OpenMP* Support in Clang/LLVM: Status Update and Future Directions

2014 LLVM Developers' Meeting

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Intel
Agenda

1. Intro
2. Status
3. Runtime Library
4. Coprocessor/Accelerator Support
5. SIMD Features & Status
What is OpenMP*?

http://www.openmp.org/

- Industry-wide standard for shared memory multiprocessing programming in C/C++ and Fortran
- Vendor-neutral, platform-neutral, portable, pragma based, managed by an independent consortium
- Very important in High Performance Computing (HPC)
- OpenMP Version 3.1 (July 2011)
  - Implemented in GCC*, ICC, Oracle Solaris Studio*, PGI* ...
- OpenMP Version 4.0 (July 2013)
  - Adds support for coprocessors/accelerators, SIMD, error handling, thread affinity, user defined reductions
  - Implemented in GCC*, ICC ...
“OpenMP* in Clang/LLVM” Team

Driving collaboration and implementation

- Implementation of OpenMP in Clang/LLVM
- Coprocessor/accelerator support
- Test coverage
- Code reviews

Current participation from

- AMD*
- Argonne National Laboratory
- IBM*
- Intel
- Micron*
- Texas Instruments*
- University of Houston

Talk to us if you want to be involved!
OpenMP* Support in Clang

- Uses “early” outlining
  - Parallel and task regions are outlined as functions, all other regions are emitted as is
- Pragmas are just regular AST nodes with associated structured code block
  - Executable directives are Stmts
  - Declarative directives are Decls
- CodeGen follows regular rules for Stmts and Decls nodes
  - Uses libiomp5 runtime library, targets Intel OpenMP* API
  - Calls to runtime functions are generated in frontend
- No LLVM IR extensions are required

Support in Clang/LLVM is under development
OpenMP Constructs Representation

```
#pragma omp parallel if (<condition>)
<body>
```

- **Stmt**
- **OMPExecutableDirective**
- **OMPPParallelDirective**
- **OMPClause**
- **OMPClause**
- **OMPClause**
- **CapturedStmt (with <body>)**
- **OMPClause**
- **OMPIfClause**
- **<condition> Expr**
Current Status

- Clang/LLVM 3.5 Release
  - Parsing and semantic analysis for OpenMP* 3.1 (except for ‘ordered’ and ‘atomic’ directives)
  - CodeGen for ‘parallel’ and ‘simd’ directives, ‘safelen’ clause
  - First release with libiomp5 OpenMP runtime library!

- Clang/LLVM Trunk
  - Complete parsing and semantic analysis for OpenMP 3.1 and partial for OpenMP 4.0

- No support in driver yet, use -Xclang -fopenmp=libiomp5

- Planning full OpenMP 3.1 support in Clang/LLVM 3.6 Release, most of OpenMP 4.0 in Clang/LLVM 3.7 Release

 Depends on the speed of code review!
Current Status: clang-omp Repo

http://clang-omp.github.io/

- Full OpenMP* 3.1 + part of OpenMP 4.0 support
  - Coprocessor/accelerator support is under development
- OpenMP Validation Suite from OpenUH* test suite
  - Passed 119 tests of 123
- Supported on Linux* and Mac OS X*
  - x86, x86-64, PowerPC*, ARM*
- Based on Clang/LLVM 3.5 Release
  - Includes trunk-based version (maintained by Hal Finkel)
- Use -fopenmp driver option

You can try it right now!
## Current Status: Summary

<table>
<thead>
<tr>
<th>Features</th>
<th>Parsing/Sema (clang-omp)</th>
<th>CodeGen (clang-omp)</th>
<th>Parsing/Sema (Trunk)</th>
<th>CodeGen (Trunk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Partially</td>
</tr>
<tr>
<td>Worksharing</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>Tasking</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Other (OpenMP* 3.1)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>SIMD (OpenMP 4.0)</td>
<td>Yes</td>
<td>Yes</td>
<td>Partially</td>
<td>Partially</td>
</tr>
<tr>
<td>Coprocessor/Accelerator (OpenMP 4.0)</td>
<td>Yes</td>
<td>Partially</td>
<td>Partially</td>
<td>No</td>
</tr>
<tr>
<td>Other (OpenMP 4.0)</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
OpenMP* Runtime Library libiomp5

http://openmp.llvm.org

- Supports OpenMP 4.0 (though not all features are yet in Clang)
- Supported on Windows*, Linux* and Mac OS X*
  - x86, x86-64, PowerPC*, ARM*
- Can be built by Clang, GCC*, ICC
  - Two build bots configured (libiomp5-clang-x86_64-linux-debian, libiomp5-gcc-x86_64-linux-debian)
OpenMP* Coprocessor/Accelerator Support Library

- Required for support of OpenMP 4.0 target constructs
- Under development by Intel, IBM*, TI*, etc. in clang-omp repository
- Plan to support x86, x86-64, PowerPC* and ARM* as hosts, multiple targets (Intel® Xeon Phi™ coprocessor, GPUs, FPGAs, ...)

