Task Parallelism
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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
          hello world
Task Parallelism: Cobegin Statements

```c
// create a task per child statement
cobegin {
  producer(1);
  producer(2);
  consumer(1);
} // implicit join of the three tasks here
```
Cobegins/Serial by Example: QuickSort

```plaintext
proc quickSort(arr: [?D],
    depth = 0,
    thresh = log2(here.maxTaskPar),
    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, depth+1, thresh, low, pivotLoc-1);
            quickSort(arr, depth+1, thresh, pivotLoc+1, high);
        }
    }
}
```
Cobegins/Serial by Example: QuickSort

```c
proc quickSort(arr: [?D],
               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, low, pivotLoc-1);
                quickSort(arr, pivotLoc+1, high);
            }
    }
}
```
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” (or at least “leave running for awhile”)

**cobegin:**
- Use to create a related set of heterogeneous tasks
  ...or a small, fixed 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

- **sync variables**: store full-empty state along with value
  - by default, reads/writes block until full/empty, leave in opposite state

- **atomic variables**: support atomic operations
  - e.g., compare-and-swap; atomic sum, multiply, etc.
  - similar to C/C++
Bounded Buffer Producer/Consumer Example

```plaintext
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] = ...;    // wait for empty, write, leave full
  }
}

proc consumer() {
  var i = 0;
  while ... {
    i = (i+1) % buffersize;
    ...buff$[i]...;    // wait for full, read, leave empty
  }
}
```
Synchronization Variables

● **Syntax**

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

● **Semantics**

- Stores *full/empty* state along with normal value
- Initially *full* if initialized, *empty* otherwise
- Default read blocks until *full*, leaves *empty*
- Default write blocks until *empty*, leaves *full*

● **Examples: Critical sections and futures**

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

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

- **Syntax**

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

- **Semantics**

  - Similar to sync variable, but stays *full* once written

- **Example: Multiple Consumers of a future**

  ```plaintext
  var future$: single real;
  begin future$ = compute();
  begin computeSomethingElse(future$);
  begin computeSomethingElse(future$);
  ```
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**
Atomic Variables

● Syntax

\[
\text{atomic-type: }\quad \text{atomic type}
\]

● Semantics

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

● Example: Trivial barrier

```cpp
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()**: return current value
- **write(v)**: store v as current value
- **exchange(v)**: store v, returning previous value
- **compareExchange(old, new)**: store new iff previous value was old; returns true on success
- **waitFor(v)**: wait until the stored value is v
- **add(v)**: add v to the value atomically
- **fetchAdd(v)**: 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
  - “these tasks are unlikely to interfere with each other, at least for very long…”
Task Intents

- Tells how to “pass” variables from outer scopes to tasks
  - Similar to argument intents in syntax and philosophy
    - also adds a “reduce intent”, similar to OpenMP
  - Design principles:
    - ”principle of least surprise”
    - avoid simple race conditions
    - avoid copies of (potentially) expensive data structures
    - support coordination via sync/atomic variables

- Congruent to forall intents, but for task-parallel constructs
Task Intent Examples

```plaintext
var sum: real;
coforall i in 1..n do       // default task intent of scalars is ‘const in’
    sum += computeMyResult(i);  // so this is illegal: (and avoids a race)

var sum: real;
coforall i in 1..n with (ref sum) do   // override default task intent
    sum += computeMyResult(i);    // we’ve now requested a race

var sum: real;
coforall i in 1..n with (+ reduce sum) do   // override default intent
    sum += computeMyResult(i);    // per-task sums will be reduced on task exit

var sum: atomic real;
coforall i in 1..n do                  // default task intent of atomics is ‘ref’
    sum.add(computeMyResult(i));   // so this is legal, meaningful, and safe
```
Task-Private Variables

- Task-parallel features support task-private variables easily
  ```
  coforall i in 1..numTasks {
      var mySum: real;  // each task gets its own copy of mySum
      for j in 1..n do
          mySum += A[i][j];
  }
  ```

- Forall loops need special support for task-private variables
  ```
  var oneSingleVariable: real;
  forall i in 1..n {
      var onePerIteration: real;
  }
  ```
Task-Private Variables

- Task-parallel features support task-private variables easily

```c
coforall i in 1..numTasks {
    var mySum: real;  // each task gets its own copy of mySum
    for j in 1..n do
        mySum += A[i][j];
}
```

- Forall loops need special support for task-private variables

```c
var oneSingleVariable: real;
forall i in 1..n with (var onePerTask: real) {
    var onePerIteration: real;
}
```
Task-Private Variables

- Task-parallel features support task-private variables easily

```plaintext
coforall i in 1..numTasks {
  var mySum: real;  // each task gets its own copy of mySum
  for j in 1..n do
    mySum += A[i][j];
}
```

- Forall loops need special support for task-private variables

```plaintext
var oneSingleVariable: real;
forall i in 1..n with (var onePerTask = 3.14) {
  var onePerIteration: real;
}
```
Task-Private Variables

- Task-parallel features support task-private variables easily
  ```
  coforall i in 1..numTasks {
    var mySum: real; // each task gets its own copy of mySum
    for j in 1..n do
      mySum += A[i][j];
  }
  ```

- Forall loops need special support for task-private variables
  ```
  var oneSingleVariable: real;
  forall i in 1..n with (ref myLocArr = A[localInds]) {
    var onePerIteration: real;
  }
  ```
Joining Sub-Tasks: Sync-Statements

- **Syntax**
  
  ```plaintext
  sync-statement:
  sync stmt
  ```

- **Definition**
  - Executes `stmt`
  - Waits for all *dynamically-scoped* begins to complete

- **Examples**

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

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

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