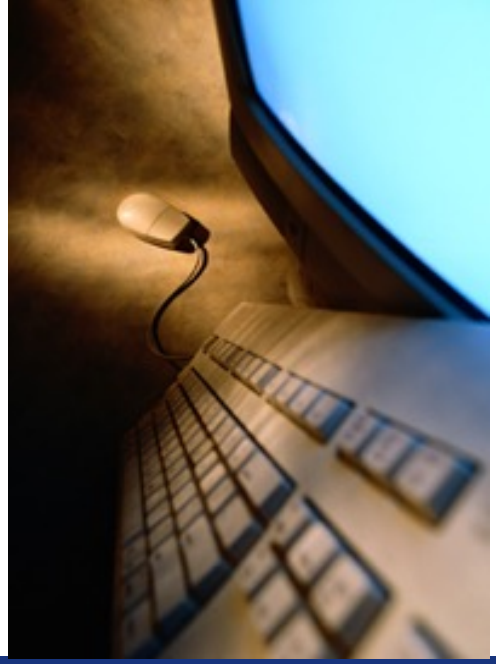
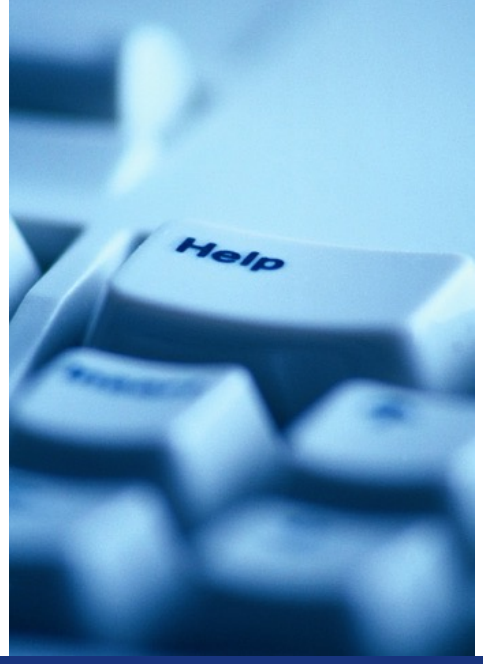

并行与分布式计算

Parallel & Distributed Computing

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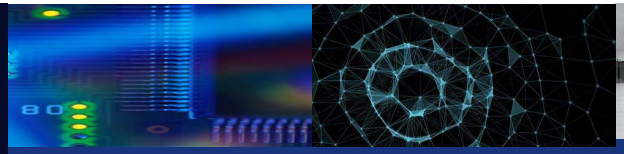

Lecture 15 — Performance Optimization (Work Distribution and Scheduling)

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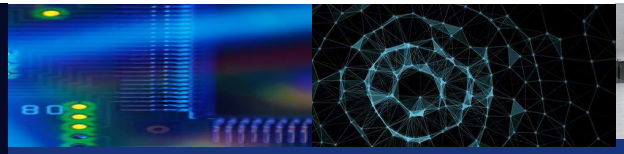
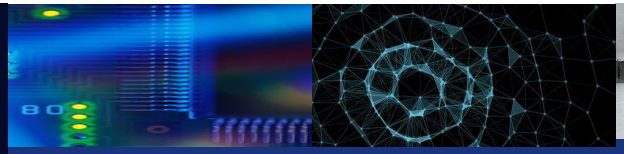


Programming for High Performance

- **Optimizing the performance of parallel programs is an iterative process of refining choices for decomposition, assignment, and orchestration...**
- **Key goals (that are at odds (相互冲突) with each other)**
  - **Balance workload onto available execution resources**
  - **Reduce communication (to avoid stalls)**
  - **Reduce extra work (overhead) performed to increase parallelism, manage assignment, reduce communication, etc.**
- **We are going to talk about a rich space of techniques**



TIP #1: Always implement the simplest solution first, then measure performance to determine if you need to do better.

If you anticipate only running low-core count machines, it may be unnecessary to implement a complex approach that creates and hundreds or thousands of pieces of independent work

Balancing the workload

Ideally: all processors are computing all the time during program execution (they are computing simultaneously, and they finish their portion of the work at the same time)

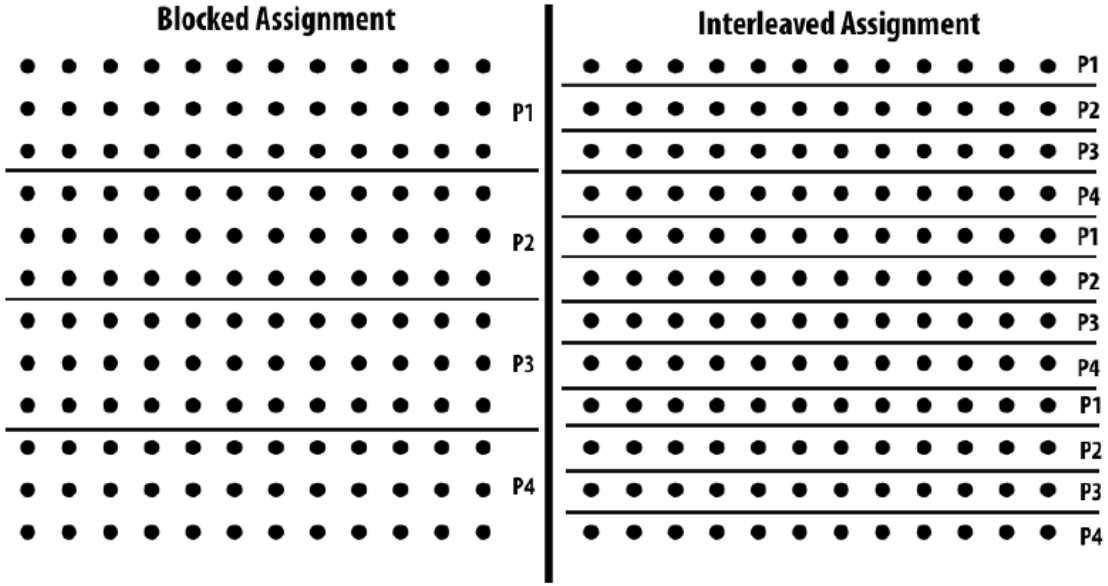
Recall Amdahl's Law:
Only small amount of load imbalance can significantly bound maximum speedup

P4 does 20% more work → P4 takes 20% longer to complete
→ 20% of parallel program's runtime is serial execution

(work in serialized section here is about 5% of the work of the whole program: S=.05 in Amdahl's law equation)

Static assignment

- Assignment of work to threads is pre-determined
  - Not necessarily determined at compile-time (assignment algorithm may depend on runtime parameters such as input data size, number of threads, etc.)
- Recall solver example: assign equal number of grid cells (work) to each thread (worker)
  - We discusse two static assignments of work to workers (blocked and interleaved)

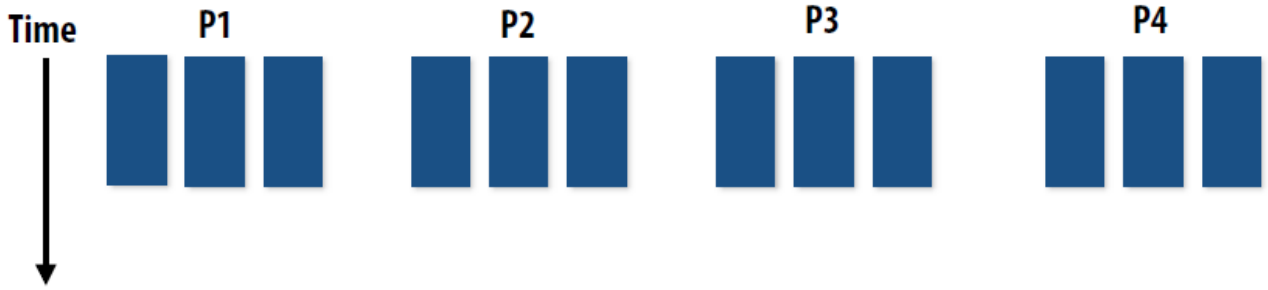


- Good properties of static assignment: simple, essentially zero runtime overhead

(in this example: extra work to implement assignment is a little bit of indexing math)

When is static assignment applicable?

- When the cost (execution time) of work and the amount of work is predictable (so the programmer can work out a good assignment in advance)
- Simplest example: it is known up front that all work has the same cost



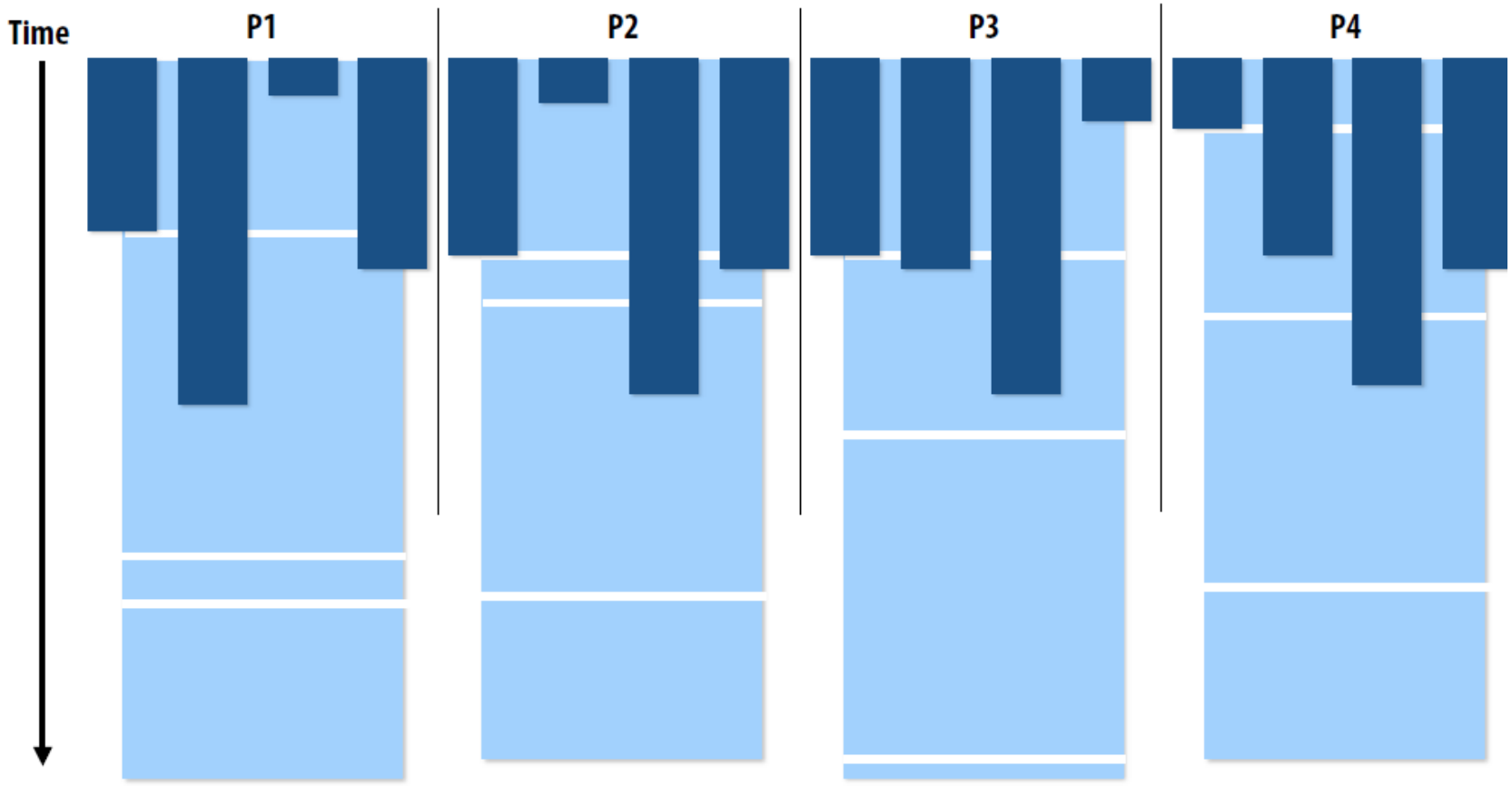
In the example above:

There are 12 tasks, and it is known that each have the same cost.

Assignment solution: statically assign three tasks to each of the four processors.

When is static assignment applicable?

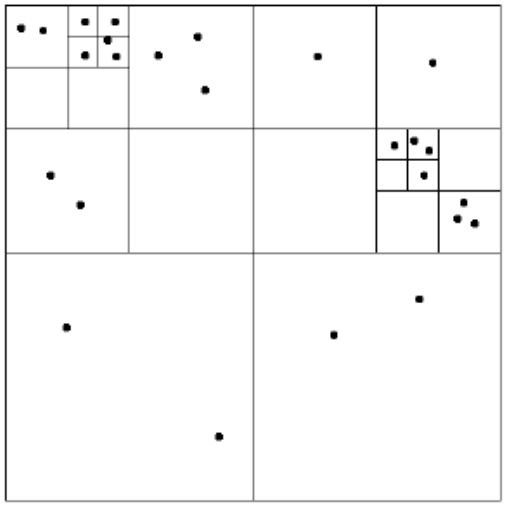
- When work is predictable, but not all jobs have same cost (see example below)
- When statistics about execution time are known (e.g., same cost on average)



Jobs have unequal, but known cost: assign to processors to ensure overall good load balance

"Semi-static" assignment

- Cost of work is predictable for near-term future
  - Idea: recent past good predictor of near future
- Application periodically profiles itself and re-adjusts assignment
  - Assignment is "static" for the interval between readjustments



N-Body simulation:

Redistribute particles as they move over course of simulation (if motion is slow, redistribution need not occur often)

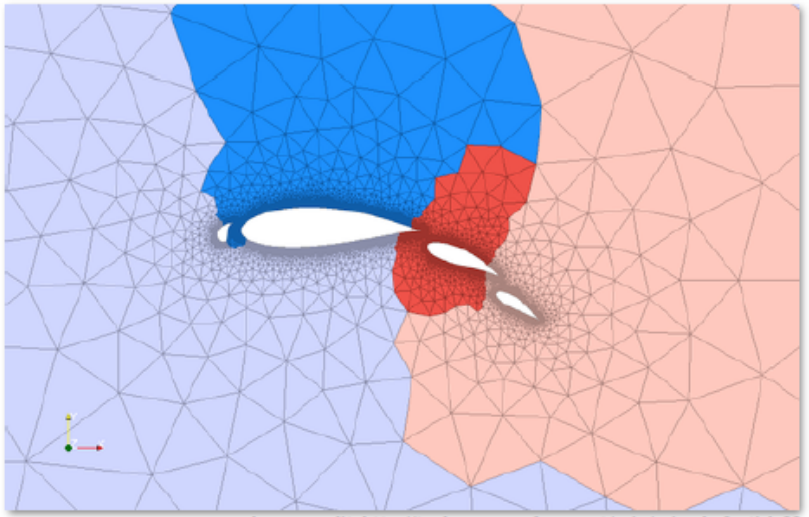
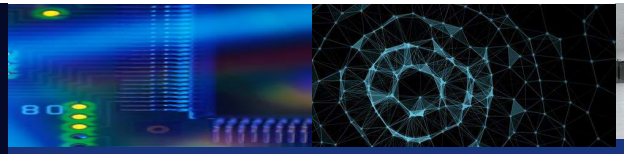


Image credit: http://typhon.sourceforge.net/spip/spip.php?article22

Adaptive mesh:

Mesh is changed as object moves or flow over object changes, but changes occur slowly (color indicates assignment of parts of mesh to processors)



Dynamic assignment

Program determines assignment dynamically at runtime to ensure a well distributed load. (The execution time of tasks, or the total number of tasks, is unpredictable.)

