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Unified Task + Data Parallelism on Manycore Architectures

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SIAM Parallel Processing

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Maximize Parallelism for Manycore Architectures; Portable & Performant

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- **Unified Task + Data Parallelism**
  - Task decomposition of heterogeneous computations
  - Data decomposition of homogeneous computations
  - Unify: tasks of data parallel computations
- **Integrate and extend Sandia's Kokkos + Qthreads libraries**
  - Kokkos: performance portable manycore data parallelism
    - Multicore CPU, NVidia GPU, Intel Xeon Phi "devices"
    - Parallel_for, parallel_reduce, parallel_scan
    - Multidimensional arrays with device-polymorphic data layout
    - \+ Interface for tasks with internally data parallel operations
  - Qthreads: efficient scheduling of single-thread tasks
    - Multicore CPU
    - \+ Individual tasks that span multiple threads
    - \+ Scheduling for tasks dispatched to GPU

Kokkos: C++ Library / Programming Model

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- **Portable to Advanced Manycore Architectures**
  - Maximize amount of user (application/library) code that can be compiled without modification and run on these architectures
  - Minimize amount of architecture-specific knowledge that a user is required to have
  - Allow architecture-specific tuning to easily co-exist
  - Only require C++1998 standard compliant
- **Performant**
  - Portable user code performs as well as architecture-specific code
  - ➢ **Thread scalable – not just thread safety (no locking!)**
  - ➢ **Multidimensional array layout compatible with vectorization**
- **Usable**
  - Small, straight-forward application programmer interface (API)
  - ➢ **Constraint: don't compromise portability and performance**

Qthreads: C Library / Programming Model

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- **Efficient scheduling and execution of tasks**
  - **Lightweight tasks (very little context in comparison to pthreads)**
  - **NUMA- (non-uniform memory access) and cache-aware scheduling of lightweight tasks onto pinned heavyweight worker threads**
  - **Synchronization based on software-managed full/empty bits**
  - **Scalability to many thousands of tasks**
- **Actively used**
  - **Multithreaded graph library (MTGL)**
  - **Cray Chapel tasking layer implementation**
  - **OpenMP run time system using ROSE XOMP as the front-end**
  - **Power-aware concurrency management (MAESTRO project with RENCI)**

Kokkos + Qthreads: In-progress R&D
(Sandia internal R&D "on a shoestring")

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- **Three year project; four months elapsed**
  - **Draft specification for unified programming model @ today**
  - **Unit testing on multicore CPU and Xeon Phi @ 12 months**
  - **Heterogeneous finite element miniapplication @ 15 months**
  - **Informatics (graph based) miniapplication @ 18 months**
  - **Sparse solver w/sparse LU miniapplication @ 18 months**
  - **Unit testing task-data parallelism on GPU @ 21 months**
  - **Heterogeneous finite element miniapplication on GPU @ 24 months**
  - **Informatics & Sparse solver/LU miniapplication on GPU @ 30 months**

Task Parallelism: Fibonacci example

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- **Walk through simple Fibonacci example**
  - Fib(N) = *if* (N < 2) *then* N *else* Fib(N-1) + Fib(N-2)
  - Simple task parallel (not data parallel)

```
class Fib : public task_serial<long,device> {
public:
  const long n ;
  Fib( long arg ) : n( arg ) {}
  void apply() {
    if ( n < 2 ) {
      task_result = n ;
    } else {
      Future<long> child[2] = { task_dependence(0) , task_dependence(1) };
      if ( child[0] ) {
        task_result = child[0].get() + child[1].get();
      } else {
        child[0] = spawn( Fib(n-1) );
        child[1] = spawn( Fib(n-2) );
        task_respawn( child , 2 );
      }
    }
  }
};
```

