## OpenMP in LLVM

### What do HPC users need?

<table>
<thead>
<tr>
<th>Large legacy code base</th>
<th>OpenMP/LLVM</th>
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<tbody>
<tr>
<td>• Fortran 66, Fortran 77, C/C++</td>
<td>OpenMP allows quick porting of existing code regions to new architectures</td>
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<tr>
<td>• MPI, pthreads, MPI+OpenMP, PGAS, etc.</td>
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<tr>
<td>• Quick Porting is critical</td>
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<tr>
<td>• No need to rewrite entire application in new language</td>
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<table>
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<tr>
<th>New code development</th>
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<tbody>
<tr>
<td>• Latest C/C++ Specifications</td>
<td>Clang/LLVM up-to-date with latest specs</td>
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<tr>
<td>• Interoperability with &quot;assembly&quot; high performance libraries: CUDA, CUDNN, PETSc</td>
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<tr>
<td>• High-level parallel abstractions for different patterns (loops, tasks, etc.)</td>
<td>OpenMP has several parallel patterns</td>
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<table>
<thead>
<tr>
<th>Continuity</th>
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<tr>
<td>• Industrial standard</td>
<td>OpenMP Supported by: IBM, AMD, Intel, Cray, PGI, Pathscale, etc.</td>
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<tr>
<td>• Supported everywhere</td>
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<tr>
<td>• Survives project/architecture/fashion/companies/etc.</td>
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<tr>
<td>• Open source</td>
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<th>Performance (Portability)</th>
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<tr>
<td>• Should always beat MPI alone</td>
<td></td>
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<tr>
<td>• Single version of code: as little device specific code as possible</td>
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<tr>
<td>• Run as fast as possible on every host and device</td>
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OpenMP Contributions by Community

In this talk:
- Driver extensions
- libomptarget

Full implementation of offloading

Language extension: parse+sema+codegen

Driver

Code generation for accelerators

LLVM

Clang

libomptarget

Some device functions required

Some device functions required

In this talk:
- Driver extensions
- libomptarget

projects

projects

tools
OpenMP Offloading

**Main application file**

```c
#pragma omp declare target
target void linSolver(double * A, double * b);

#pragma omp end declare target

int main() {
    // set up A and b and map

#pragma omp target teams
{
    linSolver(A, b);
}
}
```

**Library implementation**

```c
#pragma omp declare target
target void linSolver(double * A, double * b) {
    // .. linear solver implementation
}
#pragma omp end declare target
```

- Same target body can run on host or device
- Different compilation units
Previous Driver Support

Job
- clang –cc1 ...
  - Collect multiple actions that can be performed by a tool
  - Define input and output files
  - Define parameters

Job creation is performed by visiting graph from root to leaves
Driver Extensions for CUDA

Support for CUDA extends existing support with

- Host and device actions
- Selection of right toolchain per function based on host, device, global markups
- Linker tool (fatbinary) is used to combine objects for different compute capability
  - Not nvlink
- Host action is used to embed device code into host-produced binary

What is missing for OpenMP

- No relocation of symbols across host/device
- No dependencies between host and device toolchains possible
Driver Extension – Design Properties

Add as few new options as possible to enable offloading
  • Avoid option proliferation (e.g. 10 new options for each device type)

Require minimal changes to existing build systems
  • No new set of files for offloading

Operate seamlessly on libraries that contain offloading code
  • Libraries can contain both host and device code

Support a convenient way to read and modify intermediate files that have a textual format
  • Bundler tool
Generic Offloading Action

Replaces CUDA’s host and device actions
- The offloading kind (e.g. OpenMP, CUDA)
- The toolchain used by the dependencies (e.g. nvptx, amd)
- Device architecture (e.g. sm_60)

Host to device dependency
- The host builds a list of target regions to be compiled for device

Device to host dependency
- Bundling of object code in single binary
Offloading for PPC64 and NVPTX64

```
foo.cpp

Clang

LLVM

LLVM IR (*.bc)
PPC64 target

.ppc64 asm

Id

nvlink

ptxas

.sass

Libomptarget-nvptx.bc

Libomptarget-nvptx

Fat Binary

PPC64

NVPTX SM_20

NVPTX SM_60
```
Offloading for PPC64 and NVPTX64

Host bitcode file contains metadata that indicates what regions and functions should be compiled for device.

```
foo.cpp

Clang

LLVM IR (*.bc)
PPC64 target

LLVM

LLVM IR (*.bc)
PPC64 target

.Id

.ppc64 asm

Clang

LLVM IR (*.bc)
NVPTX64 target

.LLVM

.ptx

.ptxas

.sass

.nvlink

Libomptarget-nvptx.bc

.nvlink

Libomptarget-nvptx

Fat Binary

PPC64

NVPTX SM_20

NVPTX SM_60
```
Offloading for PPC64 and NVPTX64

foo.cpp

Clang

LLVM IR (*.bc)
PPC64 target

LLVM

.ffc64 asm

Id

Clang

LLVM IR (*.bc)
NVPTX64 target

LLVM

.ptx

ptxas

.sass

nvlink

Libomptarget-nvptx.bc

Linking of libomptarget-nvptx

Fat Binary

PPC64

NVPTX SM_20

NVPTX SM_60
Offloading for PPC64 and NVPTX64

- foo.cpp
  - Clang
    - LLVM
      - LLVM IR (*.bc)
      - PPC64 target
      - .ppc64 asm
    - Id
      - .ptx
      - ptxas
      - sass
    - nvlink
      - Libomptarget-nvptx.bc
      - Libomptarget-nvptx
  - Inlining of libomptarget-nvptx (precompiled with clang-cuda)