Sequential program (independent loop iterations)

```
int N = 1024;
int* x = new int[N];
bool* prime = new bool[N];

// initialize elements of x here

for (int i=0; i<N; i++)
{
    // unknown execution time
    is_prime[i] = test_primality(x[i]);
}
```

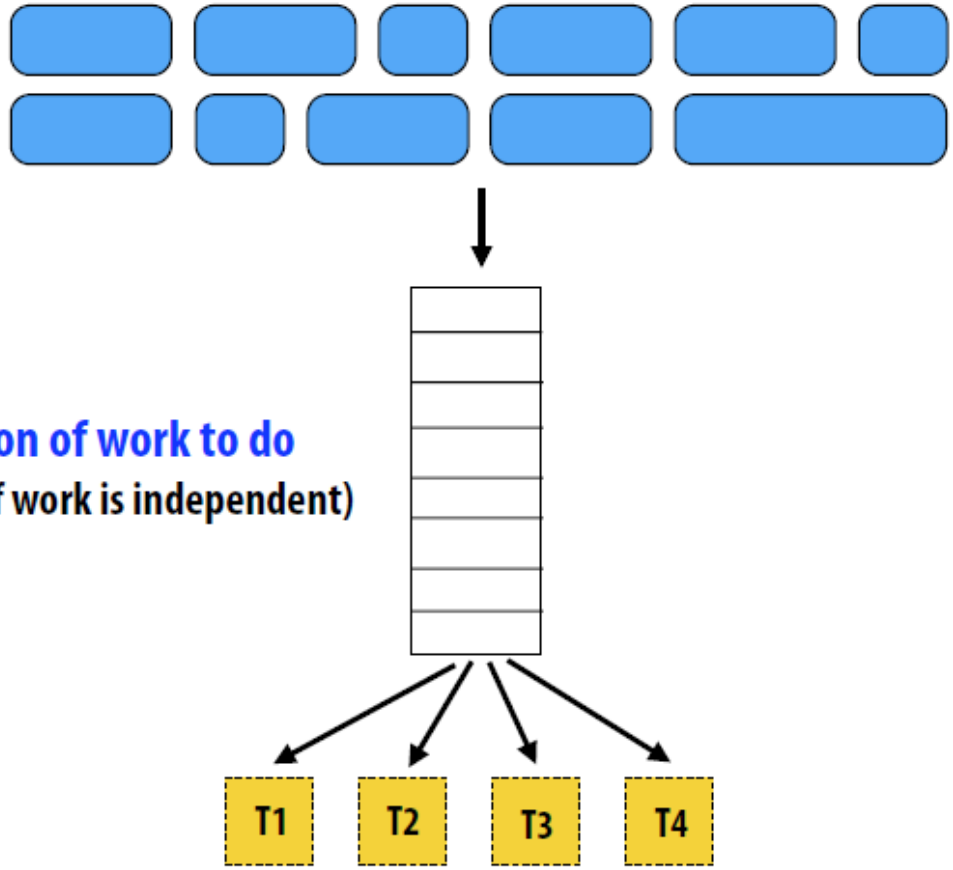
Parallel program (SPMD execution by multiple threads, shared address space model)

```
int N = 1024;
// assume allocations are only executed by 1 thread
int* x = new int[N];
bool* is_prime = new bool[N];

// initialize elements of x here

LOCK counter_lock;
int counter = 0;    // shared variable

while (1) {
  int i;
  lock(counter_lock);
  i = counter++;
  unlock(counter_lock);
  if (i >= N)
     break;
  is_prime[i] = test_primality(x[i]);
}
```

atomic_incr(counter);

Dynamic assignment using a work queue

Sub-problems
(a.k.a. "tasks", "work")



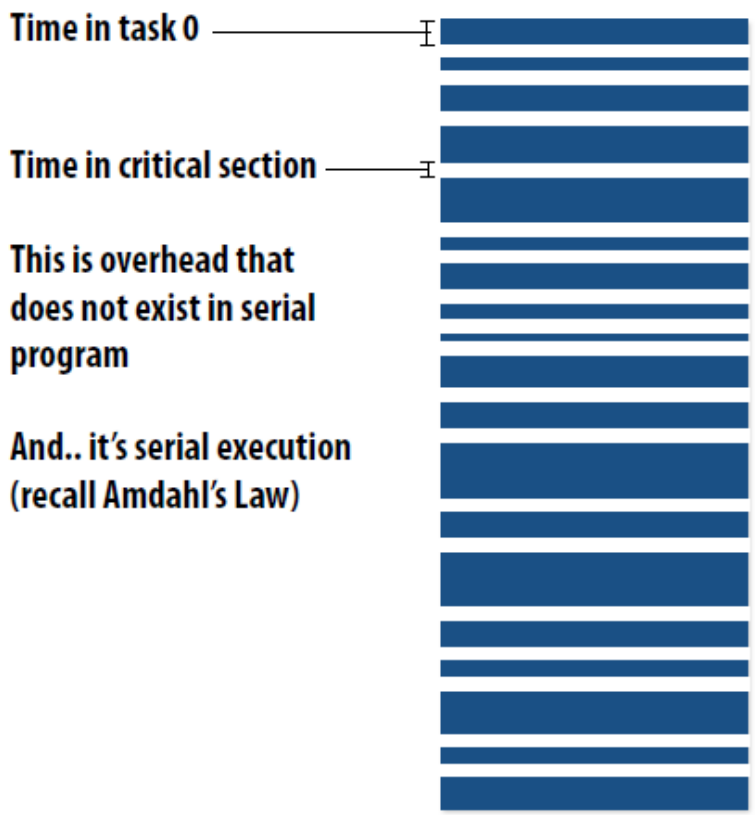
Shared work queue: a collection of work to do
(for now, let's assume each piece of work is independent)

Worker threads:
Pull data from shared work queue
Push new work to queue as it is created

What constitutes a piece of work?

What is a potential problem with this implementation?

```
const int N = 1024;
// assume allocations are only executed by 1 thread
float* x = new float[N];
bool* prime = new bool[N];

// initialize elements of x here

LOCK counter_lock;
int counter = 0;

while (1) {
  int i;
  lock(counter_lock);
  i = counter++;
  unlock(counter_lock);
  if (i >= N)
     break;
  is_prime[i] = test_primality(x[i]);
}
```



Fine granularity partitioning: 1 "task" = 1 element

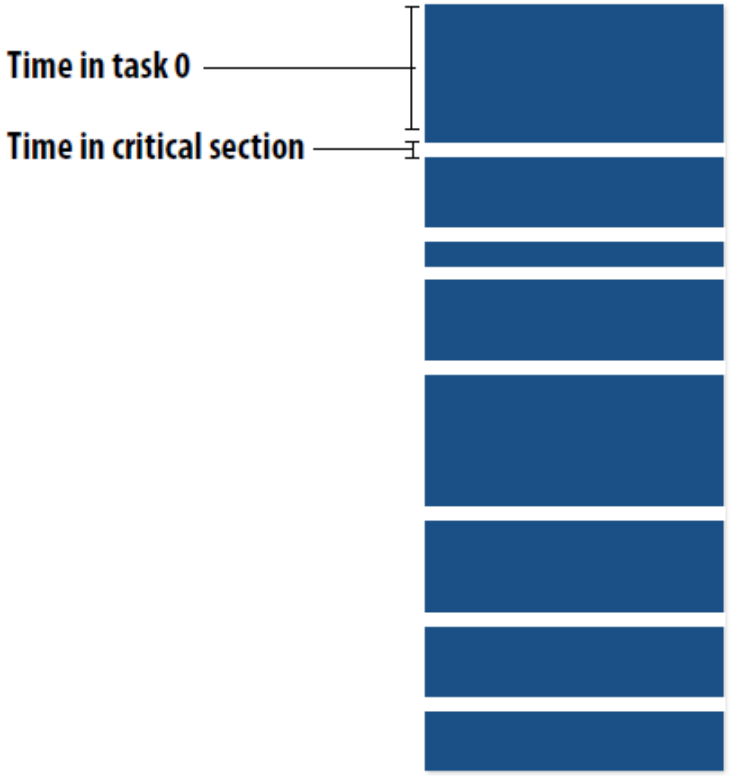
Likely good workload balance (many small tasks)

Potential for high synchronization cost (serialization at critical section)

So... IS IT a problem?

Increasing task granularity

```
const int N = 1024;
const int GRANULARITY = 10;
// assume allocations are only executed by 1 thread

float* x = new float[N];
bool* prime = new bool[N];

// initialize elements of x here

LOCK counter_lock;
int counter = 0;

while (1) {
  int i;
  lock(counter_lock);
  i = counter;
  counter += GRANULARITY;
  unlock(counter_lock);
  if (i >= N)
     break;
  int end = min(i + GRANULARITY, N);
  for (int j=i; j<end; j++)
     is_prime[j] = test_primality(x[j]);
}
```



Coarse granularity partitioning: 1 "task" = 10 elements

Decreased synchronization cost

(Critical section entered 10 times less)

Choosing task size

- **Useful to have many more tasks* than processors**

(many small tasks enables good workload balance via dynamic assignment)

- Motivates small granularity tasks

- **But want as few tasks as possible to minimize overhead of managing the assignment**

- Motivates large granularity tasks

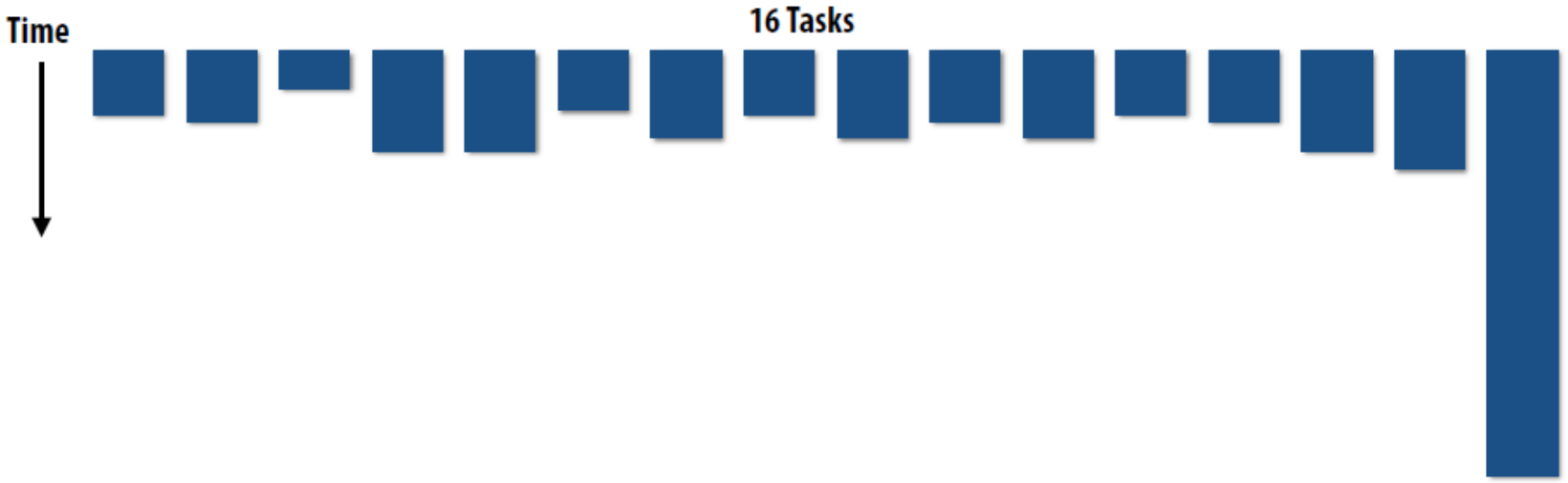
- **Ideal granularity depends on many factors**

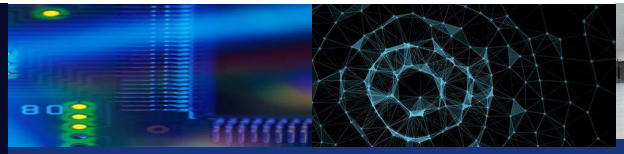
(Common theme in this course: must know your workload, and your machine)

Smarter task scheduling

Consider dynamic scheduling via a shared work queue

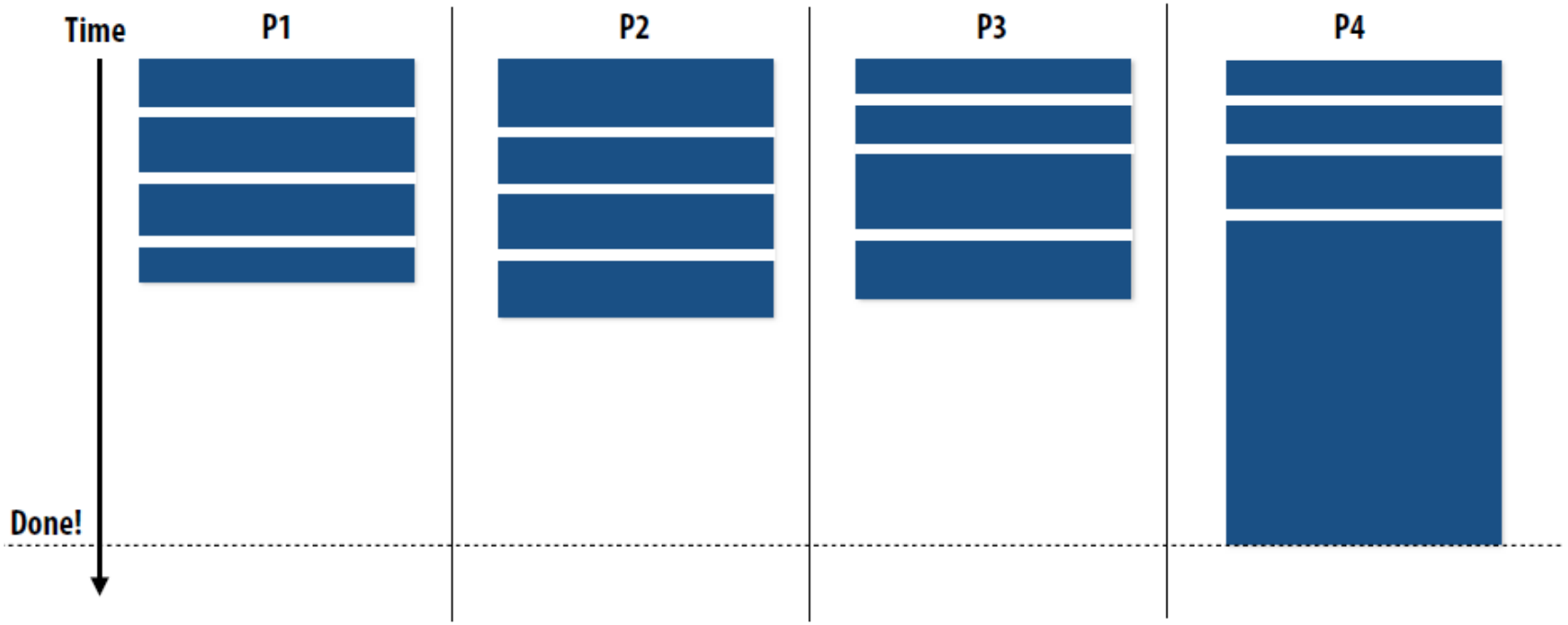
What happens if the system assigns these tasks to four workers in left-to-right order?





Smarter task scheduling

What happens if scheduler runs the long task last? Potential for load imbalance!



