(how to be l33t)

Lecture 5:

~~Performance Optimization~~ Part 1: Work Distribution and Scheduling

Parallel Computing

Stanford CS149, Fall 2024

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 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.

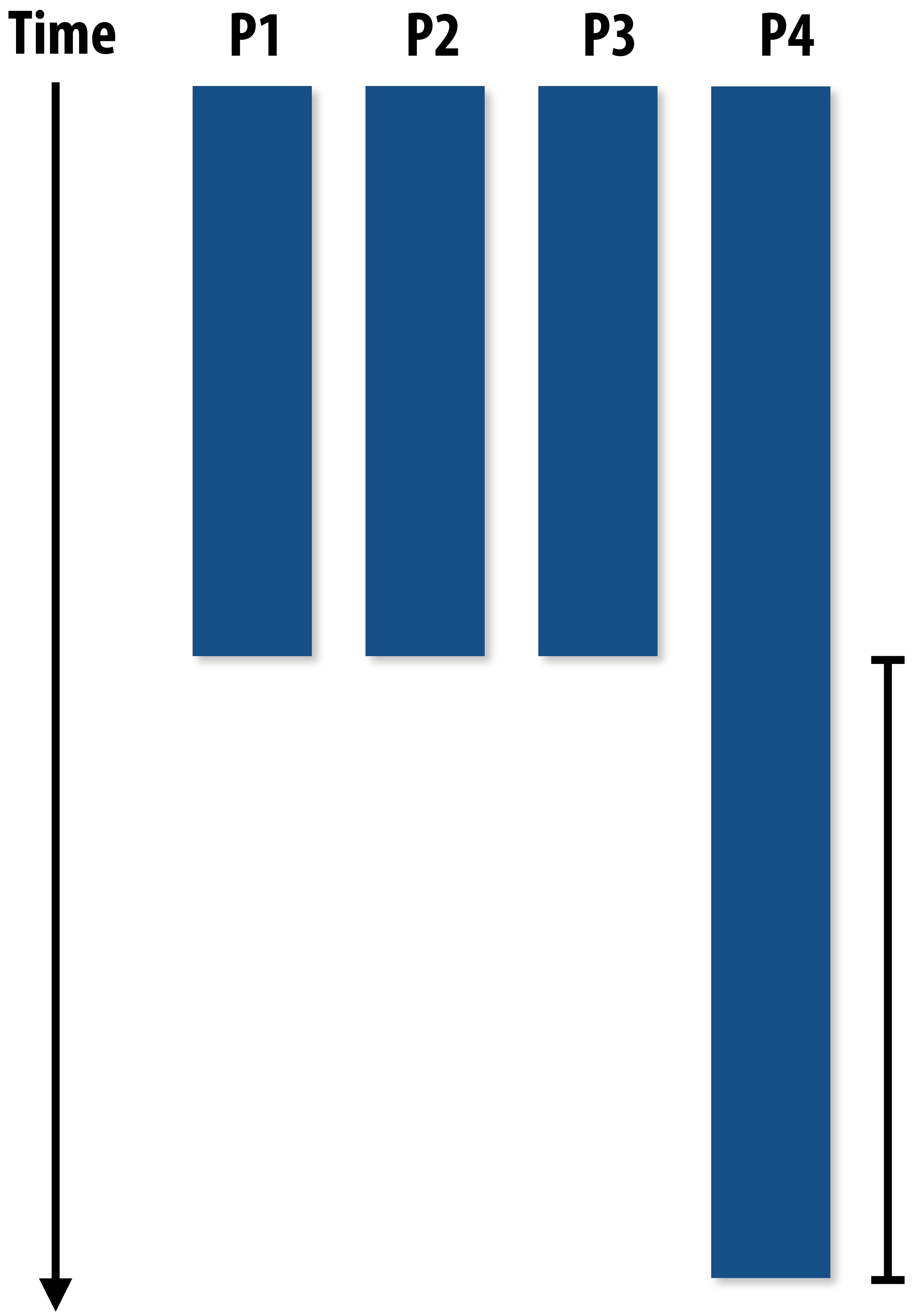
- We are going to talk about a rich space of techniques

Programming for high performance

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

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)



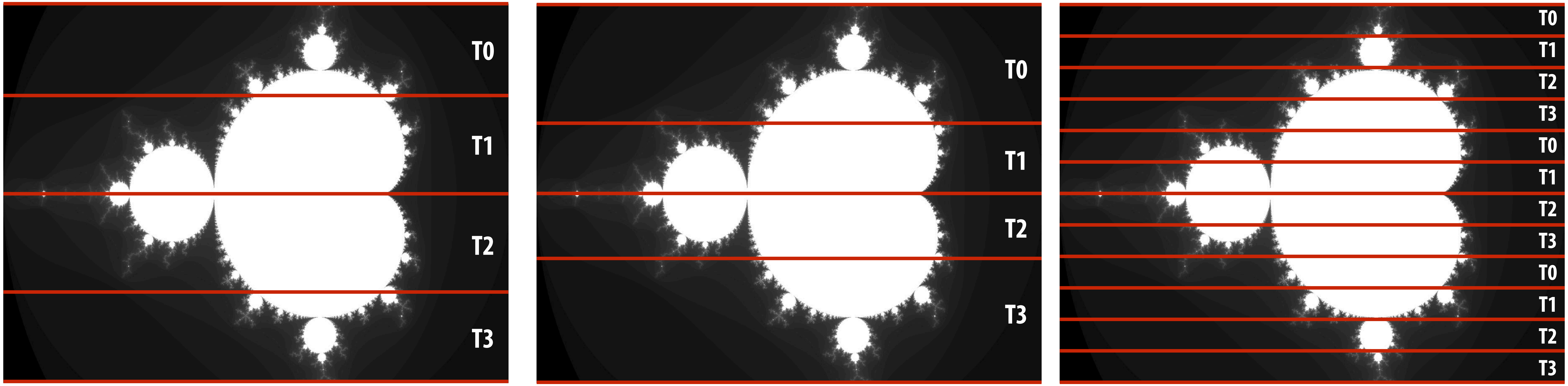
Only small amount of load imbalance can significantly bound maximum speedup

P4 does 2x more work → P4 takes 2x longer to complete
→ 50% of parallel program's runtime is serial

(Note: work in serialized section here is about 1/5 of the work done by the entire program, so S=0.2 in Amdahl's law equation)

Static assignment

- Assignment of work to threads does not depend on dynamic behavior
  - Assignment not necessarily set at compile-time (we call it static is the assignment is determined when the amount of work and number of workers is known: assignment may depend on runtime parameters such as input data size, number of threads, etc.)
- Recall Programming Assignment 1, program 1: assign equal number of grid cells to each thread
  - Students explored different static assignments of work to workers

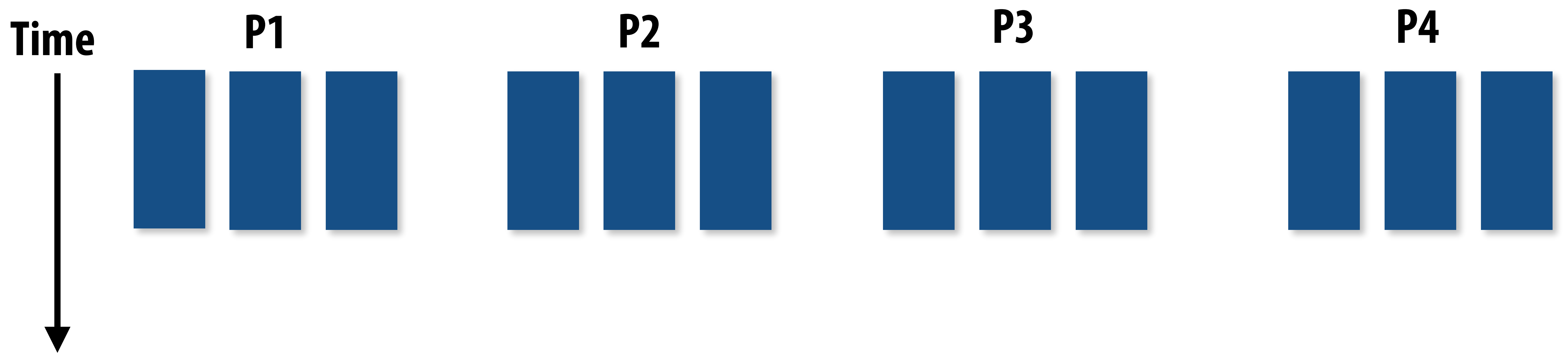


- Good aspects of static assignment: simple, essentially zero runtime overhead to perform assignment (in this example: extra work to implement assignment is a little bit of indexing math)

When is static assignment applicable?

- When the cost (execution time) of work and the amount of work is <u>predictable,</u> allowing the programmer to work out a good assignment in advance

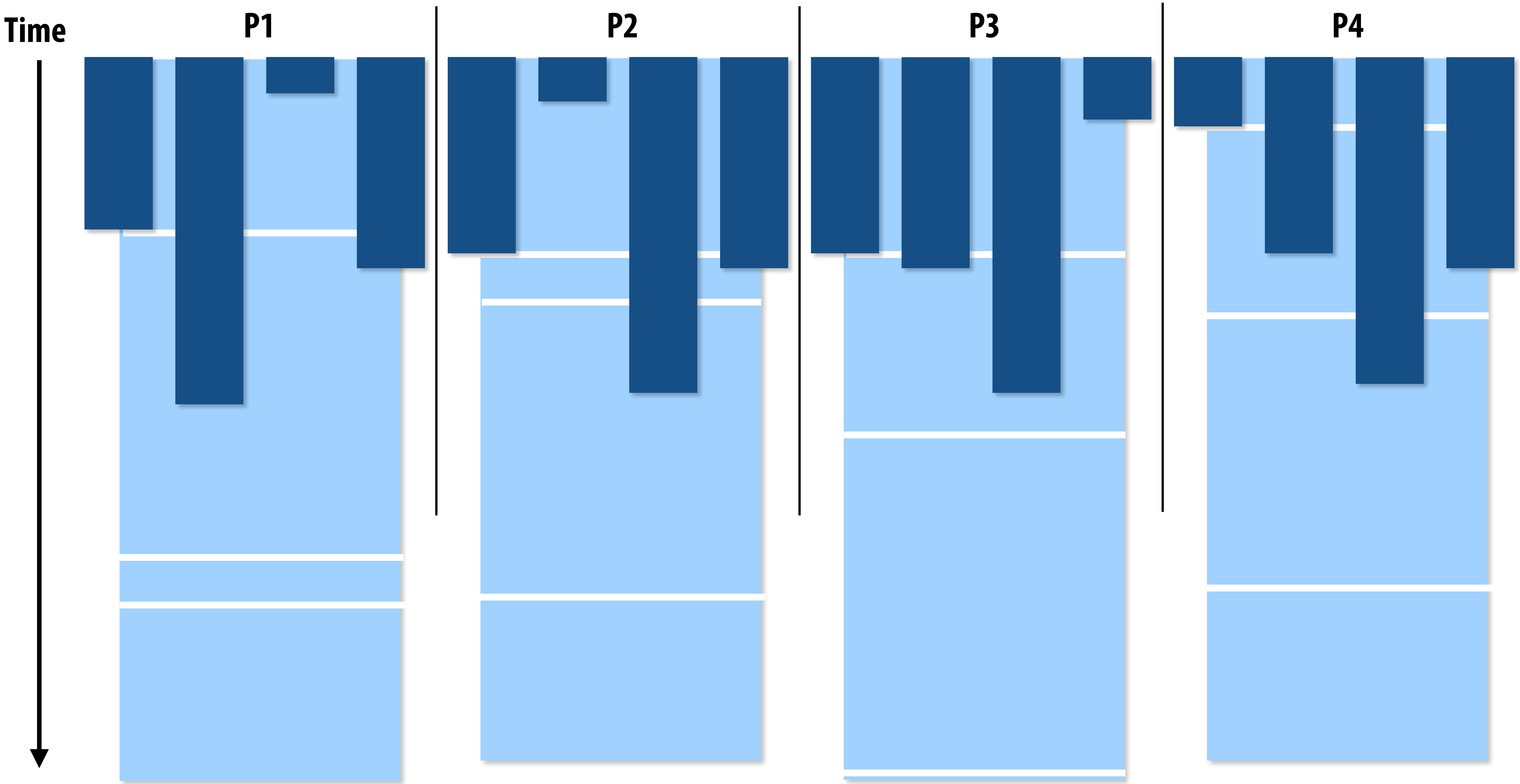
- Simplest example: it is known up front that all work has the same cost



In the example above:
There are 12 tasks, and it is known that each have the same cost.
Static assignment: statically assign three tasks to each of the four processors.

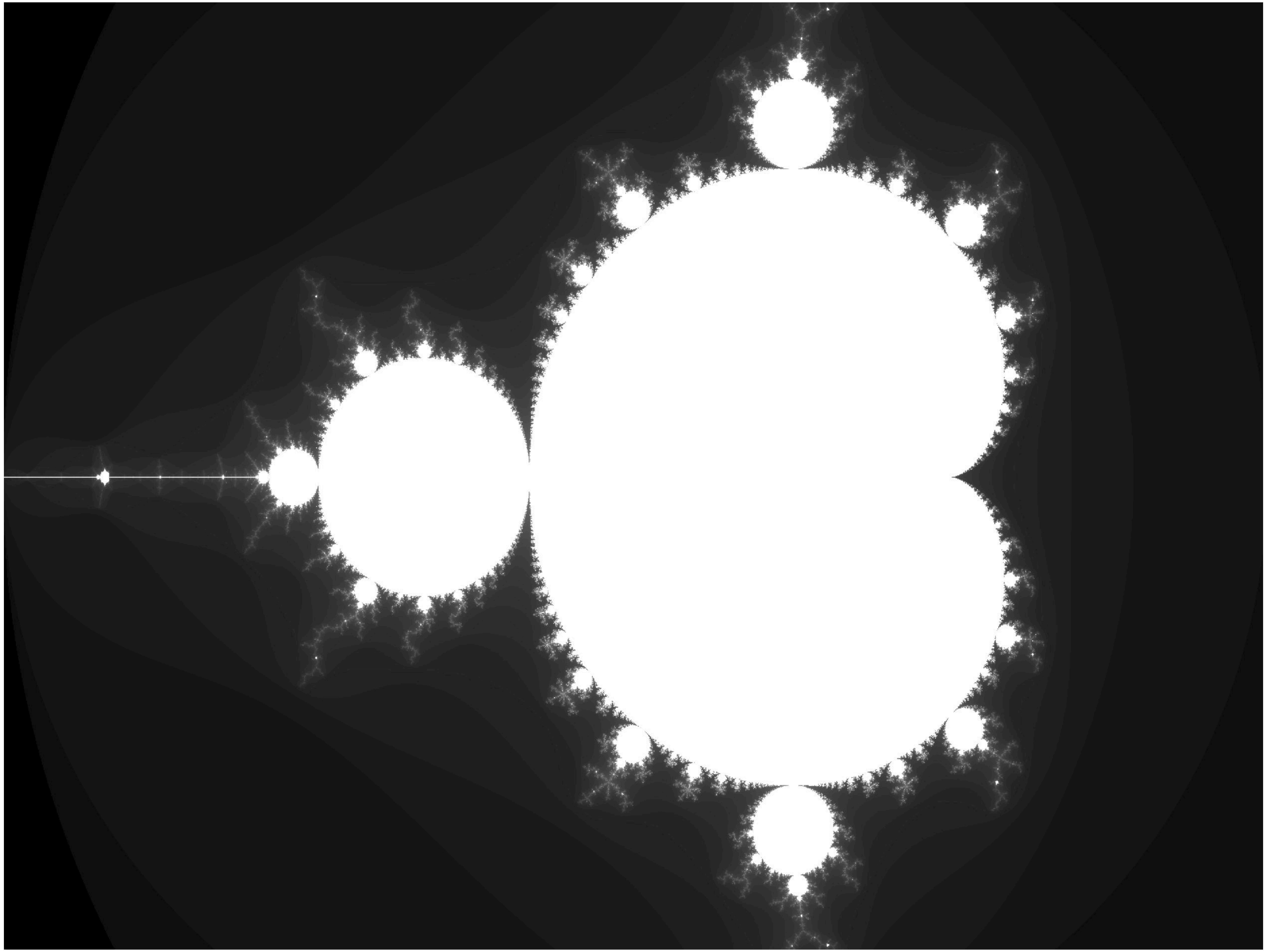
When is static assignment applicable?

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



Jobs have unequal, but known cost: assign equal number of tasks to processors to ensure good load balance (on average)

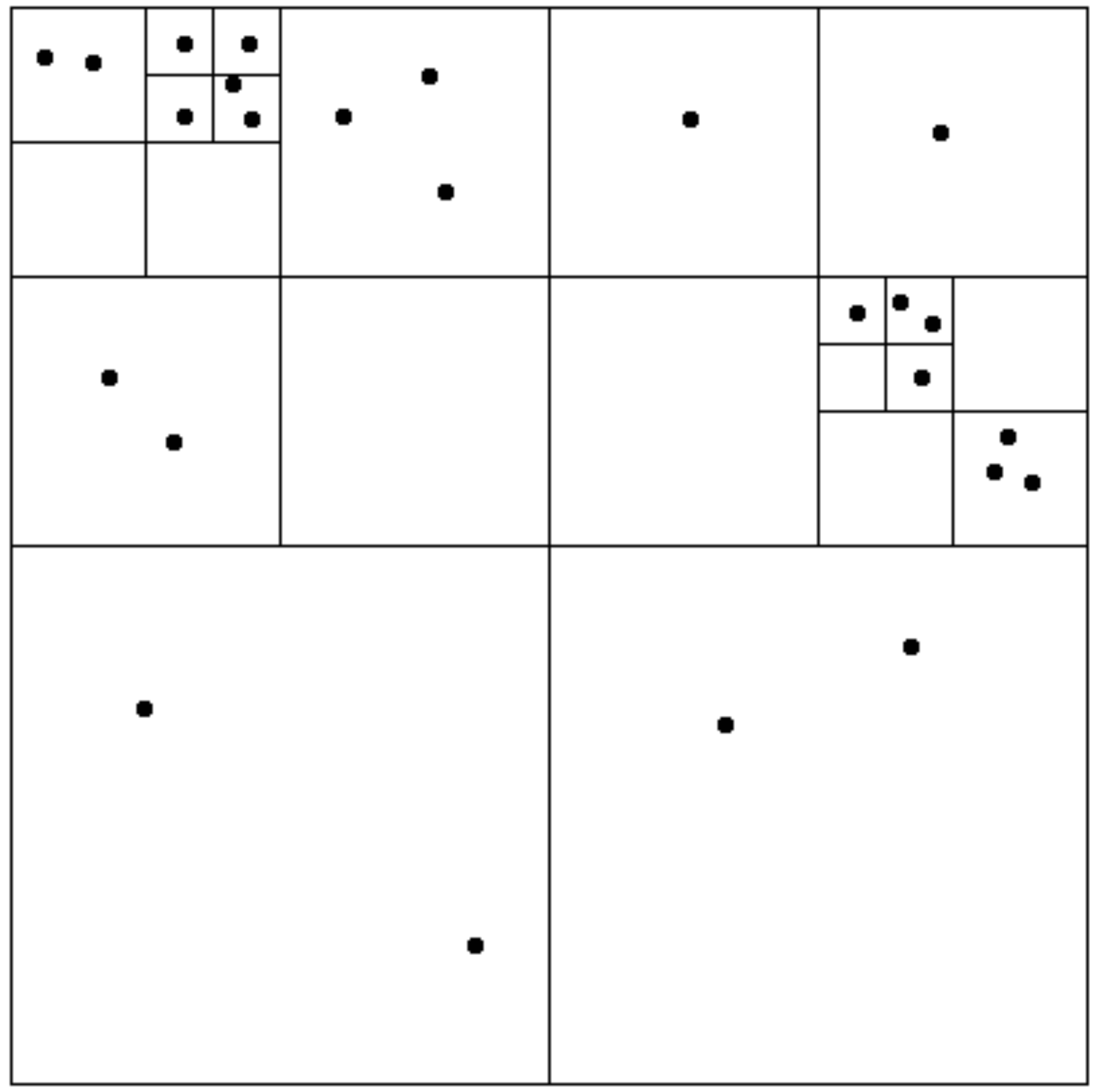
Example from programming assignment 1 (prog 1)



