OpenMP

SC'21 Booth Talk Series

SC21

St. Louis, MO | science & beyond.

Using OpenMP Loop Transformations with Clang

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Outline

Unrolling

Non-Standard Extensions

- Cray
  ```
  #pragma [_CRI] unroll 4
  ```
- icc
  ```
  #pragma unroll 4
  ```
- xlc
  ```
  #pragma unroll(4)
  ```
- HP
  ```
  #pragma UNROLL_FACTOR 4
  ```
- gcc
  ```
  #pragma GCC unroll 4
  ```
- clang
  ```
  #pragma unroll 4
  #pragma clang loop unroll_count(4)
  ```
- msvc

  ???

Full Unrolling

OpenMP 5.1

```
#pragma omp unroll full
for (int i = 0; i < 4; i += 1)
  body(i);
```


Full Unrolling

OpenMP 5.1

```
#pragma omp unroll full
for (int i = 0; i < 4; i += 1)
  body(i);
```

```
body(0);
body(1);
body(2);
body(3);
```


Partial Unrolling

OpenMP 5.1

```
#pragma omp unroll partial(4)
for (int i = 0; i < n; i += 1)
  body(i);
```

```
int i = 0;
for (; i+3 < n; i += 4) {
  body(i);
  body(i + 1);
  body(i + 2);
  body(i + 3);
}
for (; i < n; i += 1)
  body(i);
```


Heuristic Unrolling

OpenMP 5.1

```
#pragma omp unroll
for (int i = 0; i < n; i += 1)
  body(i);
```

or

```
#pragma omp unroll partial
for (int i = 0; i < n; i += 1)
  body(i);
```

```
int i = 0;
for (; i+? < n; i += ?) {
  body(i);
  ...
}
for (; i < n; i += 1)
  body(i);
```

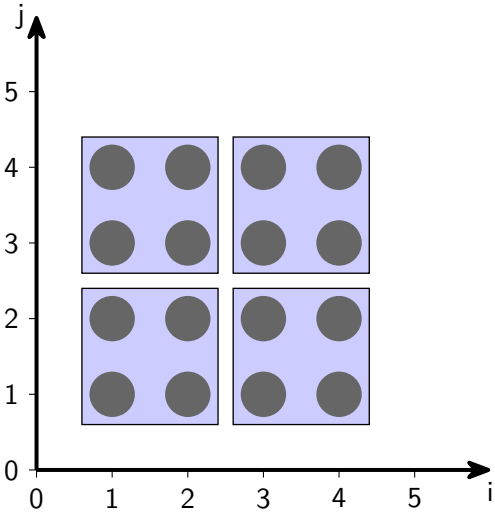

Complete Tiles

OpenMP 5.1

```
#pragma omp tile sizes(2,2)
for (int i = 1; i <= 4; ++i)
  for (int j = 1; j <= 4; ++j)
    body(i,j);
```


Complete Tiles

OpenMP 5.1

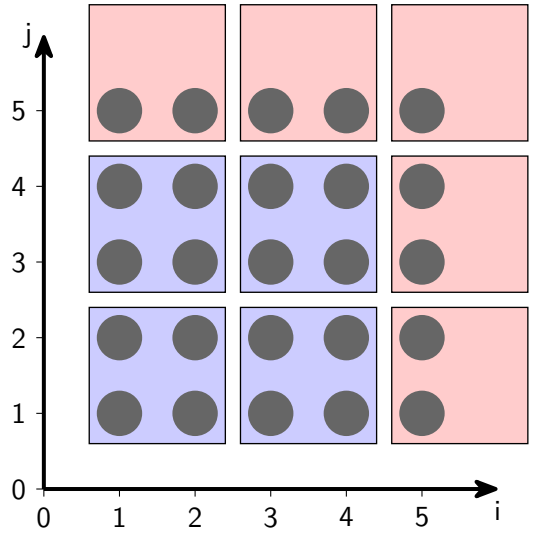



```
#pragma omp tile sizes(2,2)
for (int i = 1; i <= 4; ++i)
  for (int j = 1; j <= 4; ++j)
    body(i,j);
```

```
/* floor loops iterating over tiles */
for (int i1 = 0; i1 < 4; i1 += 2)
  for (int j1 = 0; j1 < 4; j1 += 2)
    /* tile loops over iterations */
    for (int i2 = i1; i2 < i1 + 2; i2 += 1)
      for (int j2 = j1; j2 < j2 + 2; j2 += 1)
        /* an iteration */
        body(1+i2,1+j2);
```