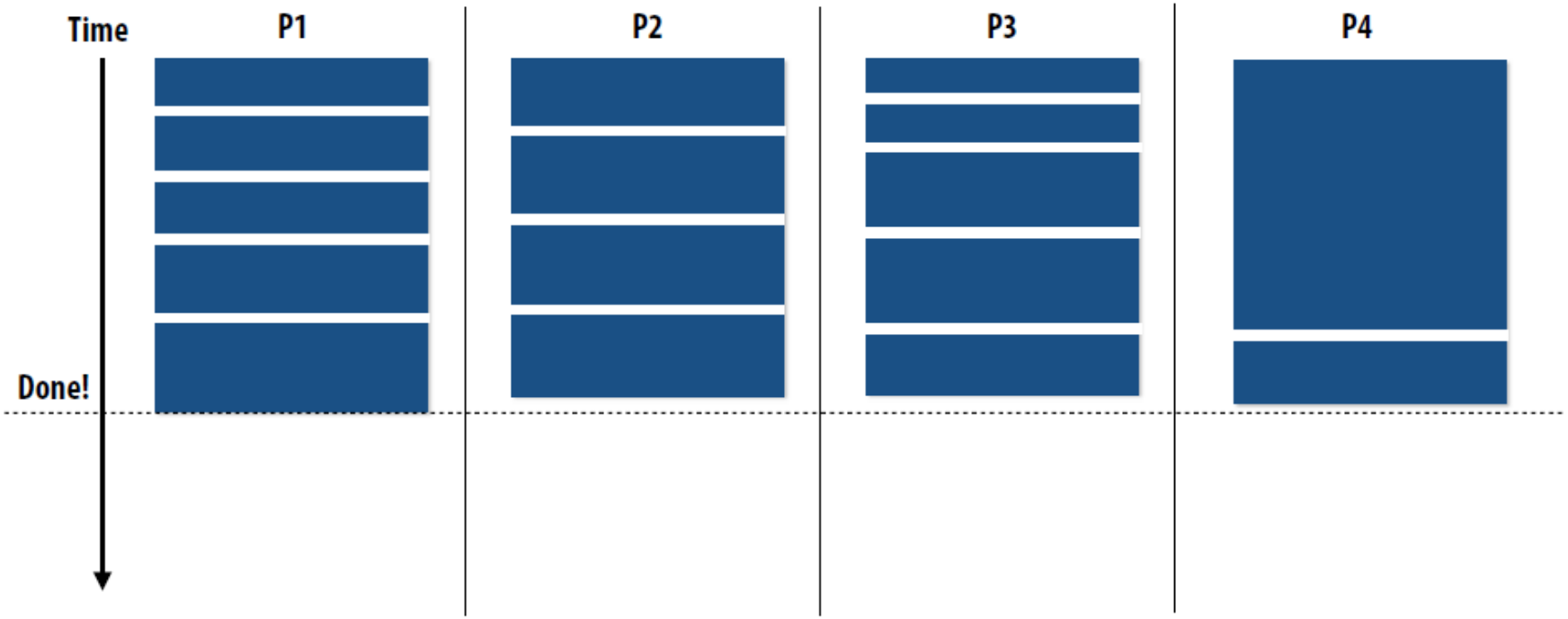
One possible solution to imbalance problem:

Divide work into a larger number of smaller tasks

- Hopefully "long pole" gets shorter relative to overall execution time
- May increase synchronization overhead
- May not be possible (perhaps long task is fundamentally sequential)

Smarter task scheduling

Schedule long task first to reduce "slop" at end of computation



Another solution: smarter scheduling

Schedule long tasks first

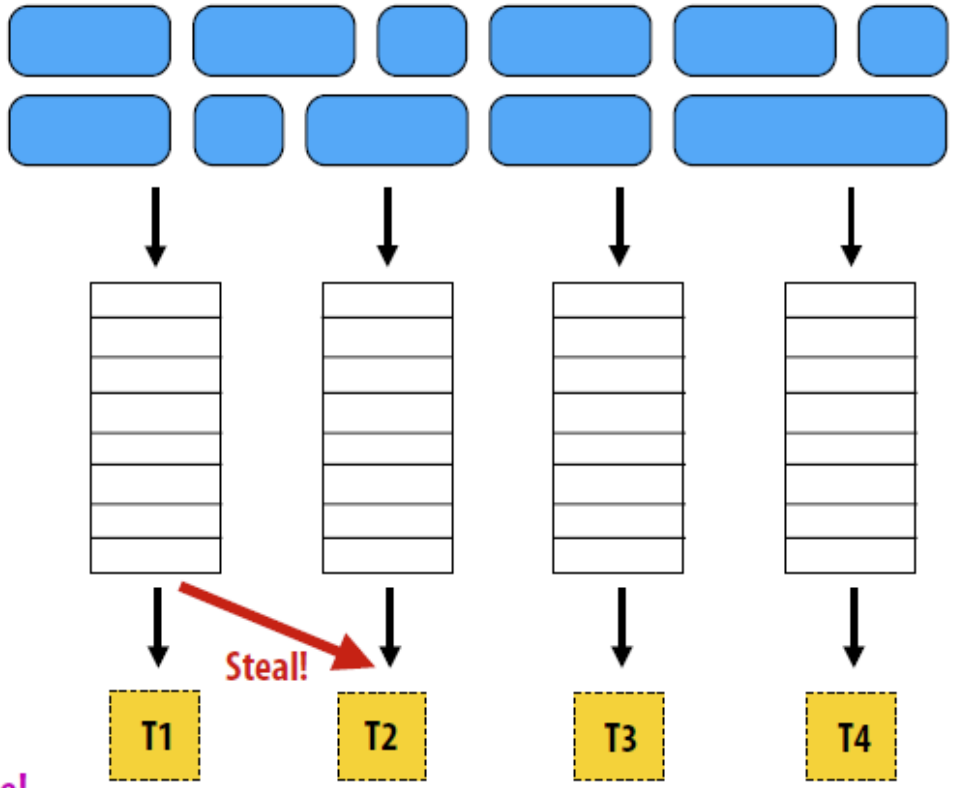
- **Thread performing long task performs fewer overall tasks, but approximately the same amount of work as the other threads.**
- **Requires some knowledge of workload (some predictability of cost)**

Decreasing synchronization overhead using a distributed set of queues

(avoid need for all workers to synchronize on single work queue)

Subproblems
(a.k.a. "tasks", "work to do")

Set of work queues
(In general, one per worker thread)



Worker threads:
Pull data from OWN work queue
Push new work to OWN work queue

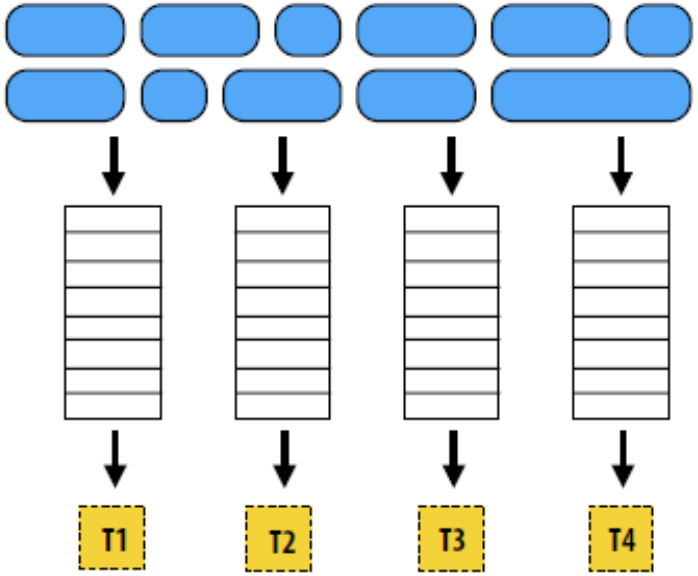
And when local work queue is empty?
STEAL work from another work queue!

Distributed work queues

- Costly synchronization/communication occurs during stealing
  - But not every time a thread takes on new work
  - Stealing occurs only when necessary to ensure good load balance
- Leads to increased locality
  - Common case: threads work on tasks they create (producer-consumer locality)
- Implementation challenges

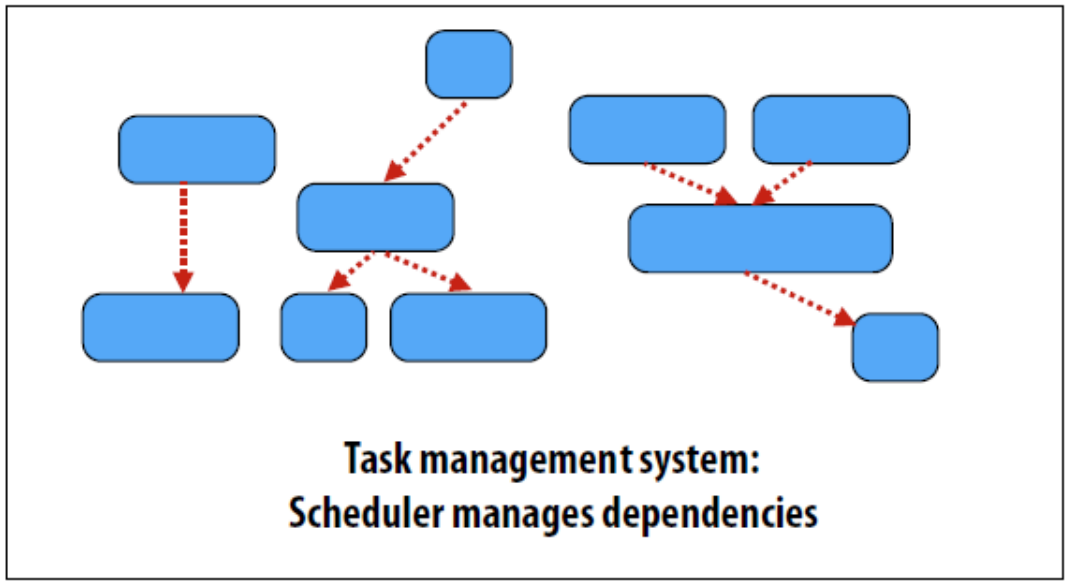
- Who to steal from?
- How much to steal?
- How to detect program termination?
- Ensuring local queue access is fast

(while preserving mutual exclusion)

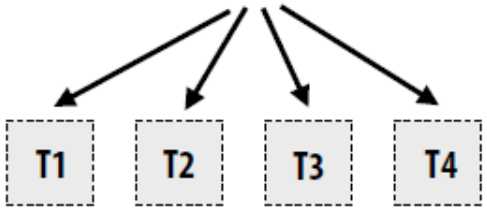


Work in task queues need not be independent

= application-specified dependency



A task is not removed from queue and assigned to worker thread until all task dependencies are satisfied



Workers can submit new tasks (with optional explicit dependencies) to task system

```
foo_handle = enqueue_task(foo);              // enqueue task foo (independent of all prior tasks)
bar_handle = enqueue_task(bar, foo_handle);  // enqueue task bar, cannot run until foo is complete
```

Summary

- Challenge: achieving good workload balance
  - Want all processors working all the time (otherwise, resources are idle!)
  - But want low-cost solution for achieving this balance
  - Minimize computational overhead (e.g., scheduling/assignment logic)
  - Minimize synchronization costs
- Static assignment vs. dynamic assignment
  - Really, it is not an either/or decision, there's a continuum （共存）of choices
  - Use up-front knowledge about workload as much as possible to reduce load imbalance and task management/synchronization costs (in the limit, if the system knows everything, use fully static assignment)
- Issues discussed today span decomposition, assignment, and orchestration

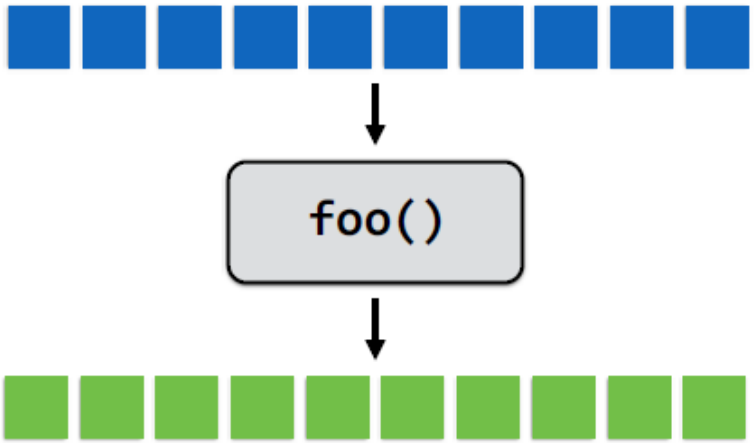
Scheduling fork-join parallelism

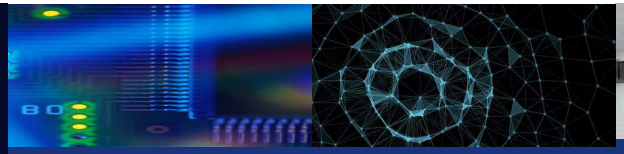
Common parallel programming patterns

Data parallelism:

Perform same sequence of operations on many data elements

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

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

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

// using higher-order function 'map'
map(foo, A, B);

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





Common parallel programming patterns

Explicit management of parallelism with threads:

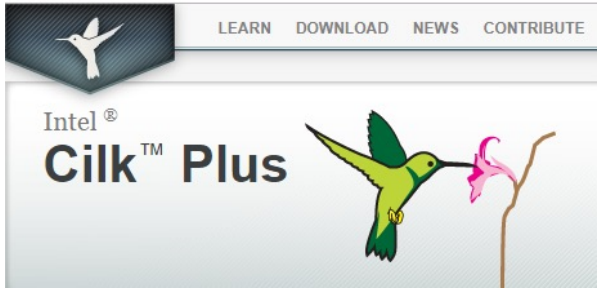
Create one thread per execution unit (or per amount of desired concurrency)

- Example below: C code with pthreads

```
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, myFunctionFoo, &args);
}

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

Fork-join pattern

- Natural way to express independent work in divide-and-conquer algorithms
- This lecture's code examples will be in Cilk Plus
  - C++ language extension
  - Originally developed at MIT, acquired by Intel
  - But Intel is deprecating it. Best to stick with MIT version



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.

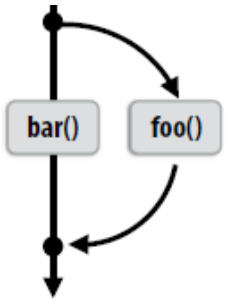
cilk_sync; "join"

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 a cilk_spawn (implication: when a Cilk function returns, all work associated with that function is complete)

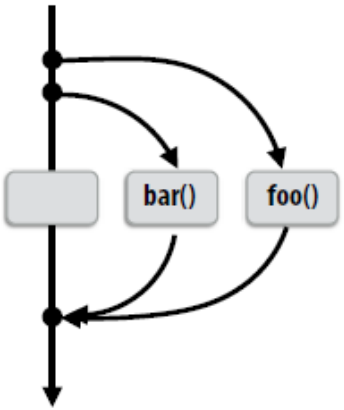
Basic Cilk Plus examples

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

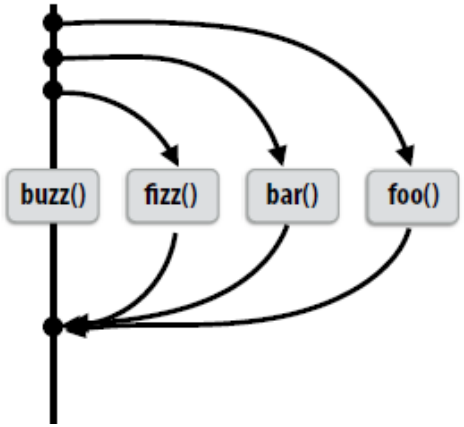


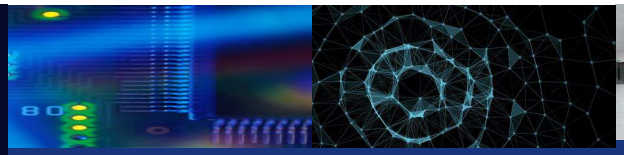

```
// foo() and bar() may run in parallel
cilk_spawn foo();
cilk_spawn bar();
cilk_sync;
```

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