- **Why was a static row-interleaved assignment a good solution to this problem?**

"Semi-static" assignment

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



Particle simulation:

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

Colored regions denote assignment of mesh cels to workers

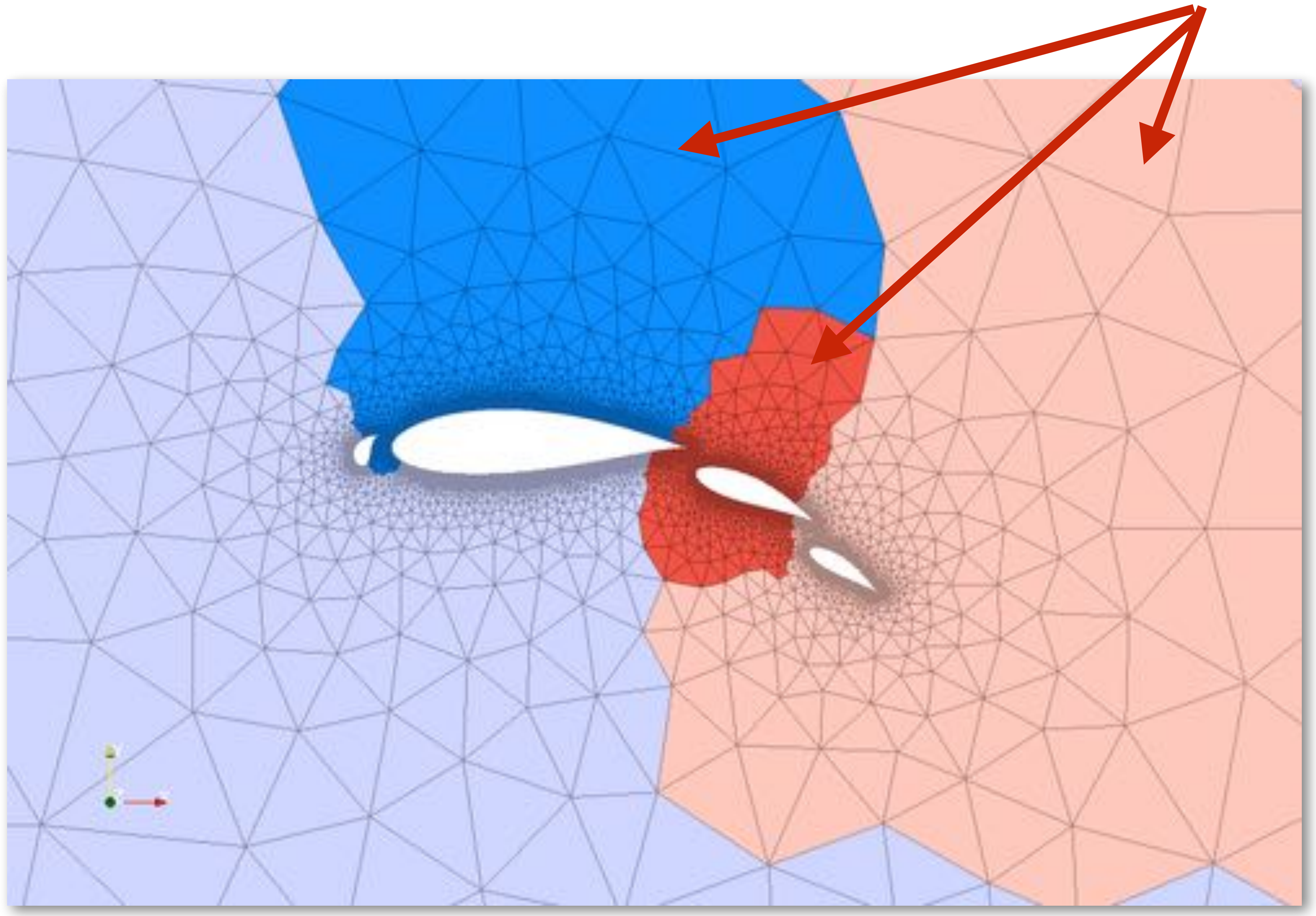


Image credit: http://typhon.sourceforge.net/spip/spip.php?article22

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 unknown or unpredictable.)

Sequential program
(independent loop iterations)

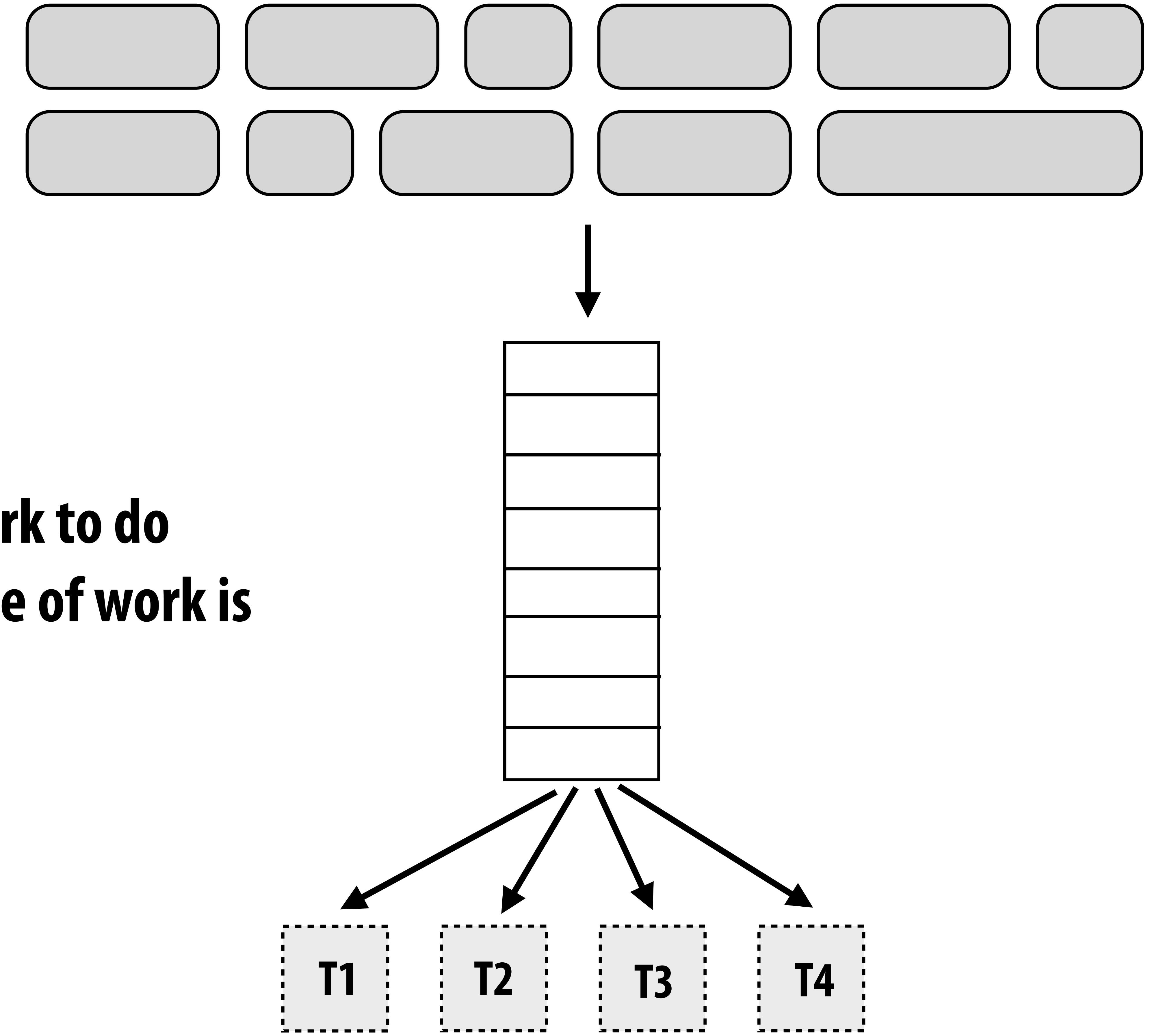
```
int N = 1024;
int* x = new int[N];
bool* prime = new bool[N];

// assume elements of x initialized 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)

```
int N = 1024;

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

// assume elements of x are initialized 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

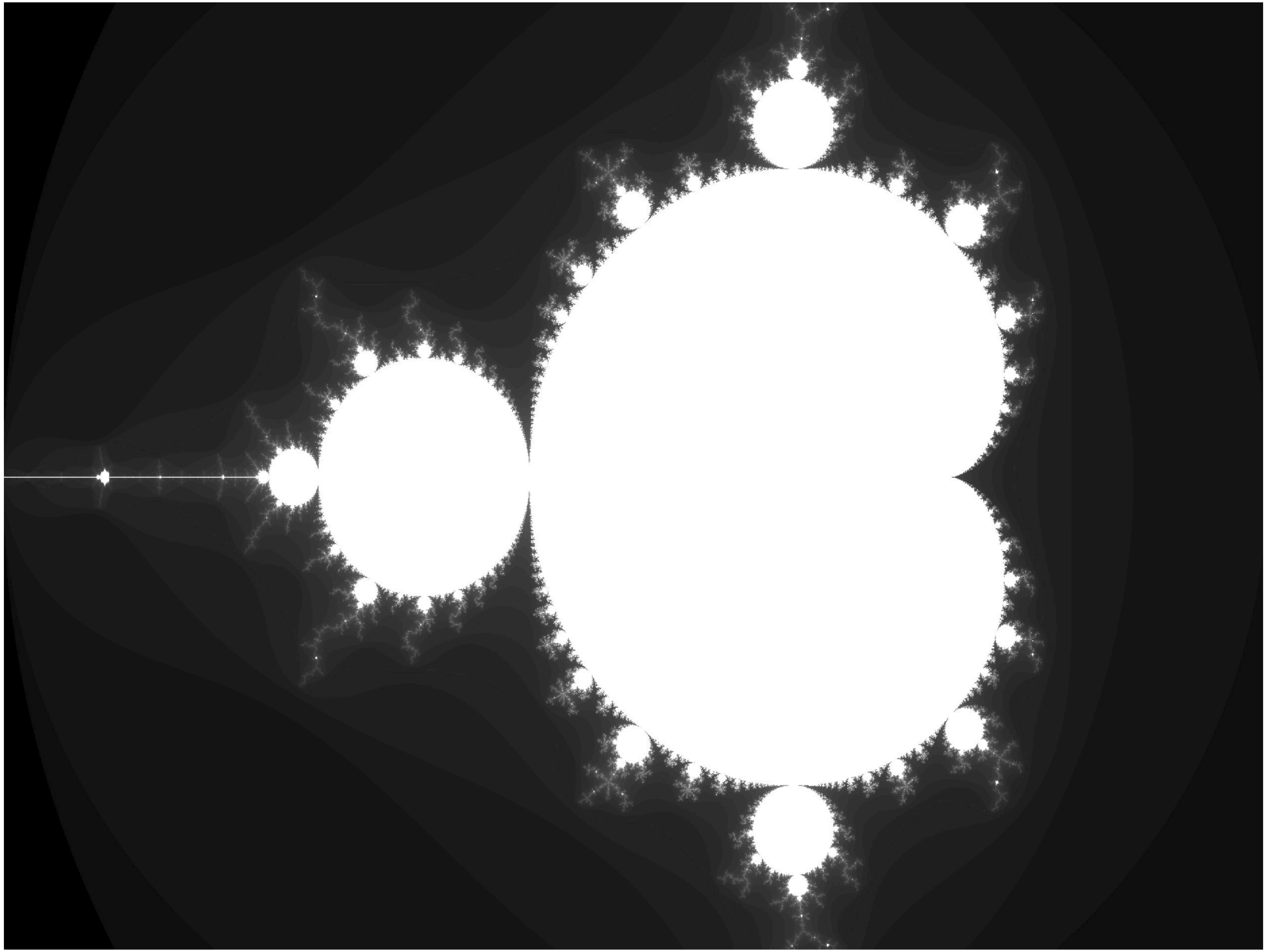


Sub-problems
(a.k.a. "tasks", "work")

Shared work queue: a list 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

Example from programming assignment 1 (prog 3)



Why did breaking the problem up into many ISPC tasks improve performance?

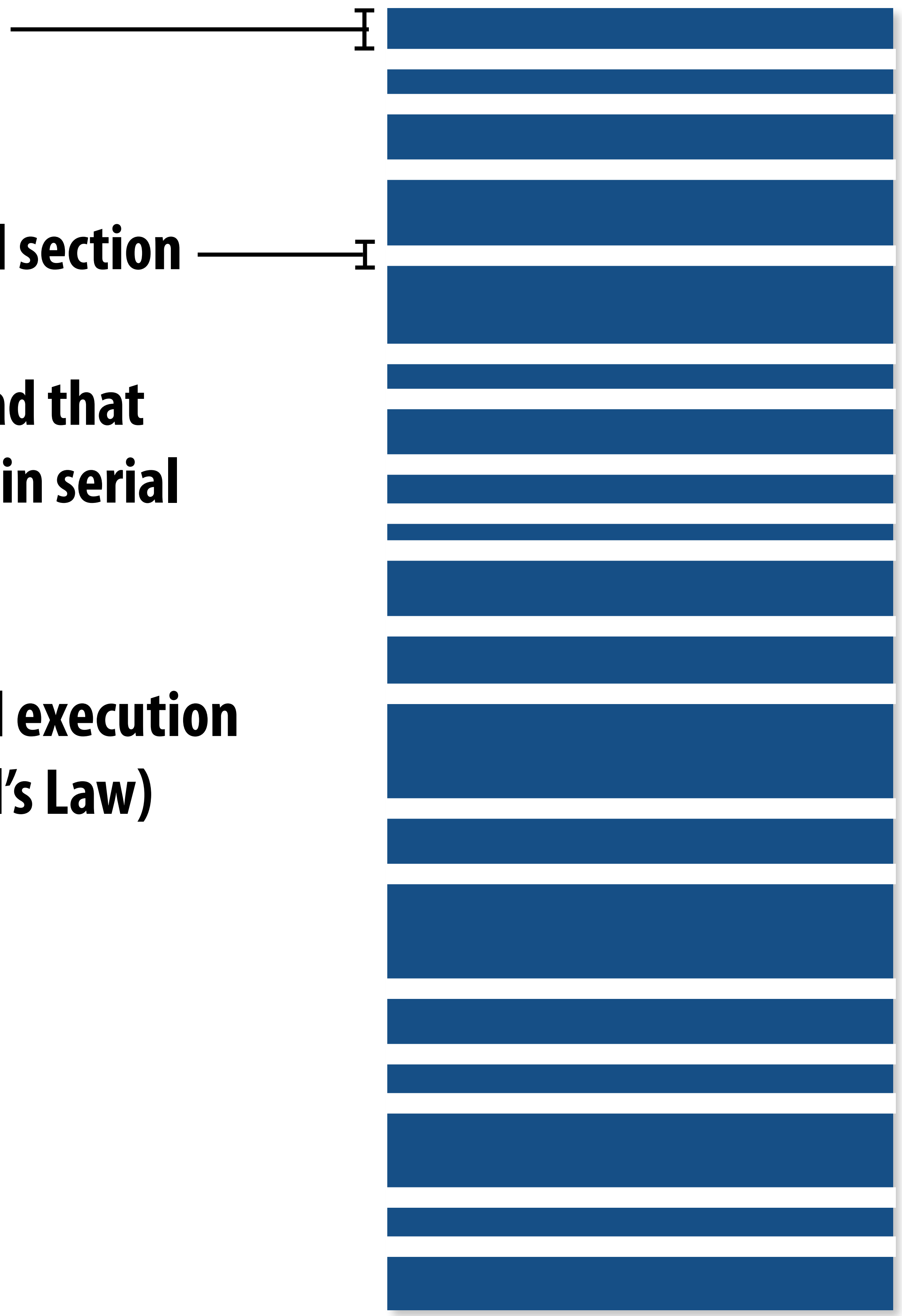
What constitutes a piece of work?

