Lecture 25:
Scheduling Fork-Join Parallelism
“Just expose independent work as it comes, and let the scheduler do the rest.”

- Robinella
Common parallel programming patterns

Data Parallelism:
Perform same sequence of operations on many data elements

//openMP parallel for
#pragma omp parallel for
for (int i=0; i<N; i++) {
    B[i] = foo(A[i]);
}

// CUDA bulk launch
foo<<<numBlocks, threadsPerBlock>>>(A, B);

// ISPC foreach
foreach (i=0 ... N) {
    B[i] = foo(A[i]);
}

// ISPC bulk task launch
launch[numTasks] myFooTask(A, B);

// higher order using map
map(foo, A, B);
Explicit parallelism management with threads:
Create one thread per execution unit (or per amount of desired concurrency)
- Example below: C code with pthreads
- Other examples: mpirun -np 4

```c
struct thread_args {
    float* A;
    float* B;
};

int thread_id[MAX_THREADS];

thread_args args;
args.A = A;
args.B = B;

for (int i=0; i<num_cores; i++) {
    pthread_create(&thread_id[i], NULL, myFooThread, &args);
}

for (int i=0; i<num_cores; i++) {
    pthread_join(&thread_id[i]);
}
```
Common parallel programming patterns

**Pipeline Parallelism:**
Each unit/worker is responsible for one stage of computation on a data element.

Below: three stages of bus transaction: request stage, response stage, data-send stage
Other examples: processor instruction pipeline, pipelining network transmission, …
Consider divide-and-conquer algorithms

Quick-sort:

// sort elements from begin up to (but not including) end
void quick_sort(int* begin, int* end) {
    if (end - begin <= 1)
        return;
    else {
        // choose partition key and partition elements
        // by key, return position of key as `middle`
        int* middle = partition(begin, end);
        quick_sort(begin, middle);
        quick_sort(middle+1, last);
    }
}

Dependencies

independent work!
**Fork-join pattern**

- Natural way to express independent work inherent in divide-and-conquer algorithms
- Today’s code examples will be in Cilk Plus
  - C++ language extensions
  - Originally developed at MIT, now adapted as open standard (in Intel ICC, GCC)

```cilk
  cilk_spawn foo(args);
  
  "fork" (create new logical thread of control)

  Semantics: invoke `foo`, but unlike standard function call, caller may continue executing asynchronously with execution of `foo`.

  cilk_sync;

  "join"

  Semantics: returns when all calls spawned by current function have completed.
  ("sync up" with the spawned calls)

Note: there is an implicit `cilk_sync` at the end of every function that contains `cilk_spawn` (implication: when a Cilk function returns, all work associated with that function is complete)
Basic Cilk Plus examples

```cilk
// foo() and bar() may run in parallel
cilk_spawn foo();
bar();
cilk_sync;
```

```cilk
// foo() and bar() may run in parallel
cilk_spawn foo();
cilk_spawn bar();
cilk_sync;
```

Same amount of independent work first example, but potentially higher runtime overhead (due to two spawns vs. one)

```cilk
// foo, bar, fizz, buzz, may run in parallel

cilk_spawn foo();
cilk_spawn bar();
cilk_spawn fizz();
buzz();
cilk_sync;
```

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Abstraction vs. implementation

- Notice that the `cilk_spawn` abstraction does not specify how or when spawned calls are scheduled to execute
  - Only that they may be run concurrently with caller (and with all other calls spawned by the caller)

- But `cilk_sync` does serve as a constraint on scheduling
  - All spawned calls must complete before `cilk_sync` returns
Parallel quicksort in Cilk Plus