Partial Tiles

OpenMP 5.1




```
#pragma omp tile sizes(2,2)
for (int i = 1; i <= 5; ++i)
  for (int j = 1; j <= 5; ++j)
    body(i,j);
```

```
/* hot, streamlined code */
for (int i1 = 0; i1 < 4; i1 += 2)
  for (int j1 = 0; j1 < 4; j1 += 2)
    for (int i2 = i1; i2 < i1 + 2; i2 += 1)
      for (int j2 = j1; j2 < j2 + 2; j2 += 1)
        body(i2+1,j2+1);

/* special case code */
for (int i = 1; i < 5; ++i)
  for (int j = 1; j < 5; ++j)
    if (i >= 5 || j >= 5)
      body(i,j);
```


Loop Transformation Composition

- Rule: Loop-associated directives apply to the next line
  1. A base language canonical loop

```
#pragma omp taskloop
for (int i = 0; i < 128; ++i)
  body(i);
```

  2. The output of another loop transformation

```
#pragma omp taskloop
#pragma omp tile sizes(8)
for (int i = 0; i < 128; ++i)
  body(i);
```

```
#pragma omp taskloop
for (int i1 = 0; i1 < 128; i1 += 8)
  for (int i2 = i1; i2 < i1 + 8; i2 += 1)
    body(i2);
```


Multi-Level Tiling

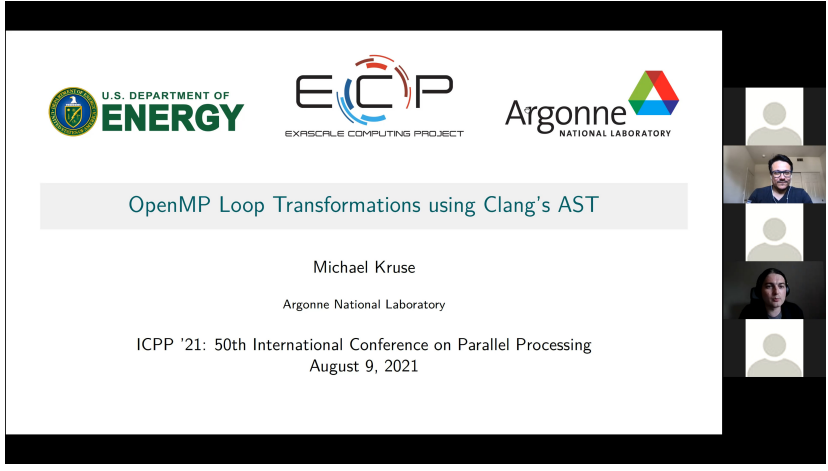
```
#pragma omp tile sizes(4, 4)
#pragma omp tile sizes(5,16)
for (int i = 0; i < 100; ++i)
  for (int j = 0; j < 128; ++j)
    A[i][j] = i*1000 + j;
```

```
#pragma omp tile sizes(4,4)
for (int i1 = 0; i1 < 100; i1+=5)
  for (int j1 = 0; j1 < 128; j1+=16)
    for (int i2 = i1; i2 < i1+5; ++i2)
      for (int j2 = j1; j2 < j1+16; ++j2)
        A[i2][j2] = i2*1000 + j2;
```

```
for (int i11 = 0; i11 < 100; i11+= 5*4)
for (int j11 = 0; j11 < 128; j11+=16*4)
    for (int i12 = i11; i12 < i11+( 5*4); i12+= 5)
    for (int j12 = j11; j12 < j11+(16*4); j12+=16)
        for (int i2 = i12; i2 < i12+ 5; ++i2)
        for (int j2 = j12; j2 < j12+16; ++j2)
            A[i2][j2] = i2*1000 + j2;
```