What is a potential performance 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];

// assume elements of x are initialized 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)



Time in task 0

Time in critical section

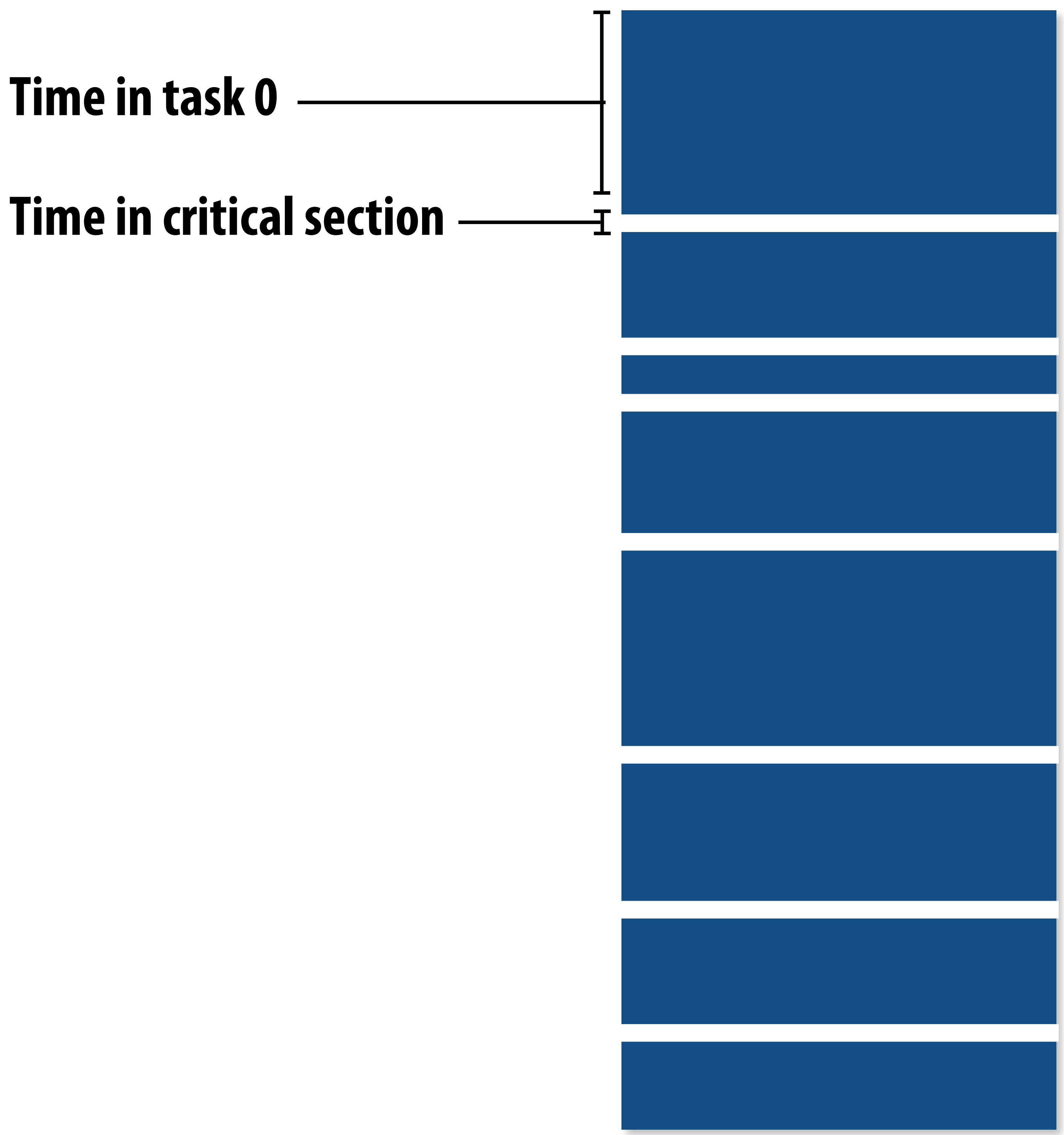
This is overhead that does not exist in serial program

And.. it's serial execution (recall Amdahl's Law)

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];

// assume elements of x are initialized 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[i] = test_primality(x[i]);
}
```



Time in task 0

Time in critical section

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**

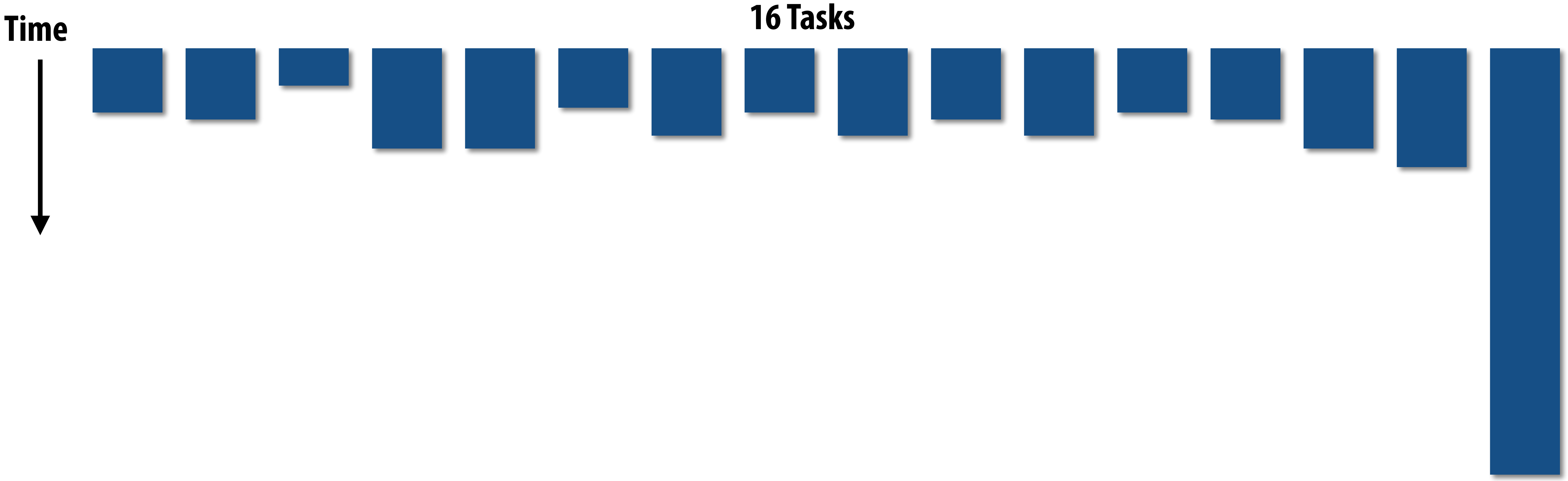
- **Ideal granularity depends on many factors**
  (Common theme in this course: must know your workload, and your machine)

*** I had to pick a term for a piece of work. I'm not specifically referring to ISPC tasks**

Smarter task scheduling

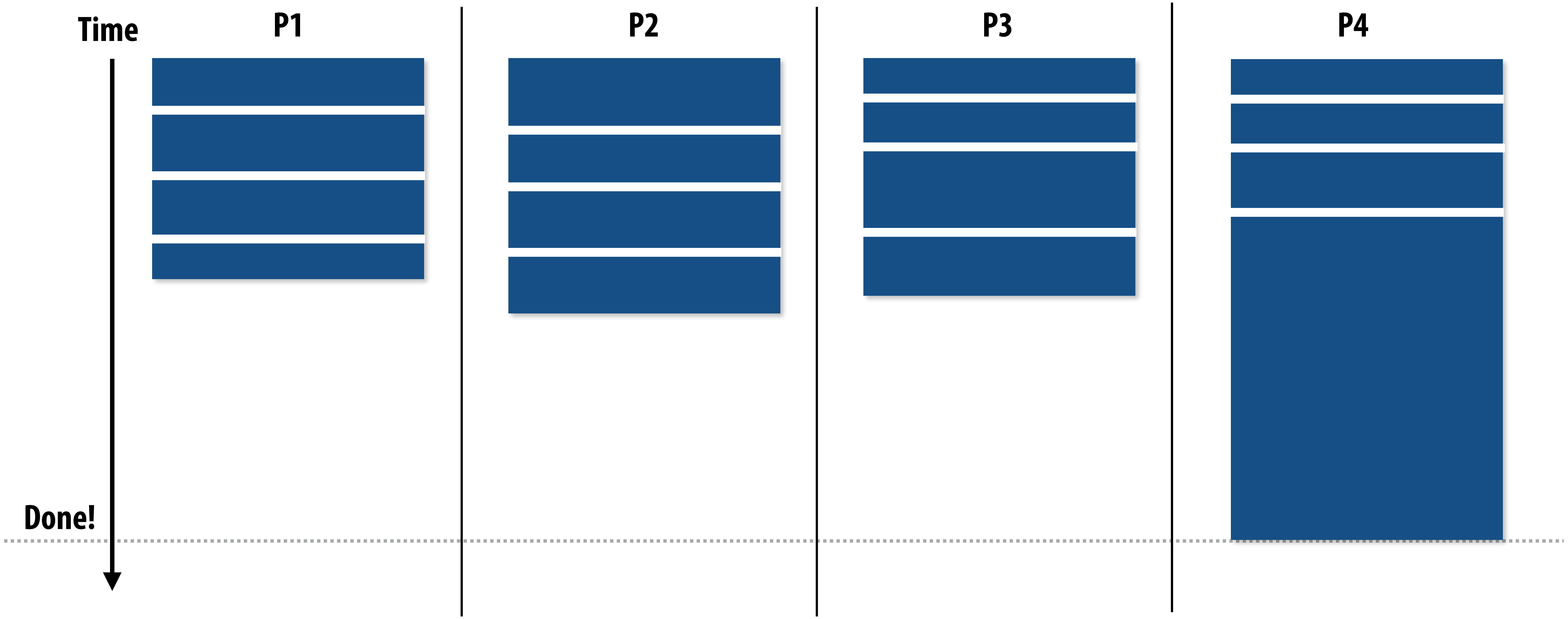
Consider dynamic scheduling via a shared work queue

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



Smarter task scheduling

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

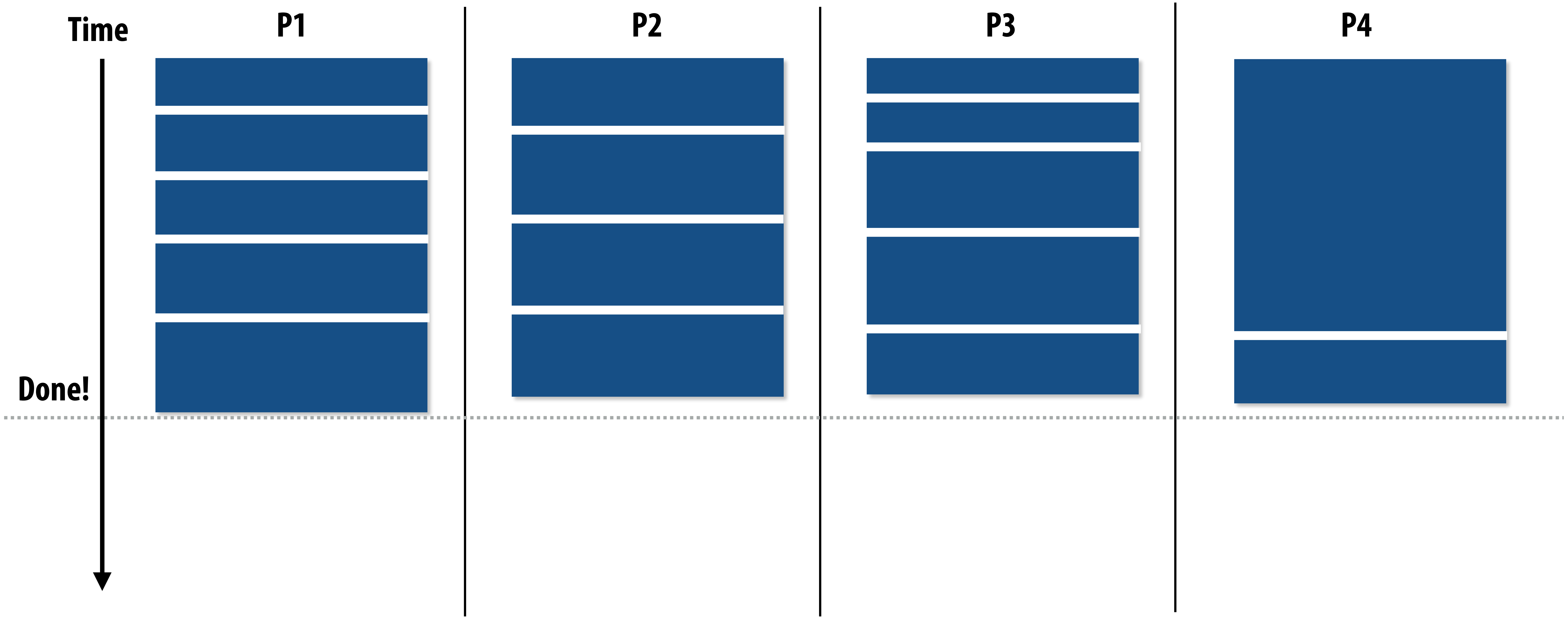


One possible solution to imbalance problem:

Divide work into a larger number of smaller tasks
- Hopefully this makes the "long pole" 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)

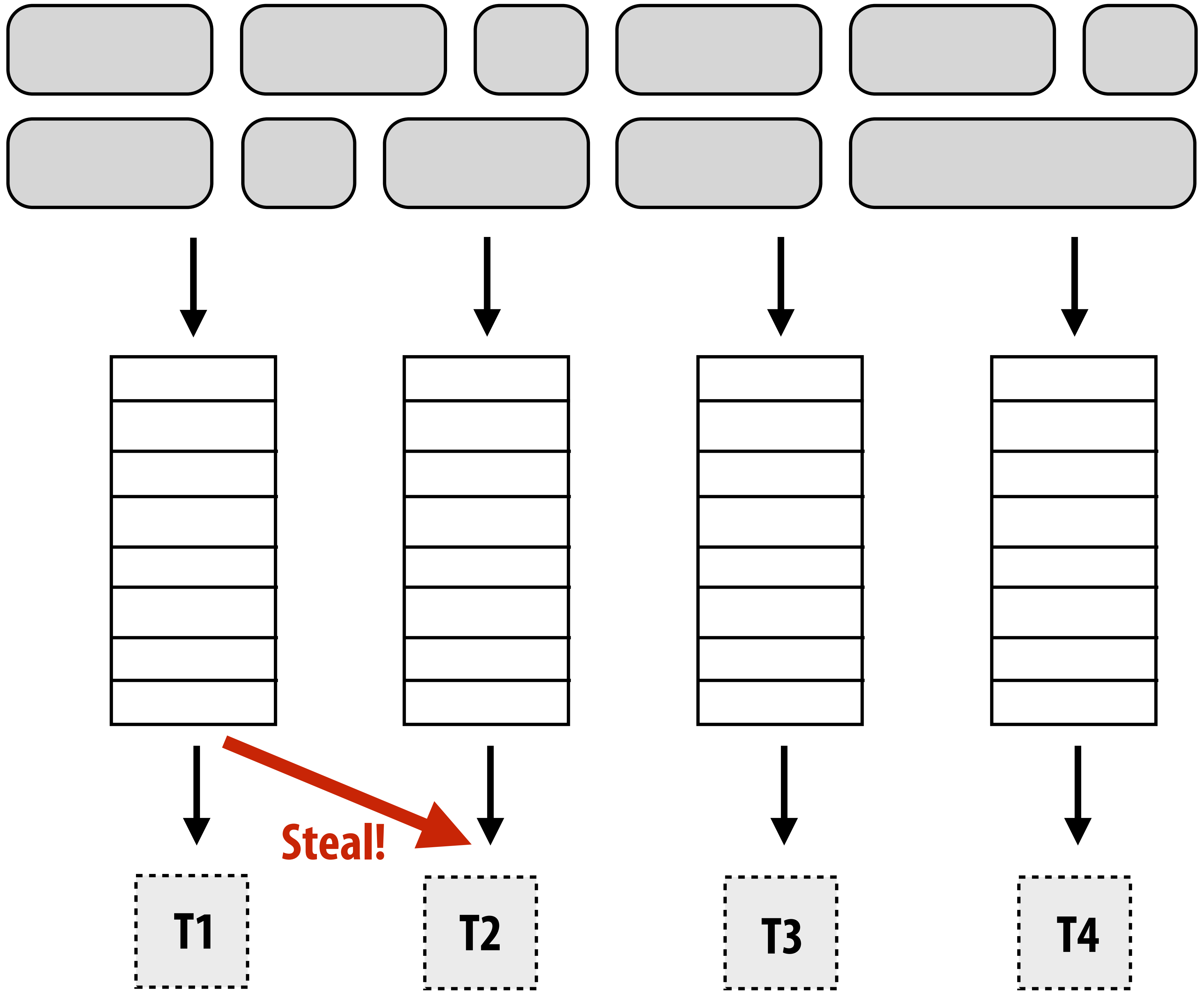
Decreasing synchronization overhead using distributed queues

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

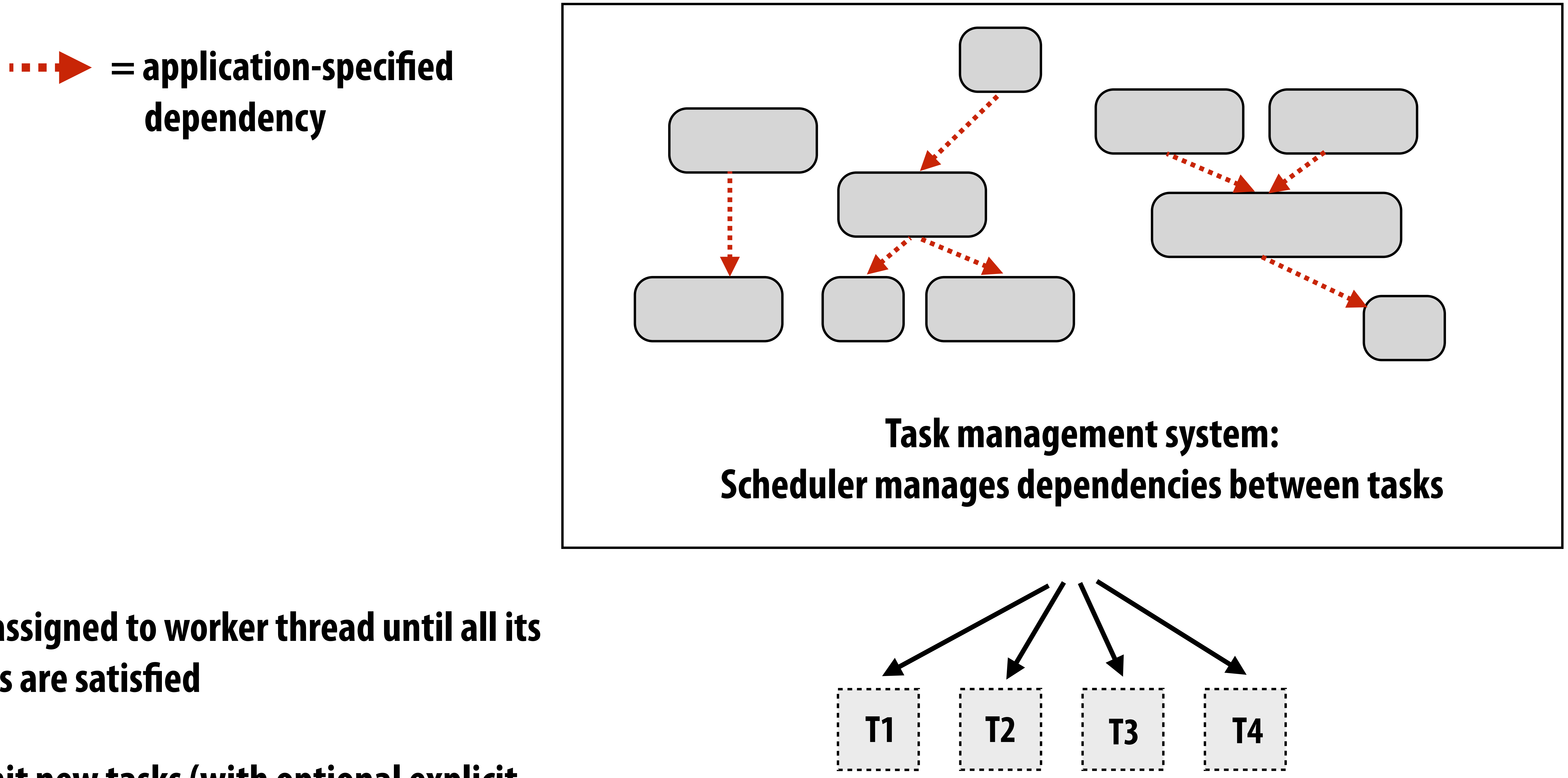
Subproblems
(a.k.a. “tasks”, “work to do”)

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
When local work queue is empty...
STEAL work from another work queue



Work in task queues need not be independent


= application-specified dependency
Task management system:
Scheduler manages dependencies between tasks
T1
T2
T3
T4

A task cannot be assigned to worker thread until all its 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 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)

Scheduling fork-join parallelism

Common parallel programming patterns

Data parallelism:

Perform same sequence of operations on many data elements

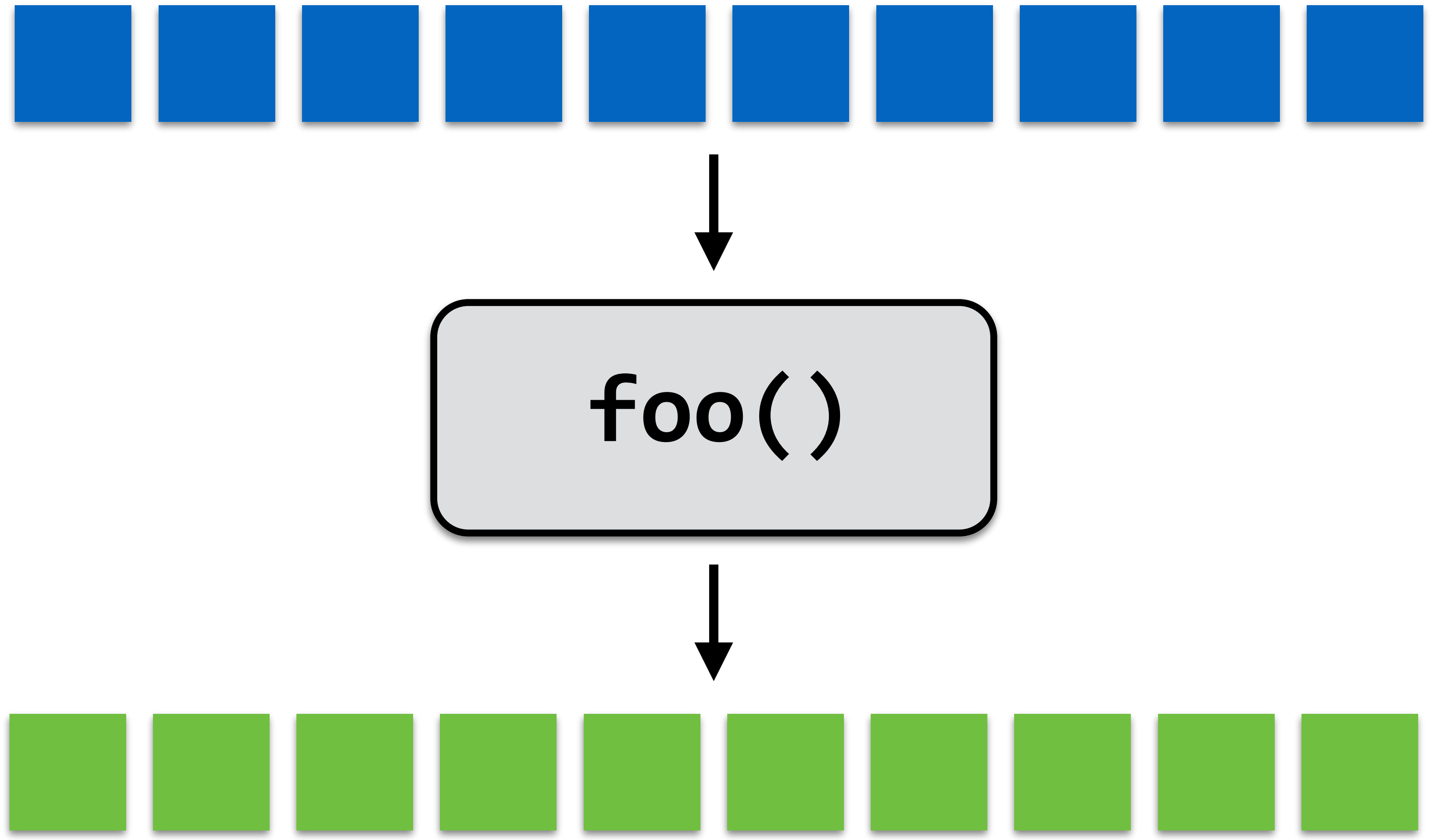
```
// ISPC foreach
foreach (i=0 ... N) {
   B[i] = foo(A[i]);
}
```

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

