OpenMP

SC'20 Booth Talk Series

OMP5.1: Loop Transformations

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Outline

Vectorization Compiler Hints

- Cray
  `#pragma ivdep`

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  `#pragma ivdep`
- SGI/Open64
  `#pragma ivdep`
- HP
  `#pragma IVDEP`
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  `#pragma ivdep`
- PGI
  `#pragma ivdep`

Vectorization Compiler Hints

- Cray
  `#pragma [_CRI] ivdep`
- SGI/Open64
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- Intel
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- PGI
  `#pragma ivdep`
- gcc
  `#pragma GCC ivdep`

Vectorization Compiler Hints

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  `#pragma IVDEP`

- Intel
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- PGI
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- gcc
  `#pragma GCC ivdep`
- msvc
  `#pragma loop(ivdep)`
- clang
  `#pragma clang loop vectorize(enable)`

Vectorization Compiler Hints

- Cray
  `#pragma [_CRI] ivdep`
- SGI/Open64
  `#pragma ivdep`
- HP
  `#pragma IVDEP`

- Intel
  `#pragma ivdep`
  `#pragma vector`
  `#pragma simd`
- PGI
  `#pragma ivdep`
  `#pragma vector`

- gcc
  `#pragma GCC ivdep`
- msvc
  `#pragma loop(ivdep)`
- clang
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Vectorization Compiler Hints

- Cray
  `#pragma [_CRI] ivdep`
- SGI/Open64
  `#pragma ivdep`
- HP
  `#pragma IVDEP`
  `#pragma NODEPCHK`
- Intel
  `#pragma ivdep`
  `#pragma vector`
  `#pragma simd`
- PGI
  `#pragma ivdep`
  `#pragma vector`
  `#pragma nodepchk`
- gcc
  `#pragma GCC ivdep`
- msvc
  `#pragma loop(ivdep)`
- clang
  `#pragma clang loop vectorize(enable)`
- Oracle Developer Studio
  `#pragma nomemorydepend`

WARNING: Different Semantics

- Cray's `ivdep` semantics is defined by its implementation:
  Assume only dependencies exist that the compiler detects
- Others are implementation-independent:
  Assume no loop-carried dependencies exist
  (implies no reductions)
- Some implement both:
  `ivdep`/`nodepchk`

SIMD Directive

OpenMP 4.0

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


SIMD Directive

OpenMP 4.0

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

- Clang supports a SIMD-only mode
  `clang -fopenmp-simd`

Outline

Unrolling Compiler Hints

- 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

  ???

Unroll Directive

OpenMP 5.1

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


Unroll Directive Effect

Full Unrolling

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

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


Unroll Directive Effect

Partial Unrolling

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

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


Unroll Directive Effect

Partial Unrolling

```
#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);
```


Unroll Directive Effect

Compiler-determined unroll factor

```
#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);
```


Unroll Directive Effect

Compiler-determined unrolling mode

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

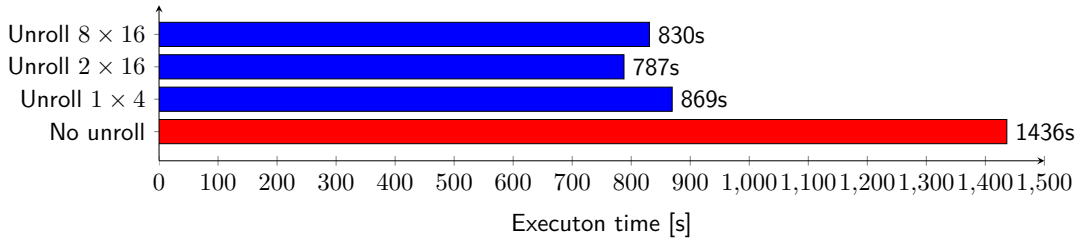

When To Use

- Full Unrolling
  - Small constant trip-count in hot code
    (Unless L1i is a bottleneck)
  - Compiler will probably unroll them automatically
- Partial Unrolling
  - X86 (Intel/AMD): Probably unnecessary
  - Accelerators (Nvida/AMD/Intel): Innermost loops with small bodies

GEMM Performance

NVidia 8800 GTX

```
for (int i = 0; i < NI; i++)
  #pragma omp unroll partial(x)
  for (int j = 0; j < NJ; j++)
    #pragma omp unroll partial(y)
    for (int k = 0; k < NK; k++)
      C[i][j] += alpha * A[i][k] * B[k][j];
```