Outline

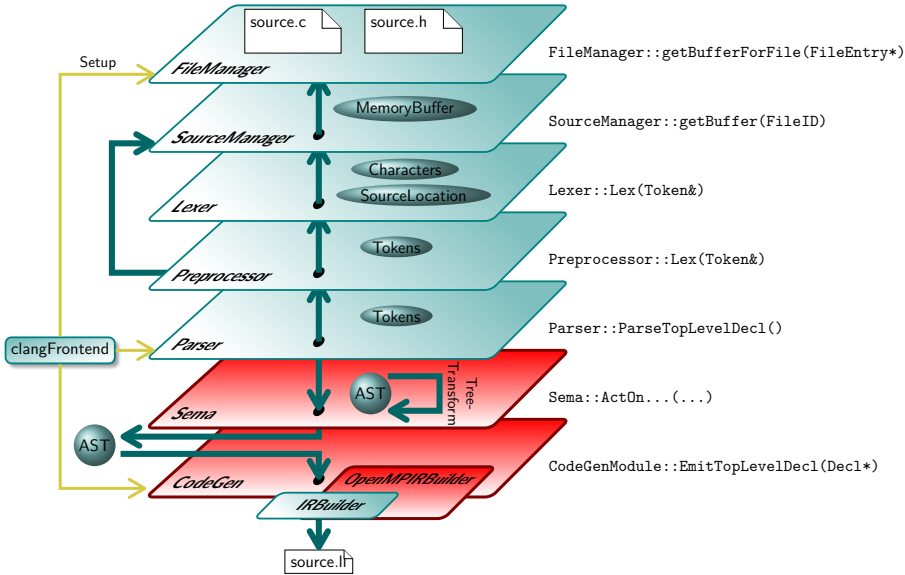
LLVM in Parallel Processing Workshop



https://oaciss.uoregon.edu/icpp21/videos/LLPP_ICPP_21.mp4
Starting at 0:36:50

Clang Layers

clang -cc1



Status

Available in Clang 13

Shadow AST Implementation

- Tiling:
  `https://reviews.llvm.org/D76342`
- Unrolling:
  `https://reviews.llvm.org/D99459`

OpenMPIRBuilder Implementation

Experimental: `-fopenmp-enable-irbuilder`

- `CanonicalLoopInfo`:
  `https://reviews.llvm.org/D90830`
- `collapseLoops`:
  `https://reviews.llvm.org/D93268`
- `unrollLoop`:
  `https://reviews.llvm.org/D107764`
- `tileLoops`:
  `https://reviews.llvm.org/D92974`
- `createWorkshareLoop`:
  `https://reviews.llvm.org/D92476`

Outline

Google Benchmark

Multi-Threading

```
template <int P>
static void benchmark_threads(benchmark::State &state) {
  double *A = aligned_alloc(...);


  for (auto _ : state) {
     #pragma omp parallel for \
                 schedule(static,P)
     for (int i = 0; i < M; ++i)
       ...
     /* implicit barrier */
  }

  free(A);
}
BENCHMARK_TEMPLATE(benchmark_threads, 1)->MeasureProcessCPUTime()->UseRealTime();
BENCHMARK_TEMPLATE(benchmark_threads, 2)->MeasureProcessCPUTime()->UseRealTime();
...
```


Google Benchmark

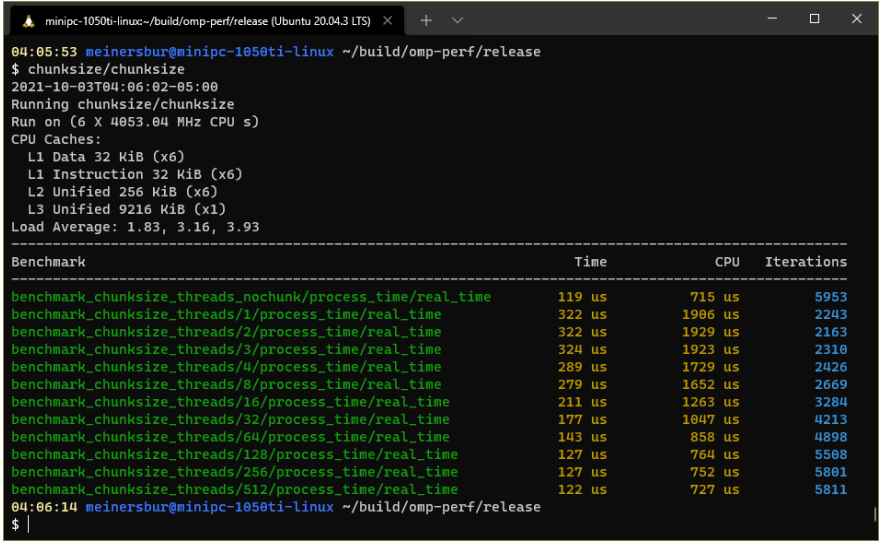
Offloading

```
template <int P>
static void benchmark_target(benchmark::State &state) {
  double *A = aligned_alloc(...);

  #pragma omp target data map(tofrom:A[0..N])
  for (auto _ : state) {
    #pragma omp target teams distribute parallel for \
                dist_schedule(static,P) schedule(static,P)
    for (int i = 0; i < M; ++i)
      ...
    #pragma omp taskwait
  }

  free(A);
}
BENCHMARK_TEMPLATE(benchmark_target, 1)->UseRealTime();
BENCHMARK_TEMPLATE(benchmark_target, 2)->UseRealTime();
...
```