```
// 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]);
}
```

```
// bulk CUDA thread launch (GPU programming, in a future lecture)
foo<<<numBlocks, threadsPerBlock>>>(A, B);
```



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 C++ threads**

```
float* A;
float* B;

// initialize arrays A and B here

void myFunction(float* A, float* B { … }

std::thread thread[NUM_HW_EXEC_CONTEXTS];

for (int i=0; i<NUM_HW_EXEC_CONTEXTS; i++) {
  thread[i] = std::thread(myFunction, A, B);
}

for (int i=0; i<num_cores; i++) {
  thread[i].join();
}
```

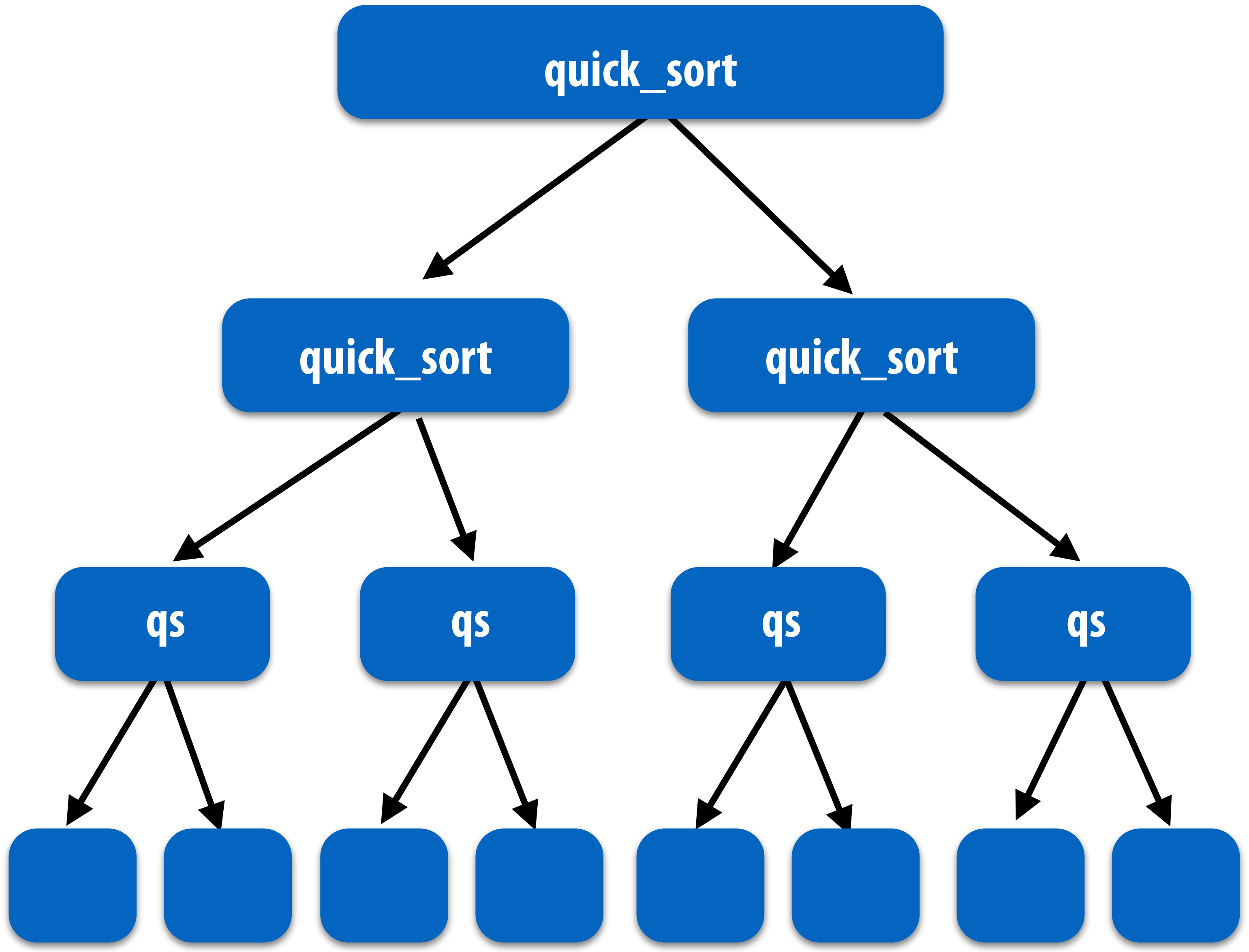
Consider divide-and-conquer algorithms

Quick sort:

```
// sort elements from ‘begin’ up to (but not including) ‘end’
void quick_sort(int* begin, int* end) {

  if (begin >= end-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);

  }

}
```

independent work!

Dependencies



Fork-join pattern

- Natural way to express the independent work that is inherent in divide-and-conquer algorithms
- This lecture's code examples will be in Cilk Plus
  - C++ language extension
  - Originally developed at MIT, now adapted as open standard (in GCC, Intel ICC)

```
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)

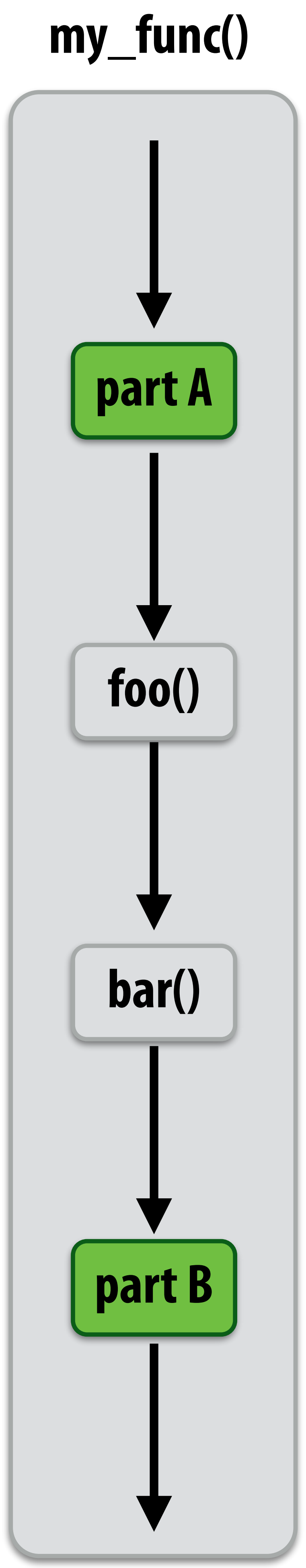
Note: there is an implicit `cilk_sync` at the end of every function that contains a `cilk_spawn`
(implication: when a Cilk function returns, all work associated with that function is complete)

Call-return of a function in C*

```
void my_func() {

  // calling function (part A)

  foo();
  bar();

  // calling function (part B)

}
```

Semantics of a function call:
Control moves to the function that is called
(Thread executes instructions for the function)

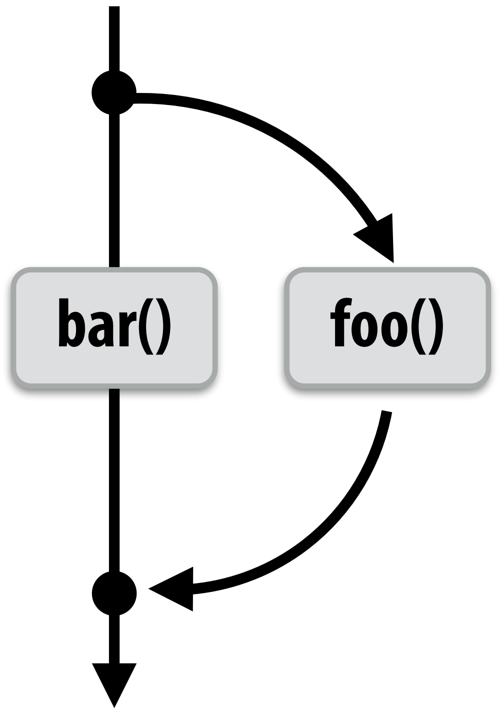
When function returns, control returns back to caller
(thread resumes executing instructions from the caller)



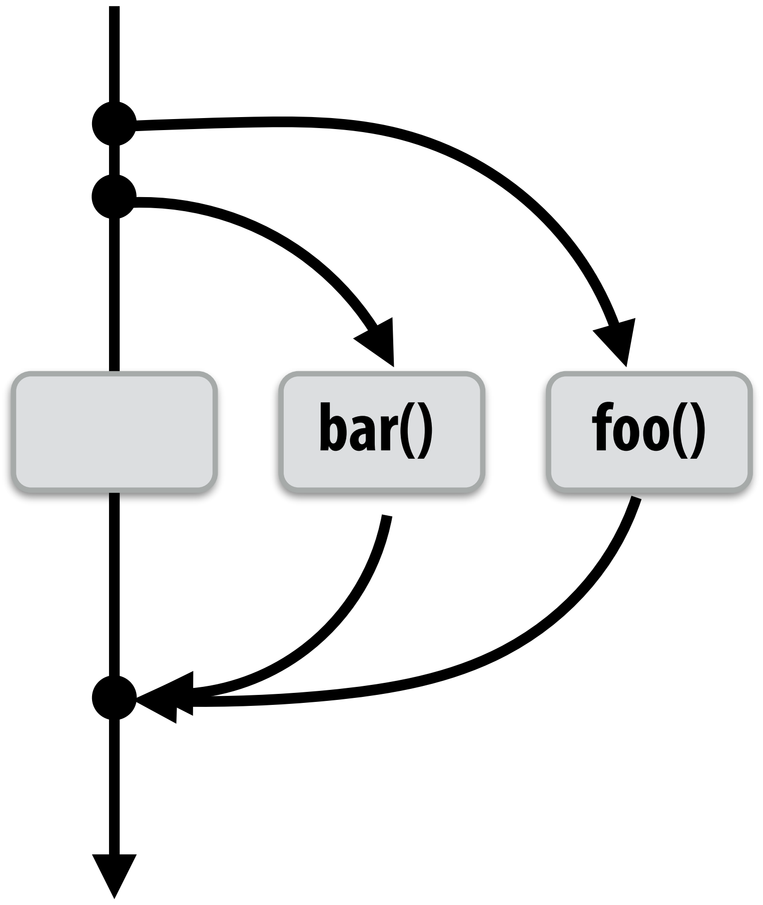
* And many other languages

Basic Cilk Plus examples

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

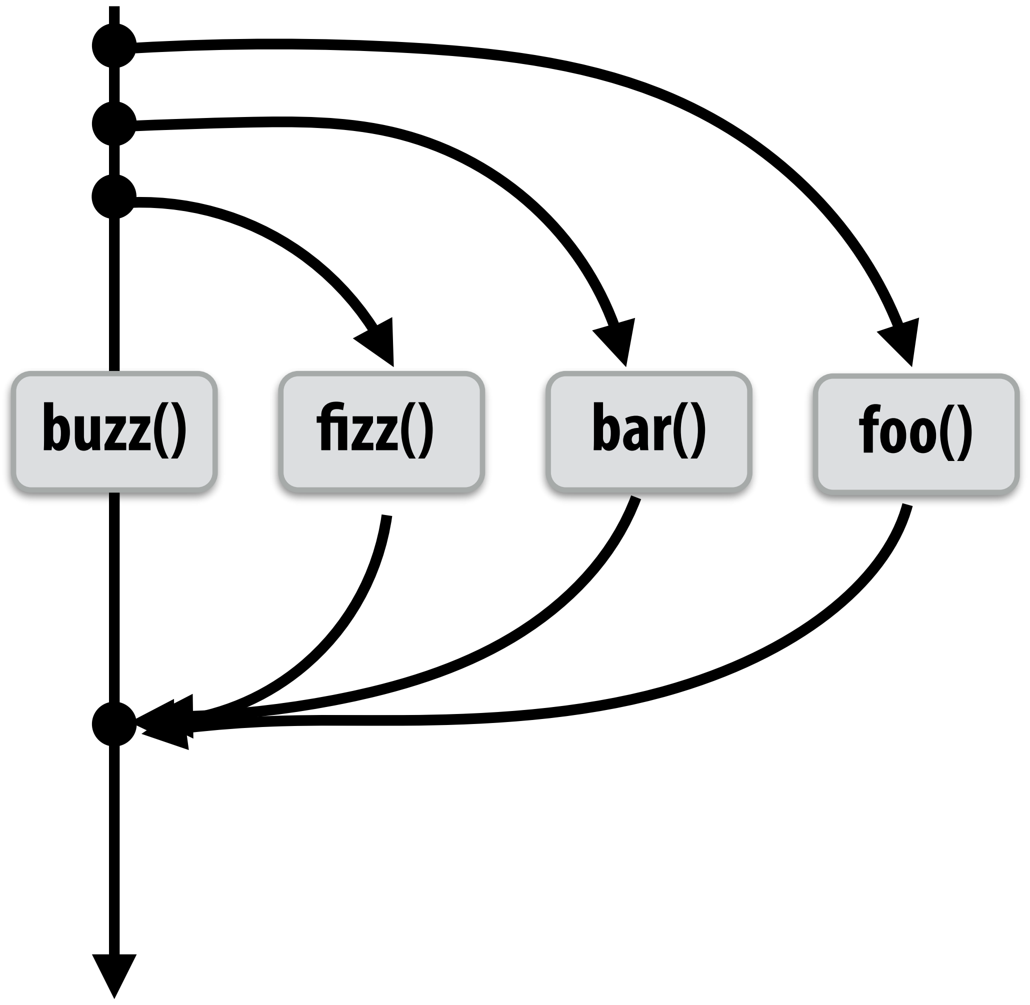


```
// foo() and bar() may run in parallel
cilk_spawn foo();
cilk_spawn bar();
cilk_sync;
```



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

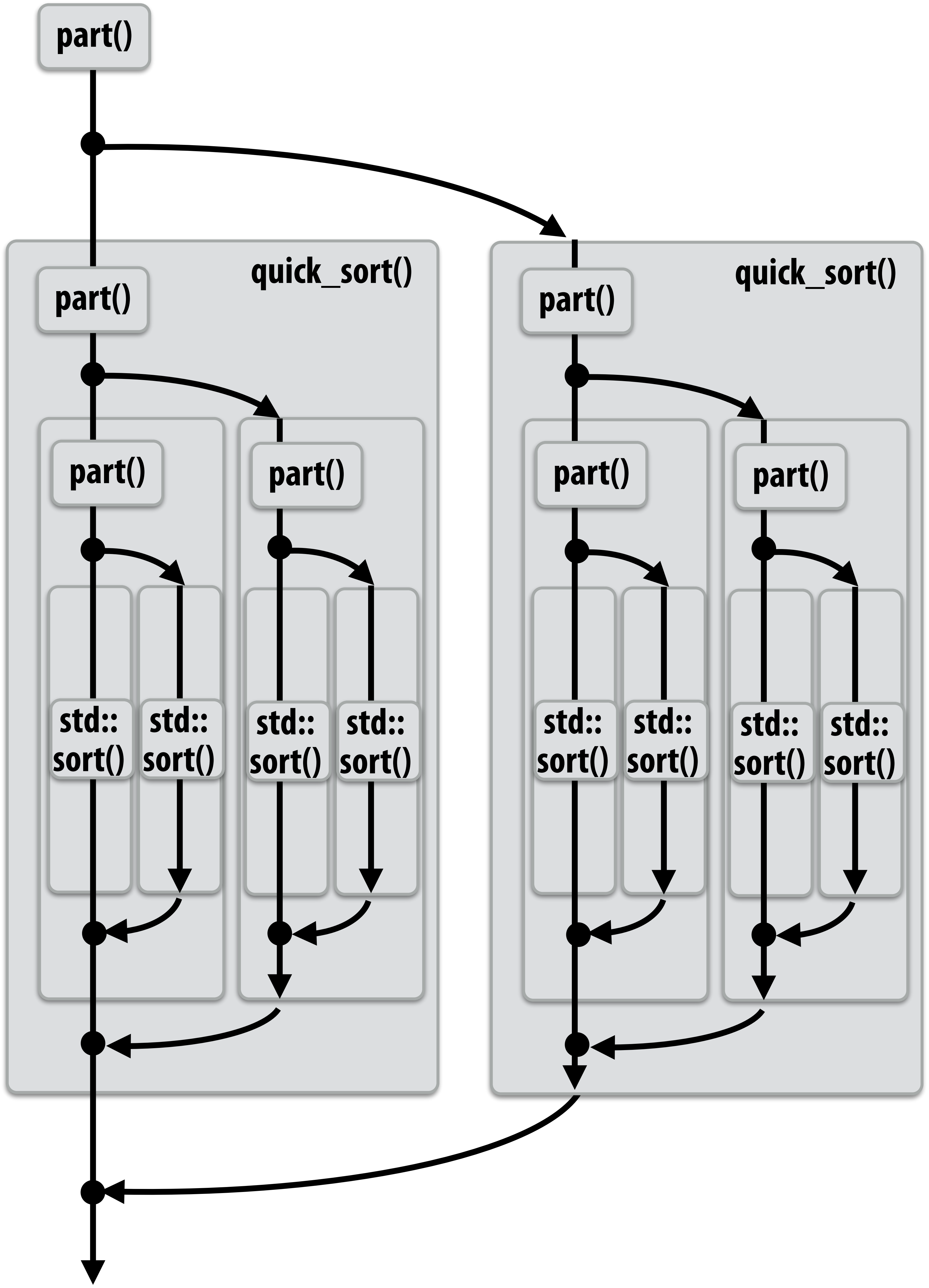
- **Notice that the `cilk_spawn` abstraction does not specify how or when spawned calls are scheduled to execute**
  - **Only that they <u>may</u> be run concurrently with caller (and with all other calls spawned by the caller)**
  - **Question: Is an implementation of Cilk correct if it implements cilk_spawn foo() the same way as it implementation a normal function call to foo()?**

