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Notice revision #20110804

SOFTWARE AND SERVICES
Outline

• Very brief Introduction to OpenMP
• Task-generating loops
• Locks with Hints
• Extensions to the `target` Constructs
Brief introduction to OpenMP
OpenMP API

• De-facto standard, OpenMP 4.0 out since July 2013

• API for C/C++ and Fortran for shared-memory parallel programming

• Based on directives (pragmas in C/C++)

• Portable across vendors and platforms

• Supports various types of parallelism
OpenMP History
## OpenMP Platform Features

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OpenMP 3.0 in Three Slides

```c
#pragma omp parallel
{
    #pragma omp for
    for (i = 0; i < N; i++)
    {
        ...
    }

    #pragma omp for
    for (i = 0; i < N; i++)
    {
        ...
    }

    #pragma omp fork
    distribute work
    barrier
    distribute work
    barrier
    join
}

SOFTWARE AND SERVICES
double a[N];
double l,s = 0;
#pragma omp parallel for reduction(+:s) private(l) \
schedule(static,4)
for (i = 0; i<N; i++)
{
    l = log(a[i]);
    s += l;
}

SOFTWARE AND SERVICES
OpenMP 3.0 in Three Slides /3

#pragma omp parallel
#pragma omp single
for(e = l->first; e ; e = e->next)
    #pragma omp task
    process(e);

fork
join
OpenMP 4.0 SIMD
Why Auto-vectorizers Fail

• Data dependencies
• Other potential reasons
  • Alignment
  • Function calls in loop block
  • Complex control flow / conditional branches
  • Loop not “countable”
    • E.g. upper bound not a runtime constant
  • Mixed data types
  • Non-unit stride between elements
  • Loop body too complex (register pressure)
  • Vectorization seems inefficient
• Many more … but less likely to occur
In a Time before OpenMP 4.0

• Programmers had to rely on auto-vectorization...
• ... or to use vendor-specific extensions
  • Programming models (e.g., Intel® Cilk™ Plus)
  • Compiler pragmas (e.g., \#pragma vector)
  • Low-level constructs (e.g., \_mm_add_pd())

```c
#pragma omp parallel for
#pragma vector always
#pragma ivdep
for (int i = 0; i < N; i++) {
    a[i] = b[i] + ...;
}
```

You need to trust the compiler to do the “right” thing.
OpenMP SIMD Loop Construct

• Vectorize a loop nest
  • Cut loop into chunks that fit a SIMD vector register
  • No parallelization of the loop body

• Syntax (C/C++)
  #pragma omp [for] simd [clause[[[,,] clause]],...]
  for-loops

• Syntax (Fortran)
  !$omp [do] simd [clause[[[,,] clause]],...]
  do-loops
Example

```c
void sprod(float *a, float *b, int n) {
    float sum = 0.0f;
    #pragma omp for simd reduction(+:sum)
    for (int k=0; k<n; k++)
        sum += a[k] * b[k];
    return sum;
}
```

parallelize

Thread 0

Thread 1

Thread 2

vectorize

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Data Sharing Clauses

- **private(var-list):**
  Uninitialized vectors for variables in var-list

- **firstprivate(var-list):**
  Initialized vectors for variables in var-list

- **reduction(op:var-list):**
  Create private variables for var-list and apply reduction operator op at the end of the construct
SIMD Loop Clauses

• safelen (length)
  • Maximum number of iterations that can run concurrently without breaking a dependence
  • in practice, maximum vector length
• linear (list[:linear-step])
  • The variable’s value is in relationship with the iteration number
    \[ x_i = x_{\text{orig}} + i \times \text{linear-step} \]
• aligned (list[:alignment])
  • Specifies that the list items have a given alignment
  • Default is alignment for the architecture
• collapse (n)
SIMD Function Vectorization

```c
float min(float a, float b) {
    return a < b ? a : b;
}

float distsq(float x, float y) {
    return (x - y) * (x - y);
}

void example() {
    #pragma omp parallel for simd
    for (i=0; i<N; i++) {
        d[i] = min(distsq(a[i], b[i]), c[i]);
    }
}
```
SIMD Function Vectorization

• Declare one or more functions to be compiled for calls from a SIMD-parallel loop

• Syntax (C/C++):
  
  ```c
  #pragma omp declare simd [clause[[], clause],...]
  [#pragma omp declare simd [clause[[], clause],...]]
  [...] 
  function-definition-or-declaration
  ```

• Syntax (Fortran):
  
  ```fortran
  !$omp declare simd (proc-name-list)
  ```
SIMD Function Vectorization