Google Benchmark



SU3 Matrix-Vector Multiplication

Quantum Chromodynamics

```
#pragma omp unroll full
for (int j = 0; j < 3; ++j) {
  #pragma omp unroll full
  for (int k = 0; k < 3; ++k)
    C[i].v[j] += A[i].v[k] * B[i].c[k].v[j];
}
```

- $128 \cdot 1024$ $(= 2^{17})$ elements in `A`/`B`/`C`
- Single precision (`float`)

SU3 Matrix-Vector Multiplication

```
$ clang -O3 -fno-exceptions -march=native \
  -fopenmp -fopenmp-version=51 \
  -fno-unroll-loops -fno-vectorize \
  -Rpass=loop-unroll
```


SU3 Matrix-Vector Multiplication

```
$ clang -O3 -fno-exceptions -march=native \
  -fopenmp -fopenmp-version=51 \
  -fno-unroll-loops -fno-vectorize \
  -Rpass=loop-unroll
```

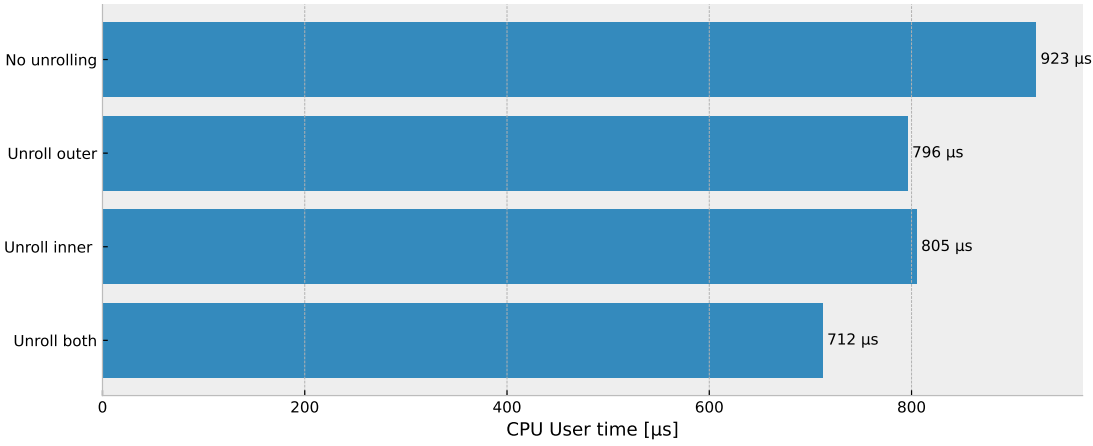

SU3 Matrix-Vector Multiplication

```
$ clang -O3 -fno-exceptions -march=native \
  -fopenmp -fopenmp-version=51 \
  -fno-unroll-loops -fno-vectorize \
  -Rpass=loop-unroll
```

```
remark: su3.cpp:217:15: completely unrolled loop with 3 iterations [-Rpass=loop-unroll]
remark: su3.cpp:215:7: completely unrolled loop with 3 iterations [-Rpass=loop-unroll]
```

