Chapel: Task Parallelism

Task Parallelism Terminology

Task: a unit of parallel work in a Chapel program

- all Chapel parallelism is implemented using tasks

Thread: a system-level concept for executing tasks

- not exposed in the language
- sometimes exposed in the implementation

"Hello World" in Chapel: Two Parallel Versions

- Multicore

```
config const numTasks = here.numCores;

coforall tid in 0..#numTasks do
  writeln("Hello, world! ",
          "from task ", tid, " of ", numTasks);
```

- Multi-node

```
coforall loc in Locales do
  on loc do
    writeln("Hello, world! ",
            "from node ", loc.id, " of ", numLocales);
```

Outline

- Primitive Task-Parallel Constructs
  - The **begin** statement
  - The **sync** types
- Structured Task-Parallel Constructs
- Atomic Transactions and Memory Consistency

Unstructured Task Creation: Begin

- Syntax

```
begin-stmt:
  begin stmt
```

- Semantics
  - Creates a task to execute *stmt*
  - Original (“parent”) task continues without waiting
- Example

```
begin writeln(“hello world”);
writeln(“good bye”);
```

- Possible output

```
hello world
good bye
```

```
good bye
hello world
```

Synchronization Variables

- Syntax

```
sync-type:
  sync type
```

- Semantics
  - Stores *full/empty* state along with normal value
  - Defaults to *full* if initialized, *empty* otherwise
  - Default read blocks until *full,* leaves *empty*
  - Default write blocks until *empty,* leaves *full*
- Examples: Critical sections and futures

```
var lock$: sync bool;

lock$ = true;
critical();
var lockval = lock$;
```

```
var future$: sync real;

begin future$ = compute();
computeSomethingElse();
useComputedResults(future$);
```

Single Variables

- Syntax

```
single-type:
  single type
```

- Semantics
  - Similar to sync variable, but stays *full* once written
- Example: Multiple Consumers of a future

```
var future$: single real;

begin future$ = compute();
begin computeSomethingElse(future$);
begin computeSomethingEls(future$);
```

Synchronization Type Methods

- `readFE():t` block until *full*, leave *empty*, return value
- `readFF():t` block until *full*, leave *full*, return value
- `readXX():t` return value (non-blocking)
- `writeEF(v:t)` block until *empty*, set value to `v`, leave *full*
- `writeFF(v:t)` wait until *full*, set value to `v`, leave *full*
- `writeXF(v:t)` set value to `v`, leave *full* (non-blocking)
- `reset()` reset value, leave *empty* (non-blocking)
- `isFull: bool` return true if full else *false* (non-blocking)

- **Defaults:** read: **`readFE`**, write: **`writeEF`**

Single Type Methods

- ~~**`readFE():t`** block until *full*, leave *empty*, return value~~
- **`readFF():t`** block until *full*, leave *full*, return value
- **`readXX():t`** return value (non-blocking)
- **`writeEF(v:t)`** block until *empty*, set value to `v`, leave *full*
- ~~**`writeFF(v:t)`** wait until *full*, set value to `v`, leave *full*~~
- ~~**`writeXF(v:t)`** set value to `v`, leave *full* (non-blocking)~~
- ~~**`reset()`** reset value, leave *empty* (non-blocking)~~
- **`isFull: bool`** return true if full else *false* (non-blocking)

- **Defaults:** read: **`readFF`**, write: **`writeEF`**

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- Primitive Task-Parallel Constructs
- Structured Task-Parallel Constructs
  - The **cobegin** statement
  - The **coforall** loop
  - The **sync** statement
  - The **serial** statement
- Atomic Transactions and Memory Consistency
- Implementation Notes and Examples

Block-Structured Task Creation: Cobegin

- Syntax

```
cobegin-stmt:
  cobegin { stmt-list }
```

- Semantics
  - Creates a task for each statement in *stmt-list*
  - Parent task waits for *stmt-list* tasks to complete
- Example

```
cobegin {
  consumer(1);
  consumer(2);
  producer();
}
```

Cobegin is Not Strictly Necessary

Any cobegin statement…

```
cobegin {
  stmt1();
  stmt2();
  stmt3();
}
```

…can be rewritten in terms of begin statements…

```
var s1$, s2$, s3$: sync bool;
begin { stmt1(); s1$ = true; }
begin { stmt2(); s2$ = true; }
begin { stmt3(); s3$ = true; }
s1$; s2$; s3$;
```

…but cobegin is supported as an important common case and to enable compiler optimizations.