```c
#pragma omp declare simd
float min(float a, float b) {
    return a < b ? a : b;
}

#pragma omp declare simd
float distsq(float x, float y) {
    return (x - y) * (x - y);
}

void example() {
    #pragma omp parallel for simd
    for (i=0; i<N; i++) {
        d[i] = min(distsq(a[i], b[i]), c[i]);
    }
}

vec8 min_v(vec8 a, vec8 b) {
    return a < b ? a : b;
}

vec8 distsq_v(vec8 x, vec8 y) {
    return (x - y) * (x - y);
}

vd = min_v(distsq_v(va, vb, vc))
```
SIMD Function Vectorization

• **simdlen** (*length*)
  • generate function to support a given vector length
• **uniform** (*argument-list*)
  • argument has a constant value between the iterations of a given loop
• **inbranch**
  • function always called from inside an if statement
• **notininbranch**
  • function never called from inside an if statement
• **linear** (*argument-list[::linear-step]*)
• **aligned** (*argument-list[::alignment]*)
• **reduction** (*operator:list*)

SOFTWARE AND SERVICES
OpenMP 4.0 for Devices
Device Model

- OpenMP 4.0 supports accelerators/coprocessors
- Device model:
  - One host
  - Multiple accelerators/coprocessors of the same kind
OpenMP 4.0 for Devices - Constructs

- Transfer control [and data] from the host to the device

- Syntax (C/C++)
  
  #pragma omp target [data] [clause[[], clause],...]
  structured-block

- Syntax (Fortran)
  
  !$omp target [data] [clause[[], clause],...]
  structured-block
  !$omp end target [data]

- Clauses
  
  device(scalar-integer-expression)
  map([alloc | to | from | tofrom:] list)
  if(scalar-expr)
Execution Model

• The **target construct** transfers the control flow to the target device
  • Transfer of control is sequential and synchronous
  • The transfer clauses control direction of data flow
  • Array notation is used to describe array length

• The **target data** construct creates a scoped device data environment
  • Does not include a transfer of control
  • The transfer clauses control direction of data flow
  • The device data environment is valid through the lifetime of the target data region

• Use **target update** to request data transfers from within a target data region
Execution Model

• Data environment is lexically scoped
  • Data environment is destroyed at closing curly brace
  • Allocated buffers/data are automatically released

```c
#pragma omp target
map(aloc: ...) \nmap(to: ...) \nmap(from: ...)
{ ... }
```
Example

```c
#pragma omp target data device(0) map(alloc:tmp[:N]) map(to:input[:N]) map(from:res)
{

#pragma omp target device(0)
#pragma omp parallel for
for (i=0; i<N; i++)
    tmp[i] = some_computation(input[i], i);

    update_input_array_on_the_host(input);

#pragma omp target update device(0) to(input[:N])

#pragma omp target device(0)
#pragma omp parallel for reduction(+:res)
for (i=0; i<N; i++)
    res += final_computation(input[i], tmp[i], i)
}
```
teams Construct

- Support multi-level parallel devices

- Syntax (C/C++):
  
  ```c
  #pragma omp teams [clause[, clause],...]
  structured-block
  ```

- Syntax (Fortran):
  
  ```fortran
  !$omp teams [clause[, clause],...]
  structured-block
  ```

- Clauses
  
  ```
  num_teams(integer-expression)
  num_threads(integer-expression)
  default(shared | none)
  private(list), firstprivate(list)
  shared(list), reduction(operator : list)
  ```
Offloading SAXPY to a Coprocessor

```c
int main(int argc, const char* argv[]) {
    float *x = (float*) malloc(n * sizeof(float));
    float *y = (float*) malloc(n * sizeof(float));
    // Define scalars n, a, b & initialize x, y

    #pragma omp target data map(to:x[0:n])
    {
    #pragma omp target map(tofrom:y)
    #pragma omp teams num_teams(num_blocks) num_threads(nthreads)

    for (int i = 0; i < n; i += num_blocks){
        for (int j = i; j < i + num_blocks; j++) {
            y[j] = a*x[j] + y[j];
        }
    }
    }
    free(x); free(y); return 0;
}
```

all do the same
Offloading SAXPY to a Coprocessor

```c
int main(int argc, const char* argv[]) {
    float *x = (float*) malloc(n * sizeof(float));
    float *y = (float*) malloc(n * sizeof(float));
    // Define scalars n, a, b & initialize x, y