```c
void quick_sort(int* begin, int* end) {
    if (end - begin <= PARALLEL_CUTOFF)
        std::sort(begin, end);
    else {
        int* middle = partition(begin, end);
        cilk_spawn quick_sort(begin, middle);
        quick_sort(middle+1, last);
    }
}
```

Sort sequentially if problem size is sufficiently small (overhead of spawn trumps benefits of potential parallelization)
Writing fork-join programs

- Main-idea: expose independent work (potential parallelism) to the system using \texttt{cilk\_spawn}

- Recall parallel programming rules of thumb
  - Want \textit{at least as much work} as parallel execution capability (e.g., program should spawn at least was much work as there are cores)
  - Want \textit{more independent work} than execution capability to allow for good workload balance of all the calls onto the cores.
    - "parallel slack" = ratio of independent work to machine’s parallel execution capability (\(~8\) is a good ratio)
  - But \textit{not too much independent work} so that granularity of work is too small (too much slack incurs overhead of managing fine-grained work)
Scheduling fork-join programs

- Consider very simple scheduler:
  - Launch pthread for each cilk_spawn using pthread_create
  - Translate cilk_sync into appropriate pthread_join calls

- Potential performance problems?
  - Heavyweight spawn operation
  - Many more concurrently running threads than cores
    - Context switching overhead
  - Larger working set than necessary, less cache locality
Pool of worker threads

- Cilk Plus runtime maintains pool of worker threads
  - Think: all threads created at application launch *
  - Exactly as many worker threads as execution contexts in the machine

* It’s perfectly fine to think about it this way, but in reality, the runtime is lazy and initializes its worker threads on the first Cilk spawn. (This is a common implementation strategy, ISPC does the same with worker threads that run ISPC tasks.)
Consider one thread executing the following code

Specificially, consider execution at point of spawn of foo()

cilk_spawn foo();
bar();
cilk_sync;

What threads should foo() and bar() be executed by?

Thread 0
Thread 1
Serial execution

Run child first via function call (continuation is implicit in thread’s stack)
- Thread runs foo(), returns from foo(), then runs bar()

Executing foo()…

Thread call stack
(indicates bar will be performed next after return)

Thread 0

Thread 1 goes idle…

Inefficient: thread 1 could be performing bar() at this time!
Per-thread work queues store “work to do”

Thread 0 work queue

```
bar()
```

Thread call stack

Thread 0

Executing foo()...
Idle threads “steal” work from busy threads

1. Idle thread looks in busy thread’s queue for work

Executing foo()...
Idle threads “steal” work from busy threads

1. Idle thread looks in busy threads queue for work
2. Idle thread moves work from busy thread’s queue to its own queue

Executing `foo()`...
Idle threads “steal” work from busy threads

1. Idle thread looks in busy threads queue for work
2. Idle thread moves work from busy thread’s queue to its own queue
3. Thread resumes execution
Alternative implementation:
At each spawn, system stores continuation (path not executed)

```
cilk_spawn foo();
bar();
cilk_sync;
```

- Continuation is made available for stealing by other threads (“continuation stealing”)
- Child is made available for stealing by other threads (“child stealing”)

Run continuation first: record child for later execution
- Child is made available for stealing by other threads (“child stealing”)

Run child first: record continuation for later execution
- Continuation is made available for stealing by other threads (“continuation stealing”)

Which implementation do we choose?
Consider thread executing the following code

```c
for (int i=0; i<N; i++) {
    cilk_spawn foo(i);
}
cilk_sync;
```

### Child stealing (run continuation first)

- Caller thread spawns work for all iterations before executing any of it
- Think: breadth-first traversal of call graph. $O(N)$ space for spawned work (maximum space)
- If no stealing, execution order is very different than that of program with `cilk_spawn` removed
Consider thread executing the following code

```c
for (int i=0; i<N; i++) {
    cilk_spawn foo(i);
}
cilk_sync;
```

- **Continuation stealing (run child first)**
  - Caller thread only creates one item to steal (continuation that represents all remaining iterations)
  - If no stealing occurs, thread continually pops continuation from work queue, enqueues new continuation (with updated value of `i`)
  - Order of execution is the same as for program with spawn removed.
  - Think: depth-first traversal of call graph
Consider thread executing the following code