- **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 <u>at least as much work</u> as parallel execution capability (e.g., program should probably spawn at least as much work as needed to fill all the machine's processing resources)**
  - **Want <u>more independent work</u> 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 <u>not too much independent work</u> so that granularity of work is too small (too much slack incurs overhead of managing fine-grained work)**

Scheduling fork-join programs

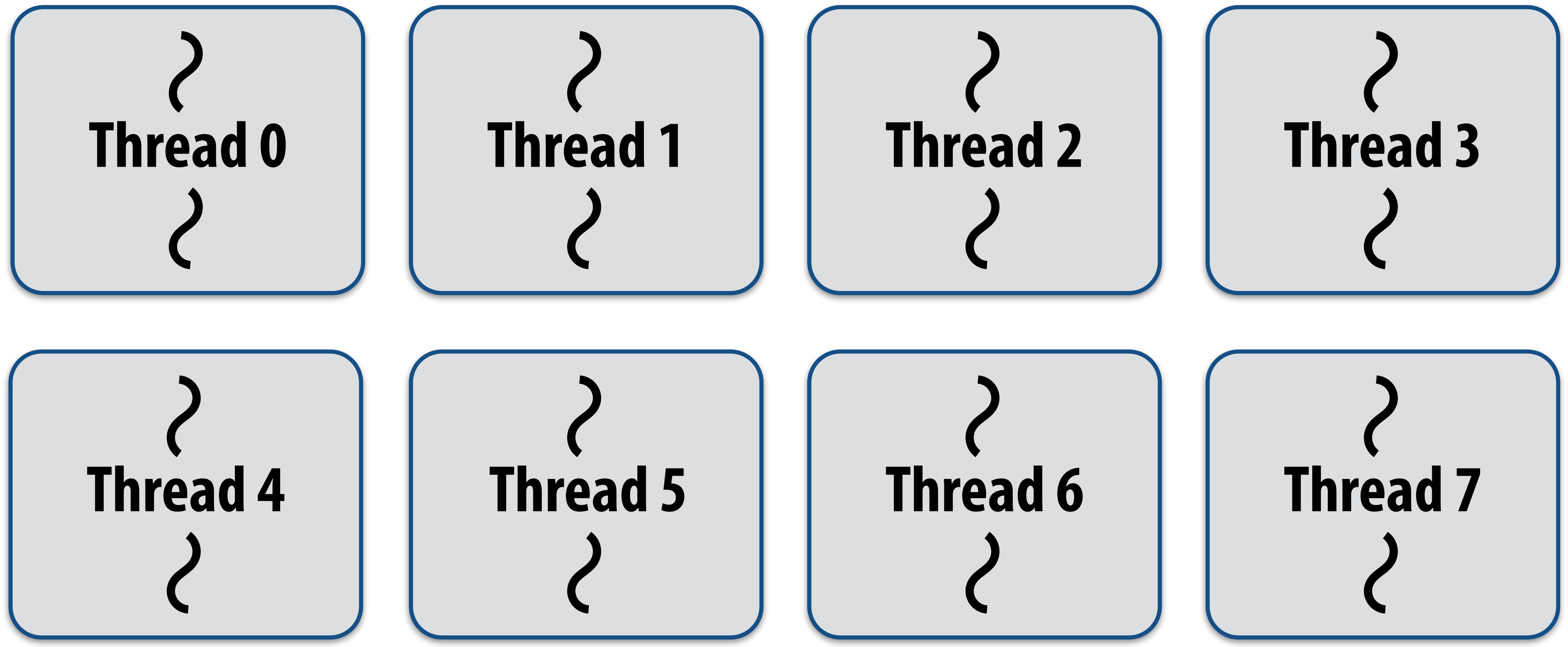
- Consider very simple scheduler:
  - Launch pthread for each `cilk_spawn` using `pthread_create`
  - Translate `cilk_sync` into appropriate `pthread_join` calls

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

Note: now we are going to talk about the implementation of Cilk

Pool of worker threads

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



Thread 0

Thread 1

Thread 2

Thread 3

Thread 4

Thread 5

Thread 6

Thread 7

Example: Eight thread worker pool for my 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.)

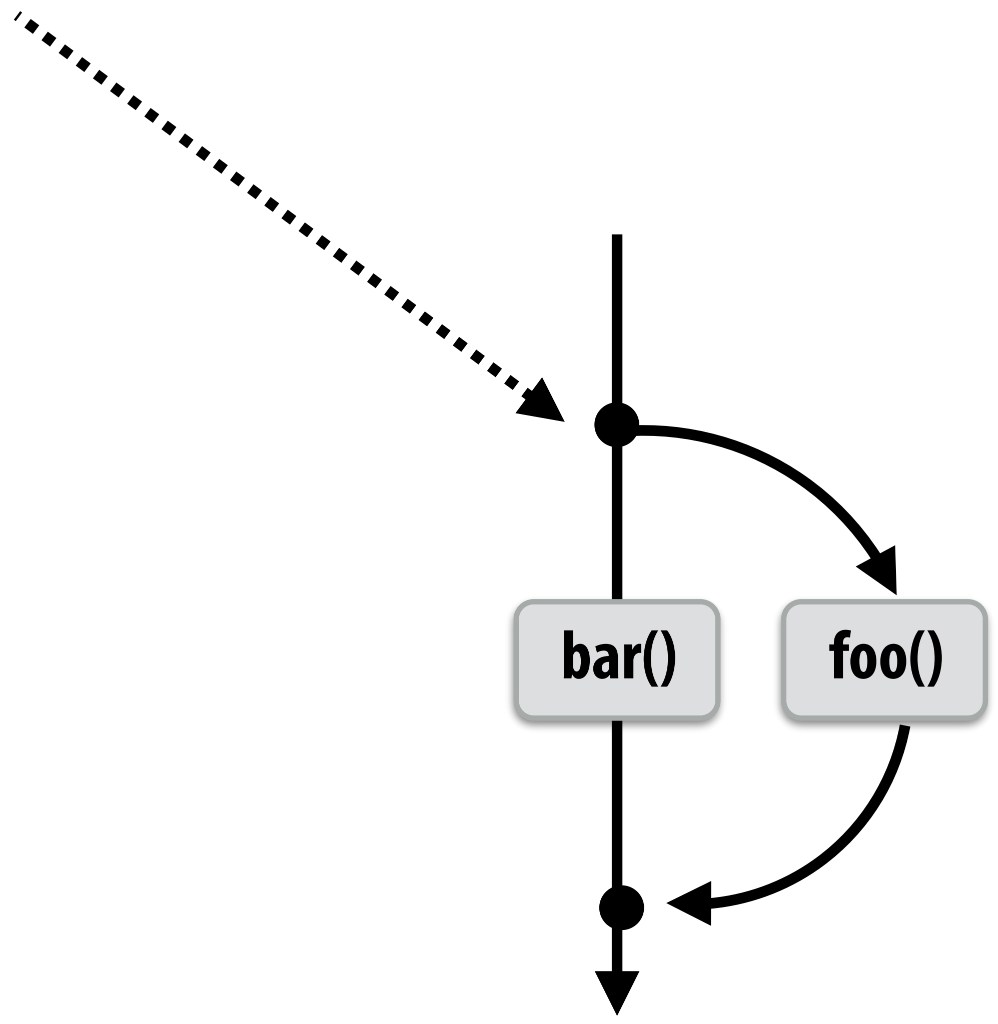
Consider execution of the following code

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

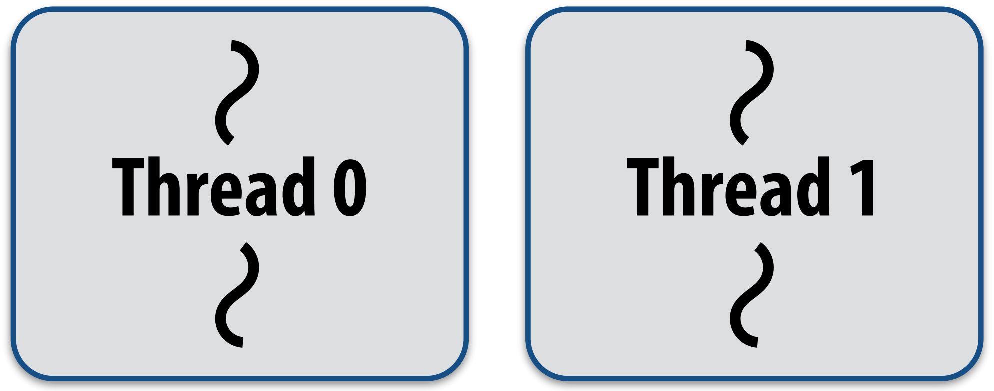
```
cilk_spawn foo();
bar();

cilk_sync;
```

spawned child

continuation (rest of calling function)



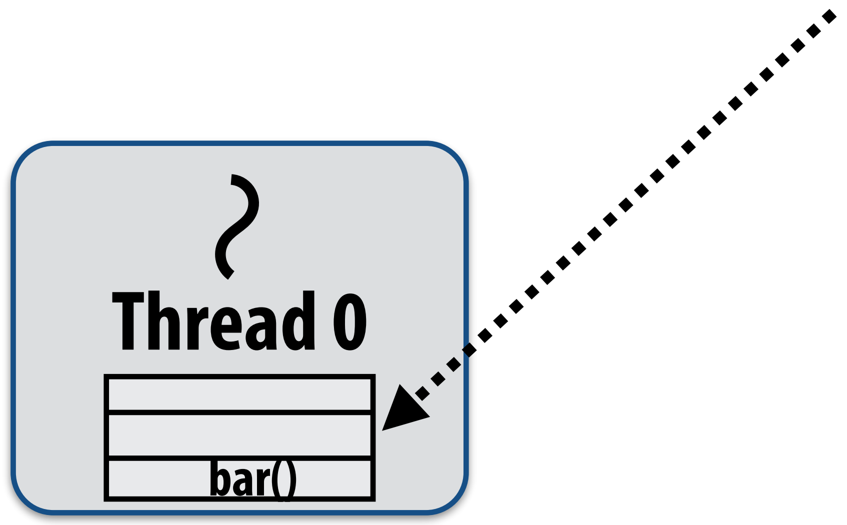
Assignment question: what threads should foo() and bar() be executed by?



First, consider a serial implementation

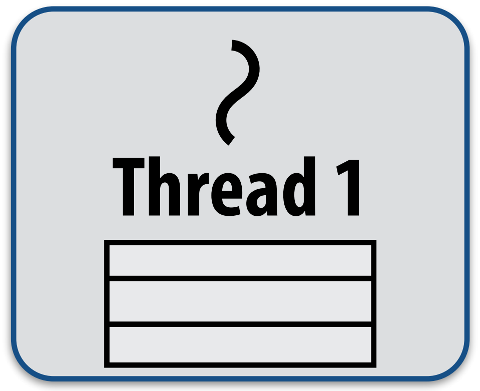
Run child first… via a regular function call

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



Traditional thread call stack (indicates bar() will be run next after return from foo())

Executing foo()…

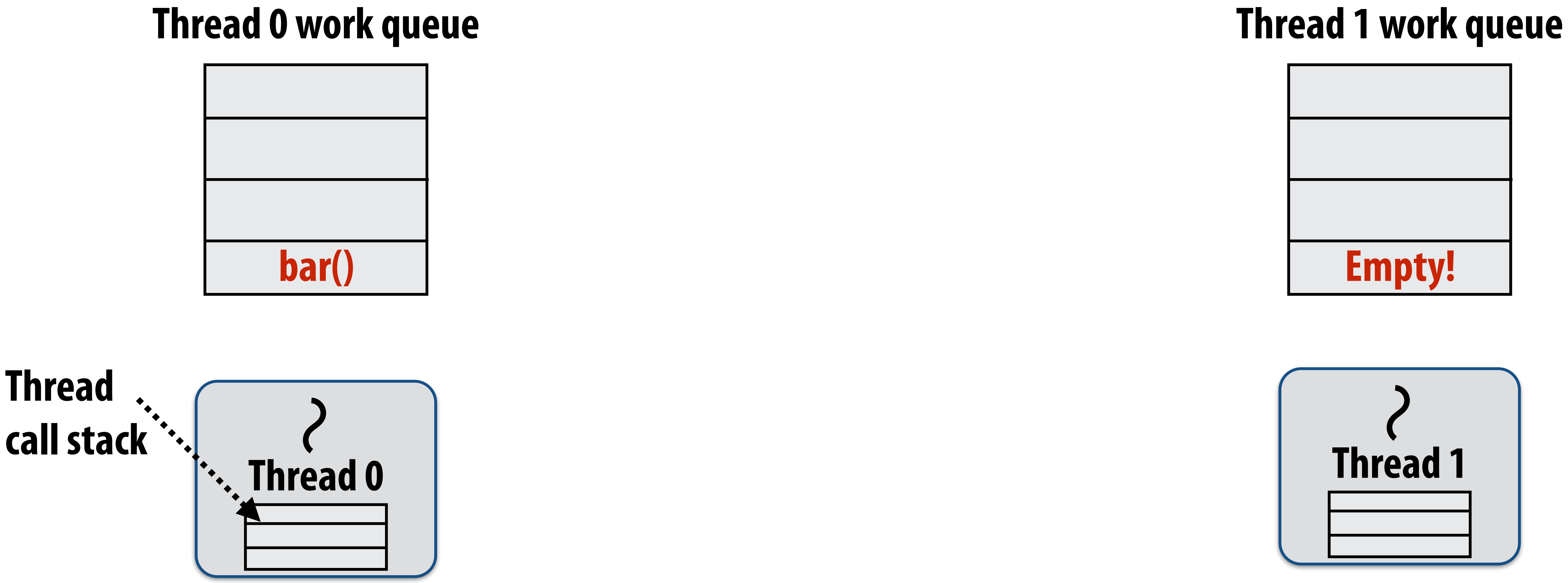


What if, while executing foo(), thread 1 goes idle…

Thread 1 could be performing bar() at this time!

Per-thread work queues store “work to do”

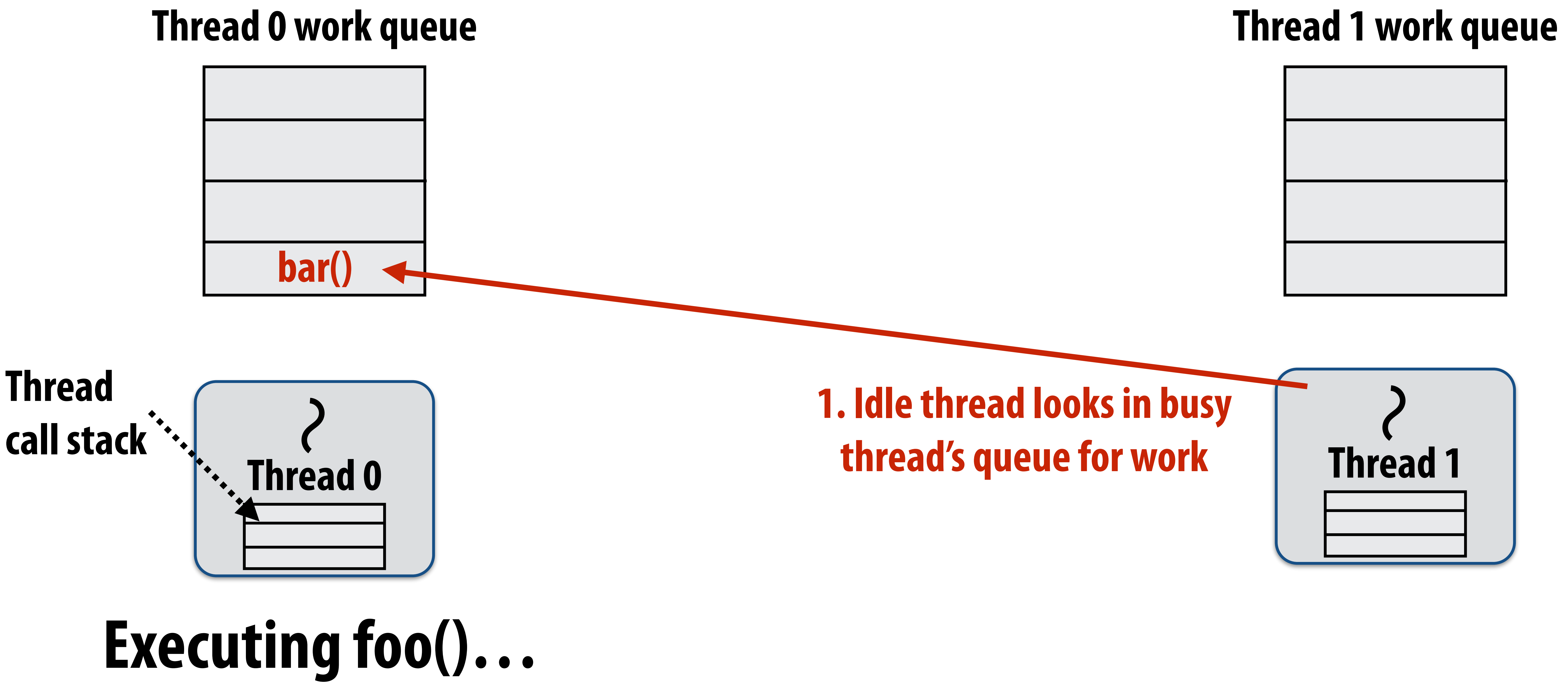
Upon reaching `cilk_spawn foo()`, thread places continuation in its work queue, and begins executing foo().



