Task Parallelism By Example
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Task Parallel Features
Task Parallel “Hello, world!”

● **Multicore Hello World**

```chapel
config const numTasks = here.maxTaskPar;

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

Hello, world! from task 2 of 4
Hello, world! from task 0 of 4
Hello, world! from task 3 of 4
Hello, world! from task 1 of 4
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

```plaintext
// 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);
            }
    }
}
```

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Task Parallelism: Cobegin Statements

```
// 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
What’s worrisome about this loop?

```plaintext
var A: [1..1000000] real;
coforall a in A do
  a = 1.0;
```
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 $1 < \#\text{tasks} \ll \#\text{iters}$
- use when a loop *should* be executed in parallel…
- …but *can* legally be executed serially
- use when desired $\#\text{tasks} \ll \#\text{of iterations}$

**Coforall loops:** executed using a task per iteration
- use when the loop iterations *must* be executed in parallel
- use when you want $\#\text{tasks} = \#\text{of iterations}$
- use when each 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
- …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, mult, 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

cobegin { 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**

```chapel
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**

```chapel
var future$: sync real;
begin future$ = compute();
res = computeSomethingElse();
useComputedResults(future$, res);
```

```chapel
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) 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
  \((\text{sub, or, and, xor} \text{ also supported similarly})\)
- **testAndSet()** like \( \text{exchange(true)} \) for atomic \( \text{bool} \)
- **clear()** like \( \text{write(false)} \) for atomic \( \text{bool} \)
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
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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Dynamic Programming Approach:

Step 2: Compute cells when we’re able to

\[ H_{i-1, j-1}, H_{i, j}, H_{i, j-1}, H_{i-1, j} \]
### Dynamic Programming Approach:

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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

### Dynamic Programming Approach:

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**Step 2:** Compute cells when we're able to.

How could we do this in parallel?

\[
H_{i,j-1}, \quad H_{i-1,j-1}, \quad H_{i-1,j}, \quad H_{i,j}
\]
Data-Parallel Approach:

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

**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

---

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Naïve Data-Driven Task-Parallel Approach:

```c
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
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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:

```plaintext
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  );
    }
}
```

- `sync` to ensure they’re all done before we go on
- Rather than create the tasks *a priori*, fire them off once we know they’re ready to compute.
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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:

```
  0 1 2 3 4 5 6 7 8
0 0 0 0 0 0 0 0 0
1 0 0 0 0 0 0 0 0
2 0 0 0 0 0 0 0 0
3 0 0 0 0 0 0 0 0
4 0 0 0 0 0 0 0 0
5 0 0 0 0 0 0 0 0
6 0 0 0 0 0 0 0 0
7 0 0 0 0 0 0 0 0
8 0 0 0 0 0 0 0 0
```
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);
        }
    }
```

- Use strided array for atomics
- Change helper to iterate over a chunk serially
- Stride indices to get to next chunk’s origin
Questions about Task Parallelism in Chapel?
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