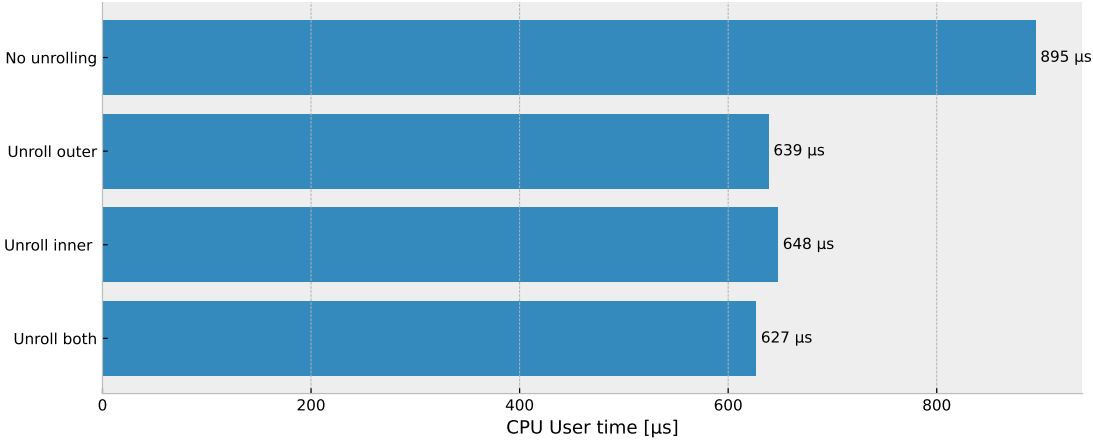

SU3 Single-Thread Performance

Intel(R) Xeon(R) Gold 6152 CPU @ 2.10GHz



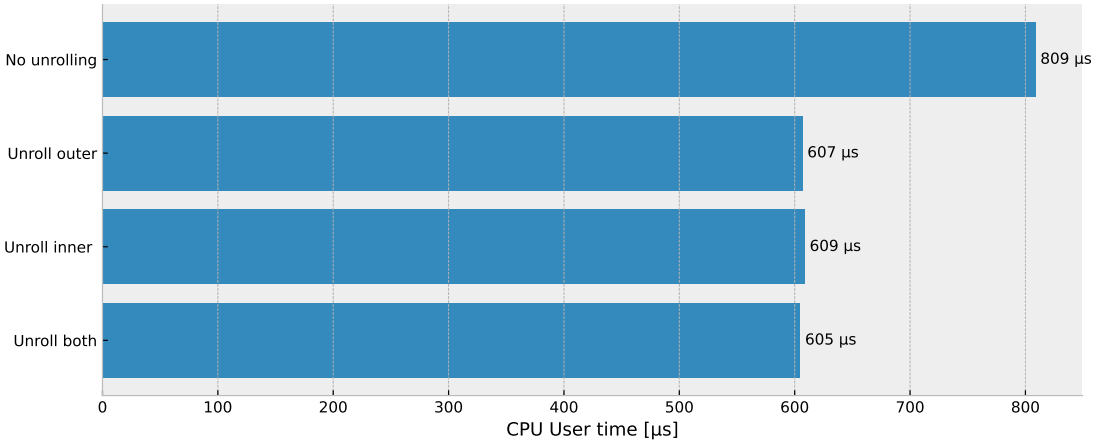
SU3 Single-Thread Performance

Intel(R) Core(TM) i5-9400F CPU @ 2.90GHz



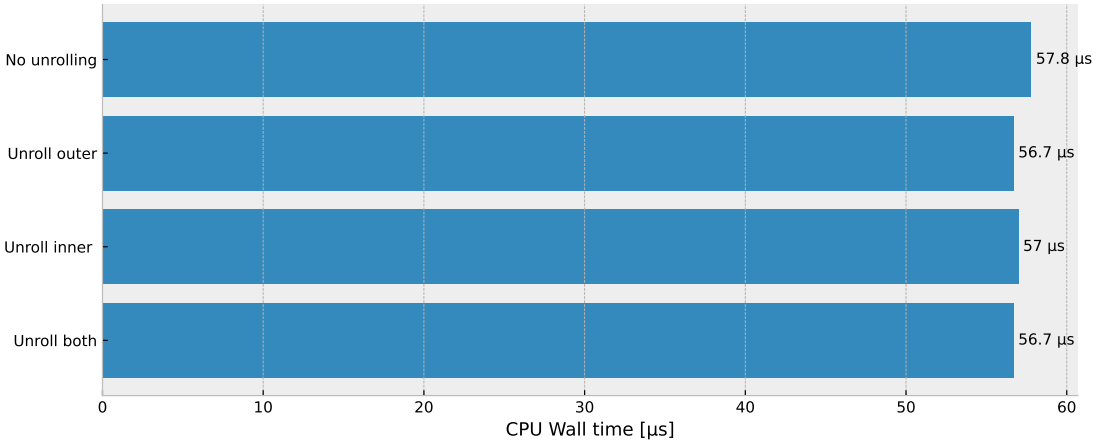
SU3 Single-Thread Performance

AMD EPYC 7532 32-Core Processor



SU3 Offloading Performance

NVIDIA Tesla V100-SXM2-32GB



Output Verification

```
$ clang -save-temps
```

su3-openmp-nvptx64.s

```
    mov.u64     %rd70, %rd28;
LBB0_7:
    .pragma "nounroll";
    add.s64         %rd65, %rd67, %rd71;
    ld.global.f32   %f4, [%rd65];
    ld.global.f32   %f5, [%rd70];
    mul.rn.f32      %f6, %f4, %f5;
    add.rn.f32      %f7, %f7, %f6;
    st.global.f32   [%rd29], %f7;
    add.s64         %rd71, %rd71, 4;
    cvt.u32.u64     %r21, %rd71;
    add.s64         %rd70, %rd70, 12;
    setp.eq.s32     %p4, %r21, 12;
