NotifyDebugger`
    - Fills the required GDB JIT interface data structures
    - Calls `__jit_debug_register_code`
- **GDB** just needs a pointer to the memory buffer holding the ELF image, and its size.
Demo – Debugging JIT-ted code

```c
int compute_factorial(int n)
{
    if (n <= 1)
        return 1;

    int f = n;
    while (--n > 1)
        f *= n;
    return f;
}

int main(int argc, char** argv)
{
    if (argc < 2)
        return -1;
    char firstletter = argv[1][0];
    int result = compute_factorial(firstletter - '0');
    // Returned result is clipped at 255...
    return result;
}
```

```bash
$BINPATH/clang -cc1 -g -O0 -emit-llvm showdebug.c
```
Demo – Debugging JIT-ted code

$ gdb -q --args $BINPATH/lli -use-mcjit showdebug.ll 5
Reading symbols from $BINPATH/lli...done.
(gdb) b showdebug.c:6
No source file named showdebug.c.
Make breakpoint pending on future shared library load? (y or [n]) y
Breakpoint 1 (showdebug.c:6) pending.
(gdb) r
Starting program: $BINPATH/lli -use-mcjit showdebug.ll 5
[Thread debugging using libthread_db enabled]
Breakpoint 1, compute_factorial (n=5) at showdebug.c:6
  6 int f = n;
(gdb) bt
#0  compute_factorial (n=5) at showdebug.c:6
#1 0x000007fff7e50a9 in main (argc=2, argv=0x169b140) at showdebug.c:18
#2 0x35000000160988 in ?? ()
#3 0x00000000169b140 in ?? ()
#4 0x0000000000000002 in ?? ()
#5 0x00000000000d9a893 in llvm::MCJIT::runFunction [...]#6 0x00000000000dc8b82 in llvm::ExecutionEngine::runFunctionAsMain [...]#7 0x0000000000059b525 in main [...]

Demo – Debugging JIT-ted code

```
(gdb) p f
$1 = 0
(gdb) n
7      while (--n > 1)
(gdb) p f
$2 = 5
(gdb) b showdebug.c:9
Breakpoint 2 at 0x7ffffff504c: file showdebug.c, line 9.
(gdb) c
Continuing.

Breakpoint 2, compute_factorial (n=1) at showdebug.c:9
 9   return f;
(gdb) p f
$3 = 120
(gdb) c
Continuing.

Program exited with code 0170.
```
Remaining challenges

• Efficiency:
  – Redundant copying of buffers (encumbered by the need to allocate both executable and non-executable buffers).
  – Compiling too much (old JIT only compiles reachable code).

• Windows* OS (ELF & triple):
  – Idea: load ELF on Windows* as well.
  – Challenge: the Triple enforces COFF generation on Windows*.

• Multiple modules:
  – Currently only a single module can be loaded into MCJIT.
  – MCJIT-ting multiple modules is challenging – linkage required.
Help is welcome
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