    #pragma omp target data map(to:x[0:n])
    {
    #pragma omp target map(tofrom:y)
    #pragma omp teams num_teams(num blocks) num_threads(bsize)

    #pragma omp distribute
    for (int i = 0; i < n; i += num_blocks){

    #pragma omp parallel for
    for (int j = i; j < i + num blocks; j++) {

    y[j] = a*x[j] + y[j];
    }
    }
    #pragma omp target data map(tofrom:y)
    {
    #pragma omp target data map(to:x[0:n])
    }
    free(x); free(y); return 0; }
```
Offloading SAXPY to a Coprocessor

```c
int main(int argc, const char* argv[]) {
    float *x = (float*) malloc(n * sizeof(float));
    float *y = (float*) malloc(n * sizeof(float));
    // Define scalars n, a, b & initialize x, y

    #pragma omp target map(to:x[0:n]) map(tofrom:y)
    {
        #pragma omp teams distribute parallel for 
        num_teams(num_blocks) num_threads(bsize)
        for (int i = 0; i < n; ++i){
            y[i] = a*x[i] + y[i];
        }
    }

    free(x); free(y); return 0;
}
```
Task-generating Loops
Issues with Traditional Worksharing

- Worksharing constructs do not compose well
- Pathological example: parallel `dgemm` in MKL

```c
void example() {
    #pragma omp parallel
    {
        compute_in_parallel(A);
        compute_in_parallel_too(B);
        // dgemm is either parallel or sequential
        cblas_dgemm(CblasRowMajor, CblasNoTrans, CblasNoTrans,
                    m, n, k, alpha, A, k, B, n, beta, C, n);
    }
}
```

- Writing such code either
  - oversubscribes the system,
  - yields bad performance due to OpenMP overheads, or
  - needs a lot of glue code to use sequential `dgemm` only for sub-matrixes

SOFTWARE AND SERVICES
Issues with Traditional Worksharing /2

- Worksharing constructs do not compose well
- Pathological example: load imbalance

```java
void load_imbalance() {
    long_running_task() // can execute concurrently

    for (int i = 0; i < N; i++) { // can execute concurrently
        for (int j = 0; j < M; j++) {
            loop_body(i, j);
        }
    }
}
```

- Writing such code requires
  - nested parallelism,
  - manual, non-portable fine-tuning, and
  - a lot of care to get the load balance right.
Ragged Fork/Join

- Traditional worksharing can lead to ragged fork/join patterns

```c
void example() {
    compute_in_parallel(A);
    compute_in_parallel_too(B);
    cblas_dgemm(..., A, B, ...);
}
```
Example: Sparse CG

```c
for (iter = 0; iter < sc->maxIter; iter++) {
    precon(A, r, z);
    vectorDot(r, z, n, &rho);
    beta = rho / rho_old;
    xpay(z, beta, n, p);
    matvec(A, p, q);
    vectorDot(p, q, n, &dot_pq);
    alpha = rho / dot_pq;
    axpy(alpha, p, n, x);
    axpy(-alpha, q, n, r);
    sc->residual = sqrt(rho) * bnrm2;
    if (sc->residual <= sc->tolerance) break;
    rho_old = rho;
}
```

```c
void matvec(Matrix *A, double *x, double *y) {
    // ...
    #pragma omp parallel for 
    private(i,j,is,ie,j0,y0) 
    schedule(static)
    for (i = 0; i < A->n; i++) {
        y0 = 0;
        is = A->ptr[i];
        ie = A->ptr[i + 1];
        for (j = is; j < ie; j++) {
            j0 = index[j];
            y0 += value[j] * x[j0];
        }
        y[i] = y0;
    }
    // ...
}
```
The taskloop Construct

• Parallelize a loop using OpenMP tasks
  • Cut loop into chunks
  • Create a task for each loop chunk

• Syntax (C/C++)
  #pragma omp taskloop [simd] [clause[[,] clause],...]
  for-loops

• Syntax (Fortran)
  !$omp taskloop[simd] [clause[[,] clause],...]
  do-loops
  [!$omp end taskloop [simd]]
Clauses for taskloop Construct

• Taskloop constructs inherit clause both from worksharing constructs and the task construct
  • shared, private
  • firstprivate, lastprivate
  • default
  • collapse
  • final, untied, mergeable

• grainsize(grain-size)
  Chunks have at least grain-size and max 2*grain-size loop iterations

• num_tasks(num-tasks)
  Create num-tasks tasks for iterations of the loop
Example: task and taskloop

```c
void load_imbalance() {
#pragma omp taskgroup
{
#pragma omp task
  long_running_task() // can execute concurrently

