LLVM MCJIT and debugging JIT-ted code

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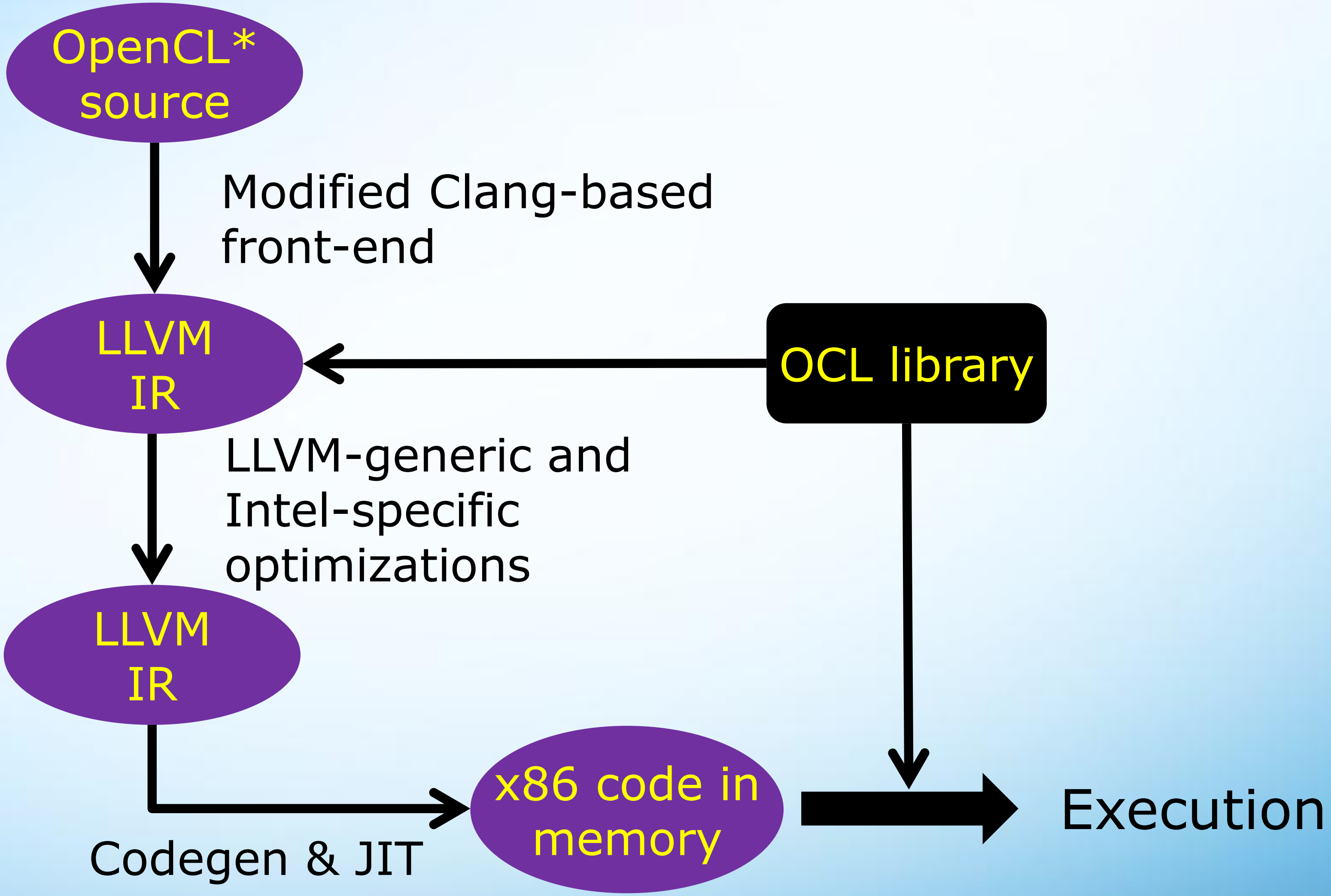
Intel® Developer Products Division
April 2012