```c
for (int i=0; i<N; i++) {
    cilk_spawn foo(i);
}
cilk_sync;
```

- **Continuation stealing (run child first)**
  - If continuation is stolen, stealing thread spawns and executes next iteration
  - Enqueues continuation with \( i \) advanced by 1
  - Can prove that work queue storage for system with \( T \) threads is no more than \( T \) times that of stack storage for single threaded execution
void quick_sort(int* begin, int* end) {
    if (end - begin <= PARALLEL_CUTOFF)
        std::sort(begin, end);
    else {
        int* middle = partition(begin, end);
        cilk_spawn quick_sort(begin, middle);
        quick_sort(middle+1, last);
    }
}

What work to steal?

Thread 0 work queue

| cont: 101-200 |
| cont: 51-100 |
| cont: 26-50 |

Thread 1 work queue

| cont: |
| cont: |
| cont: |

..., Thread 2 work queue

| cont: |
| cont: |
| cont: |

Working on 0-25...
Implementing work stealing: dequeue per worker

Work queue implemented as a dequeue (double ended queue)
- Local thread pushes/pops from the “tail” (bottom)
- Remote threads steal from “head” (top)
- Efficient lock-free dequeue implementations exist

Thread 0 work queue

Thread 1 work queue

Thread 2 work queue

Steal!
Steal!
Steal!

Working on 0-25…
Implementing work stealing: dequeue per worker

Work queue implemented as a dequeue (double ended queue)
- Local thread pushes/pops from the "tail" (bottom)
- Remote threads steal from "head" (top)
- Efficient lock-free dequeue implementations exist

Thread 0 work queue
```
cont: 26-50
```
Working on 0-25...

Thread 1 work queue
```
cont: 76-100
```
Working on 51-75...

Thread 2 work queue
```
cont: 151-200
```
Working on 101-150...
Implementing work stealing: random choice of victim

- **Idle threads randomly choose a thread to attempt to steal from**

- **Stealing from top of dequeue…**
  - Reduces contention with local thread: local thread is not accessing same part of dequeue that stealing threads do!
  - Steals work towards beginning of call tree: this is a “larger” piece of work, so cost of steal amortized over long future computation
  - Maximizes locality: (in conjunction with run-child-first policy) local thread works on local part of call tree)

<table>
<thead>
<tr>
<th>Thread 0 work queue</th>
<th>Thread 1 work queue</th>
<th>Thread 2 work queue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>cont: 151-200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cont: 126-150</td>
</tr>
<tr>
<td>cont: 26-50</td>
<td>cont: 76-100</td>
<td>cont: 114-125</td>
</tr>
<tr>
<td>cont: 13-25</td>
<td>cont: 64-75</td>
<td></td>
</tr>
</tbody>
</table>

Working on 0-12…  Working on 51-63…  Working on 101-113…
Child-first work stealing scheduler anticipates divide-and-conquer parallelism

```c
void recursive_for(int start, int end) {
  while (end - start > GRANULARITY) {
    int mid = (end - start) / 2;
    cilk_spawn recursive_for(start, mid);
    start = mid;
  }
  for (int i=start; i<end; i++)
    foo(i);
}
recursive_for(0, N);
```

Code at right generates work in parallel: more quickly fills machine
Implementing sync

for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;
bar();

Thread 0 work queue

cont: i=10

Thread 1 work queue

Working on foo(7)…

Thread 2 work queue

Working on foo(8)…

Thread 3 work queue

Working on foo(6)…
Implementing sync: case 1: no stealing

block (id: A)

for (int i = 0; i < 10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  \textit{Sync for all calls spawned in block A}

bar();

If no work has been stolen, then thread behaves like a serial program.

cilk\_sync is a noop.
Implementing sync: case 2: stealing

```c
block (id: A)
    for (int i=0; i<10; i++) {
        cilk_spawn foo(i);
    }
    cilk_sync;  // Sync for all calls spawned in block A
bar();
```

Example 1: stalling join policy
Thread that initiates the fork must from the sync.
Therefore it waits for all spawned work to be complete.
In this case, thread 0 is the thread initiating the fork

Working on `foo(0)`, id=A...
Implementing sync: case 2: stealing