    @%p4 bra         LBB0_8;
    bra.uni         LBB0_7;
```


Polybench 4.2.1b atax

Linear Algebra

```
for (int i = 0; i < m; i++) {
  tmp[i] = 0;

  #pragma omp unroll partial(P)
  for (int j = 0; j < n; j++)
    tmp[i] = tmp[i] + A[i][j] * x[j];

  #pragma omp unroll partial(P)
  for (int j = 0; j < n; j++)
    y[j] = y[j] + A[i][j] * tmp[i];
}
```

- `LARGE_DATASET` (default)
  - $\mathtt{m} = 1900$
  - $\mathtt{n} = 2100$
- `DATA_TYPE_IS_INT`

atax Unroll Heuristic

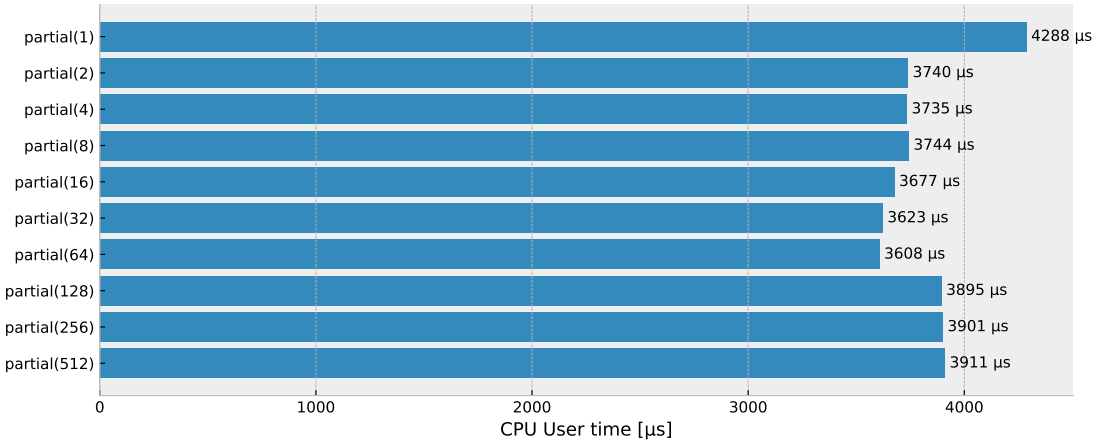
```
$ clang -O3 -fno-exceptions -march=native \
  -fopenmp -fopenmp-version=51 \
  -fno-unroll-loops -fno-vectorize \
  -Rpass=loop-unroll
```

```
#pragma omp unroll
```

```
remark: atax.cpp:947:5: unrolled loop by a factor of 8 with run-time trip count [-Rpass=loop-unroll]
remark: atax.cpp:951:5: unrolled loop by a factor of 8 with run-time trip count [-Rpass=loop-unroll]
```