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

OCL library

LLVM-generic and Intel-specific optimizations

LLVM IR

Codegen & JIT

x86 code in memory

Execution

Our motivation – debugging JIT-ted code

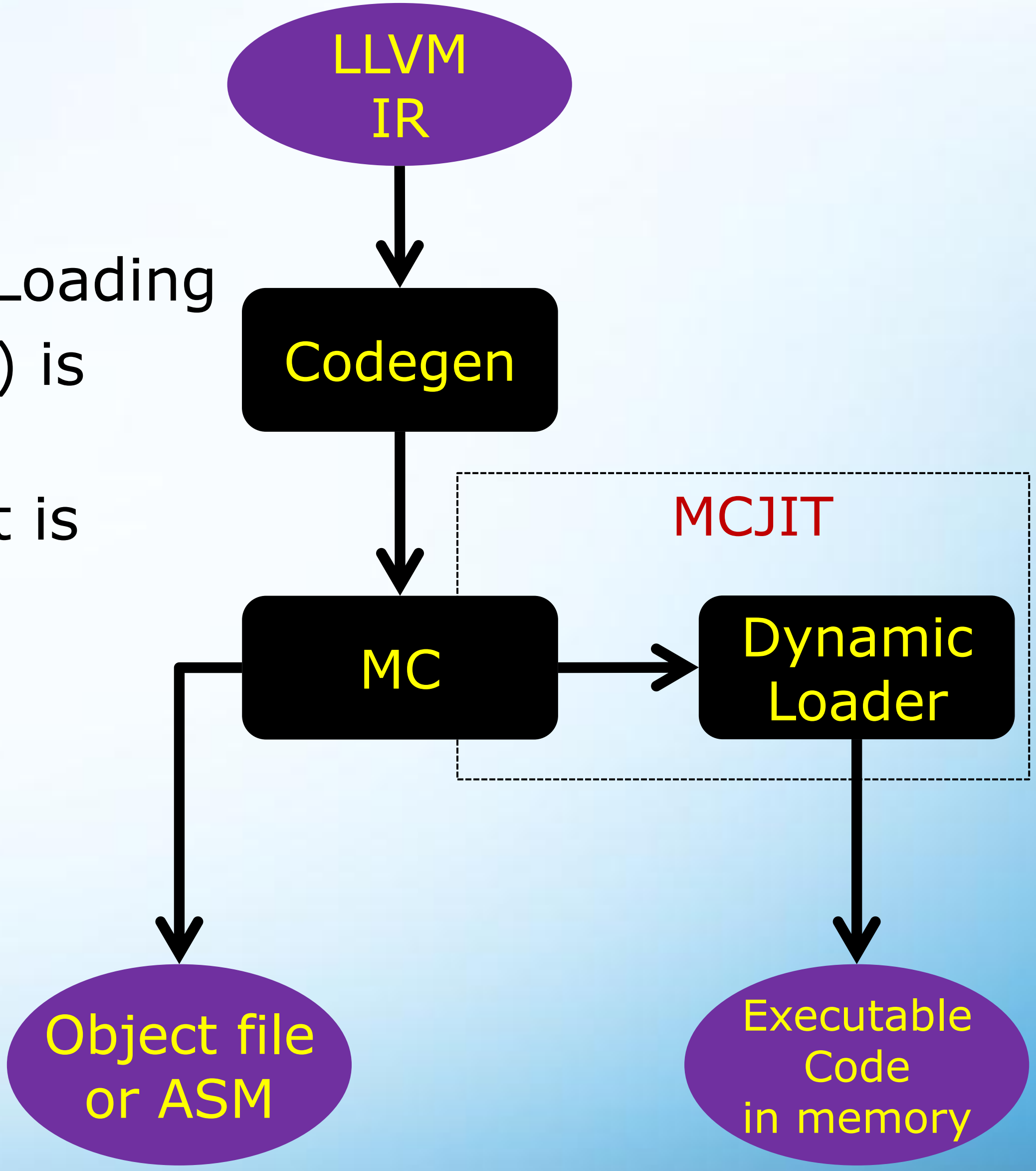
- A JIT interface has been added to GDB in version 7.0:
  - Runtime registration of JIT-ted objects for debugging.
- In LLVM, the JIT only emits frame information.
  - Function names in JIT-ted code when examining core dumps.
- The (old) JIT path does not support emitting full DWARF information.
  -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