Executing foo()…

Idle threads "steal" work from busy threads

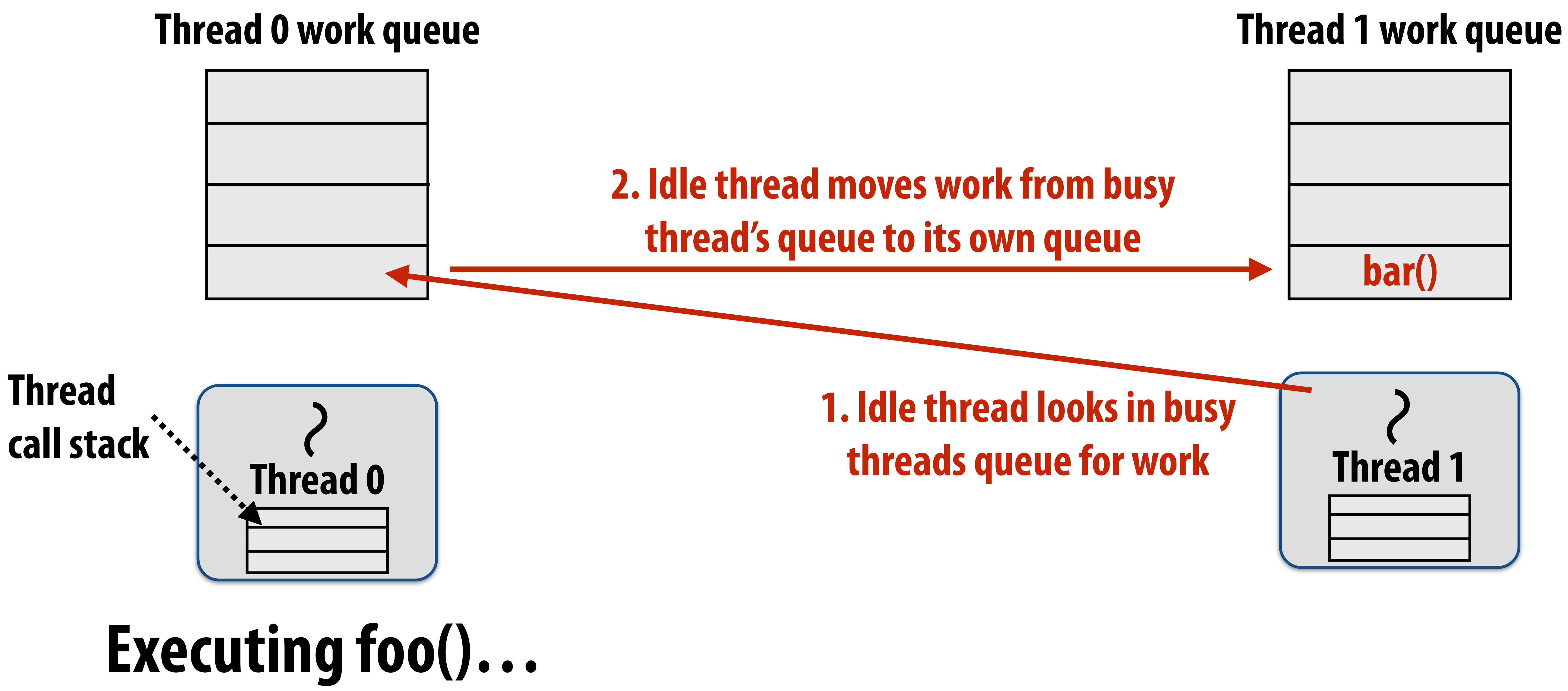
If thread 1 goes idle (a.k.a. there is no work in its own queue), then it looks in thread 0's queue for work to do.



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

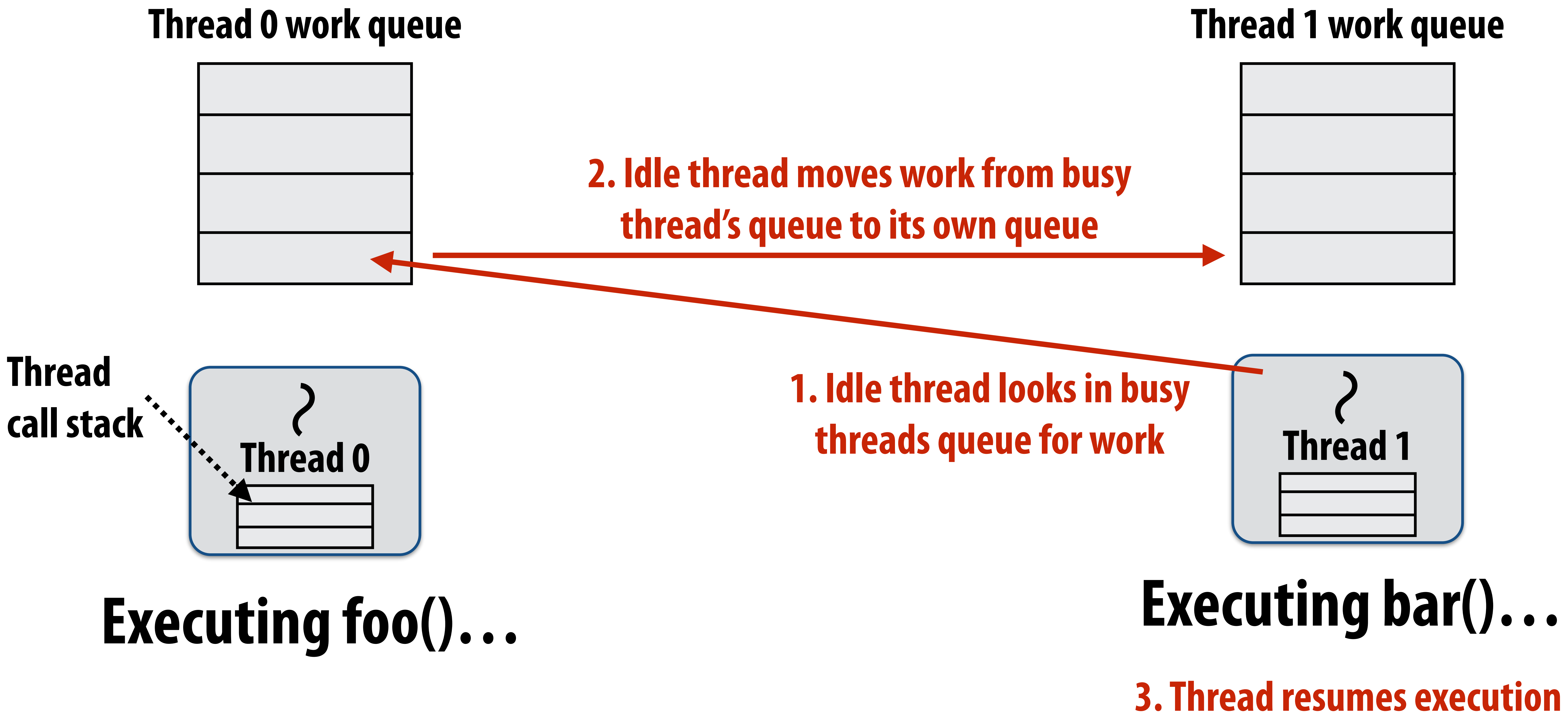
Idle threads "steal" work from busy threads

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.


Thread 0 work queue
Thread 1 work queue
2. Idle thread moves work from busy thread's queue to its own queue
bar()
Thread call stack
Thread 0
1. Idle thread looks in busy threads queue for work
Thread 1
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.

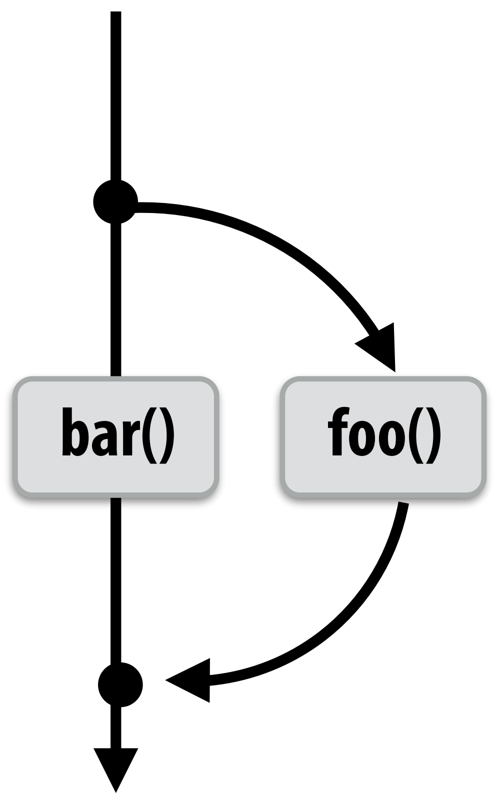

Thread 0 work queue
Thread 1 work queue
2. Idle thread moves work from busy thread's queue to its own queue
Thread call stack
Thread 0
1. Idle thread looks in busy threads queue for work
Thread 1
Executing foo()…
Executing bar()…
3. Thread resumes execution

At spawn, should calling thread run the child or the continuation?

