Productive Programming in Chapel: A Computation-Driven Introduction

Short Introduction to Task Parallelism

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Outline

✓ Motivation
✓ Chapel Background and Themes
✓ Learning the Base Language with n-body

➢ Short Introduction to Task Parallelism
  ● Hands-On 1: Hello World
  ● Short Introduction to Locality
  ● Data Parallelism with Jacobi
  ● Hands-On 2: Mandelbrot
  ● Project Status, Next Steps
Defining our Terms

**Task**: a unit of computation that can/should execute in parallel with other tasks

**Thread**: a system resource that executes tasks
  - not exposed in the language
  - occasionally exposed in the implementation

**Task Parallelism**: a style of parallel programming in which parallelism is driven by programmer-specified tasks

(in contrast with):

**Data Parallelism**: a style of parallel programming in which parallelism is driven by computations over collections of data elements or their indices
Task Parallelism: Begin Statements

// create a fire-and-forget task for a statement
begin writeln("hello world");
writeln("goodbye");

Possible outputs:

- hello world
- goodbye
- goodbye
- hello world
Cobegins/Serial by Example: QuickSort

```chapel
proc quickSort(arr: [?D],
    thresh = log2(here.maxTaskPar),
    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);
        }
    }
}
```
Cobegins/Serial by Example: QuickSort

```chapel
proc quickSort(arr: [?D],
    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 (here.runningTasks > here.maxTaskPar) do
            cobegin {
                quickSort(arr, depth+1, low, pivotLoc-1);
                quickSort(arr, depth+1, pivotLoc+1, high);
            }
    }
}
```
Task Parallelism: Cobegin Statements

```chapel
// create a task per child statement
 cobegin {
    producer(1);
    producer(2);
    consumer(1);
} // implicit join of the three tasks here
```
Task Parallelism: Coforall Loops

// create a task per iteration
coforall t in 0..#numTasks {
    writeln("Hello from task ", t, " of ", numTasks);
} // implicit join of the numTasks tasks here

writeln("All tasks done");

Sample output:

Hello from task 2 of 4
Hello from task 0 of 4
Hello from task 3 of 4
Hello from task 1 of 4
All tasks done
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
- …or a small, finite set of homogenous 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
Task Parallelism: Data-Driven Synchronization

1) **atomic variables**: support atomic operations (as in C++)
   - e.g., compare-and-swap; atomic sum, etc.

2) **single-assignment variables**: reads block until assigned

3) **synchronization variables**: store full/empty state
   - by default, reads/writes block until the state is full/empty
Bounded Buffer Producer/Consumer Example

begin producer();
consumer();

// 'sync' types store full/empty state along with value
var buff$: [0..#buffersize] sync real;

proc producer() {
    var i = 0;
    for ... {
        i = (i+1) % buffersize;
        buff$[i] = ...;  // writes block until empty, leave full
    }
}

proc consumer() {
    var i = 0;
    while ... {
        i= (i+1) % buffersize;
        ...buff$[i]...;  // reads block until full, leave empty
    }
}
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 future$: sync real;
begin future$ = compute();
res = computeSomethingElse();
useComputedResults(future$, res);

var lock$: sync bool;
lock$ = true;
critical();
var lockval = lock$;
```
Atomic Variables

- **Syntax**
  
  ```chapel
  sync-type: atomic type
  ```

- **Semantics**
  - Supports operations on variable atomically w.r.t. other tasks
  - Based on C/C++ atomic operations

- **Example: Trivial barrier**

  ```chapel
  var count: atomic int, done: atomic bool;
  proc barrier(numTasks) {
    const myCount = count.fetchAdd(1);
    if (myCount < numTasks - 1) then
      done.waitFor(true);
    else
      done.testAndSet();
  }
  ```
Atomic Methods

- **read():t**
  - return current value

- **write(v:t)**
  - store v as current value

- **exchange(v:t):t**
  - store v, returning previous value

- **compareExchange(old:t,new:t):bool**
  - store new iff previous value was old; returns true on success

- **waitFor(v:t)**
  - wait until the stored value is v

- **add(v:t)**
  - add v to the value atomically

- **fetchAdd(v:t)**
  - same, returning pre-sum value
    - (sub, or, and, xor also supported similarly)

- **testAndSet()**
  - like exchange(true) for atomic bool

- **clear()**
  - like write(false) for atomic bool
Comparison of Synchronization Types

**sync/single:**
- Best for producer/consumer style synchronization
  - “this task should block until something happens”
- Use single for write-once values

**atomic:**
- Best for uncoordinated accesses to shared state
Other Task Parallel Concepts

- **atomic variables**: support atomics ops, similar to modern C++
- **sync/single variables**: support producer/consumer patterns
- **sync statements**: join unstructured tasks
- **serial statements**: conditionally squash parallelism
Other Task Parallel Features

Current:
- serial statements to conditionally squash parallelism
- sync statements to join dynamically generated tasks

Planned:
- task-private variables
- task teams to support
  - collective operations (barriers, joins, reductions, etc.)
  - thread scheduling policies
Smith-Waterman Algorithm for Sequence Alignment
Smith-Waterman

Goal: Determine the similarities/differences between two protein sequences/nucleotides.

- e.g., ACACACTA and AGCACACA*

Basis of Computation: Defined via a recursive formula:

\[
H(i,0) = 0 \\
H(0,j) = 0 \\
H(i,j) = f(H(i-1, j-1), H(i-1, j), H(i, j-1))
\]

Caveat: This is a classic, rather than cutting-edge sequence alignment algorithm, but it illustrates an important parallel paradigm: wavefront computation

Smith-Waterman

Naïve Task-Parallel Approach:

```chapel
proc computeH(i, j) {
    if (i == 0 || j == 0) then
        return 0;
    else
        var h_NW, h_N, h_W: int;

        cobegin {
            h_NW = computeH(i-1, j-1);
            h_N  = computeH(i-1, j);
            h_W  = computeH(i,  j-1);
        }

        return f(h_NW, h_N, h_W);
}

Note: Recomputes most subexpressions redundantly

This is a case for dynamic programming!
```
Dynamic Programming Approach:

Step 1: Initialize boundaries to 0

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Smith-Waterman

Dynamic Programming Approach:

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Step 2: Compute cells when we're able to

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## Smith-Waterman

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Step 3: Follow trail of breadcrumbs back
Smith-Waterman

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Step 3: Follow trail of breadcrumbs back
Smith-Waterman

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Step 4: Interpret the path against the original sequences

AGCACAC–A
A–CACACTA
Smith-Waterman

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Step 2: Compute cells when we're able to

How could we do this in parallel?
Smith-Waterman

Data-Parallel Approach:

```
proc computeH(H: [0..n, 0..n] int) {
    for upperDiag in 1..n do
        forall diagPos in 0..#upperDiag {
            const (i,j) = (diagPos+1, upperDiag-diagPos);
            H[i,j] = f(H[i-1,j-1], H[i-1,j], H[i,j-1]);
        }
    for lowerDiag in 1..n-1 do
        forall diagPos in lowerDiag..n-1 by -1 {
            const (i,j) = (diagPos+1, lowerDiag+diagPos);
            H[i,j] = f(H[i-1,j-1], H[i-1,j], H[i,j-1]);
        }
}
```

**Advantages:**
- Reasonably clean (if I got my indexing correct)

**Disadvantages:**
- Not so great in terms of cache use
- A bit fine-grained
- Small number of iterations per task

Loop over upper diagonals serially
Process each diagonal in parallel
Repeat for lower diagonals
Naïve Data-Driven Task-Parallel Approach:

```plaintext
proc computeH(H: [0..n, 0..n] int) {
    const ProbSpace = H.domain.translate(1,1);
    var NeighborsDone: [ProbSpace] atomic int;
    var Ready$: [ProbSpace] sync int;

    NeighborsDone[1, ..].add(1);
    NeighborsDone[.., 1].add(1);
    NeighborsDone[1, 1].add(1);
    Ready$[1,1] = 1;

    coforall (i,j) in ProbSpace {
        const goNow = Ready$[i,j];
        H[i,j] = f(H[i-1,j-1], H[i-1,j], H[i,j-1]);
        const eastReady = NeighborsDone[i, j+1].fetchAdd(1);
        const seReady = NeighborsDone[i+1,j+1].fetchAdd(1);
        const southReady = NeighborsDone[i+1,j  ].fetchAdd(1);
        if (eastReady == 2) then Ready$[i, j+1] = 1;
        if (seReady == 2) then Ready$[i+1,j+1] = 1;
        if (southReady == 2) then Ready$[i+1,j  ] = 1;
    }
}
```

Create a domain describing shifted version of H’s domain

Arrays to count how many of our 3 neighbors are done; and to signal when we can compute

Set up boundaries: north and west elements have a neighbor done; top-left is ready

Create a task per matrix element and have it block until ready

Compute our element

Increment our neighbors’ counts

Signal our neighbors as ready if we’re the third
Naïve Data-Driven Task-Parallel Approach:

```chapel
proc computeH(H: [0..n, 0..n] int) {
    const ProbSpace = H.domain.translate(1,1);
    var NeighborsDone: [ProbSpace] atomic int;
    var Ready$: [ProbSpace] sync int;