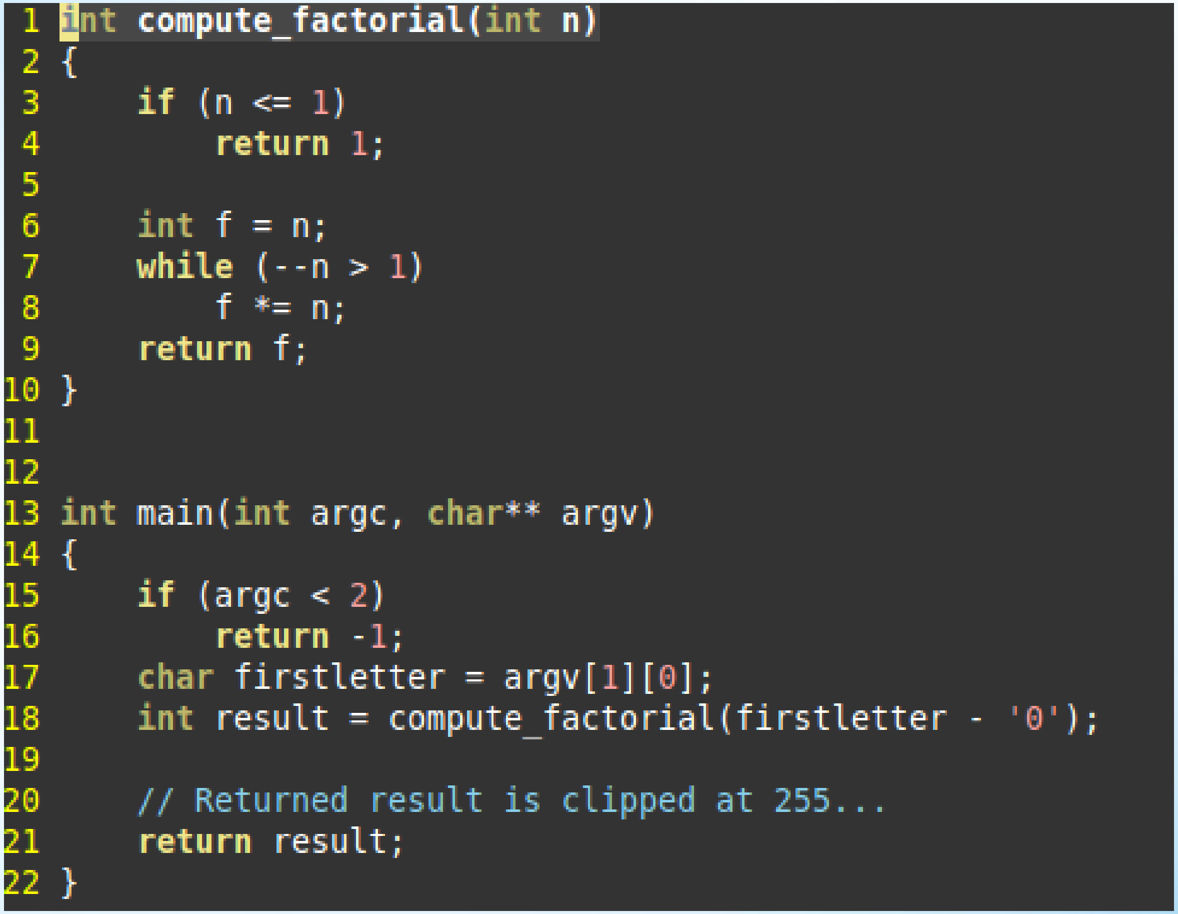
Debugging with MCJIT

- `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.