#pragma omp taskloop collapse(2) grainsize(500) nogroup
  for (int i = 0; i < N; i++) { // can execute concurrently
    for (int j = 0; j < M; j++) {
      loop_body(i, j);
    }
  }
}
```
Example: Sparse CG, `taskloop`

```c
#pragma omp parallel
#pragma omp single
for (iter = 0; iter < sc->maxIter; iter++) {
    precon(A, r, z);
    vectorDot(r, z, n, &rho);
    beta = rho / rho_old;
    xpay(z, beta, n, p);
    matvec(A, p, q);
    vectorDot(p, q, n, &dot_pq);
    alpha = rho / dot_pq;
    axpy(alpha, p, n, x);
    axpy(-alpha, q, n, r);
    sc->residual = sqrt(rho) * bnrm2;
    if (sc->residual <= sc->tolerance) break;
    rho_old = rho;
}
```

```c
void matvec(Matrix *A, double *x, double *y) {
    // ...
    #pragma omp taskloop private(j,is,ie,j0,y0) grain_size(500)
    for (i = 0; i < A->n; i++) {
        y0 = 0;
        is = A->ptr[i];
        ie = A->ptr[i + 1];
        for (j = is; j < ie; j++) {
            j0 = index[j];
            y0 += value[j] * x[j0];
        }
        y[i] = y0;
    }
    // ...
}
```
Performance of Sparse CG w/ Tasks

X. Teruel, M. Klemm, K. Li, X. Martorell, S.L. Olivier, and C. Terboven. A Proposal for Task-Generating Loops in OpenMP. In A.P. Rendell et al., editor, International Workshop on OpenMP, pages 1-14, Canberra, Australia, September 2013. LNCS 8122
Locks with Hints
Motivation

• Hardware supports new concepts for locks
  • Intel® Transactional Synchronization Extensions
  • Transactional memory in BlueGene*/Q

• Coarse-grained control does not help applications that have mixed locking requirements
  • Some locks may be highly contended
  • Some locks may be used to protect system calls (e.g., IO)
  • Some locks may be just there for safety, but are almost never conflicting (e.g., hash map)

• Programmers need the ability to choose locks on a per-use basis
Lock Elision

- Lock transfer latencies (lock overhead) and serialized execution
- Concurrent (optimistic) execution, no lock transfer latencies (less lock overhead)
Two new API Routines

- `omp_init_lock(omp_lock_t *lock)`
- `omp_init_lock_with_hint(omp_lock_t *lock, omp_lock_hint_t hint)`
- `omp_set_lock(omp_lock_t *lock)`
- `omp_unset_lock(omp_lock_t *lock)`
- `omp_destroy_lock(omp_lock_t *lock)`
Two new API Routines

- `omp_init_nest_lock(omp_nest_lock_t *lock)`
- `omp_init_nest_lock_with_hint(omp_nest_lock_t *lock,omp_lock_hint_t hint)`
- `omp_set_nest_lock(omp_nest_lock_t *lock)`
- `omp_unset_nest_lock(omp_nest_lock_t *lock)`
- `omp_destroy_nest_lock(omp_nest_lock_t *lock)`
Hints

• Hints are integer expressions
  • C/C++: can be combined using the | operator
  • Fortran: can be combined using the + operator

• Supported hints:
  • omp_lock_hint_none
  • omp_lock_hint_uncontended
  • omp_lock_hint_contended
  • omp_lock_hint_nonspeculative
  • omp_lock_hint_speculative
New Clause for \texttt{critical} Construct

- Syntax (C/C++)
  \begin{verbatim}
  #pragma omp critical [(name)] [hint(expression)] structured-block
  \end{verbatim}

- Syntax (Fortran)
  \begin{verbatim}
  !$omp critical [(name)] [hint(expression)] structured-block
  !$omp end critical [(name)]
  \end{verbatim}

- Specify a hint how to implement mutual exclusion
  - If a \texttt{hint} clause is specified, the \texttt{critical} construct must be a named construct.
  - All \texttt{critical} constructs with the same name must have the same \texttt{hint} clause.
  - The expression of the \texttt{hint} clause must be a compile-time constant.
Examples

```c
void example_locks() {
    omp_lock_t lock;
    omp_init_lock_with_hint(&lock, omp_hint_speculative);