    NeighborsDone[1, ..].add(1);
    NeighborsDone[.., 1].add(1);
    NeighborsDone[1, 1].add(1);
    Ready$[1,1] = 1;

    coforall (i,j) in ProbSpace {
        const goNow = Ready$[i,j];
        H[i,j] = f(H[i-1,j-1], H[i-1,j], H[i,j-1]);
        const eastReady = NeighborsDone[i, j+1].fetchAdd(1);
        const seReady = NeighborsDone[i+1,j+1].fetchAdd(1);
        const southReady = NeighborsDone[i+1,j].fetchAdd(1);
        if (eastReady == 2) then Ready$[i, j+1] = 1;
        if (seReady == 2) then Ready$[i+1,j+1] = 1;
        if (southReady == 2) then Ready$[i+1,j ] = 1;
    }
}
```

Disadvantages:
- Still not great in cache use
- Uses $n^2$ tasks
- Most spend most of their time blocking

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Slightly Less Naïve Data-Driven Task-Parallel Approach:

```java
proc computeH(H: [0..n, 0..n] int) {
    const ProbSpace = H.domain.translate(1,1);
    var NeighborsDone: [ProbSpace] atomic int;

    NeighborsDone[1, ..].add(1);
    NeighborsDone[.., 1].add(1);
    NeighborsDone[1, 1].add(1);
    sync { computeHHelp(1,1); }

    proc computeHHelp(i,j) {
        H[i,j] = f(H[i-1,j-1], H[i-1,j], H[i,j-1]);
        const eastReady = NeighborsDone[i,   j+1].fetchAdd(1);
        const seReady =   NeighborsDone[i+1,j+1].fetchAdd(1);
        const southReady = NeighborsDone[i+1,j  ].fetchAdd(1);
        if (eastReady == 2) then begin computeHHelp(i, j+1);
        if (seReady  == 2) then begin computeHHelp(i+1,j+1);
        if (southReady == 2) then begin computeHHelp(i+1,j  );
    }
}
```

Rather than create the tasks *a priori*, fire them off once we know they’re ready to compute.

sync to ensure they’re all done before we go on
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Slightly Less Naïve Data-Driven Task-Parallel Approach:

```chapel
proc computeH(H: [0..n, 0..n] int) {
    const ProbSpace = H.domain.translate(1,1);
    var NeighborsDone: [ProbSpace] atomic int;

    NeighborsDone[1, ..].add(1);
    NeighborsDone[.., 1].add(1);
    NeighborsDone[1, 1].add(1);
    sync { computeHHelp(1,1); }

    proc computeHHelp(i,j) {
        H[i,j] = f(H[i-1,j-1], H[i-1,j], H[i,j-1]);
        const eastReady = NeighborsDone[i, j+1].fetchAdd(1);
        const seReady = NeighborsDone[i+1,j+1].fetchAdd(1);
        const southReady = NeighborsDone[i+1,j  ].fetchAdd(1);
        if (eastReady == 2) then begin computeHHelp(i, j+1);
        if (seReady == 2) then begin computeHHelp(i+1,j+1);
        if (southReady == 2) then begin computeHHelp(i+1,j  );
    }
]
```

Disadvantages:
- Still uses a lot of tasks
- Each task is very fine-grained
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Coarsening the Parallelism into Chunks:

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Chunked Data-Driven Task-Parallel Approach:
proc computeH(H: [0..n, 0..n] int) {
  const ProbSpace = H.domain.translate(1,1);
  const StrProbSpace = ProbSpace by (rowsPerChunk, colsPerChunk);
  var NeighborsDone: [StrProbSpace] atomic int;
  NeighborsDone[1, ..].add(1);
  NeighborsDone[.., 1].add(1);
  NeighborsDone[1, 1].add(1);
  sync { computeHHelp(1,1); }

  proc computeHHelp(x,y) {
    for (i,j) in ProbSpace[x..#rowsPerChunk, y..#colsPerChunk] do
      H[i,j] = f(H[i-1,j-1], H[i-1,j], H[i,j-1]);
      const eastReady = NeighborsDone[x, y+colsPerChunk].fetchAdd(1);
      const seReady = NeighborsDone[x+rowsPerChunk, y+colsPerChunk].fetchAdd(1);
      const southReady = NeighborsDone[x+rowsPerChunk, y].fetchAdd(1);
      if (eastReady == 2) then begin computeHHelp(x, y+colsPerChunk);
      if (seReady == 2) then begin computeHHelp(x+rowsPerChunk, y+colsPerChunk);
      if (southReady == 2) then begin computeHHelp(x+rowsPerChunk, y);
    }
  }
}
Questions about Task Parallelism in Chapel?
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