Outline

1 Compiler Optimization Hints
2 Unroll Directive
3 Tile Directive
4 Transformation Composition
5 Conclusion
Vectorization Compiler Hints

- Cray
  
  `#pragma ivdep`
Vectorization Compiler Hints

- Cray
  `#pragma ivdep`
- SGI/Open64
  `#pragma ivdep`
- HP
  `#pragma IVDEP`
- Intel
  `#pragma ivdep`
- PGI
  `#pragma ivdep`
Vectorization Compiler Hints

- Cray
  #pragma [_CRI] ivdep
- SGI/Open64
  #pragma ivdep
- HP
  #pragma IVDEP
- Intel
  #pragma ivdep
- PGI
  #pragma ivdep
- gcc
  #pragma GCC ivdep
Vectorization Compiler Hints

- Cray
  
  \#pragma [_CRI] ivdep

- SGI/Open64
  
  \#pragma ivdep

- HP
  
  \#pragma IVDEP

- Intel
  
  \#pragma ivdep

- PGI
  
  \#pragma ivdep

- 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
  
  `#pragma clang loop vectorize(enable)`
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`
```c
#pragma omp simd
for (int i = 0; i < n; ++i)
    body(i);
```
```c
#pragma omp simd
for (int i = 0; i < n; ++i)
    body(i);
```

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

1. Compiler Optimization Hints

2. Unroll Directive
   - Prior Art
   - What is it doing?
   - Use Cases
   - Performance

3. Tile Directive

4. Transformation Composition

5. Conclusion
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

What is it doing?

OpenMP 5.1

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

What is it doing?

Unroll Directive Effect

Full Unrolling

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

Stmt(0);
Stmt(1);
Stmt(2);
Stmt(3);
Unroll Directive → What is it doing?

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

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

```c
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

Unroll Directive → What is it doing?

#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 (Nvidia/AMD/Intel): Innermost loops with small bodies
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

1. Compiler Optimization Hints

2. Unroll Directive

3. Tile Directive
   - Prior Art
   - What is it doing?
   - Performance
   - Use Cases

4. Transformation Composition

5. Conclusion
OpenACC Tile Clause

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

---

Tile Directive → Prior Art
What is it doing?

Tile Directive
OpenMP 5.1

```c
#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

What is it doing?

OpenMP 5.1

```c
#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);
```
Tile Directive → What is it doing?

Illustration

```c
#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);
```
Tile Directive → What is it doing?

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);
**Tile Directive → What is it doing?**

**Partial/Complete Tiles**

```c
#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);
```
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];
#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];
Tile Directive → Use Cases

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

1. Compiler Optimization Hints
2. Unroll Directive
3. Tile Directive
4. Transformation Composition
   - Tiling
   - Unrolling
   - Performance Portability
5. Conclusion
Transformation Composition → Tiling

Composition of Tiling

Tiling

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

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

#pragma omp taskloop
```
#pragma omp tile sizes(8)
for (int i = 0; i < 128; ++i)
#pragma omp taskloop
for (int i1 = 0; i1 < 128; i1 += 8)
    for (int i2 = i1; i2 < i1 + 8; i2 += 1)
        body(i2);
```
Rule: Directives apply to the next line

1 A base language canonical loop

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

2 The output of another loop transformation

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

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

Multi-Level Tiling

```c
#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;
```
#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);
}
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

```c
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

```c
#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)

```c
#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

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5. Conclusion
   - When to Use
   - Implementations
   - OpenMP 6.0 Outlook
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
Conclusion → Implementations

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
```
#pragma omp tile apply(flower: 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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