Fat Binary
- PPC64
- NVPTX SM_20
- NVPTX SM_60
Offloading for PPC64 and NVPTX64

foo.cpp

Clang

LLVM

LLVM IR (*.bc)
PPC64 target

Id

/ppc64 asm

ptxas

sass

nvlink

Libomptarget-nvptx

Libomptarget-nvptx.bc

Linking of various sections done by linker script (generated by Clang)

Fat Binary

PPC64

NVPTX SM_20

NVPTX SM_60
Fat Binaries and Libomptarget

Clang/LLVM Binary

Host
PPC64

Device
FPGA

Device
DSP

Device
GPU

A single binary for multiple devices
• FPGA, DSP accelerator, GPUs, etc.

No need to recompile source if device section is already present
OpenMP Runtimes

Clang/LLVM Binary

- **Non offloading constructs**
  - PPC64

- **Target constructs**
  - NVPTX SM_60

**Host OpenMP RT**
- **libomp**
- Libomptarget
  - device agnostic
  - device specific (plugin)

**Device OpenMP RT**
- **libomptarget-nvptx**
- Device interface
  - (CUDA driver API)

- All OpenMP runtime calls generated by compiler on non-target regions
Libomptarget Offloading Support

- Implement calls from generated code for offloading
  - map data, start target region, etc.
- Not target a device type
  - only device IDs

Libomptarget

device agnostic

Libomptarget
device specific
(plugin)

Device interface
(CUDA driver API)

- Implement calls from libomptarget above it
  - map data, start target region, etc.
- For a specific device type
  - Implementation is done by using device specific interface
Libomptarget Offloading Support – Multiple Device Types

- Each device type requires to implement a plugin

Libomptarget
(device agnostic)

Libomptarget
(cuda plugin)

Libomptarget
(elf plugin)

Libomptarget
(fpga plugin)

Device interface
(CUDA driver API)

Elf-based OS

FPGA
Driver
Libomptarget Offloading Support – Multiple Device Types

- Each device type requires to implement a plugin.
- This design does not prevent optimized implementation of libomptarget where we have a single library.

- Optimized libomp for GPU device
- Full inlining

Libomptarget (cuda plugin)
Libomptarget (elf plugin)

Libomp Host runtime

Device interface (CUDA driver API)
Elf-based OS
Libomptarget Binary Registration

Required to allow host to offload to device
  • Device code may be produced by a device-specific toolchain
  • Can be loaded dynamically: based on device availability

Some devices require special binary registration support
  • NVIDIA GPUs

The compiler generates a CUBIN object section with
  • All code (kernels and device functions)
  • All static data

Libomptarget asks CUDA driver to load CUBIN
  • cuModuleLoadDataEx
    • Requires start memory address of CUBIN
    • Libomptarget retrieves the symbol address from a host/device table
  • Host/device table is populated by Clang, linker, and loader
Patch Status

Full driver implementation is available in trunk
  • Thanks to everybody that made this happen!

Libomptarget is provided as three patches
  • Host agnostic, plugins for ELF and CUDA, device library for NVPTX
  • We are answering comments made by community (thanks!)

Code generation patches
  • In preparation
  • Working with Clang community to prepare code

Optimizations
  • Several optimizations are already standard implementation in our internal repo
  • Will have to come after full-fledged implementation
What is still missing – a lot!

Code generation for GPUs not yet available

• We are preparing patches
• Challenging to extract patches from full-fledged implementation of OpenMP 4.5. on GPUs
• Several design choices need to be discussed with community

Code generation for GPU is significantly different from CPU

• Due to SIMT GPU model
• No thread “spawning” or “recruiting”
• Cannot hide everything in runtime

Data sharing

• A single thread (team master) may need to share data with all other threads within its team
• Compiler needs to identify variables to be shared
• Requires multiple passes
How to play with full-fledged OpenMP 4.5. Implementation for GPU

Full-fledged implementation is available on Github

- [https://github.com/clang-ykt](https://github.com/clang-ykt)
- Give it a try and report bugs

This will be discontinued as soon as upstreamed

- Only meant as a collaboration hub before upstreamed
- Only expect bug fixes on this version
- New features will be done directly in trunk
Porting to OpenMP and CUDA started at the same time

- OpenMP version with collapse
  - Complex code synthesis
  - Hard to reproduce in CUDA
- CUDA version uses multiple block dimensions
- Eventually CUDA catches up, after some debugging
Performance of Mantevo

Thank you!

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