Loop-Structured Task Invocation: Coforall

- Syntax

```
coforall-loop:
  coforall index-expr in iteratable-expr { stmt-list }
```

- Semantics
  - Create a task for each iteration in *iteratable-expr*
  - Parent task waits for all iteration tasks to complete
- Example

```
begin producer();
coforall i in 1..numConsumers {
  consumer(i);
}
```

Like Cobegin, Coforall is not Strictly Necessary

```
coforall i in 1..n do stmt();
```

```
var count$: sync int = 0, flag$: sync bool = true;

for i in 1..n {
  const count = count$;
  if count == 0 then flag$;
  count$ = count + 1;
  begin {
    stmt();
    const count = count$;
    if count == 1 then flag$ = true;
    count$ = count - 1;
  }
}

flag$;
```

Comparison of Loops: For, Forall, and Coforall

- **For loops:** executed using one task
  - use when a loop must be executed serially
  - or when one task is sufficient for performance
- **Forall loops:** typically executed using $1 \leq$ #tasks $\leq$ #iters
  - # tasks typically controlled by variables or arguments
  - use when a loop should be executed in parallel…
  - …but can legally be executed serially
  - use when desired # tasks << # of iterations
- **Coforall loops:** executed using a task per iteration
  - Use when the loop iterations *must* be executed in parallel
  - Use when iteration has substantial work

Comparison of Begin, Cobegin, and Coforall

- **begin**:
  - Use to create a dynamic task with an unstructured lifetime
  - "fire and forget"
- **cobegin:**
  - Use to create a related set of heterogeneous tasks
  - The parent task depends on the completion of the tasks
- **coforall:**
  - Use to create a fixed or dynamic # of homogenous tasks
  - The parent task depends on the completion of the tasks

Note: All these concepts can be composed arbitrarily

Bounded Buffer Producer/Consumer Example

```
var buff$: [0..#buffersize] sync real;

cobegin{
  producer();
  consumer();
}

def producer() {
  var i = 0;
  for … {
    i = (i+1) % buffersize;
    buff$(i) = …;
  }
}

def consumer() {
  var i = 0;
  while … {
    i= (i+1) % buffersize;
    …buff$(i)…;
  }
}
```

Structuring Sub-Tasks: Sync-Statements

- Syntax

```
sync-statement:
  sync stmt
```

- Semantics
  - Executes *stmt*
  - Waits for all *dynamically-scoped* begins to complete
- Example

```
sync {
  for i in 1..numConsumers {
    begin consumer(i);
  }
  producer();
}
```

```
def search(N: TreeNode) {
  if (N != nil) {
    begin search(N.left);
    begin search(N.right);
  }
}
sync { search(root); }
```

Program Termination and Sync-Statements

Where the cobegin statement is static,

```
cobegin {
  functionWithBegin();
  functionWithoutBegin();
}  // waits on these two tasks, but not any others
```

the sync statement is dynamic.

```
sync {
  begin functionWithBegin();
  begin functionWithoutBegin();
}  // waits on these tasks and any other descendents
```

Program termination is defined by an implicit sync on the main() procedure:

```
sync main();
```

Limiting Concurrency: Serial

- Syntax

```
serial-statement:
  serial expr { stmt }
```

- Semantics
  - Evaluates *expr* and then executes *stmt*
  - Suppresses any dynamically-encountered concurrency
- Example

```
def search(N: TreeNode, depth = 0) {
  if (N != nil) then
    serial (depth > 4) do cobegin {
      search(N.left,  depth+1);
      search(N.right, depth+1);
    }
}
search(root);
```

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- Primitive Task-Parallel Constructs
- Structured Task-Parallel Constructs
- Atomic Transactions and Memory Consistency
  - The **atomic** statement
  - Races and memory consistency
- Implementation Notes and Examples

Atomic Transactions (unsupported work-in-progress)

- Syntax

```
atomic-statement:
  atomic stmt
```

- Semantics
  - Executes stmt so it appears as a single operation
  - No other task sees a partial result
- Example