```
for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  // Sync for all calls spawned in block A
bar();
```

Idle thread 1 steals from busy thread 0
Note: descriptor for block A created
Implementing sync: case 2: stealing

```c
for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  // Sync for all calls spawned in block A
bar();
```

Thread 0 work queue

Thread 1 work queue

Thread 1 now running foo(1)
Implementing sync: case 2: stealing

```c
for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  // Sync for all calls spawned in block A
bar();
```

Thread 0 work queue: idle
Thread 1 work queue: stolen (id=A)
Thread 2 work queue: cont: i=2, id=A

Thread 0 completes foo(0)
Thread 2 now running foo(2)
Implementing sync: case 2: stealing

block (id: A)
for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  \textit{Sync for all calls spawned in block A}
bar();
Implementing sync: case 2: stealing

```c
for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  // Sync for all calls spawned in block A
bar();
```

---

**Diagram:**

- **Thread 0 work queue**
  - `id=A`
    - `spawn: 10, done: 9`
    - `STOLEN (id=A)`

- **Thread 1 work queue**
  - `cont: i=10, id=A`

- **Thread 2 work queue**
  - `Idle!`

**Flow:**

1. Last spawn completes.
2. `foo(9)`
3. `foo(3)`, `foo(2)`, `foo(1)`, `foo(0)`
4. `bar()`
Implementing sync: case 2: stealing

```c
block (id: A)
for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  Sync for all calls spawned in block A
bar();
```

Thread 0 work queue

Thread 1 work queue

Thread 2 work queue

Thread 0 now resumes continuation and executes bar()
Note block A descriptor is now free.
Implementing sync: case 2: stealing

for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  Sync for all calls spawned in block A
bar();
Implementing sync: case 2: stealing

block (id: A)
  for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
  }
cilk_sync;  Sync for all calls spawned in block A
bar();

Idle thread 1 steals from busy thread 0 (as in the previous case)
Implementing sync: case 2: stealing

```c
for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
}
cilk_sync;  // Sync for all calls spawned in block A
bar();
```

Thread 0 work queue

<table>
<thead>
<tr>
<th>id=A</th>
<th>spawn: 2, done: 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>STOLEN (id=A)</td>
<td></td>
</tr>
</tbody>
</table>

Thread 1 work queue

| cont: i=1, id=A |

Thread 0 completes foo(0)
No work to do in local dequeue, so thread looks to steal!
Implementing sync: case 2: stealing

block (id: A)
for (int i=0; i<10; i++) {
  cilk_spawn foo(i);
}
cilk_sync;  Sync for all calls spawned in block A
bar();
Implementing sync: case 2: stealing

block (id: A)
  for (int i=0; i<10; i++) {
    cilk_spawn foo(i);
  }
cilk_sync;  Sync for all calls spawned in block A
bar();
Implementing sync: case 2: stealing

block (id: A)
for (int i=0; i<10; i++) {
  cilk_spawn foo(i);
}
cilk_sync;  Sync for all calls spawned in block A
bar();

Thread 0 work queue

Thread 1 work queue

Thread 1 continues on to run bar()
Note block A descriptor is now free.
Cilk uses greedy join scheduling

- **Greedy join scheduling policy**
  - All threads always attempt to steal if there is nothing to do (thread only goes idle if no work to steal is present in system)
  - Worker thread that initiated spawn may not be thread that executes logic after cilk_sync

- **Remember:**
  - Overhead of bookkeeping steals and managing sync points only occurs when steals occur
  - If large pieces of work are stolen, this should occur infrequently
    - Most of the time, threads are pushing/popping local work from their local dequeue
Summary

- Fork-join parallelism

- Natural way to express divide-and-conquer algorithms
  - Discussed Cilk Plus, but OpenMP also has fork/join primitives

- Cilk Plus runtime implements spawn/sync abstraction with locality-aware work stealing scheduler
  - Always run spawned child (continuation stealing)
  - Greedy behavior at join (threads do not wait at join, immediate look for other work to steal)