```
// foo, bar, fizz, buzz, may run in parallel
cilk_spawn foo();
cilk_spawn bar();
cilk_spawn fizz();
buzz();
cilk_sync;
```





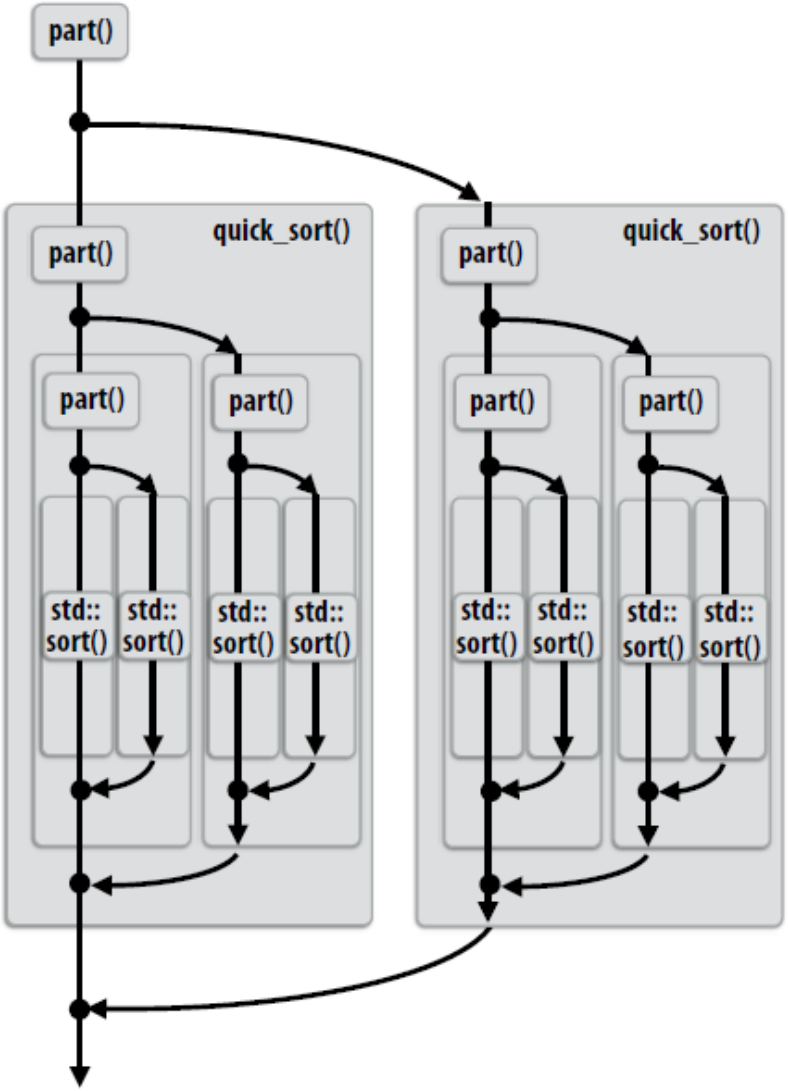
Abstraction vs. implementation

- 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

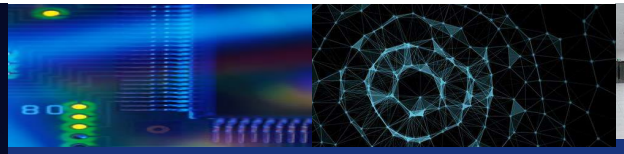
```
void quick_sort(int* begin, int* end) {
  if (begin >= end - PARALLEL_CUTOFF)
    std::sort(begin, end);
  else {
    int* middle = partition(begin, end);
    cilk_spawn quick_sort(begin, middle);
    quick_sort(middle+1, last);
  }
}
```

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 cilk_spawn**
- **Recall parallel programming rules of thumb**
  - **Want at least as much work as parallel execution capability (e.g., program should probably spawn at least as much work as there are cores)**
  - **Want more independent work than execution capability to allow for good workload balance of all the work onto the cores**
  - **"parallel slack" = ratio of independent work to machine's parallel execution capability (in practice: ~8 is a good ratio)**
  - **But 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

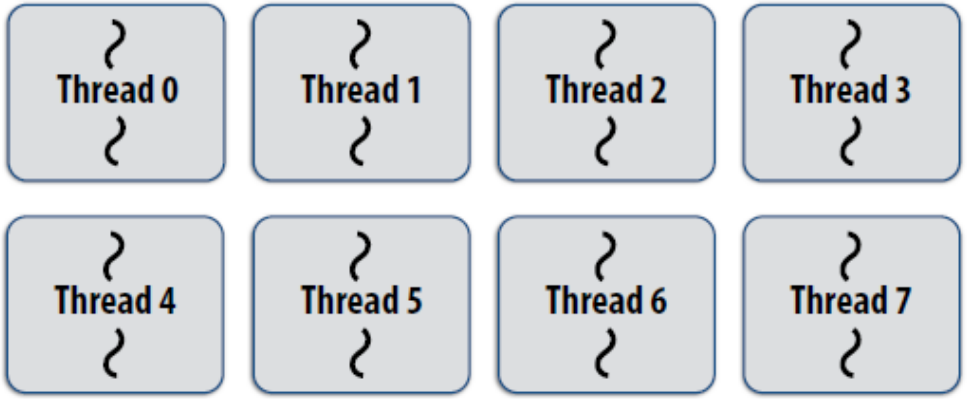
- **Consider very simple scheduler:**
  - **Launch pthread for each `cilk_spawn` using `pthread_create`**
  - **Translate `cilk_sync` into appropriate `pthread_join` calls**
- **Potential performance problems?**
  - **Heavyweight spawn operation**
  - **Many more concurrently running threads than cores**
  - **Context switching overhead**
  - **Larger working set than necessary, less cache locality**

Pool of worker threads

The 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



Example: Eight thread worker pool for a quad-core laptop with Hyper-Threading

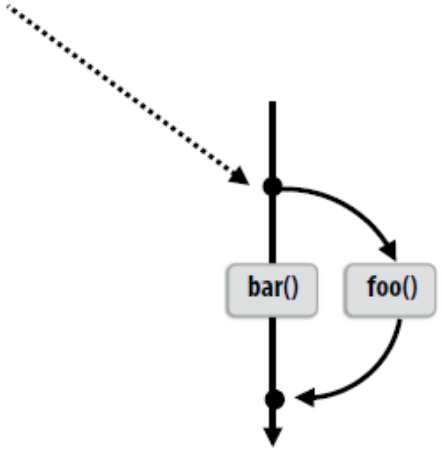
```
while (work_exists()) {
    work = get_new_work();
    work.run();
}
```

* It's perfectly fine to think about it this way, but in reality, runtimes tend to be lazy and initialize 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 execution of the following code

Specifically, consider execution from the point foo() is spawned

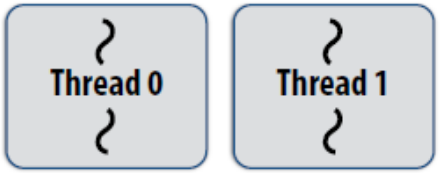
```
cilk_spawn foo();
bar();
cilk_sync;
```



spawned child

continuation (rest of calling function)

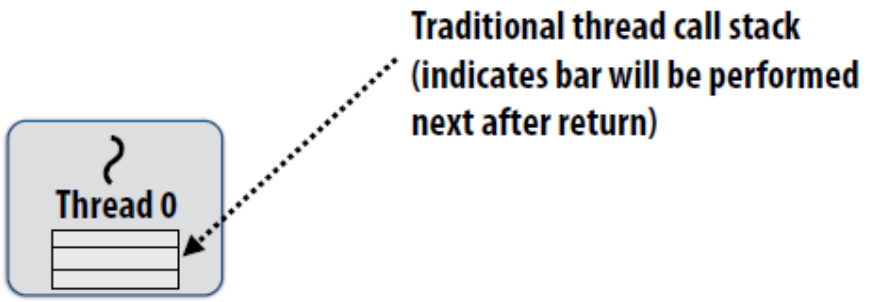