    #pragma omp parallel
    {
        omp_set_lock(&lock);
        do_something_protected();
        omp_unset_lock(&lock);
    }
}

void example_critical() {
    #pragma omp parallel for
    for (int i = 0; i < upper; ++i) {
        Data d = get_some_data(i);
        #pragma omp critical (HASH) hint(omp_hint_speculative)
        hash.insert(d);
    }
}
```
Using Hints May Increase Performance

• Blindly using speculative locks does not help (KMP_LOCK_KIND=...)
• Speculative locks can benefit more with growing thread counts

Extensions to the target Constructs
Asynchronous Offloading in 4.0

- You can this at your own risk 😊

```c
#pragma omp parallel sections num_threads(2)
{
  #pragma omp task
  {
    #pragma omp target map(to:input[:N]) map(from:result[:N])
    #pragma omp parallel for
    for (i=0; i<N; i++) {
      result[i] = some_computation(input[i], i);
    }
  }
  #pragma omp task
  {
    do_something_important_on_host();
  }
  #pragma omp taskwait
}
```
Asynchronous Offloading in 4.5

- OpenMP 4.5 requires much less coding and has much cleaner semantics

```c
#pragma omp target map(to:input[:N]) map(from:result[:N]) nowait
#pragma omp parallel for
    for (i=0; i<N; i++) {
        result[i] = some_computation(input[i], i);
    }
do_something_important_on_host();
```
OpenMP 4.5 for Devices

• Transfer control [and data] from the host to the device

• Syntax (C/C++)
  #pragma omp target [data] [clause[, clause],...] structured-block

• Syntax (Fortran)
  !$omp target [data] [clause[, clause],...] structured-block
  !$omp end target [data]

• General clauses (since OpenMP 4.0)
  device(scalar-integer-expression)
  map([alloc | to | from | tofrom:] list)
  if(scalar-expr)

• Clauses for asynchronous offloading (also supported by target update)
  nowait
  depend(dependency-type:list)
Creating and Destroying Device Data

```cpp
struct DeviceBuffer {
    // ...
    DeviceBuffer(int dev, size_t sz) {
    #pragma omp target enter data device(dev) map(alloc:buffer[:sz])
    }
    ~DeviceBuffer() {
    #pragma omp target exit data device(dev) map(delete:buffer[:sz])
    }
}

void example() {
    DeviceBuffer *buf1 = new DeviceBuffer(0, 1024);
    compute_a_lot_using_offloading(buf1);
    DeviceBuffer *buf2 = new DeviceBuffer(0, 2048);
    compute_some_more_using_offloading(buf1, buf2);
    delete buf1;
    compute_evenmore_using_offloading(buf2);
    delete buf2;
}
```

SOFTWARE AND SERVICES
Creating and Destroying Device Data

• Manage data without being bound to scoping rules

• Syntax (C/C++)
  
  ```c
  #pragma omp target enter data [clause[[], clause],...]
  #pragma omp target exit data [clause[[], clause],...]
  ```

• Syntax (Fortran)
  
  ```fortran
  !$omp target enter data [clause[[], clause],...]
  !$omp target exit data [clause[[], clause],...]
  ```

• Clauses
  
  ```
  device(scalar-integer-expression)
  map([alloc | delete | to | from | tofrom:] list)
  if(scalar-expr)
  depend(dependency-type:list)
  nowait
  ```
Example for Dependencies

```c
void dependencies() {
    double data[N];

    #pragma omp target enter data map(to:data[N]) depend(inout:data[0]) nowait
        do_something_on_the_host();
    #pragma omp target depend(inout:data[0]) nowait
        perform_kernel_on_device();
    #pragma omp target exit data map(from:data[N]) nowait depend(inout:data[0])

    #pragma omp task depend(in:data[0])
        task_on_the_host(data);
        do_something_on_the_host();
}
```
We’re Almost Through

• There are so many things in OpenMP today
  • Can’t cover all of them in an hour!

• OpenMP 4.0 and 4.5 have more to offer!
  • Improved Fortran 2003 support
  • Improved affinity
  • User-defined reductions
  • Task dependencies
  • Cancellation
  • “doacross” Loops

• We can chat about these features in 1:1s, FTFs, phone calls, or in emails 😊
The last Slide...

• OpenMP 4.5 is not only a bugfix release
  • Task-generating loops
  • Locks with hints
  • Improved support for offloading

• Work on OpenMP 5.0 has already been started
  • Expected release during Supercomputing 2018
  • We are trying hard to have it ready by Supercomputing 2017
  • Features being discussed:
    • Bugfixes 😊
    • Futures
    • Error handling
    • Transactional memory
    • Extensions to tasking
    • Fortran 2008 support
    • C++1x support
    • Data locality and affinity