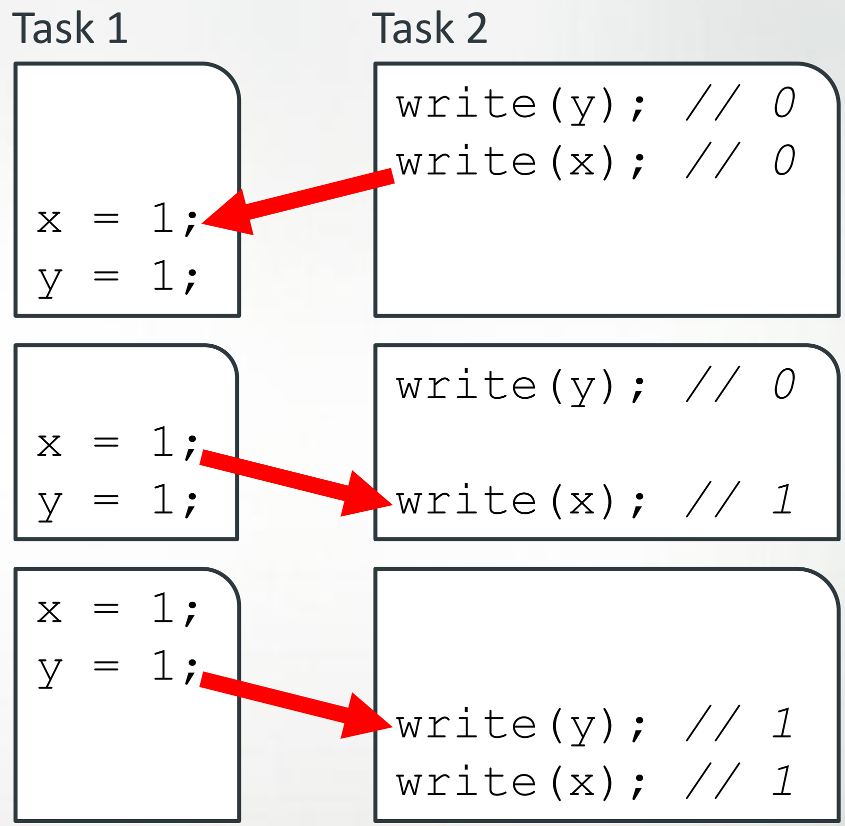
```
atomic A(i) += 1;
```

```
atomic {
  newNode.next = node;
  newNode.prev = node.prev;
  node.prev.next = newNode;
  node.prev = newNode;
}
```

Races and Memory Consistency

- Example

```
var x = 0, y = 0;
cobegin {
  {
    x = 1;
    y = 1;
  }
  {
    write(y);
    write(x);
  }
}
```



- Could the output be 10? Or 42?

Data-Race-Free Programs (The Fine Print)

A program without races is sequentially consistent.

> A multi-processing system has sequential consistency if "*the results of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program.*" – Leslie Lamport

The behavior of a program with races is undefined.

Synchronization is achieved in two ways:

- By reading or writing sync (or single) variables
- By executing atomic statements