G. S. Murthy et. al. "Optimal Loop Unrolling for GPGPU Programs" (IPDPS'10)

Outline

OpenACC Tile Clause

- OpenACC
  `#pragma acc loop tile(...)`

Tile Directive

OpenMP 5.1

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

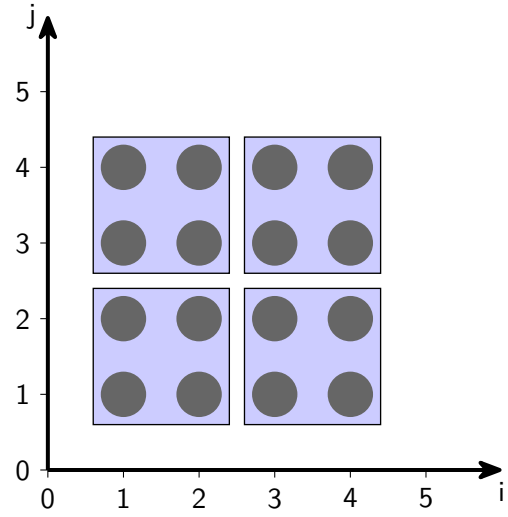

Tile Directive

OpenMP 5.1

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

```
for (int i1 = 0; i1 < 128; i1 += 8)
  for (int j1 = 0; j1 < 128; j1 += 8)
    for (int i2 = i1; i2 < i1 + 8; i2 += 1)
      for (int j2 = j1; j2 < j2 + 8; j2 += 1)
        body(i2,j2);
```

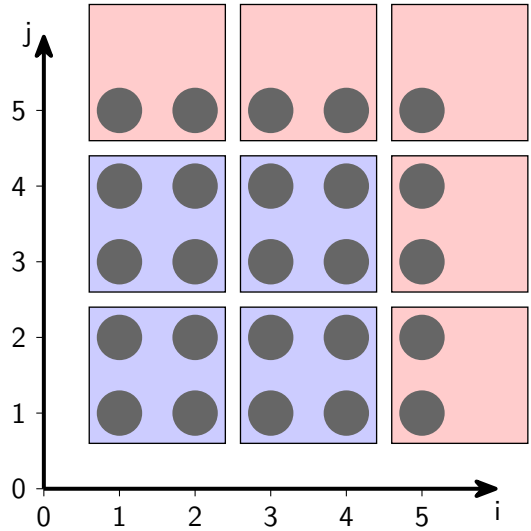

Illustration




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

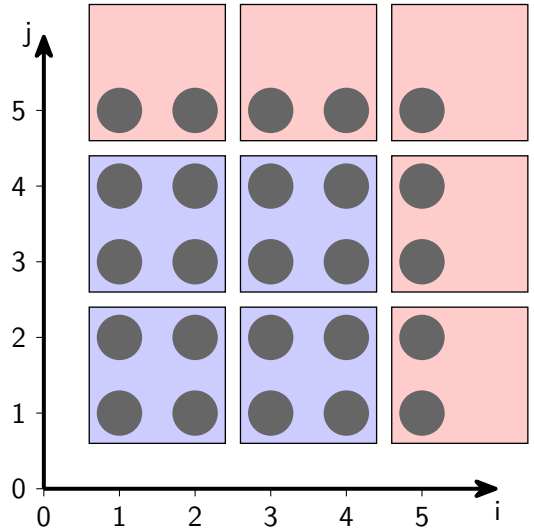
```
/* floor loops iterating over tiles */
for (int i1 = 0; i1 < 4; i1 += 2)
  for (int j1 = 0; j1 < 4; j1 += 2)
    /* tile loops over iterations */
    for (int i2 = i1; i2 < i1 + 2; i2 += 1)
      for (int j2 = j1; j2 < j2 + 2; j2 += 1)
        /* an iteration */
        body(1+i2,1+j2);
```