What threads should foo() and bar() be executed by?



First, consider a serial implementation

Run child first… via a regular function call

- **Thread runs foo(), then returns from foo(), then runs bar()**
- **Continuation is implicit in the thread's stack**



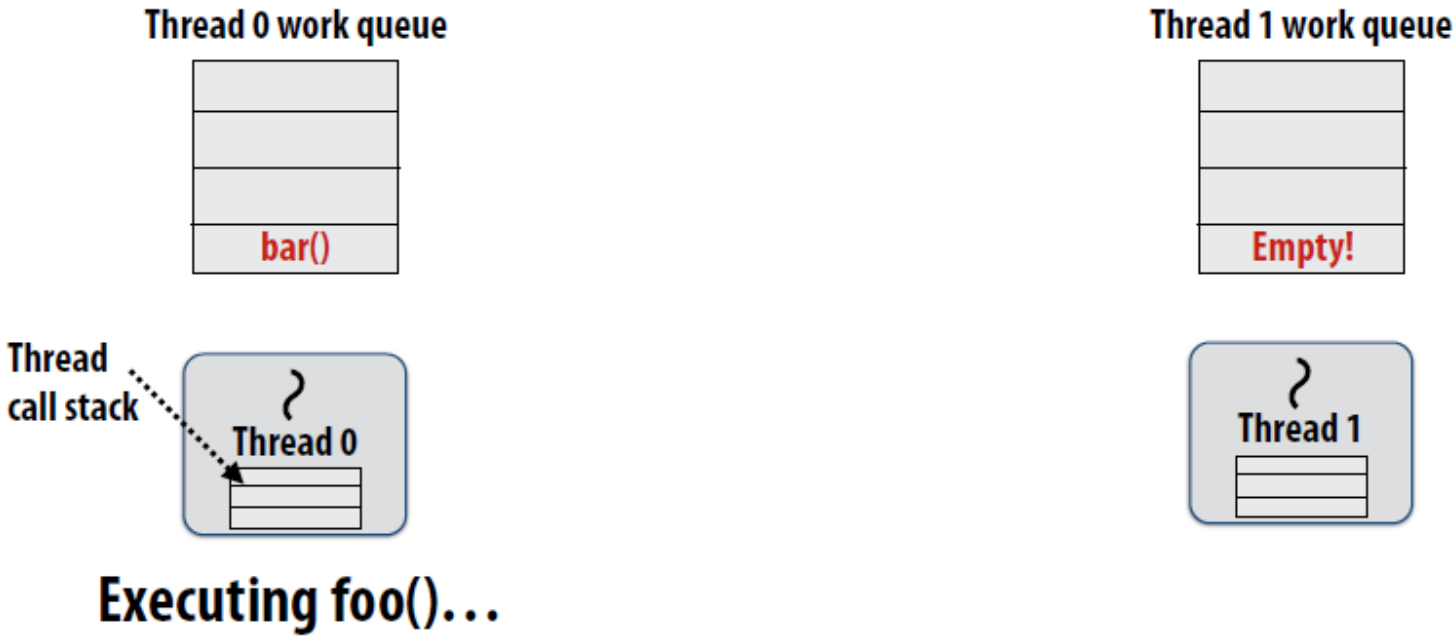
Executing foo()…

What if, while executing foo(), thread 1 goes idle…

Inefficient: thread 1 could be performing bar() at this time!

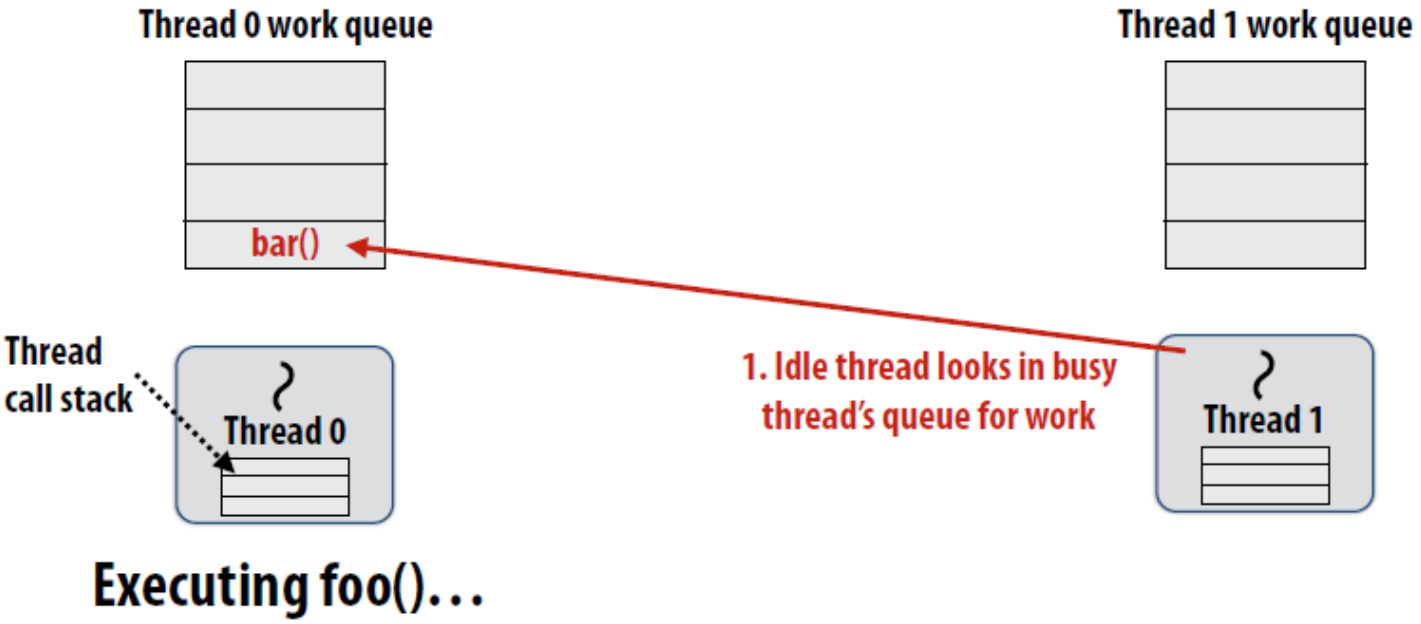
Per-thread work queues store "work to do"

Upon reaching `cilk_spawn foo()`, thread places continuation in its work queue, and begins executing foo().



Idle threads "steal" work from busy threads

If thread 1 goes idle (a.k.a. there is no work in its own queue), then it looks in thread 0's queue for work to do.



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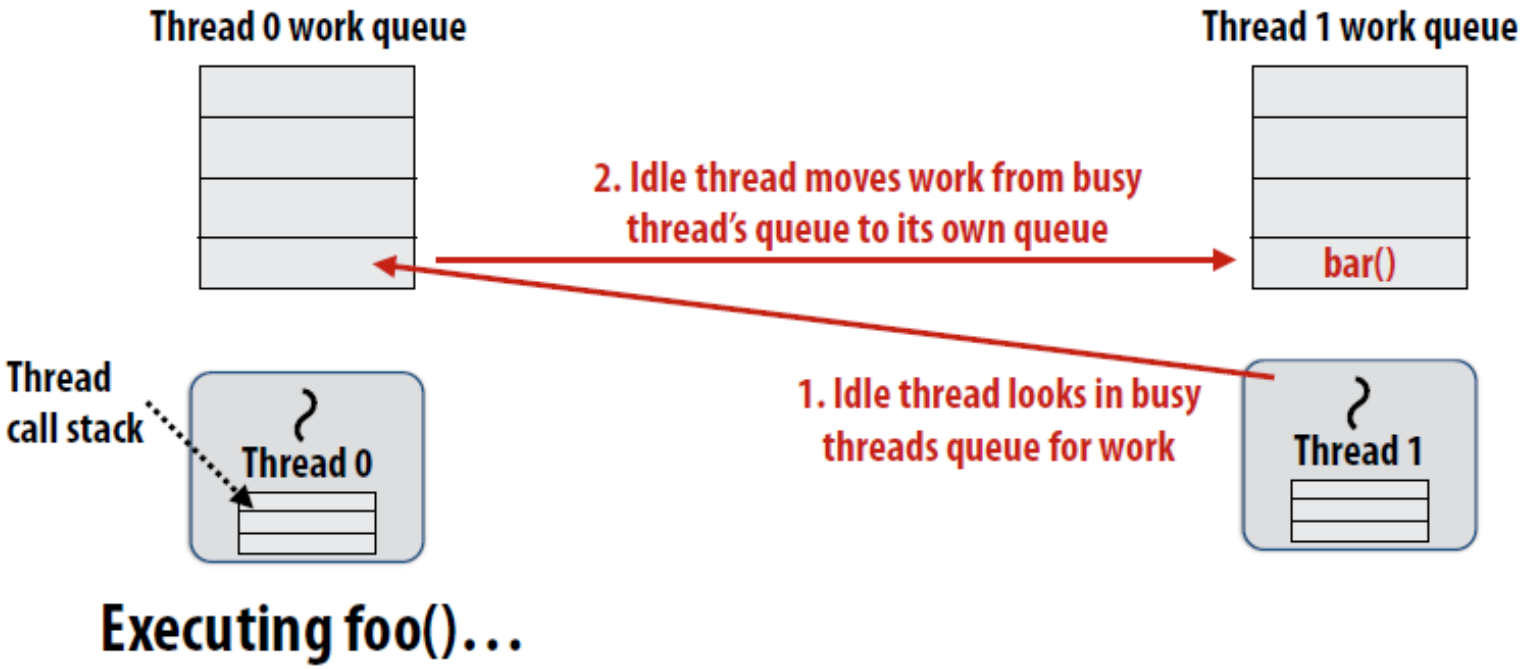

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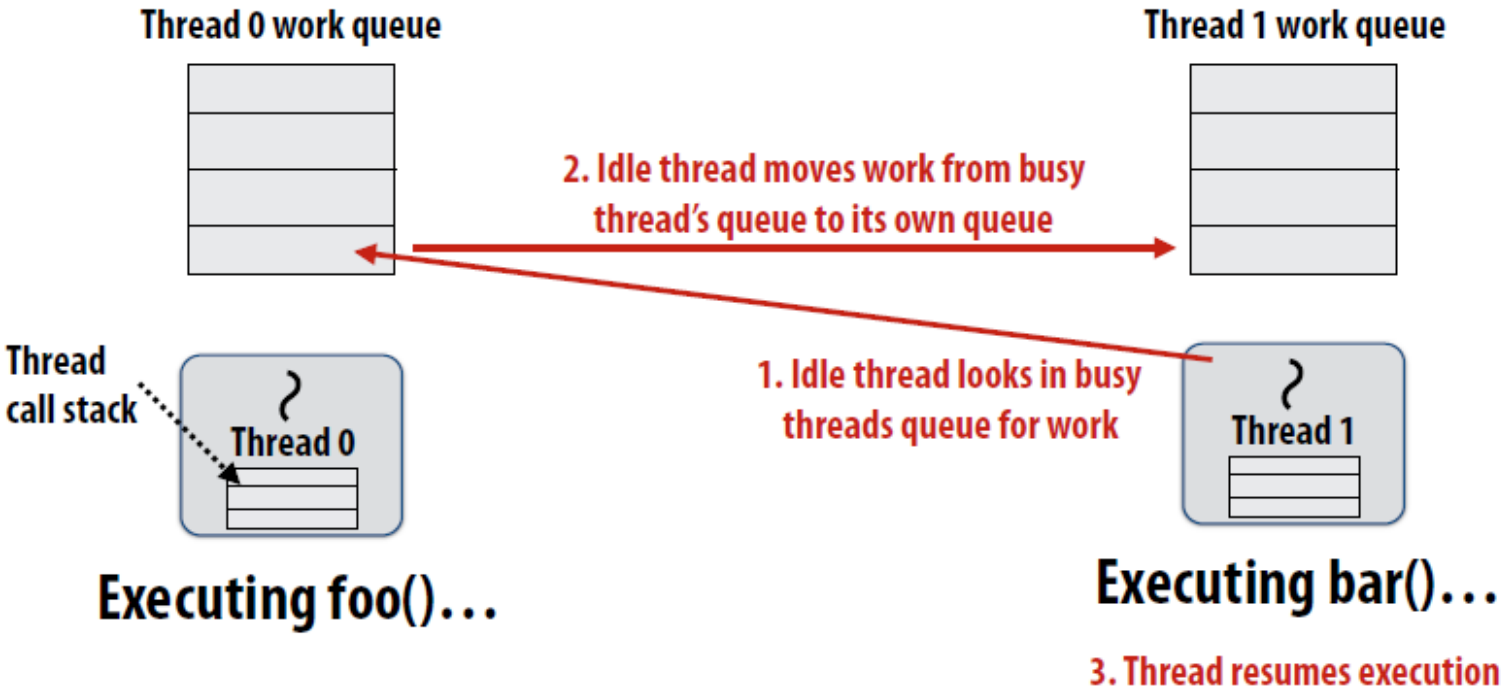
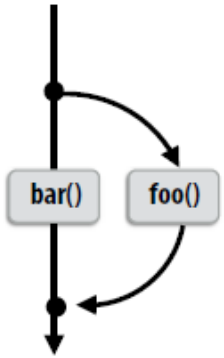


At spawn, should thread run child or

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

spawned child

continuation (rest of calling function)



Run continuation first: record child for later execution

- Child is made available for stealing by other threads ("child stealing")

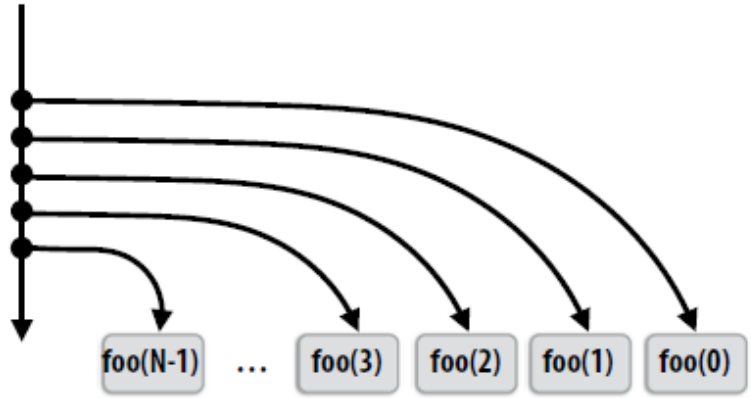
Run child first: record continuation for later execution

- Continuation is made available for stealing by other threads ("continuation stealing")

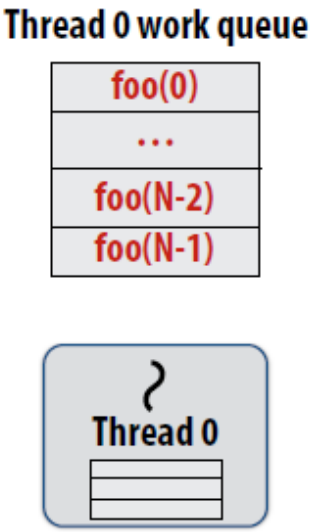
Which implementation do we choose?

Consider thread executing the following code

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



- **Run continuation first ("child stealing")**
  - 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



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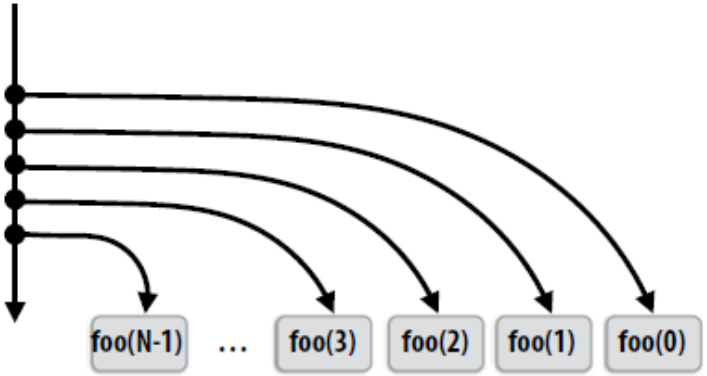
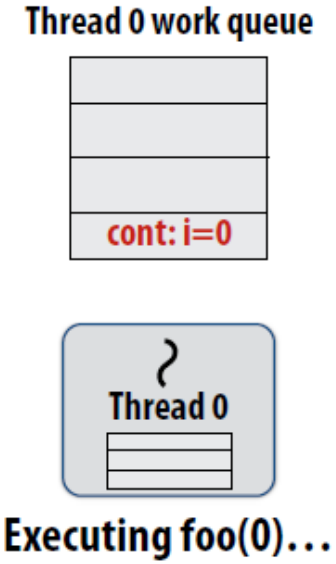
```
for (int i=0; i<N; i++) {
  cilk_spawn foo(i);
}
cilk_sync;
```

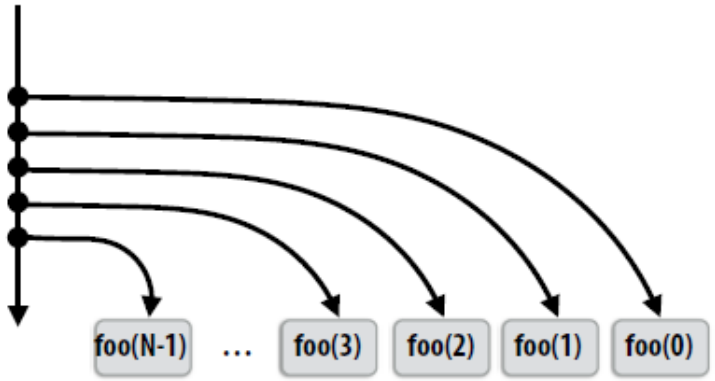


- **Run child first ("continuation stealing")**
  - Caller thread only creates one item to steal (continuation that represents all remaining iterations)
  - If no stealing occurs, thread continually pops continuation from work queue, enqueues new continuation (with updated value of `i`)