Task Parallelism: Fibonacci example

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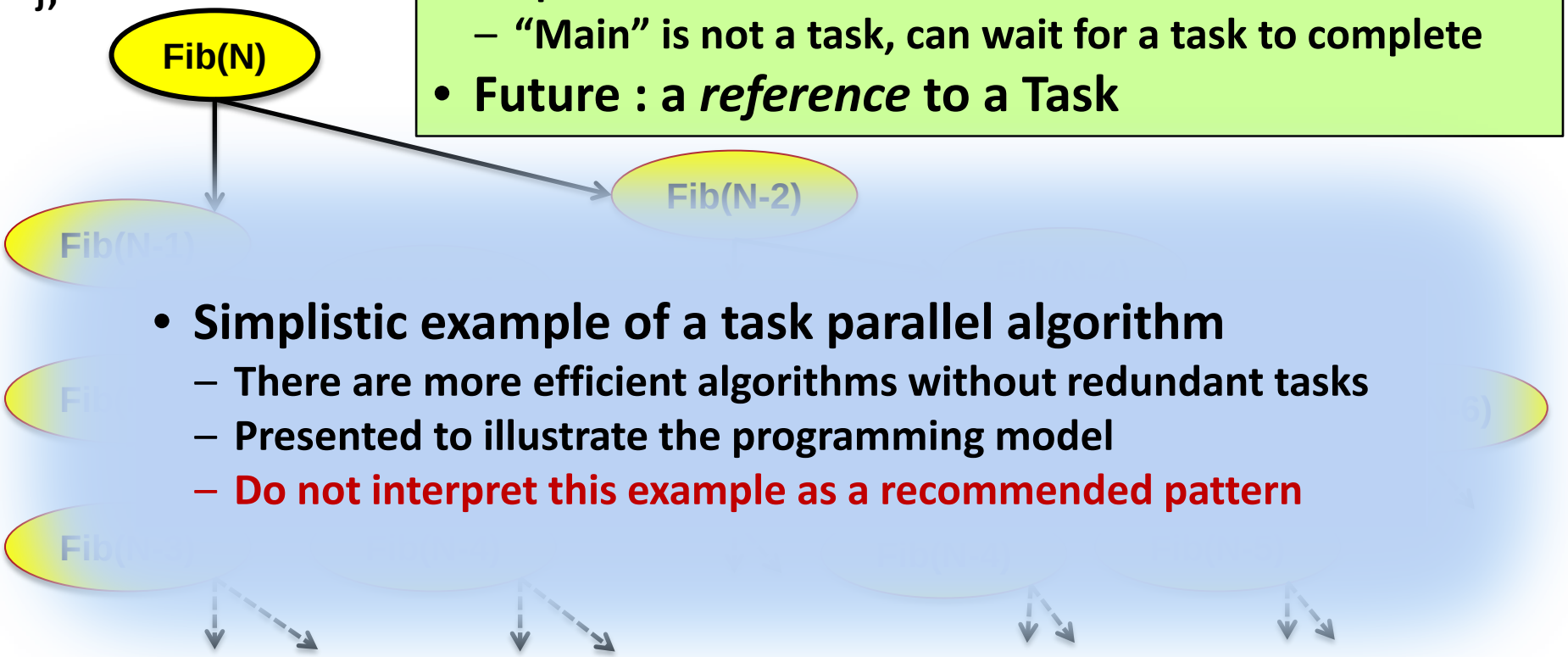
```
int main() {
  long N ; N << std::cin ;
  Future<long> f = spawn( Fib<long,device>(N) );
  wait( f );
  std::cout << f.get();
};
```

- **How it all starts**
  - Spawn the root Fibonacci task from "Main" thread
  - "Main" is not a task, can wait for a task to complete
- **Future : a *reference* to a Task**



- **Simplistic example of a task parallel algorithm**
  - There are more efficient algorithms without redundant tasks
  - Presented to illustrate the programming model
  - Do not interpret this example as a recommended pattern