Partial/Complete Tiles




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


Partial/Complete Tiles



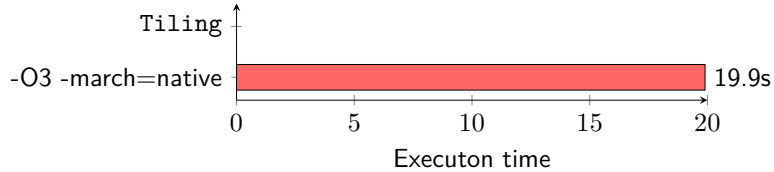

```
#pragma omp tile sizes(2,2)
for (int i = 1; i <= 5; ++i)
  for (int j = 1; j <= 5; ++j)
    body(i,j);
```

```
/* 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);
```

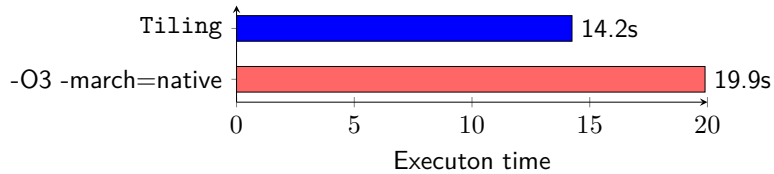

heat-3d Stencil

```
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] =  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])
                        + A[i][j][k];
```



heat-3d Stencil

```
#pragma omp tile sizes(16,1,1024)
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] =  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])
                        + A[i][j][k];
```



When To Use

- Localize workings set
  - Stencils
  - BLAS (e.g. gemm)
  - Any computation reusing relative indices multiple times
- Split workload (chunking)
  - Coarser-grain parallelism
- Preparation for other transformations
  - Partial unrolling is defined as 1-dimensional tiling followed by a full unroll

Outline

Composition of Tiling

Tiling

- Rule: Directives apply to the next line
  1. A base language canonical loop

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


Composition of Tiling

Tiling

- Rule: 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;
```


Composition of Unrolling

```
#pragma omp parallel for
#pragma omp unroll partial(4)
for (int i = 0; i < 128; ++i)
    body(i);
```

```
#pragma omp parallel for
for (int i = 0; i < 128; i += 4) {
    body(i);
    body(i + 1);
    body(i + 2);
    body(i + 3);
}
```


Generated Loops by Unrolling

Unrolling

Unroll directive generated a loop with partial unrolling only:

- `#pragma omp unroll partial(n)`
- `#pragma omp unroll partial`

The replacement of these are not transformable:

- `#pragma omp unroll full`
- `#pragma omp unroll`

Split Optimization from Semantics

- Semantics: Single Fortran/C/C++ source
- Optimization: Pragmas based on target hardware

```
for (int i = 0; i < m; ++i)
  for (int j = 0; j < n; ++j)
    body(i,j);
```


Split Optimization from Semantics

- Semantics: Single Fortran/C/C++ source
- Optimization: Pragmas based on target hardware
  - Using Preprocessor

```
#ifdef ENABLE_OFFLOADING
  #pragma omp distribute parallel for collapse(2)
#else
  #pragma omp for
  #pragma omp tile sizes(16,32)
#endif
for (int i = 0; i < m; ++i)
  #ifdef ENABLE_OFFLOADING
    #pragma omp unroll partial(8)
  #endif
  for (int j = 0; j < n; ++j)
    body(i,j);
```


Split Optimization from Semantics

- Semantics: Single Fortran/C/C++ source
- Optimization: Pragmas based on target hardware
  - Using Metadirective (OpenMP 5.0)

```
#pragma omp metadirective                                          \
    when(device={kind(gpu)}: distribute parallel for collapse(2)) \
    when(device={kind(cpu)}: for)
#pragma omp metadirective                                          \
    when(device={kind(cpu)}: tile sizes(16,32))
for (int i = 0; i < m; ++i)
  #pragma omp metadirective                                        \
      when(device={kind(gpu)}: unroll partial(8))
  for (int j = 0; j < n; ++j)
    body(i,j);
```


Outline

Use Cases

- Target audience: performance specialists
  - *Know your hardware!*
- Workflow
  1. Write application to be correct first
  2. Do some profiling
  3. Apply low-hanging fruits
     - Use vendor-optimized libraries
     - Optimize (e.g. `schedule(static,`*chunk-size*`)`)
     - Add optimization directives: `simd`, `unroll`, `tile`
  4. Extreme optimization
     - Rewrite kernel using target hardware assembly

Compiler Support

- Clang: In progress
  - Tile directive: `https://reviews.llvm.org/D76342`

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

link.openmp.org/sc20 Videos and PDFs of OpenMP SC'20 presentations

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