  - Order of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

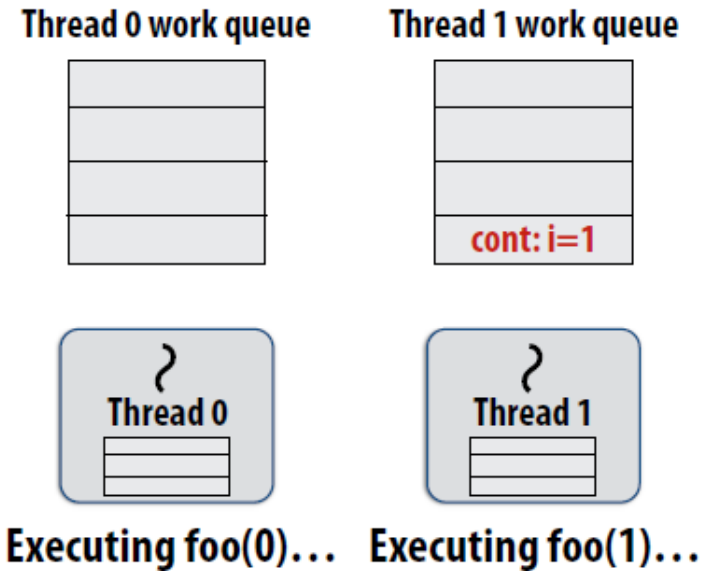


Consider thread executing the following code

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



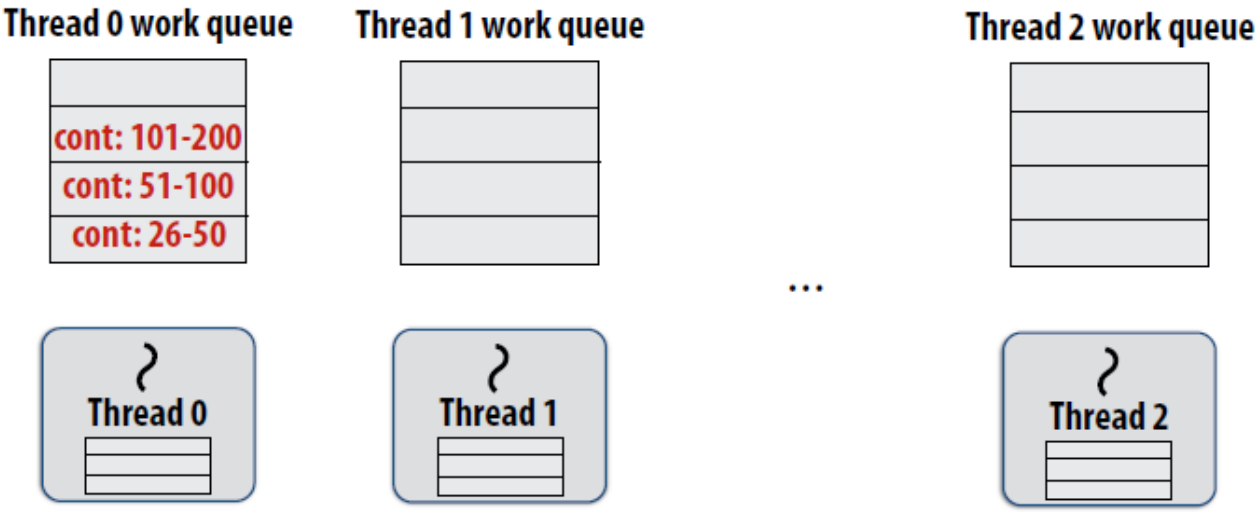
- **Run child first ("continuation stealing")**
  - If continuation is stolen, stealing thread spawns and executes next iteration
  - Enqueues continuation with `i` advanced by 1
  - Can prove that work queue storage for system with T threads is no more than T times that of stack storage for single threaded execution



Scheduling quicksort: assume 200 elements

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

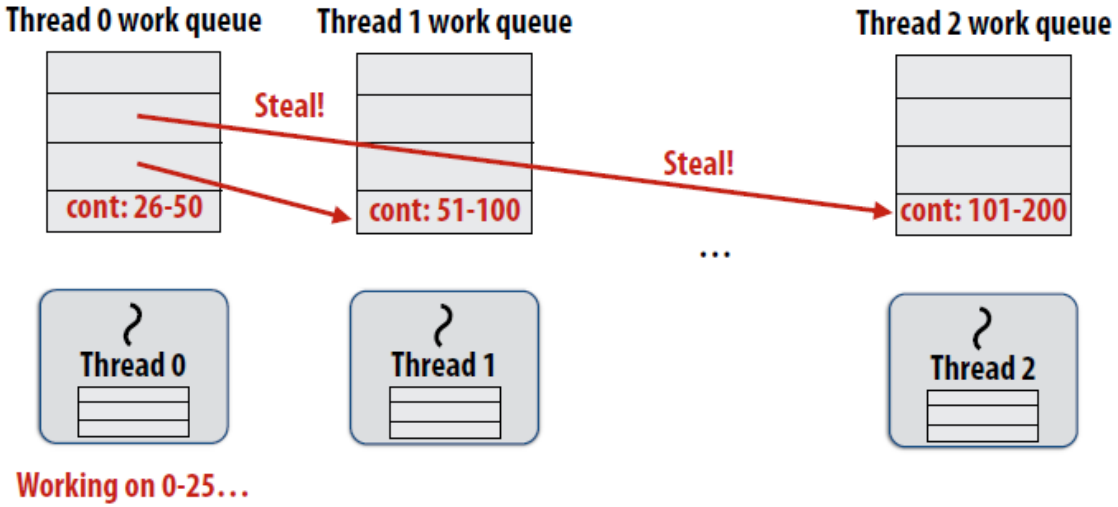
What work in the queue should other threads steal?



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**



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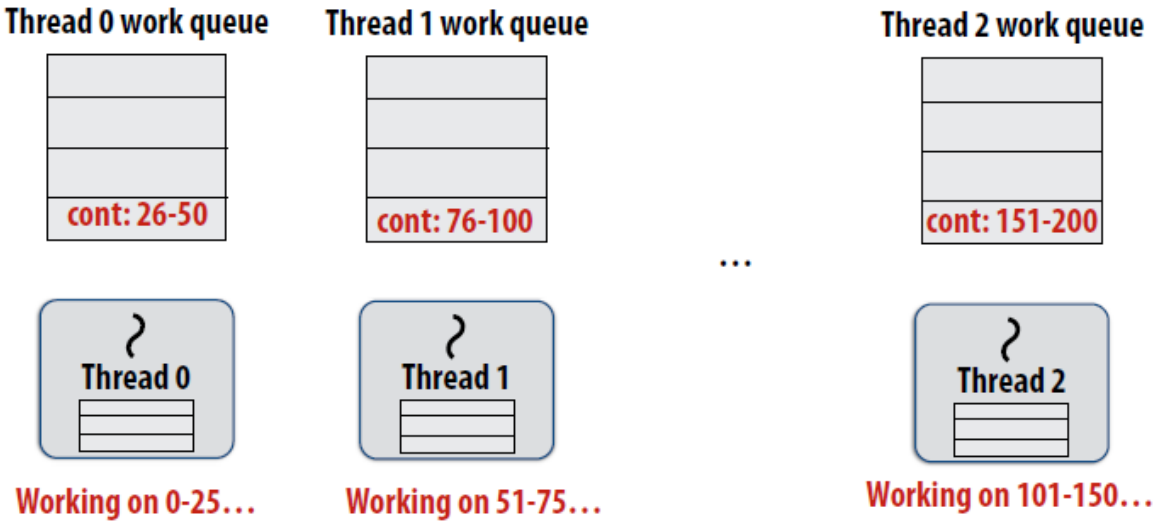
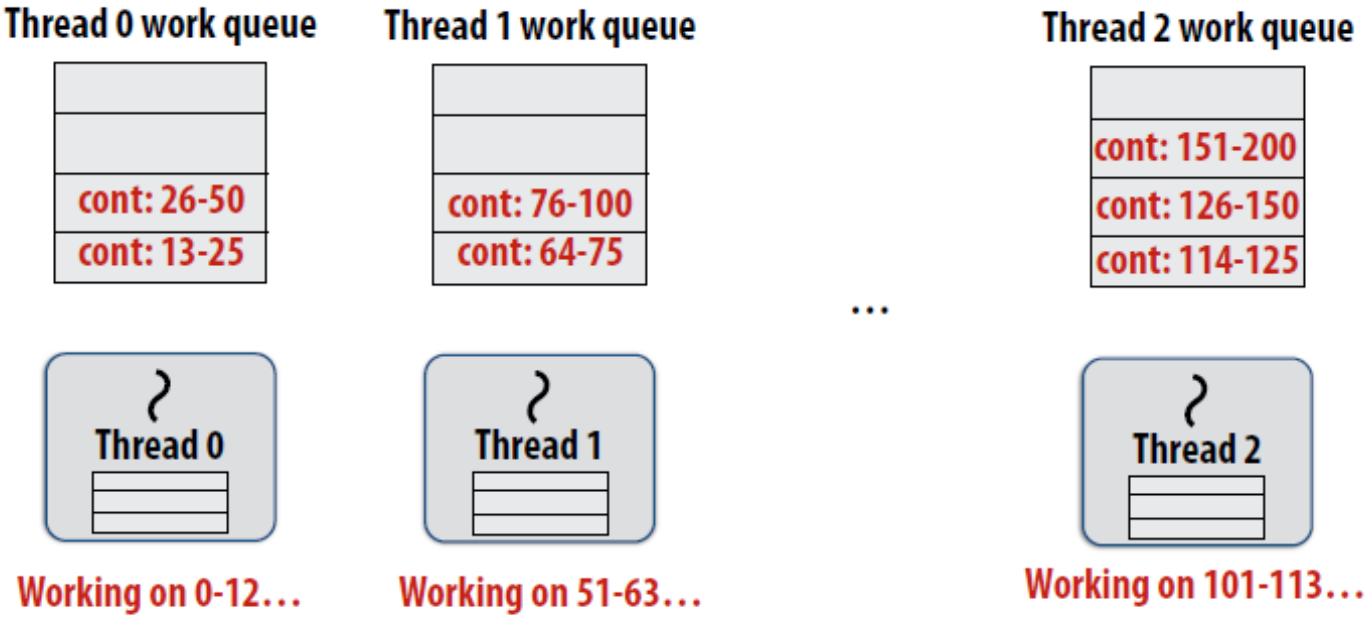


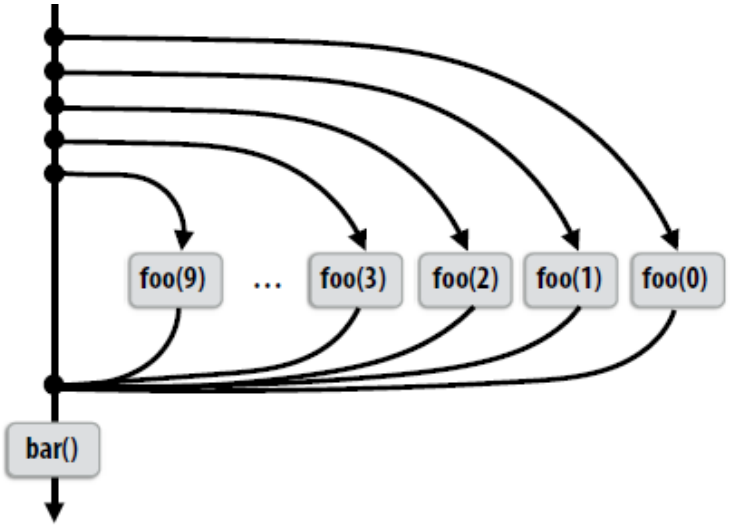
Implementing work stealing: random choice of victim

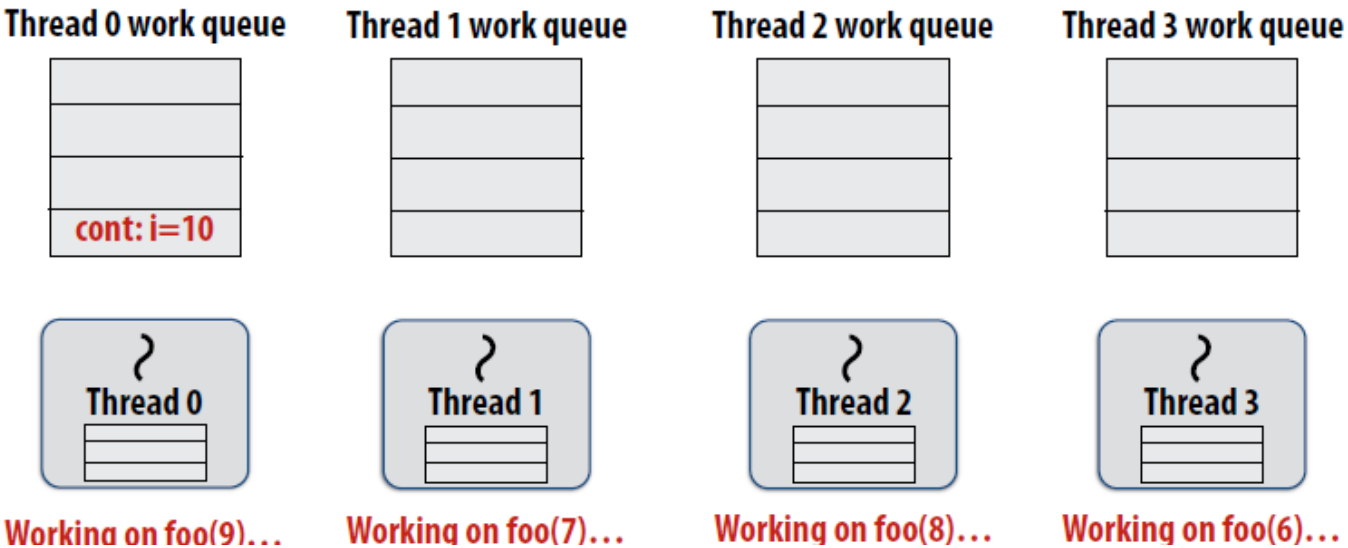
- Idle threads randomly choose a thread to attempt to steal from
- Stealing from top of dequeue…
  - Reduces contention with local thread: local thread is not accessing same part of dequeue that stealing threads do!
  - Steals work at beginning of call tree: this is a "larger" piece of work, so the cost of performing a steal is amortized (分摊) over longer future computation
  - Maximizes locality: (in conjunction with run-child-first policy) local thread works on local part of call tree



Implementing sync

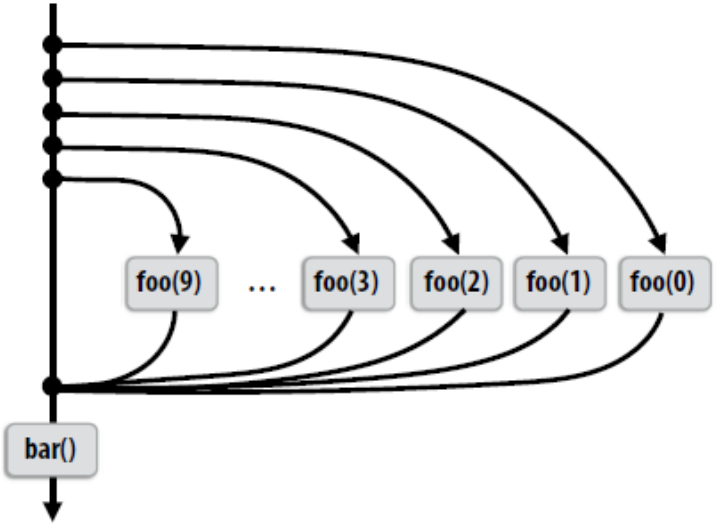
```
for (int i=0; i<10; i++) {
  cilk_spawn foo(i);
}
cilk_sync;
bar();
```

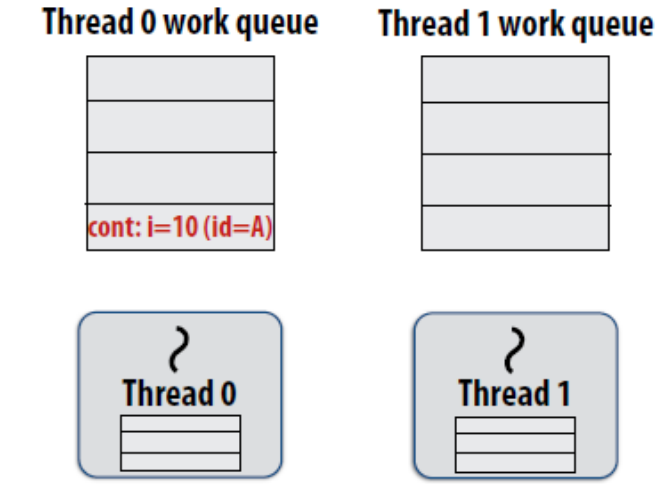




Implementing sync: no stealing

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





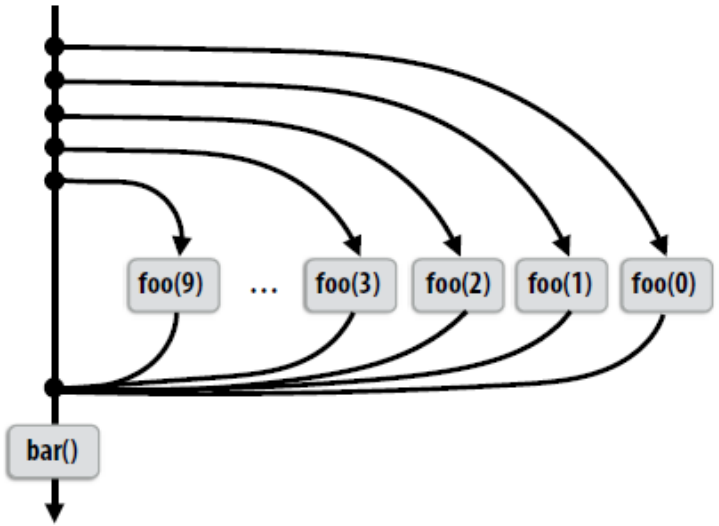
If no work has been stolen by other threads, then there's nothing to do at the sync point.

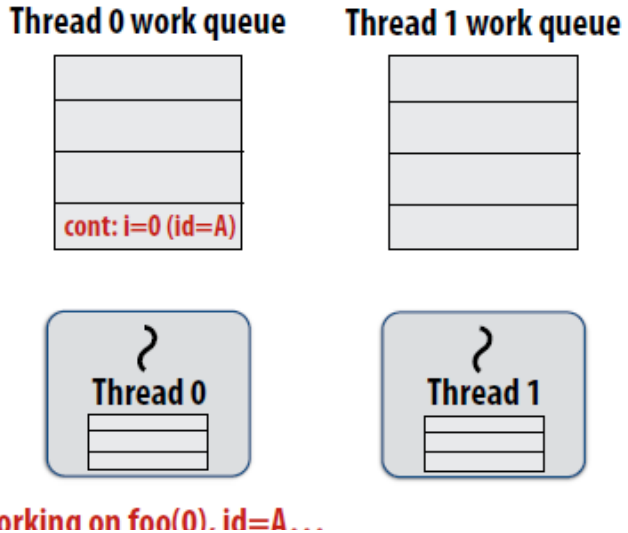
`cilk_sync` is a no-op.

Same control flow as serial execution

Implementing sync: stalling join

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





Example 1: "stalling" join policy