atax Single-Thread Performance

AMD EPYC 7532 32-Core Processor



Polybench 4.2.1b heat-3d

Stencil

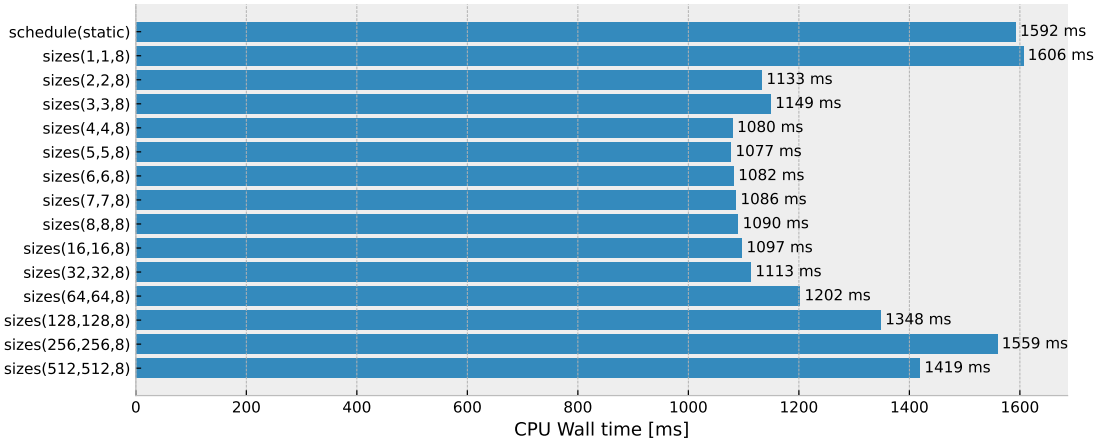
```
#pragma omp parallel
for (int t = 1; t <= steps; t++) {
  #pragma omp for collapse(3)
  #pragma omp tile sizes(P,P,8)
  for (int i = 1; i < n-1; i++)
    for (int j = 1; j < n-1; j++)
      for (int k = 1; k < n-1; k++)
        B[i][j][k] =  A[i][j][k] +
             0.125 * (A[i+1][j][k] - 2.0 * A[i][j][k] + A[i-1][j][k]) +
             0.125 * (A[i][j+1][k] - 2.0 * A[i][j][k] + A[i][j-1][k]) +
             0.125 * (A[i][j][k+1] - 2.0 * A[i][j][k] + A[i][j][k-1]);

  /* again with A and B swapped */
}
```

- steps $= 6$
- n $= 400$
- double precision

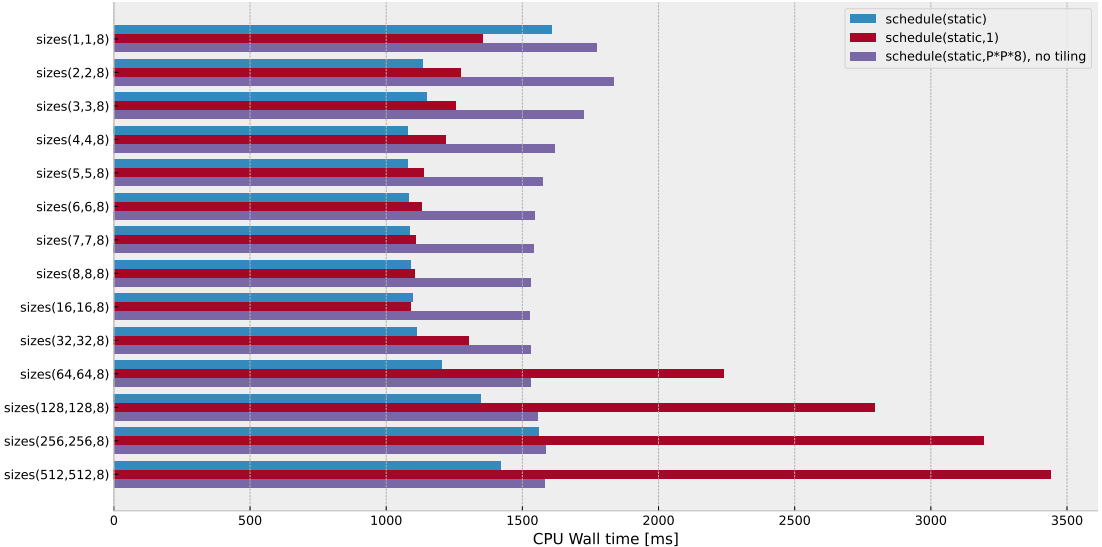
heat-3d Multi-Thread Performance

Intel(R) Core(TM) i5-9400F CPU @ 2.90GHz (6 cores, 6 threads)