Task Parallelism; Fibonacci example

```
class Fib : public task_serial<long,device> {
public:
  const long n ;
  Fib( long arg ) : n( arg ) {}
  void apply() {
    if ( n < 2 ) {
      task_resu
    } else {
      Future<lo
      if ( child[0
        task_res
      } else {
        child[0] =
        child[1] = spawn( Fib(n-2) );
        task_respawn( child , 2 );
      }
    }
  }
};
```

- A Task is a Functor derived from a parallel pattern
  - "Fib" derived from "task_serial"
  - Data type of the task's result: "long"
  - Executes on "device"
- Functor: C++ class with a required member function
  - User defined data members: "n"
  - Execution calls "apply"

Task Parallelism; Fibonacci example

```
class Fib : public task_serial<long,device> {
public:
  const long n ;
  Fib( long arg ) : n( a
  void apply() {
    if ( n < 2 ) {
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    } else {
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      if ( child[0] ) {
        task_result = child[0].get() + child[1].get();
      } else {
        child[0] = spawn( Fib(n-1) );
        child[1] = spawn( Fib(n-2) );
        task_respawn( child , 2 );
      }
    }
  }
};
```

- "Apply" function called from a single thread
- Task sets its "task_result"
  - task_serial<...>::task_result
- Task will be *complete* when "apply" returns
  - Except when ... , we will come back to this

Task Parallelism; Fibonacci example

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```
class Fib : public task_serial<long,device> {
public:
  const long
  Fib( long a
  void apply(
   if ( n < 2 )
    task_res
  } else {
   Future<long> child[2] = { task_dependence(0) , task_dependence(1) };
   if ( child[0] ) {
    task_result = child[0].get() + child[1].get();
   } else {
    child[0] = spawn( Fib(n-1) );
    child[1] = spawn( Fib(n-2) );
    task_respawn( child , 2 );
   }
  }
 }
};
```

- **Future : a *reference* to a Task**
- **Query completed tasks Fib(N-1) and Fib(N-2)**
  - **task_serial<...>::task_dependence(#)**
  - **If these tasks exist ... ; where did they come from?**
  - **task_result = Fib(N-1) + Fib(N-2)**

Task Parallelism; Fibonacci example

- If tasks Fib(N-1) and Fib(N-2) don't exist then *spawn* them
  - Future<result_type> spawn(FunctorType);
  - Schedules a new task for parallel execution
- I need to wait for these tasks to complete, *but I cannot block*
  - GPU: a thread cannot *block* and spin-waiting is very bad
  - CPU: overhead of context-switch which is bad for performance
- Solution: re-spawn myself
  - "I cannot complete now, call me again after these other tasks complete"
  - task_serial<...>::task_respawn(Future<> depend[] , #);
  - When "apply" returns I am not complete