Thread that initiates the fork must perform the sync.

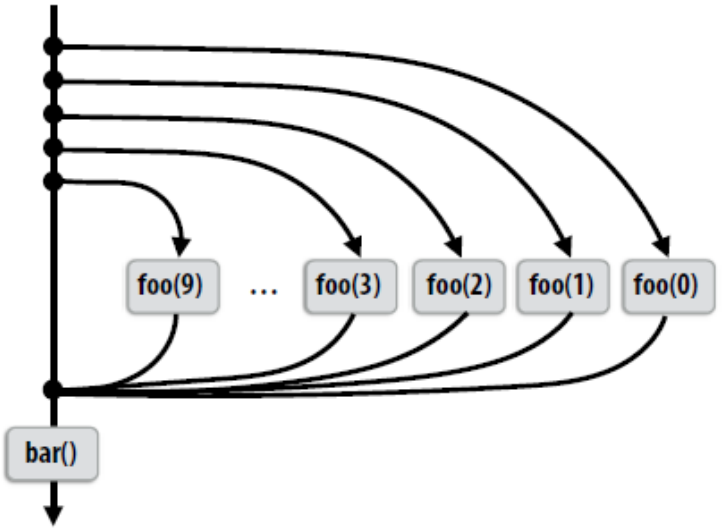
Therefore it waits for all spawned work to be complete.
In this case, thread 0 is the thread initiating the fork

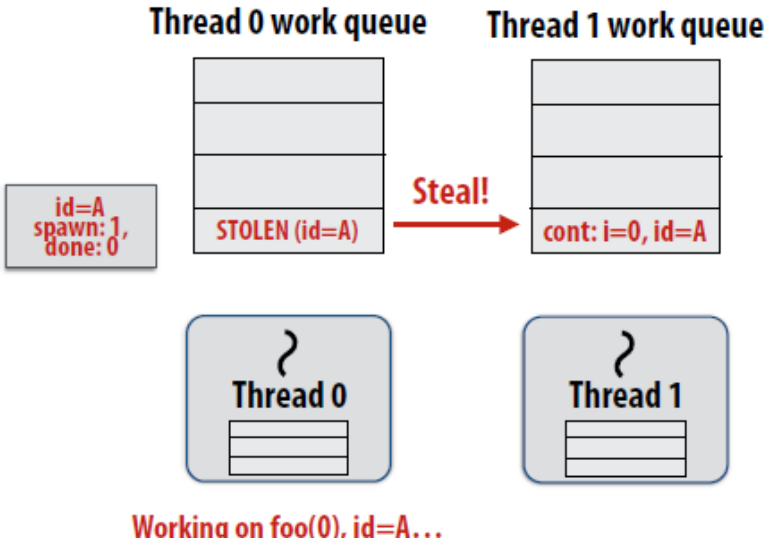
Implementing sync: stalling join

block (id: A)

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

Sync for all calls spawned within block A





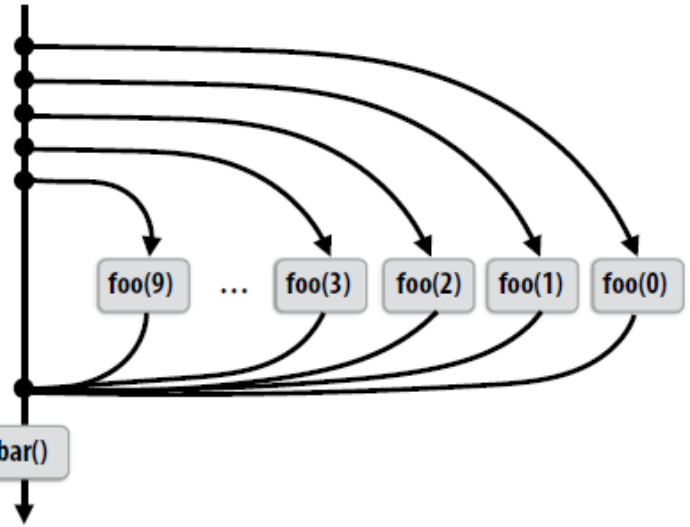
Idle thread 1 steals from busy thread 0
Note: descriptor for block A created

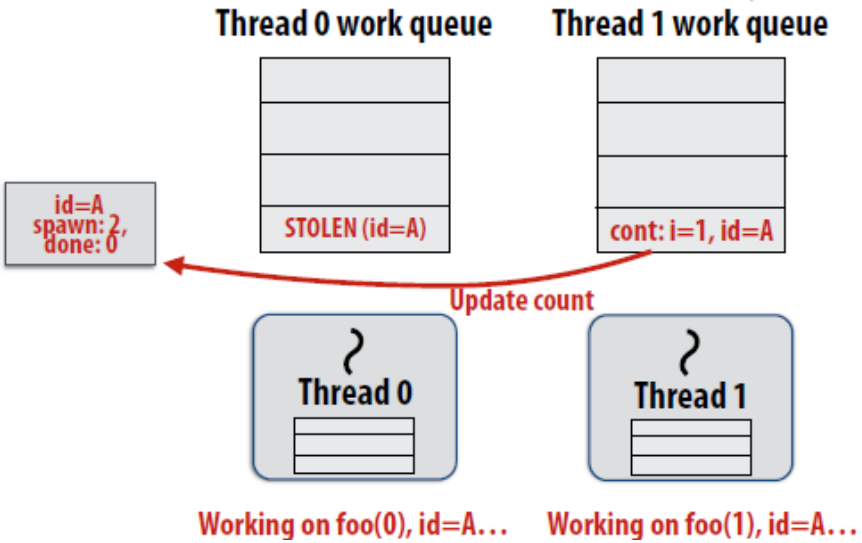
The descriptor tracks the number of outstanding spawns for the block, and the number of those spawns that have completed.

Here, the 1 spawn corresponds to foo(0) being run by thread 0.

Implementing sync: stalling join

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



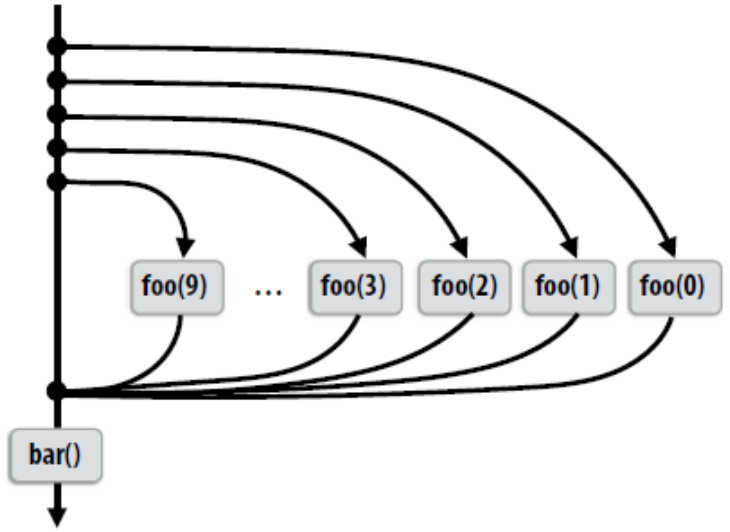


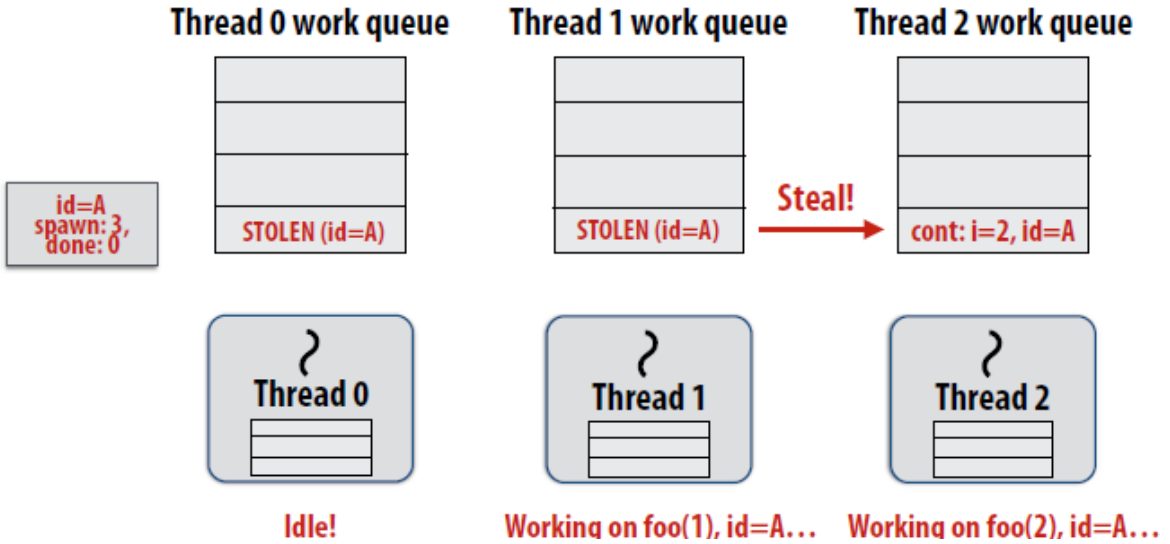
Thread 1 is now running foo(1)

Note: spawn count is now 2

Implementing sync: stalling join

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



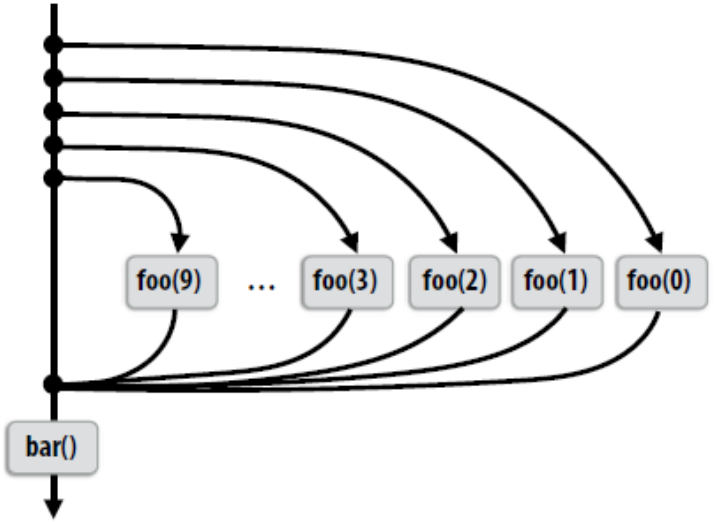


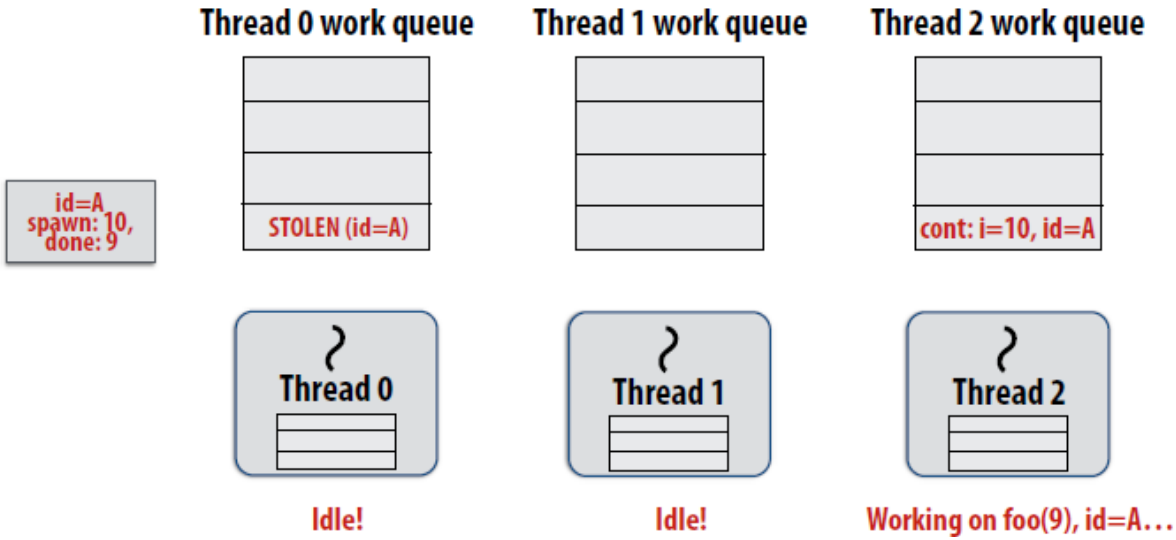
Thread 0 completes foo(0)
(updates spawn descriptor)

Thread 2 now running foo(2)

Implementing sync: stalling join

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



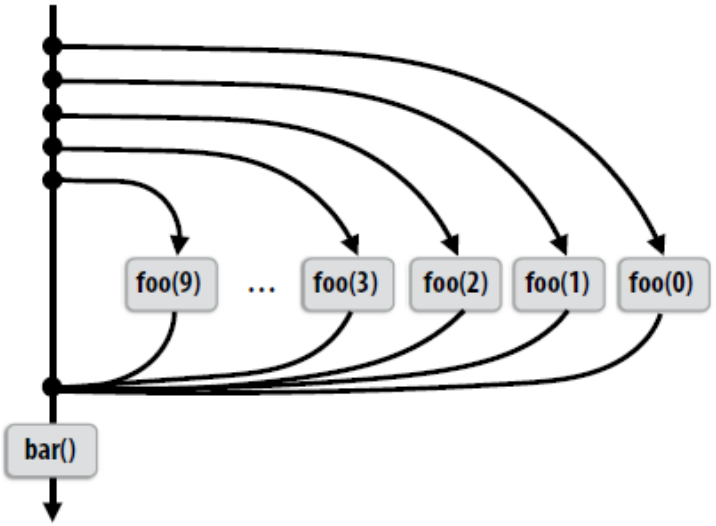


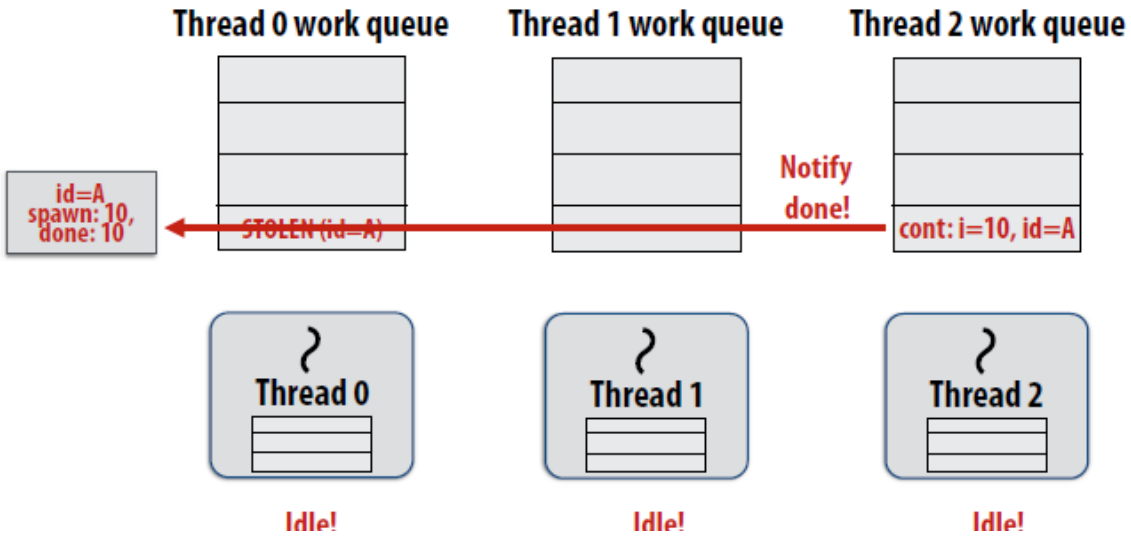
Computation nearing end...

Only foo(9) remains to be completed.

Implementing sync: stalling join

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

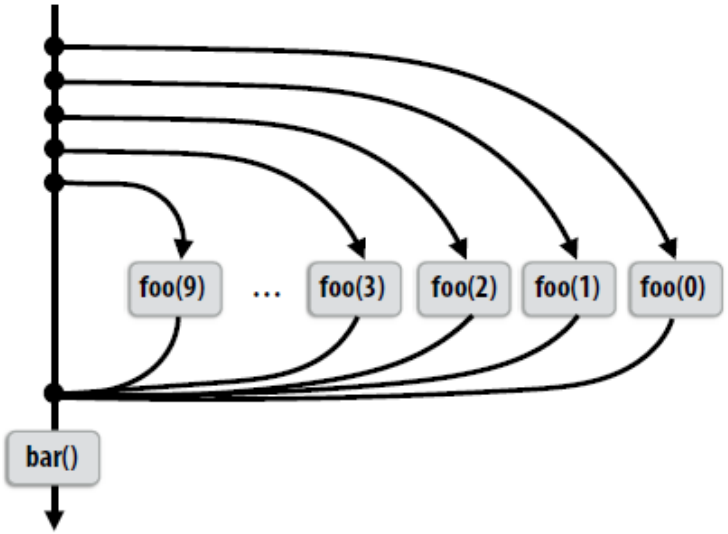


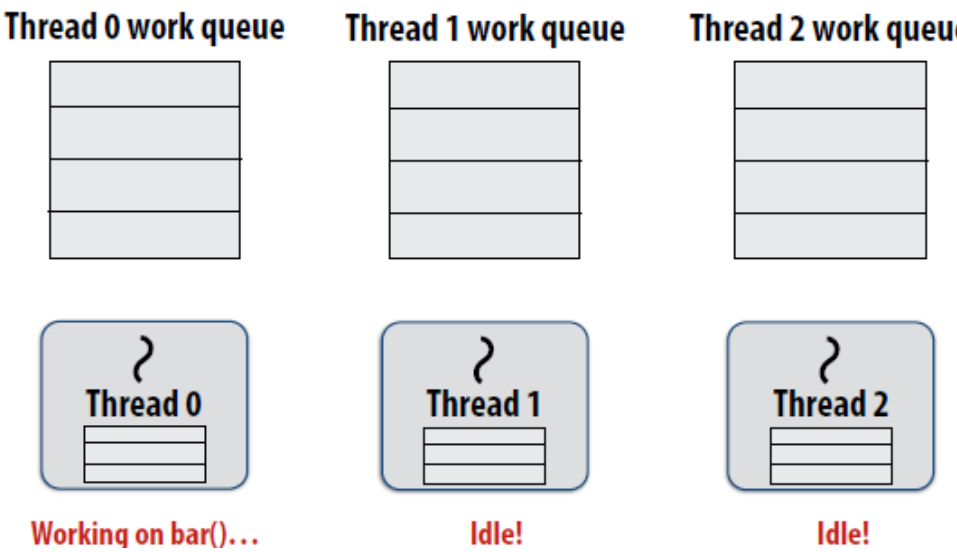


Last spawn completes.

Implementing sync: stalling join

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



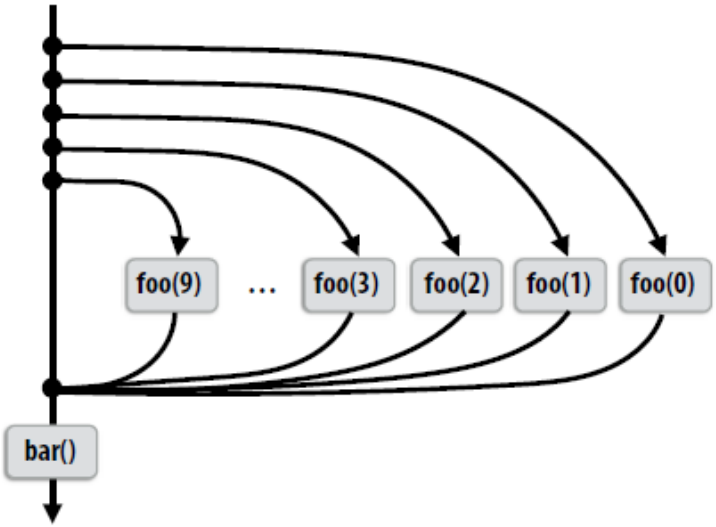


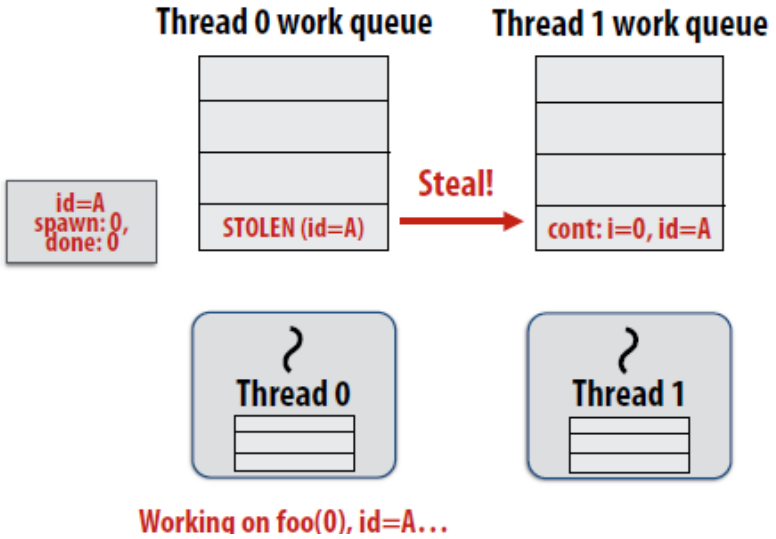
Thread 0 now resumes continuation and executes bar()
Note block A descriptor is now free.

With this approach, thread that starts block will also complete it

Implementing sync: greedy policy

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



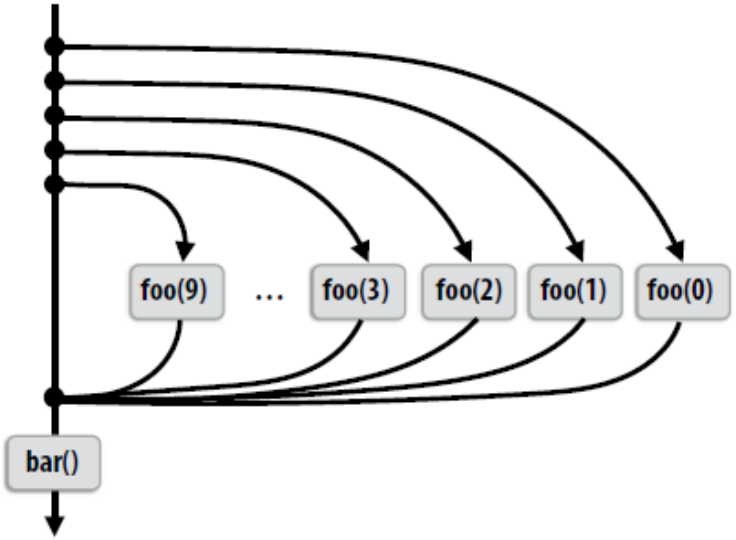


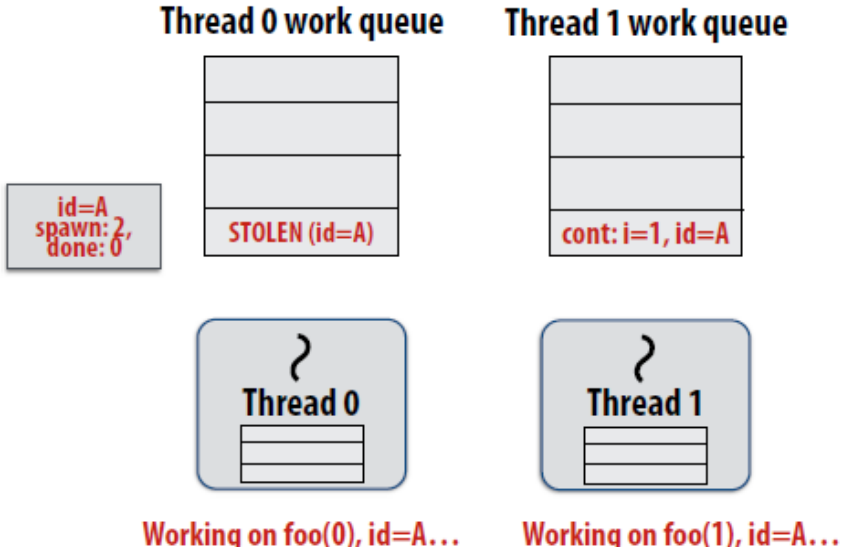
Example 2: "greedy" policy

- When thread that initiates the fork goes idle, it looks to steal new work