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

cilk_sync;
```

spawned child

continuation (rest of calling function)



Run continuation first: queue child for later execution

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

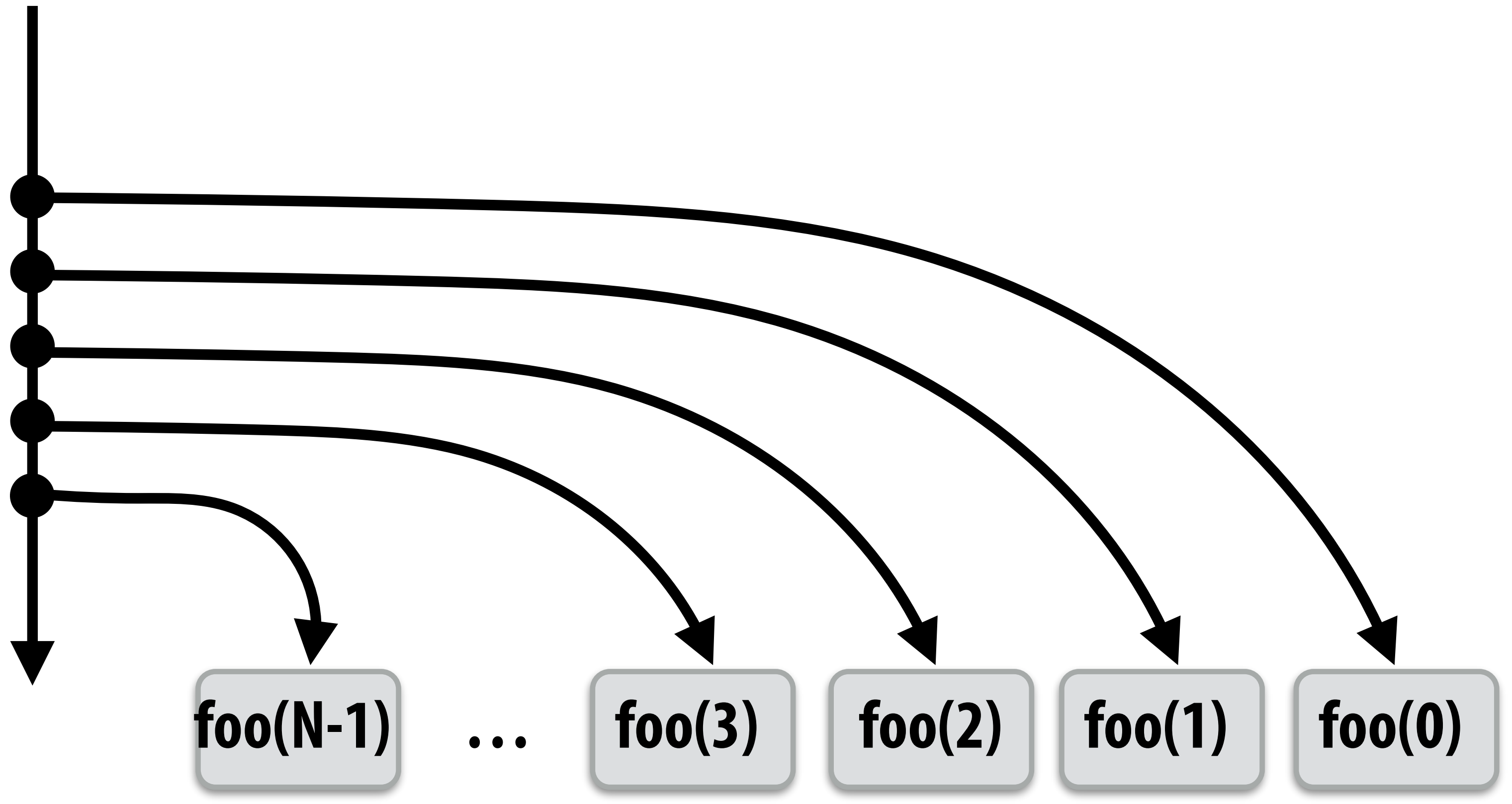
Run child first: enqueue continuation for later execution

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

Which implementation do we choose?

Consider thread executing the following code

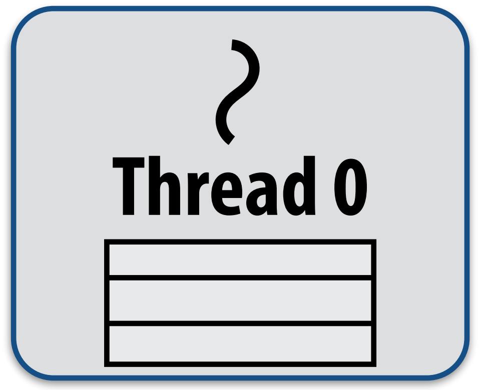
```
for (int i=0; i<N; i++) {
  cilk_spawn foo(i);
}
cilk_sync;
```



- **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

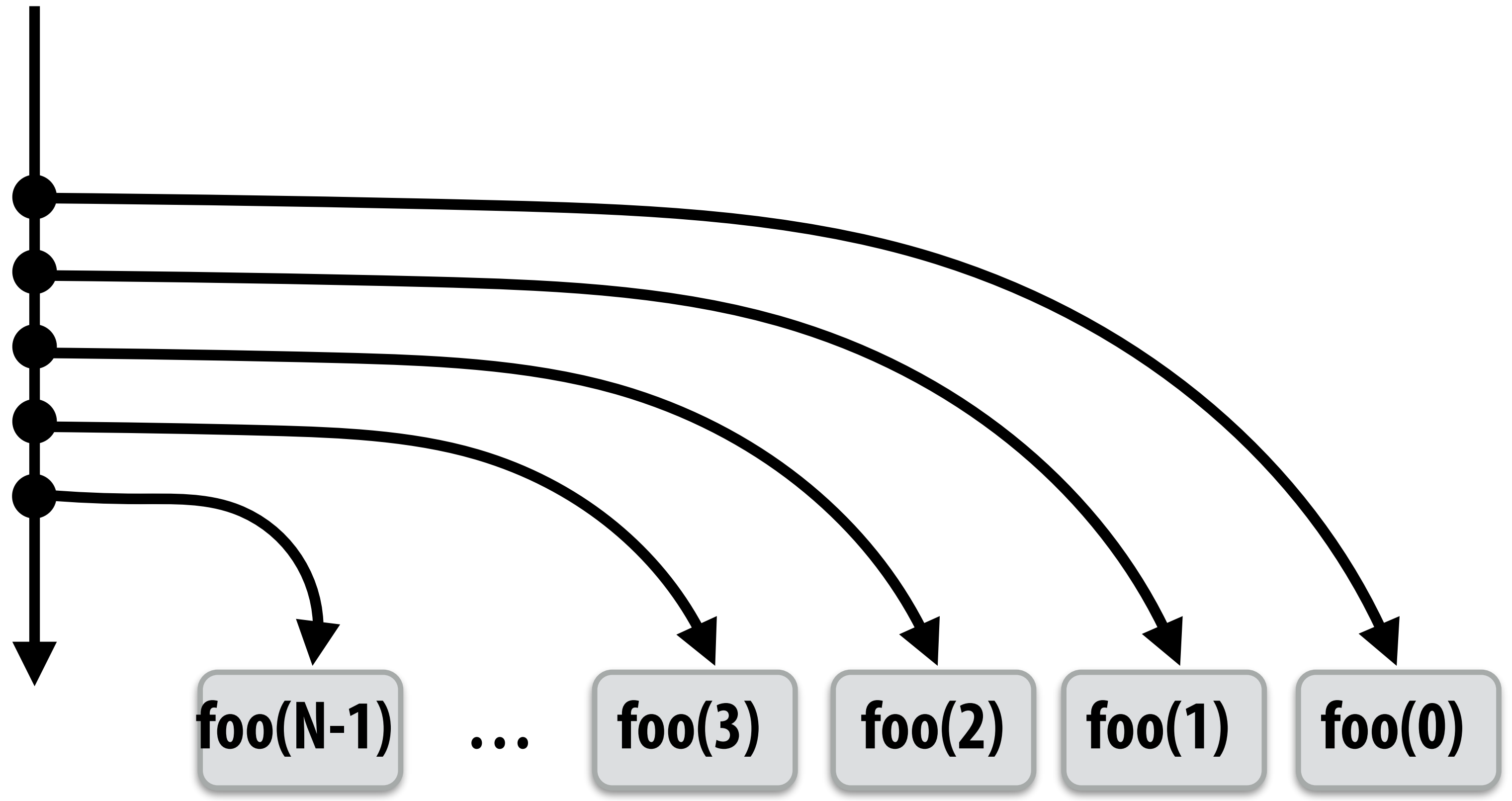
Thread 0 work queue

foo(0)
…
foo(N-2)
foo(N-1)

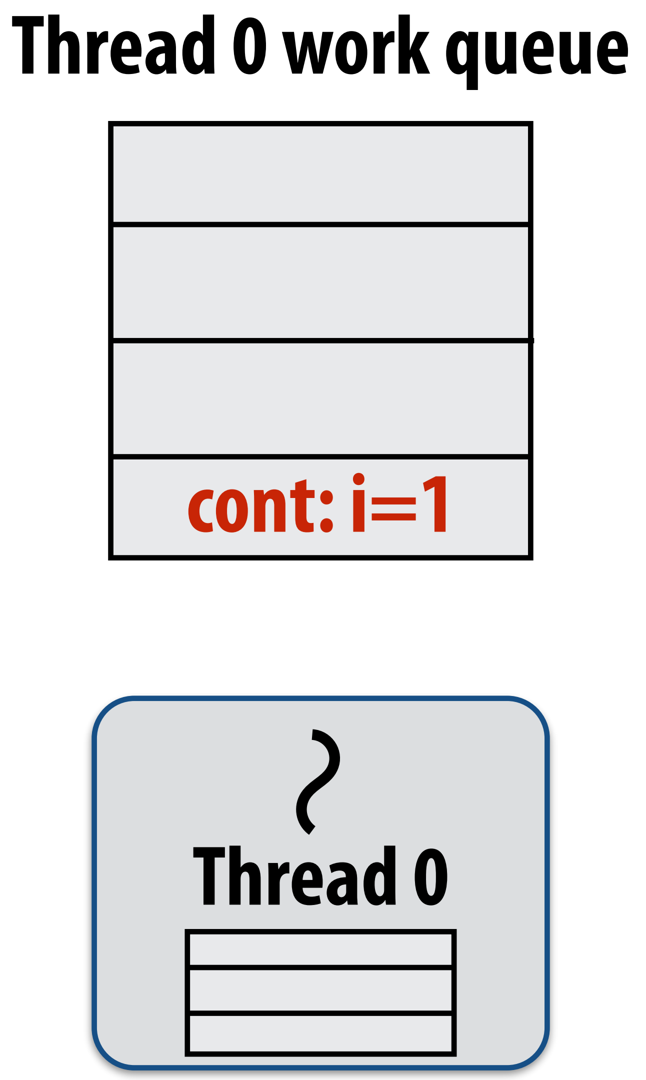


Consider thread executing the following code

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



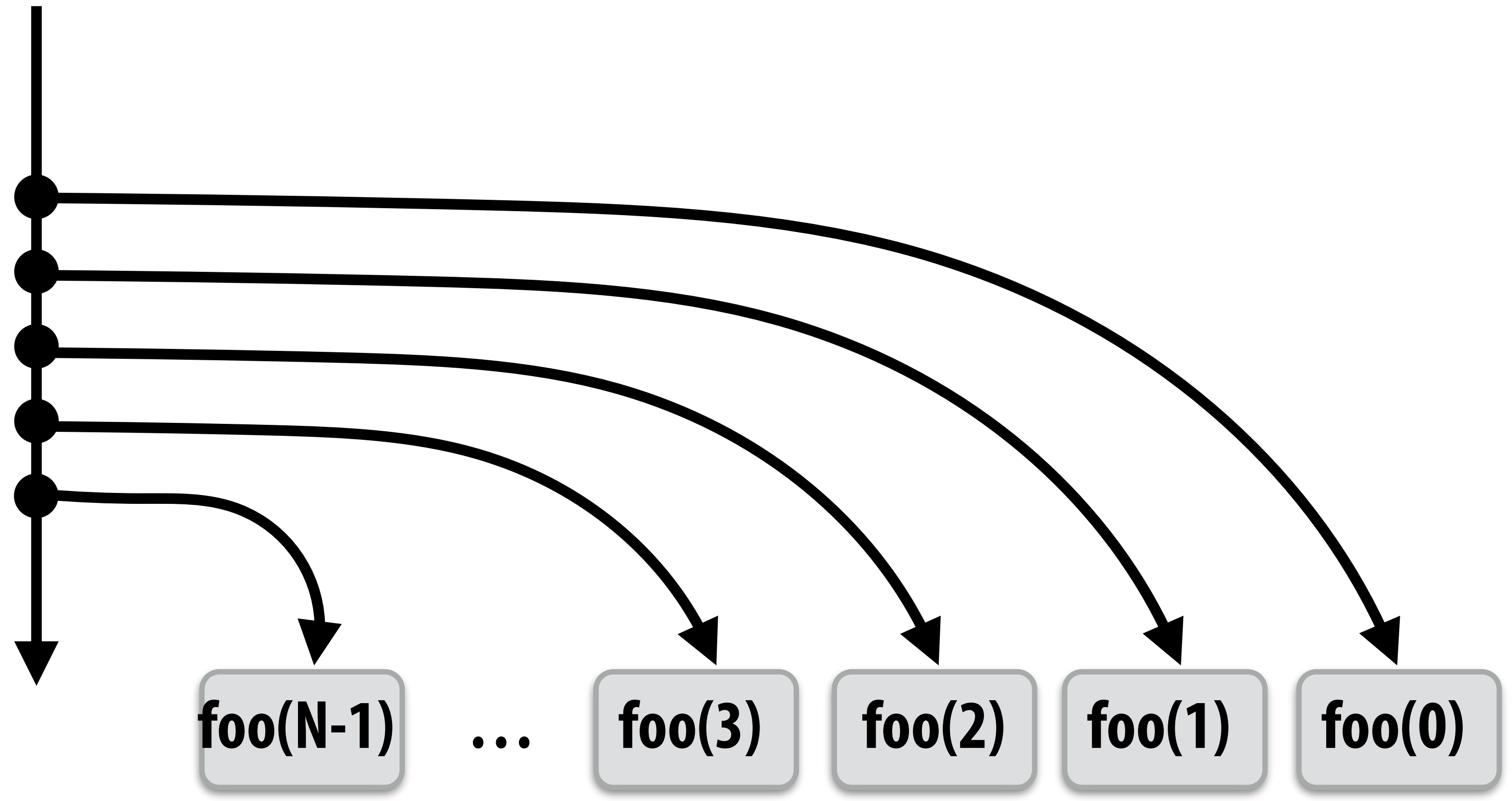
- Run child first ("continuation stealing")
  - Caller thread only creates one item to steal (continuation that represents all remaining iterations)
  - If no stealing occurs, thread continually pops continuation from work queue, enqueues new continuation (with updated value of `i`)
  - Order of execution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



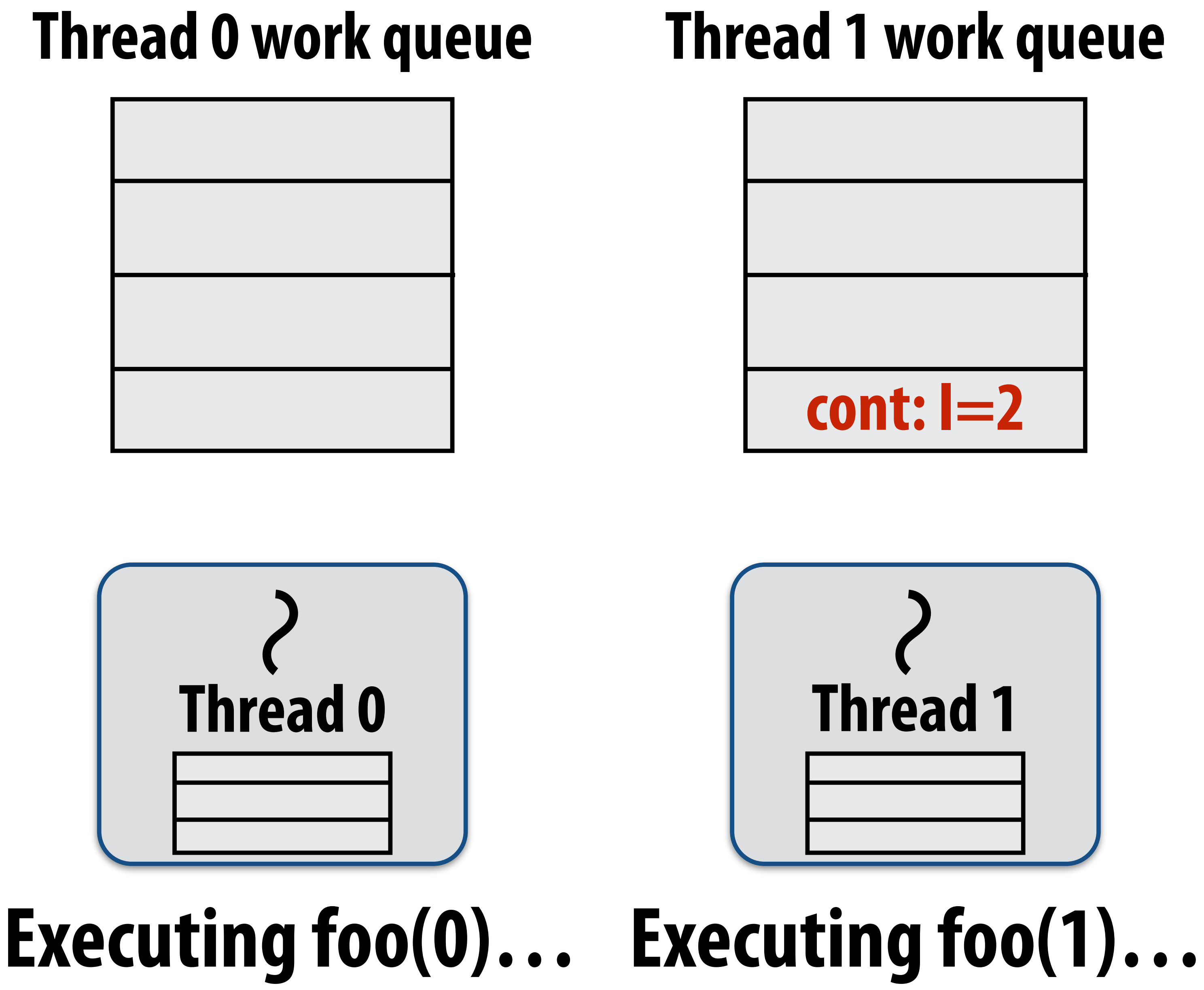
Executing foo(0)…

Consider thread executing the following code

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



- **Run child first ("continuation stealing")**
  - Enqueues continuation with `i` advanced by 1
  - If continuation is stolen, stealing thread spawns and executes next iteration
  - 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

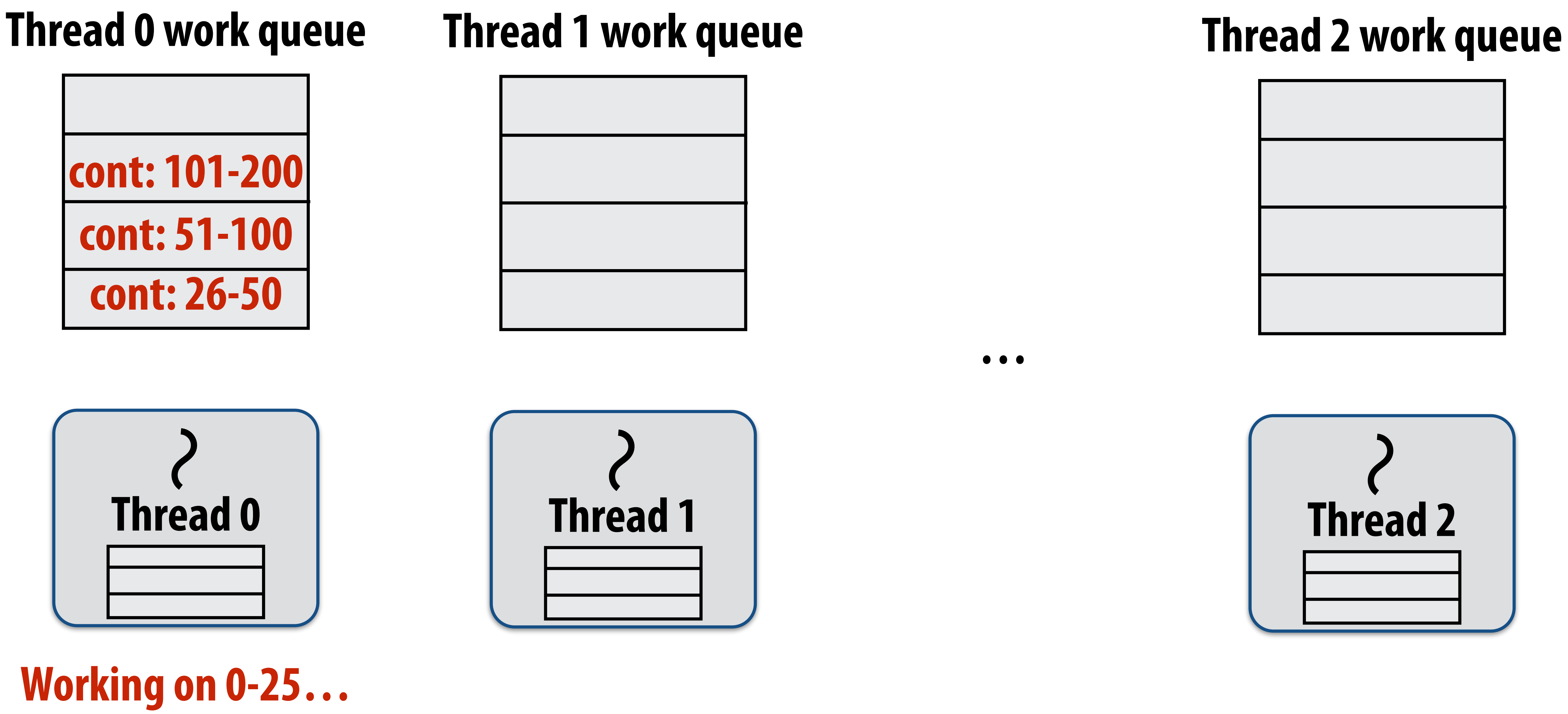


Scheduling quicksort: assume 200 elements

```
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?

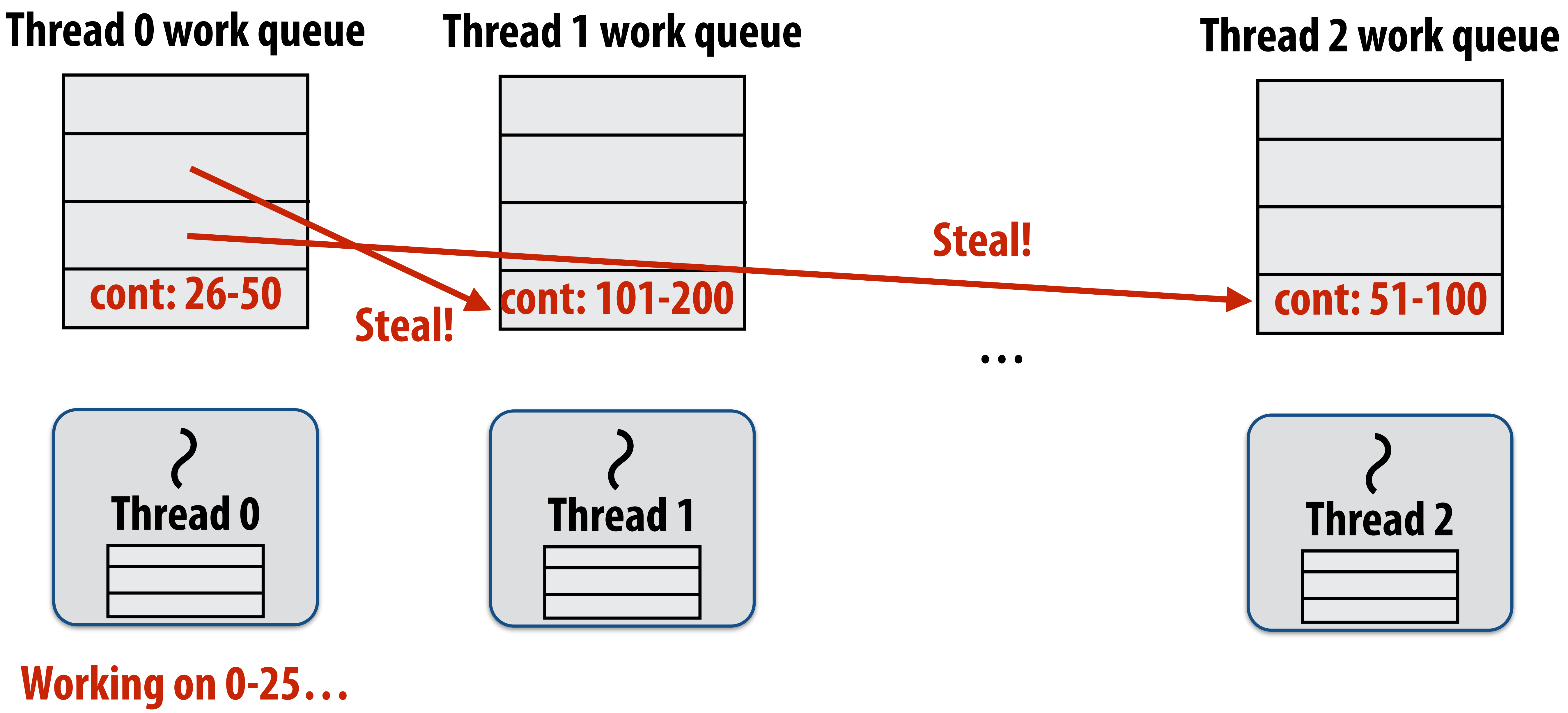
(e.g., steal from top or bottom)



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)



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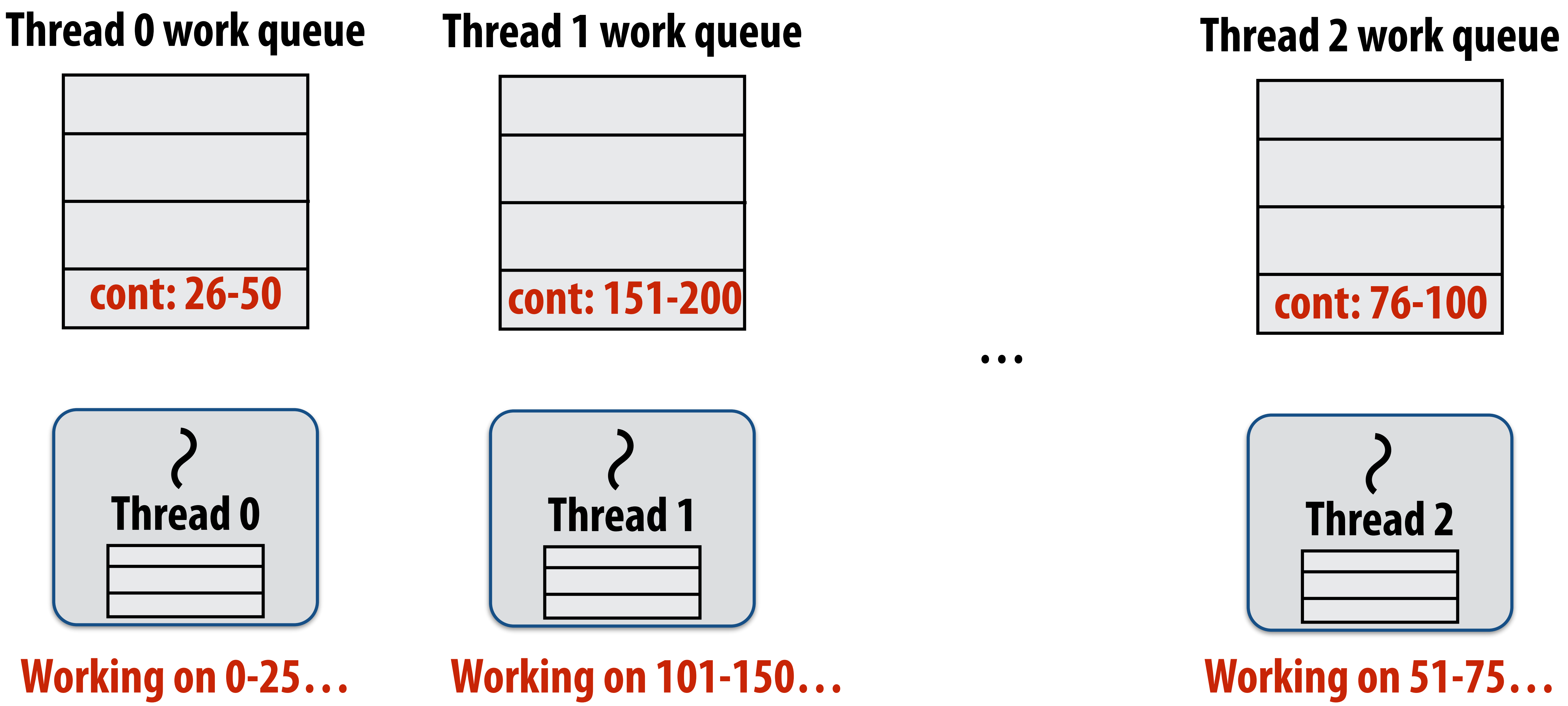