```
    child[0] = spawn( Fib(n-1) );
    child[1] = spawn( Fib(n-2) );
    task_respawn( child , 2 );
  }
```

Task Dependence Directed Acyclic Graph (DAG)

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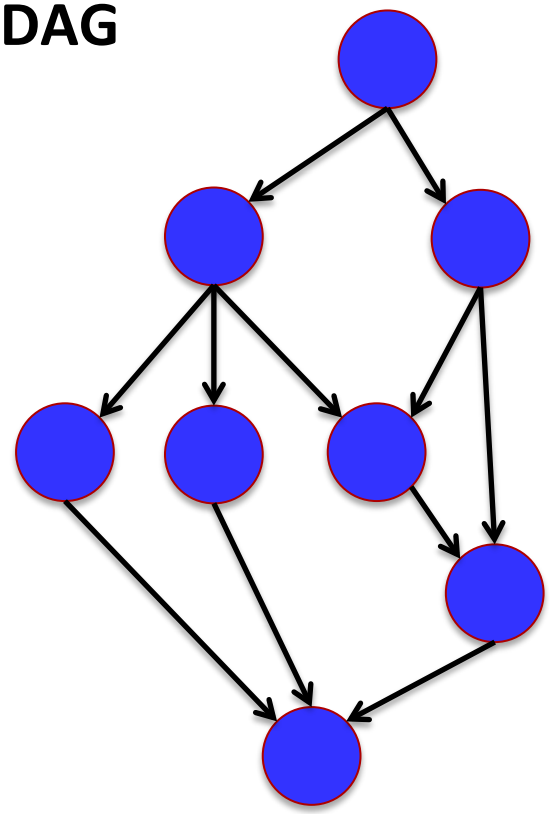
- Dependence not limited to spawner-spawnee (parent-child)
  - E.g., Intel Cilk and OpenMP 3.x
- General task dependence DAG



Task-Data Parallelism: L2 norm example

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```
class Norm2 : public task_reduce<double,device> {
public:
  const double * X ;
  const int      N ;
  int work() const { return N ; }
  void operator()( int i , double & v ) const { v += X[i] * X[i] ; }
  void init( double & v ) const { v = 0 ; }
  void join( volatile double & v , volatile const double & w ) const { v += w ; }
  void apply() { task_result = sqrt( task_result );
  Norm2( const double * argx , const int argn ) : x(argx), n(argn) {}
};
```

- **Walk through simple L2 norm example**
  - Task with data parallel pattern $\sqrt{\sum_{i=0}^{N-1} x_i^2}$

```
// elsewhere in the "main" thread:
Future<double> f = spawn( Norm2<double,device>(X,N) );
wait( f );
double value = f.get();
```

- **Spawn just like a simple task**
  - A future for waiting and querying result

Task-Data Parallelism: L2 norm example

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```
class Norm2 : public task_reduce<double,device> {
public:
  const double * X ;
  const int      N ;
  int work() const { return N ; }
  void
  void
  void                                                    st { v += w ; }
  void
  Norm2( const double * argx , const int argn ) : x(argx), n(argn) {}
};

// elsewhere in the "main" thread:
Future<double> f = spawn( Norm2(x,n) );
wait( f );
double value = f.get();
```

- **Parallel pattern : "task_reduce"**
  - Data parallel with "N" units of work
  - "work" function returns "N"

Task-Data Parallelism: L2 norm example

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```
class Norm2 : public task_reduce<double,device> {
public:
  const double * X ;
  const int      N ;
  int work() const { return N ; }
  void operator()( int i , double & v ) const { v += X[i] * X[i] ; }
  void init
  void join                                                  v += w ; }
  void app
  Norm2(
};

// elsewhere in the "main" thread:
Future<double> f = spawn( Norm2(x,n) );
wait( f );
double value = f.get();
```

- **Call "operator()" function N times**
  - **Work index: $i \in [0..N)$**
  - **Called in parallel from "P" threads; P <= N**
- **Contribute to reduction value "v"**
  - **Argument "v" is thread-private**

Task-Data Parallelism: L2 norm example

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```
class Norm2 : public task_reduce<double,device> {
public:
  const double * X ;
  const int      N ;
  int work() const { return N ; }
  void operator()( int i , double & v ) const { v += X[i] * X[i] ; }
  void init( double & v ) const { v = 0 ; }
  void join( volatile double & v , volatile const double & w ) const { v += w ; }
  void ap
  Norm2(
};