- Last thread to reach the join point continues execution after sync

Implementing sync: greedy policy

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





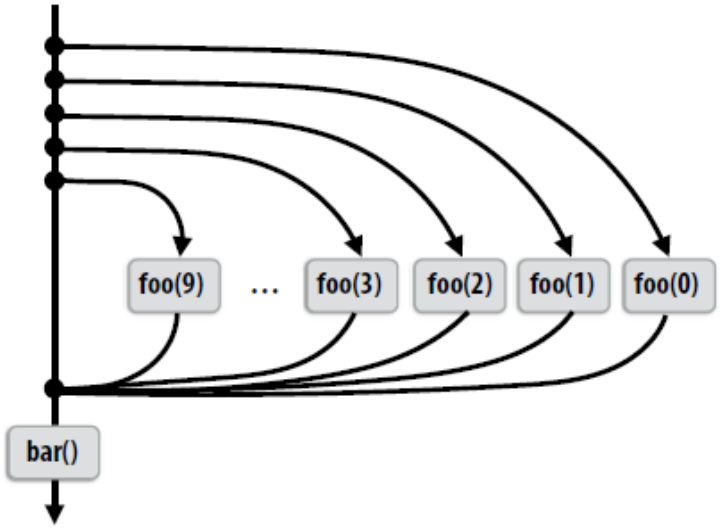
Idle thread 1 steals from busy thread 0 (as in the previous case)

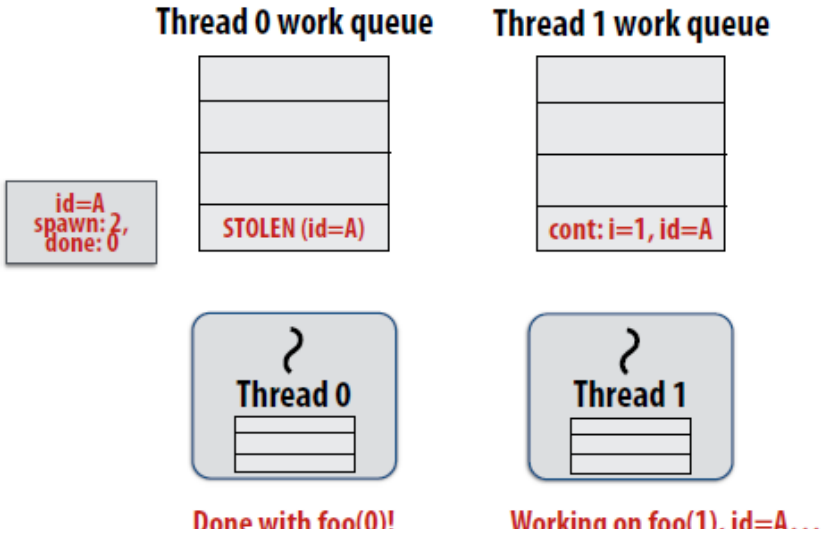
Implementing sync: greedy policy

block (id: A)

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

Sync for all calls spawned within block A

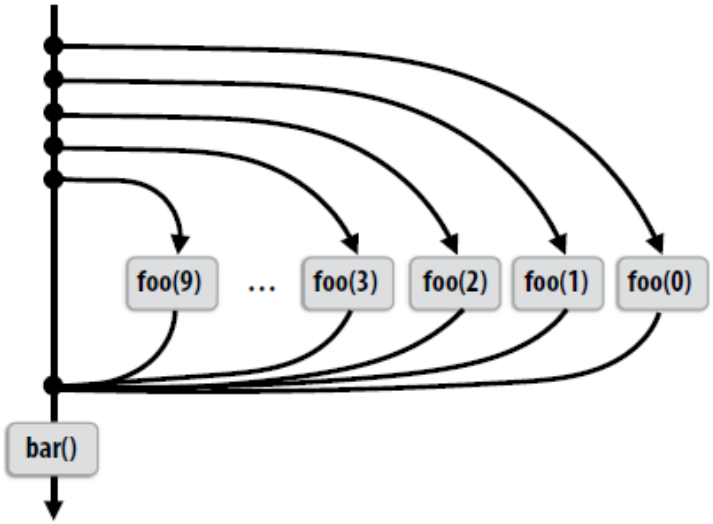


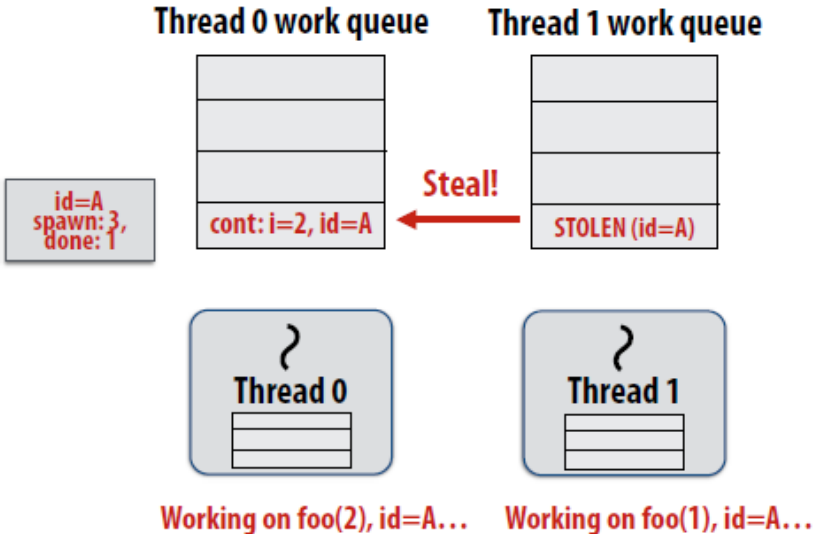


Thread 0 completes foo(0)
No work to do in local dequeue, so thread 0 looks to steal!

Implementing sync: greedy policy

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

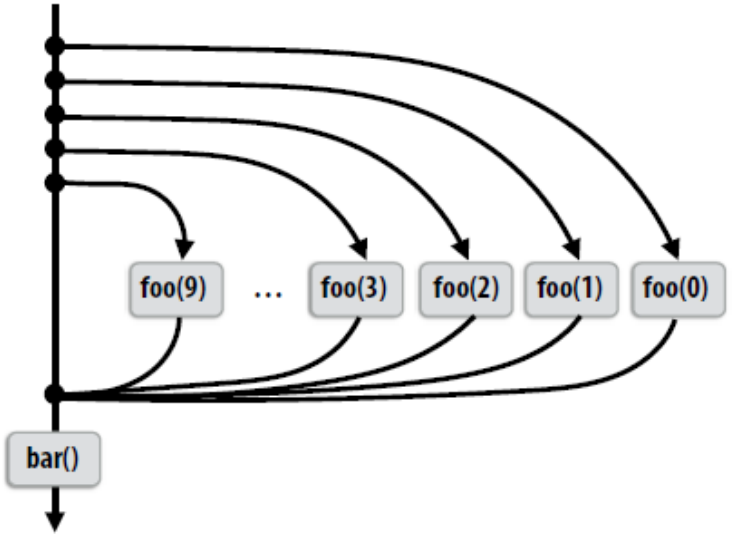


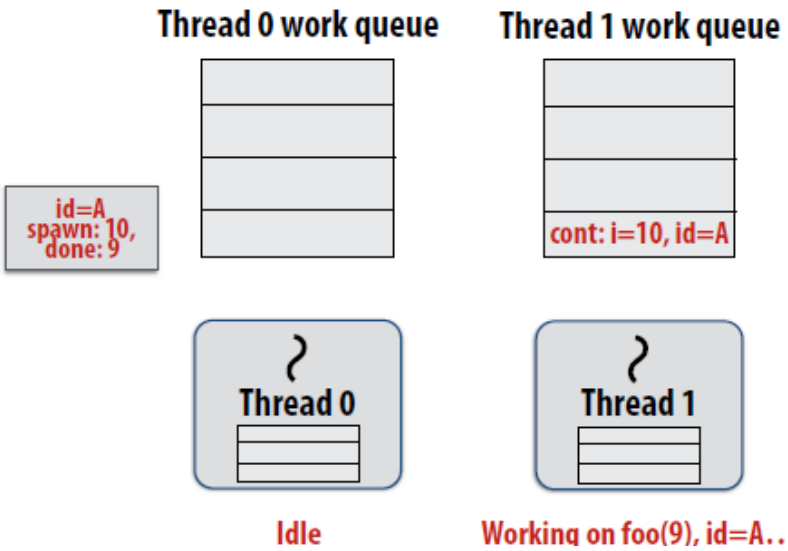


Thread 0 now working on foo(2)

Implementing sync: greedy policy

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

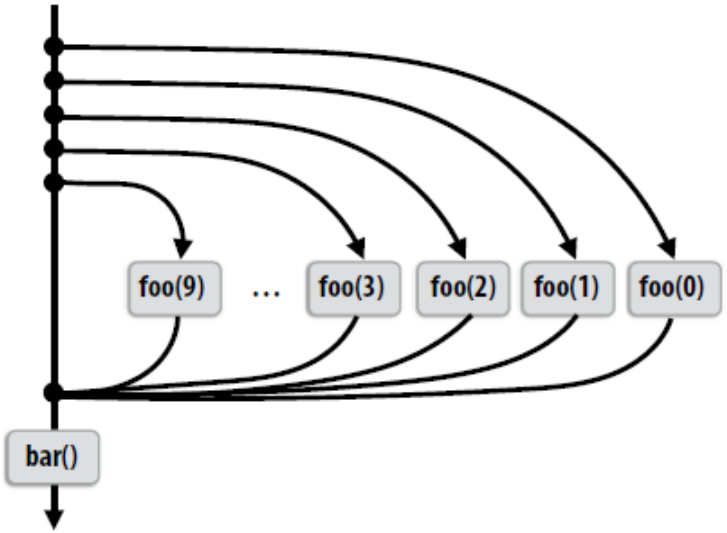


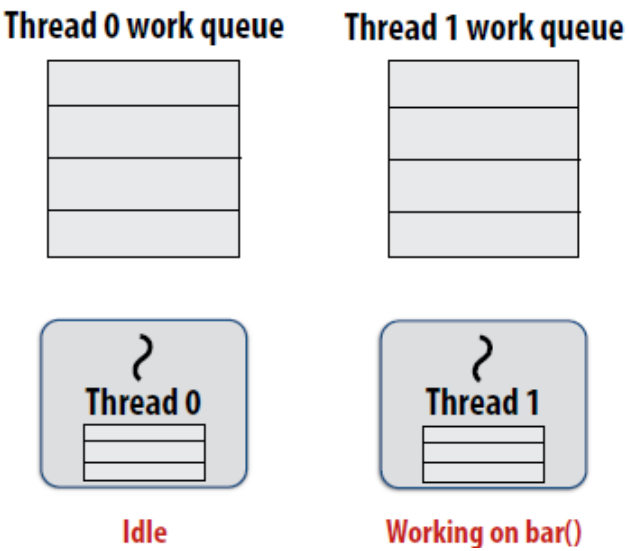


Assume thread 1 is the last to finish spawned calls for block A.

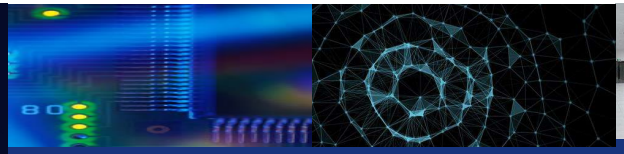
Implementing sync: greedy policy

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





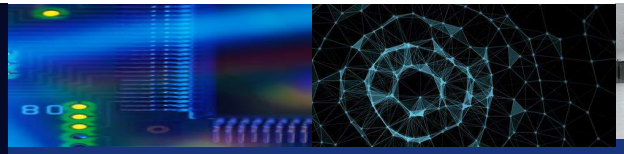
Thread 1 continues on to run bar()
Note block A descriptor is now free.



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

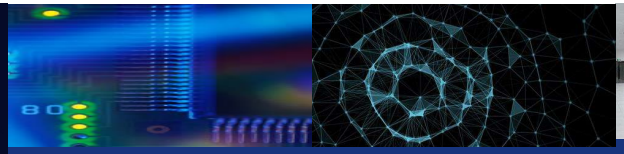


Adjusting Granularity

- **Challenge**
  - If partition computation into too many tasks (fine grained), will be swamped by scheduling overhead
  - If too few tasks (coarse grained), won't have enough parallelism and more prone to workload imbalance
  - Requiring programmer to determine granularity in advance is tedious and non-portable
- **Cilk**
  - Generates two versions of every program
    - "Fast clone" optimized for sequential execution.
      - Spawning $\approx$ procedure call
    - "Slow clone" does full fork/join parallelism

Summary

- **Fork-join parallelism: a 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 a locality-aware work stealing scheduler**
  - Always run spawned child (continuation stealing)
  - Greedy behavior at join (threads do not wait at join, immediately look for other work to steal)
  - Automatic & dynamic adjustment of granularity



Thank You !