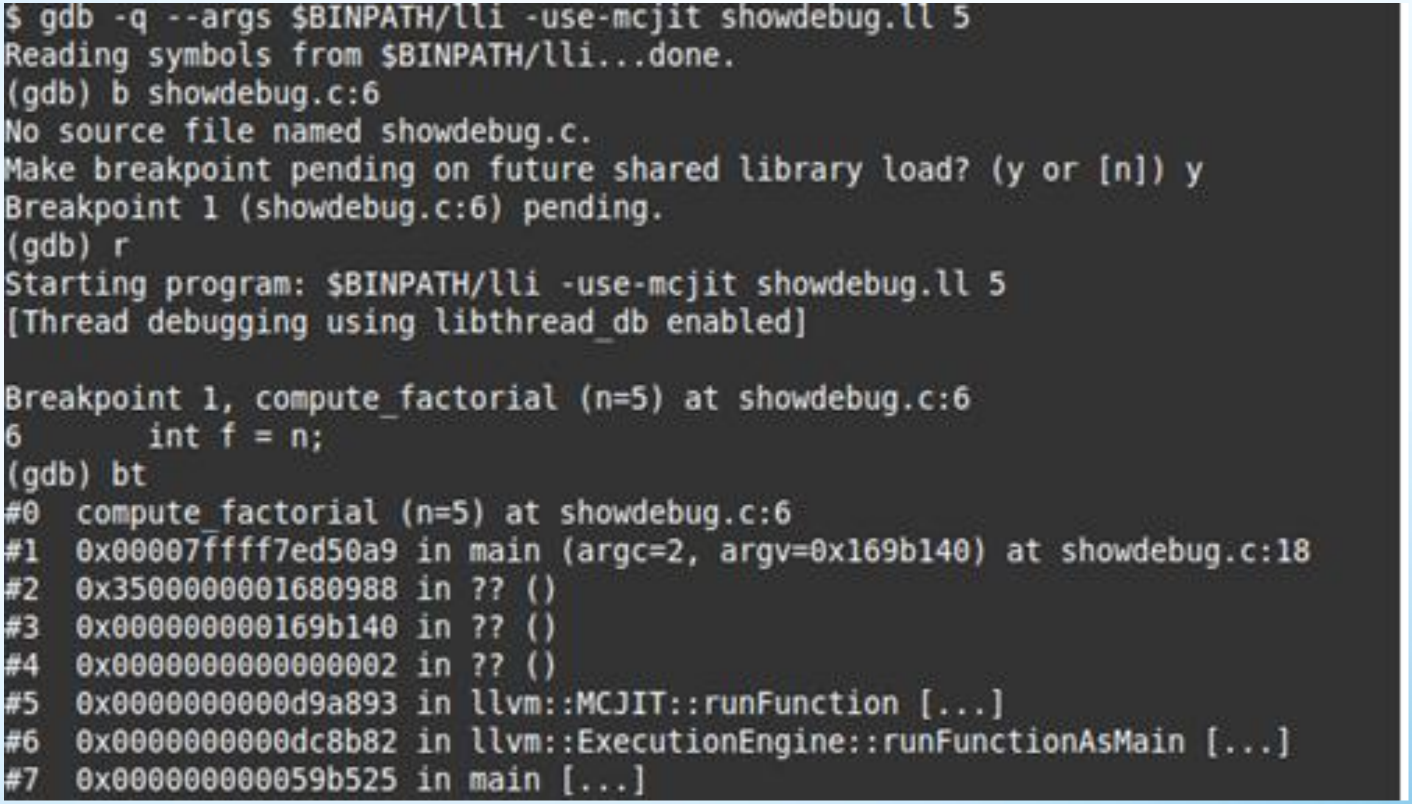
Demo – Debugging JIT-ted code



```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;
}
```