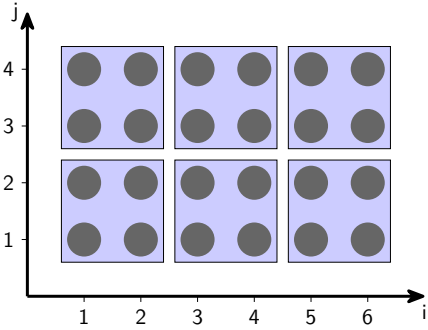
heat-3d Multi-Thread Performance

Intel(R) Core(TM) i5-9400F CPU @ 2.90GHz (6 cores, 6 threads)

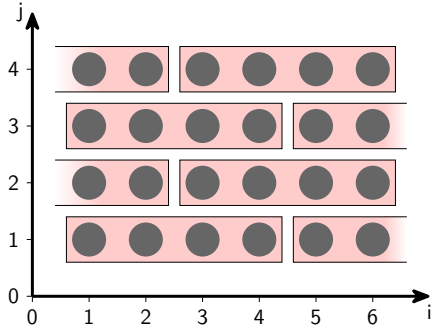


Complete Tiles

```
#pragma omp for schedule(static,1) collapse(2)
#pragma omp tile sizes(2,2)
for (int j = 1; j <= 4; ++j)
  for (int i = 1; i <= 6; ++i)
```

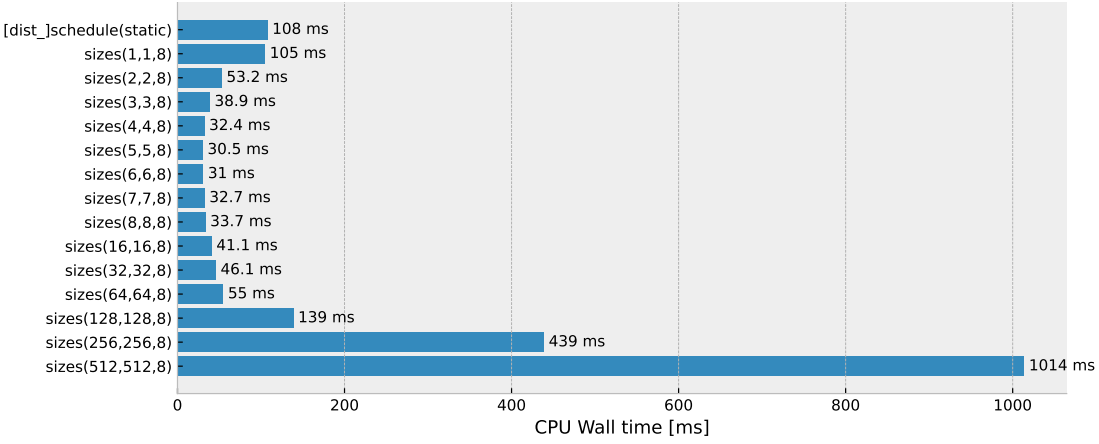



```
#pragma omp for schedule(static,4) collapse(2)
for (int j = 1; j <= 4; ++j)
  for (int i = 1; i <= 6; ++i)
```



heat-3d Offloading Performance

NVIDIA Tesla V100-SXM2-32GB



Outline

Summary

- New in OpenMP 5.1: Loop Transformations
- Available in Clang 13
- Google Benchmark for Microbenchmarking
  - Full unrolling to remove loop overhead
  - Partial unrolling to reduce loop overhead
  - Tiling for memory access locality
- Outcome depends on processor architecture

Possible Extensions for OpenMP 6.0

Additional Transformations

- Loop interchange
- Loop fission/fusion
- Peeling
- Loop unswitching
- Space-filling curves

Auxiliary Transformations

- Nestify
- Rectangify
- Collapse

More Clauses

- Control over remainder loops
- Enable safety checks

Compose Non-Outermost Generated Loops

- Loop identifiers
- `apply` clause

```
#pragma omp tile apply(floor: parallel for) \
        apply(tile : simd)
for (int i = 0; i < n; ++i)
    Body(i);
```

Semantics/Optimization Hints

- Assumptions:
  "ivdep", parallelizable, interchangeable, ...
- Expectations:
  loop trip count, hot/cold/dead, ...

OpenMP

SC'21 Booth Talk Series

openmp.org OpenMP API specs, forum, reference guides, and more

link.openmp.org/sc21 Videos and PDFs of OpenMP SC'21 presentations

Acknowledgments

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