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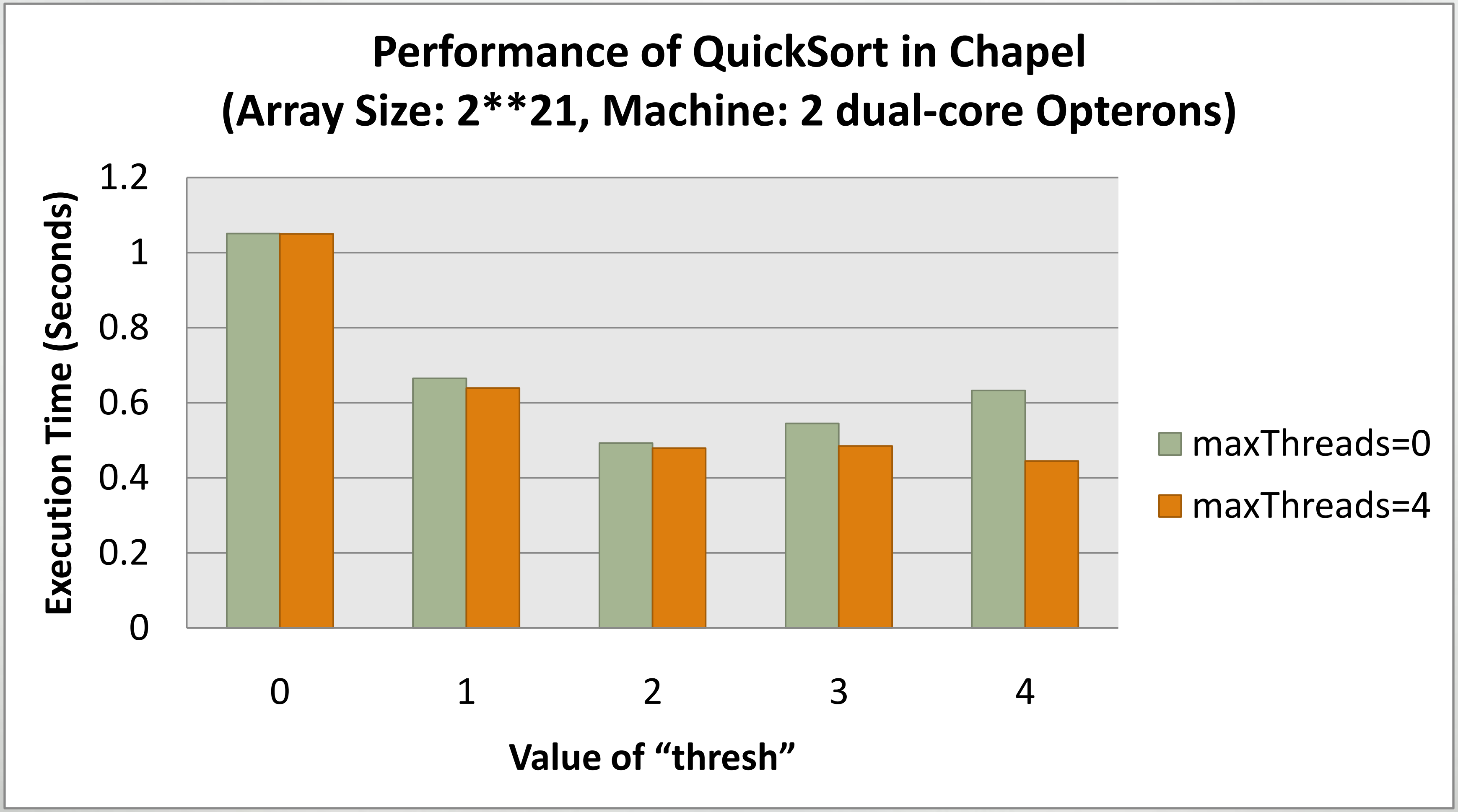
Using the Current Version of Chapel

- Concurrency limiter: **maxThreadsPerLocale**
  - Use **--maxThreadsPerLocale=<i>** for at most *i* threads
  - Use **--maxThreadsPerLocale=0** for a system limit *(default)*
- Current task scheduling policy
  - Once a thread starts running a task, it runs to completion
    - If an execution runs out of threads, it may deadlock
  - Cobegin/coforall parent threads help with child tasks

QuickSort in Chapel

```
def quickSort(arr: [?D],
              thresh = log2(here.numCores()),
              depth = 0,
              low: int = D.low,
              high: int = D.high) {
  if high - low < 8 {
    bubbleSort(arr, low, high);
  } else {
    const pivotVal = findPivot(arr, low, high);
    const pivotLoc = partition(arr, low, high, pivotVal);
    serial (depth >= thresh) do cobegin {
      quickSort(arr, thresh, depth+1, low, pivotLoc-1);
      quickSort(arr, thresh, depth+1, pivotLoc+1, high);
    }
  }
}
```

Performance of Multi-Threaded Chapel



Status: Task Parallel Features

- Most features working very well
- Tasking advances would be helpful
  - ability for threads to set blocked tasks aside
  - lighter-weight tasking (joint work with BSC, Sandia)
  - work-stealing, load-balancing
- atomic statements unimplemented in release

Future Directions

- Task teams
  - to provide a means of “coloring” different tasks
    - for the purposes of specifying policies or semantics
  - to support team-based collective operations
    - barriers, reductions, eurekas
- Task-private variables and task-reduction variables
- Work-stealing and/or load-balancing tasking layers

Questions?

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