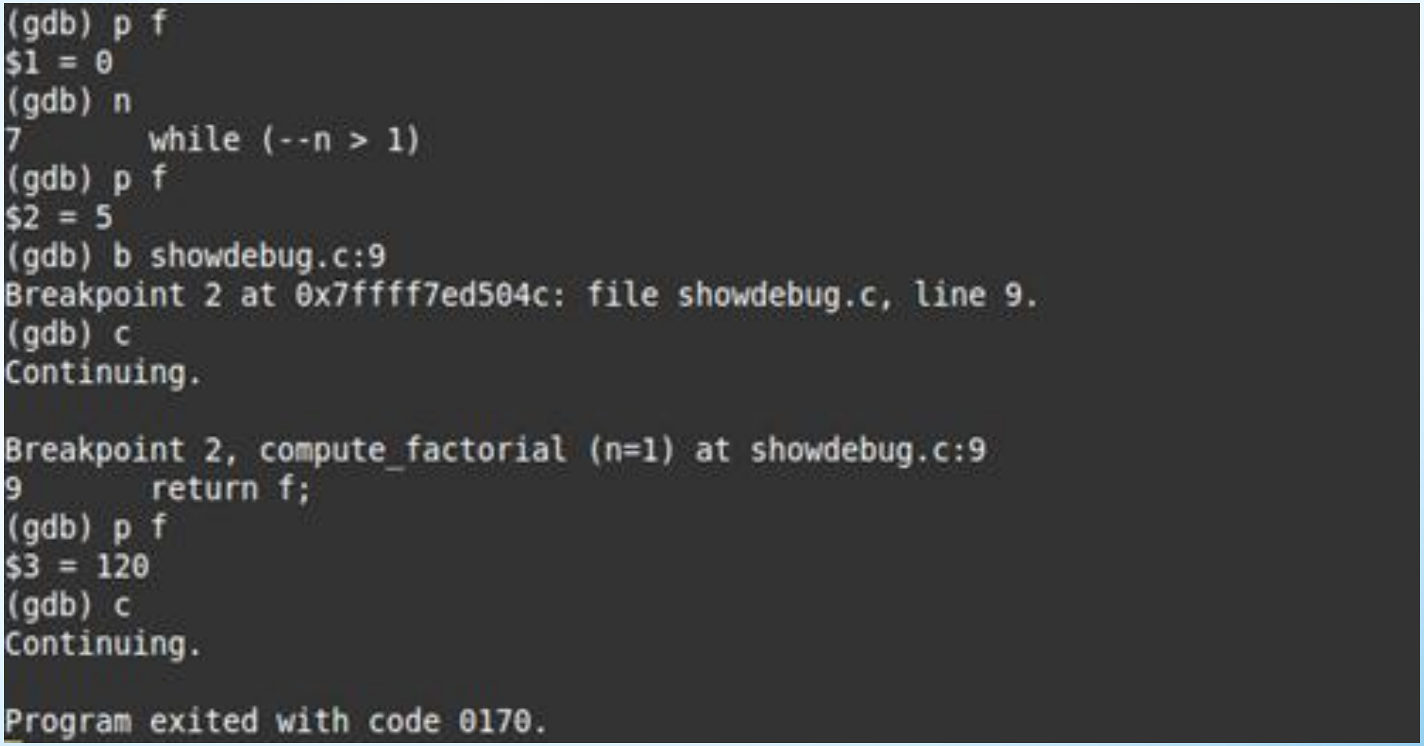
```
$BINPATH/clang -cc1 -g -O0 -emit-llvm showdebug.c
```

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  0x00007ffff7ed50a9 in main (argc=2, argv=0x169b140) at showdebug.c:18
#2  0x3500000001680988 in ?? ()
#3  0x000000000169b140 in ?? ()
#4  0x0000000000000002 in ?? ()
#5  0x0000000000d9a893 in llvm::MCJIT::runFunction [...]
#6  0x0000000000dc8b82 in llvm::ExecutionEngine::runFunctionAsMain [...]
#7  0x000000000059b525 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 0x7ffff7ed504c: 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.

Status of patches

Help is welcome

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