![Diagram of OpenMP support library](image-url)
OpenMP*: Levels of Parallelism

- **Coprocessors/Accelerators**
  - *new* #pragma omp target

- **Threads**
  - *old* #pragma omp parallel for

- **SIMD**
  - OpenMP with SIMD flavor #pragma omp simd
SIMD: What is It?

- How to run faster?
  - Run instructions simultaneously
    - Thread-level parallelism
    - `#pragma omp parallel for`
  - Handle the data simultaneously
    - Data-level parallelism
    - SIMD, Single Instruction Multiple Data, vector instructions
    - `#pragma omp simd`
  - Do Both
    - `#pragma omp parallel for simd`
**SIMD: How to Use**

**Auto**
- High and transparent portability
- High and transparent scalability
- No development cost
- Unpredictable performance

**Explicit**
- Expresses desired vectorization
- High and transparent portability
- High and transparent scalability
- Low development cost
- Predictable performance

**Manual**
- Max performance
- Low portability
- High development cost
- Low scalability

---

```c
float *A, *B, *C;
...
for(int i...)
    C[i] = A[i] + B[i];
$> clang -O2 ...
```

```c
float *A, *B, *C;
...
#pragma omp simd
for(int i...)
    C[i] = A[i] + B[i];
$> clang -O2 -Xclang -fopenmp=
```

```c
#include "xmmintrin.h"
...
float *A, *B, *C;
__m128 a, b, c;
...
for(int i...)
{
    a = _mm_load_ps(A + i*4);
    b = _mm_load_ps(B + i*4);
    c = _mm_add_ps(a, b);
    _mm_store_ps(C+i * 4, c);
}
$> clang ...
```
SIMD: Autovectorization vs Pragmas

- Autovectorization in LLVM fails if:
  - cost heuristic says “no”
  - non-trivial data dependencies
  - overhead is high for runtime checks
  - loop is not innermost
- OpenMP* SIMD pragmas:
  - vectorize, don’t check!

```c
// RT pointer aliasing checks: float*
void doThings(float *a, float *b, float *c, float *d, float *e, unsigned N, unsigned K)
{
    for(int i = 0; i < N; ++i) // not innermost
        for(int j = 0; j < N; ++j)
            // non-trivial data-deps due to unknown K
            a[i + j] = b[i + K] + c[i + K] + d[i + K] + e[i + K];
}
```

```
$> clang -mllvm -debug-only=loop-vectorize ...
LV: Checking a loop in "doThings" from test.c:4:3 ...
LV: Found a runtime check ptr: %arrayidx18.us = ...
LV: We need to do 4 pointer comparisons
LV: We can't vectorize because we can't find the array bounds
LV: Can't vectorize due to memory conflicts
```

```
// the only change
#pragma omp simd collapse(2)
    for(int i = 0; i < N; ++i)
        for(int j = 0; j < N; ++j)
            a[i + j] = ... 
...
```

```
$> clang -mllvm -debug-only=loop-vectorize -Xclang -fopenmp=...
LV: Checking a loop in "doThings" from test.c:4:3
LV: Loop hints: force=enabled width=0 unroll=0
LV: A loop annotated parallel, ignore memory dependency checks.
LV: We can vectorize this loop!
```
OpenMP* SIMD: Status in Clang

- OpenMP SIMD requires support from both frontend and backend

- Frontend parses OpenMP SIMD pragmas and creates LLVM IR metadata hints, which are then used by vectorizer

```c
#pragma omp simd safelen(4)
for(int i = 0; i < N; ++i) ...
```

- LV: Checking a loop in ...
  - LV: Loop hints: `force=enabled width=4 unroll=0`
  - `!42 = metadata !{metadata !"llvm.loop.vectorize.enable", i1 true}`
  - `!43 = metadata !{metadata !"llvm.loop.vectorize.width", i32 4}`

- In case of `collapse` clause frontend creates a new loop, **collapsing** the existing loop nest into single loop
OpenMP* SIMD: Status in LLVM backend

- LLVM loop vectorizer recognizes loop vectorizing metadata
- *Collapse*, *safelen* and *aligned* clauses are ready to use
- Other clauses and constructs are under development

**TODO:**
- Vectorizing metadata must be propagated through all the passes prior to the vectorizer
- Compile-time memory checks must be disabled in the presence of OpenMP SIMD pragmas
Questions?

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Backup
OpenMP Constructs Representation: Continued

```
br i1 <condition>, label %omp.if.then, label%omp.if.else
omp.if.else:
    <body>
br label %omp.if.end
omp.if.then:
    %3 = bitcast %struct.anon* %agg.captured to i8*
call void @__kmpc_fork_call(<loc>, i32 1, void (i32*, i32*, ...)*) bitcast (void (i32*, i32*, i8*)*) @omp_microtask to void (i32*, i32*, ...)*, i8* <captured_vars>)
br label %omp.if.end
omp.if.end:
...
define internal void @omp_microtask.(i32*, i32*, i8*) #0 {
    %gtid. = load i32* %0
    <body>
call i32 @__kmpc_cancel_barrier(<loc>, i32 %gtid.)
}
```