// elsew
Future<d
wait( f );
double v
```

- **Thread-private values are *partial* contributions**
  - **Values must be properly initialized (might not be zero)**
  - **Values must be properly joined across threads (might not be sum)**
- **Why "volatile" ?**
  - **For performance thread private values are joined in-place**
  - **Implementation violates threads' privacy**
  - **"volatile" so that compiler is "in the know"**

Task-Data Parallelism: L2 norm example

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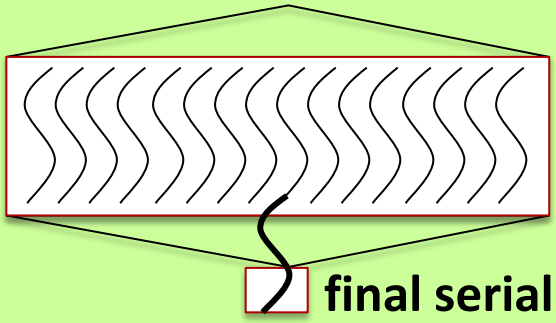
```
class Norm2 : public task_reduce<double,device> {
public:
  const double * X ;
  const int      N ;
  int work() const { return N ; }
  void operator()( int i , double & v ) const { v += X[i] * X[i] ; }
  void init( double & v ) const { v = 0 ; }
  void join( volatile double & v , volatile const double & w ) const { v += w ; }
  void apply() { task_result = sqrt( task_result );
  Norm2( cons
};

// elsewhere
Future<doubl
wait( f );
double value
```

- **Task's final serial step**
  - **Opportunity to serially process the task's result**



data parallel "operator()"

final serial "apply"

Task Groups: Tree Search example

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```
class Search : public task_serial<void,device> {
public:
  const KeyType
  const NodeType
  void apply() {
    Future<NodeType
    if ( node->key == key ) {
      group_complete( group , node );
    } else {
      for ( i
        spav
    }
  }
};
```

- **Search an n-tree for a node with a given key**
  - Spawn a search task at each node
  - Until the "winning" task finds the matching node

- **Create a task group, returns a Future**
- **Spawn search task on the tree's root node**
  - Dependence on the task group
- **Wait for the group to complete**

```
// elsewhere in the "main" thread
Future<NodeType*> group = group_create<NodeType*>(0);
spawn( Search( key , root_node ) , & group , 1 );
wait( group );
NodeType * found_node = group.get();
```

Task Groups: Tree Search example

```
class Search : public task_serial<void,device> {
public:
  const KeyType      key ;
  const NodeType * node ;
  void apply() {
    Future<NodeType*> group = task_dependence(0);
    if ( node->key == key ) {
      group_complete( group , node );
    } else {
      for ( in
        spaw
    }
  }
};
// elsewh
Future<No
spawn( Se
wait( group );
NodeType * found_node = group.get();
```

- Query group's future, is a dependence
- If node matches *complete* the group
  - Set the group's result value
  - An atomic operation: only one task can "win"
- Completing the group cancels execution of all remaining tasks in that group
  - Prevents them from starting, removes them from schedule

Task Groups: Tree Search example

```
class Search : public task_serial<void,device> {
public:
  const KeyType      key ;
  const NodeType * node ;
  void apply() {
    Future<NodeType*> group = task_dependence(0);
    if ( node->key == key ) {
      group_complete( group , node );
    } else {
      for ( int i = 0 ; i < node->num_child ; ++i )
        spawn( Search(key, node->child[i]) , & group , 1 );
    }
  }
};
// else
Future<NodeType*> group = group_create<NodeType*>(0);
spawn( Search( key , root_node ) , & group , 1 );
wait( group );
NodeType * found_node = group.get();
```

- If node does not match then spawn tasks for child nodes
  - Spawn as member of the group
  - If another task already "won" then spawned tasks will not execute

Wrapping Up (conclusions pending, stay tuned)

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- **Unified Task + Data Parallelism**
  - ➢ Seamless integration of task and data parallel computations
  - Task decomposition of heterogeneous computations
  - Data decomposition of homogeneous computations
- **Integrate and extend Sandia's Kokkos + Qthreads libraries**
  - Kokkos: performance portable manycore data parallelism
  - Qthreads: efficient scheduling of single-thread tasks
- **Proof will be in the mini-applications**
  - Heterogeneous finite element
  - Informatics (graph based)
  - Sparse solver with parallel sparse LU factorization & preconditioning
  - ➢ Performance portable mini-application code to CPU, Xeon-Phi, GPU