Implementing work stealing: dequeue per worker

Work queue implemented as a dequeue (double ended queue)

- Local thread pushes/pops from the "tail" (bottom)
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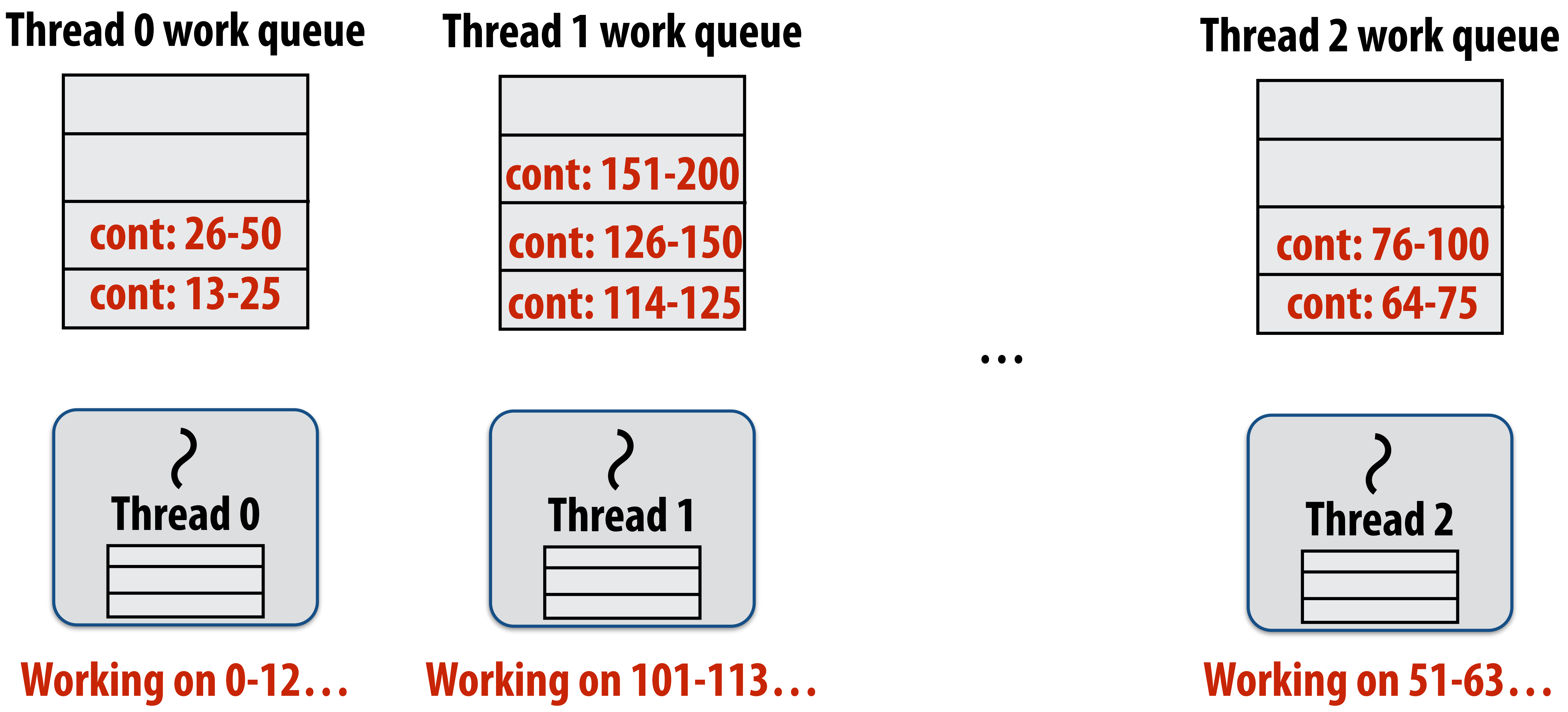
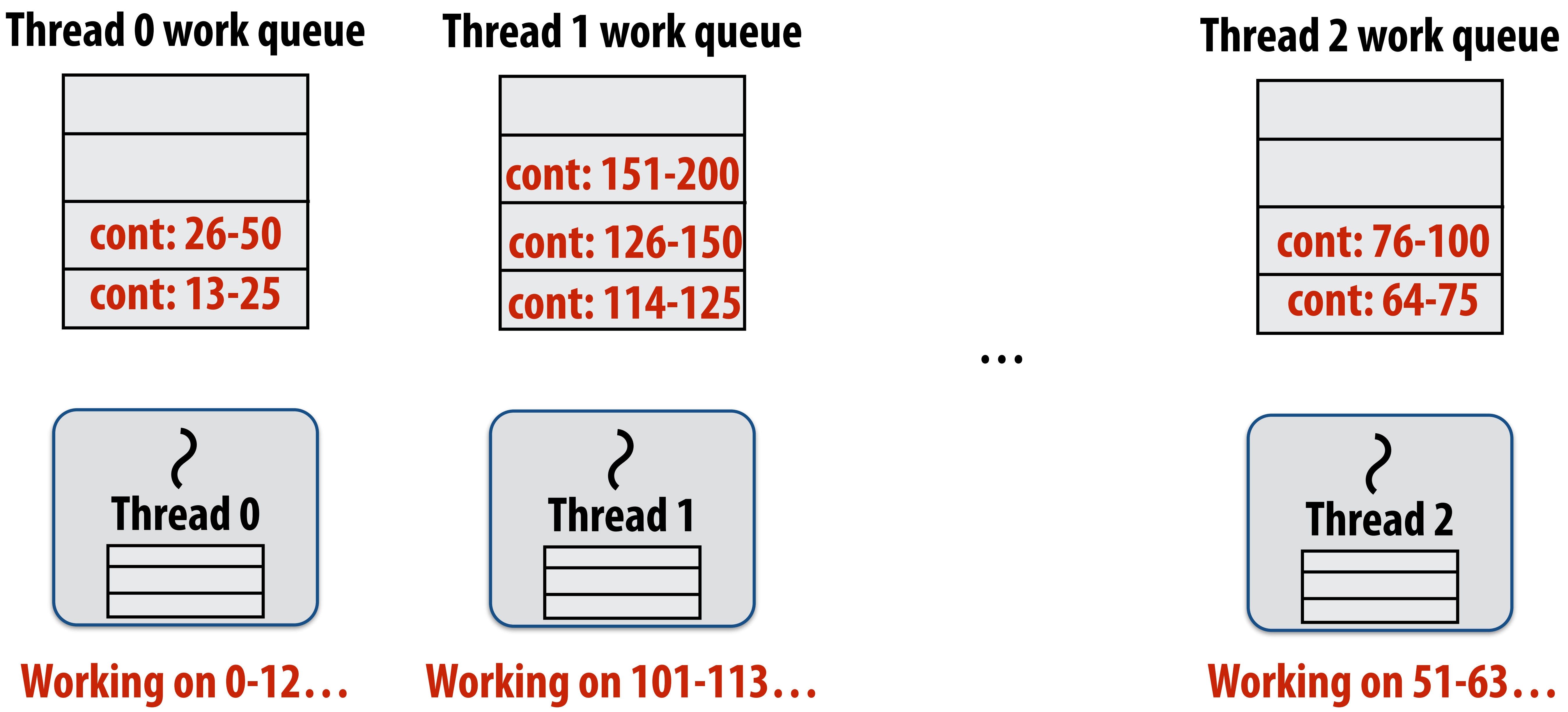


Implementing work stealing: choice of victim

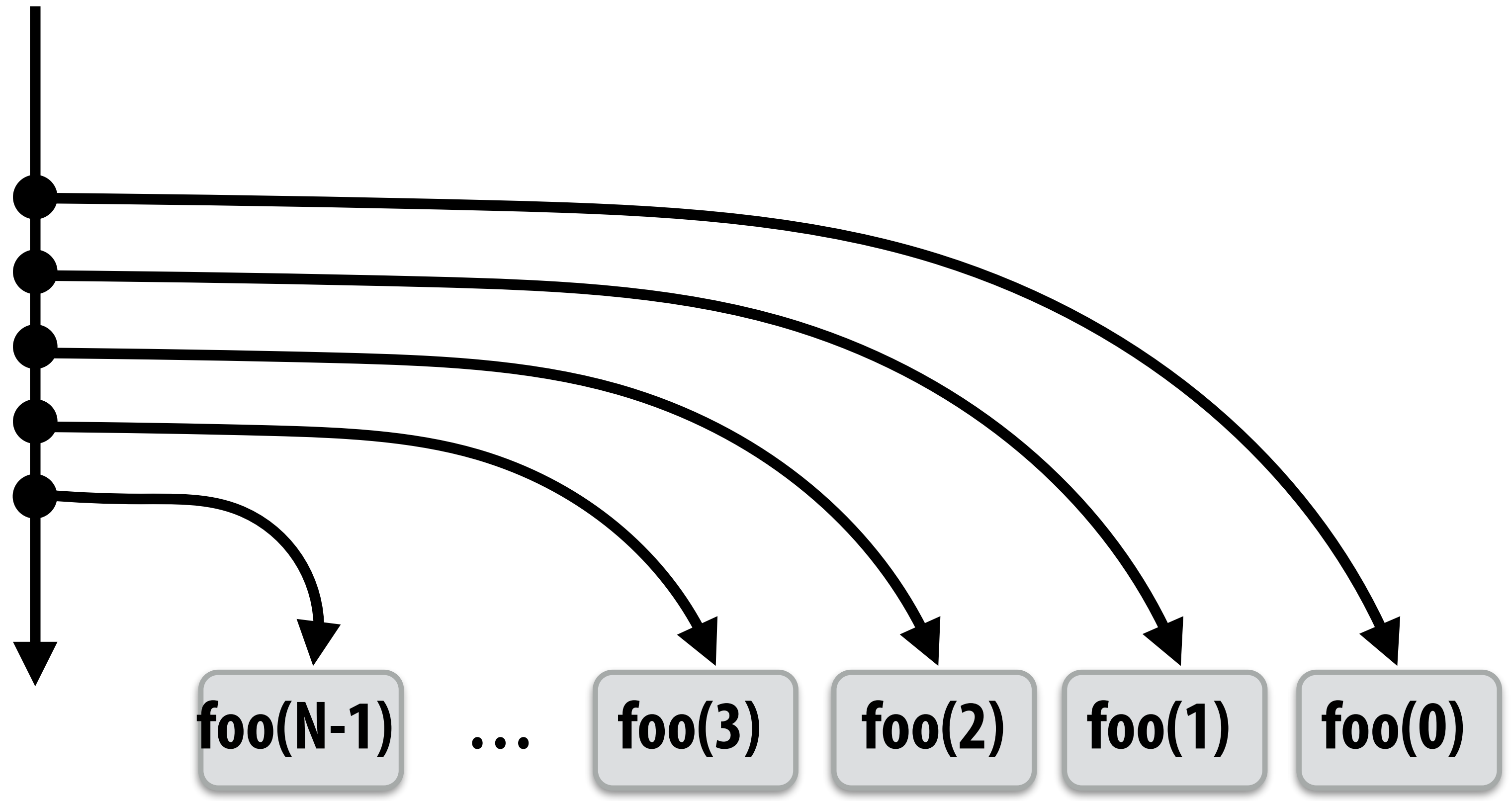
- Idle threads randomly choose a thread to attempt to steal from
- Steal work from top of dequeue:
  - Steals largest amount of work (reduce number of steals)
  - Maximum locality in work each thread performs (when combined with run child first scheme)
  - Stealing thread and local thread do not contend for same elements of dequeue (efficient lock-free implementations of dequeue exist)

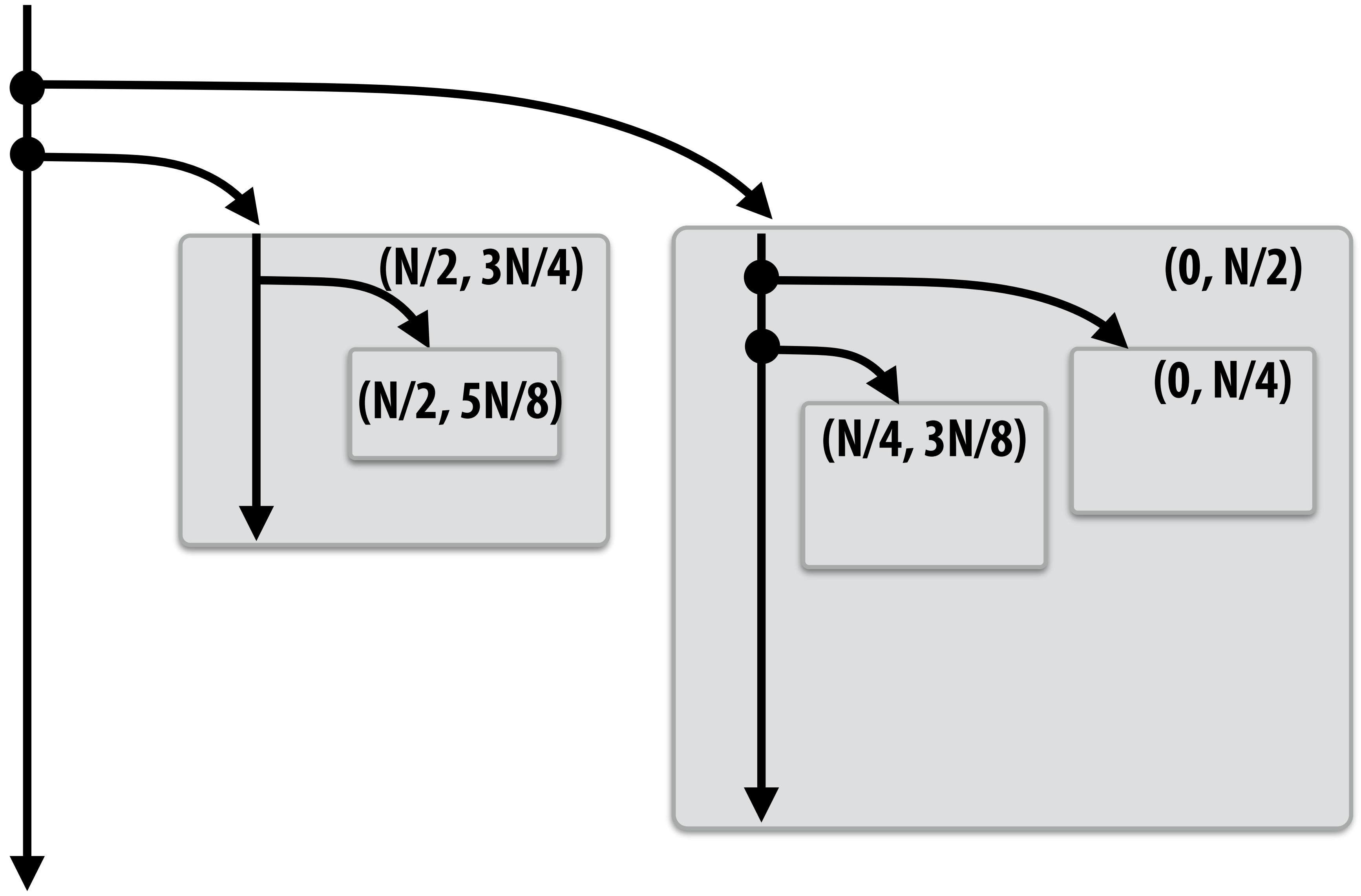


Child-first work stealing scheduler anticipates divide-and-conquer parallelism

```
for (int i=0; i<N; i++) {

  cilk_spawn foo(i);

}

cilk_sync;
```

```
void recursive_for(int start, int end) {

  while (start <= end - 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);
```

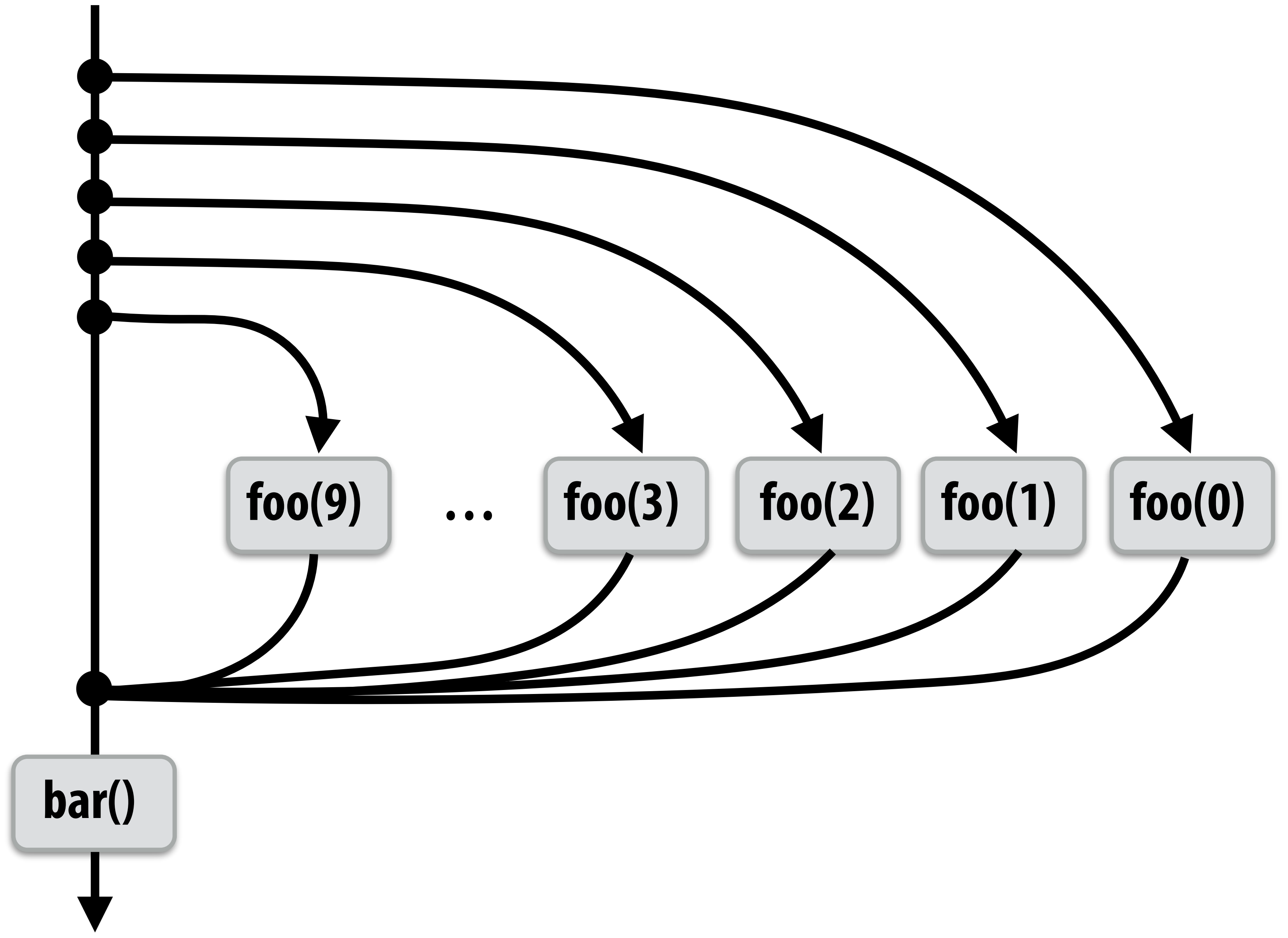


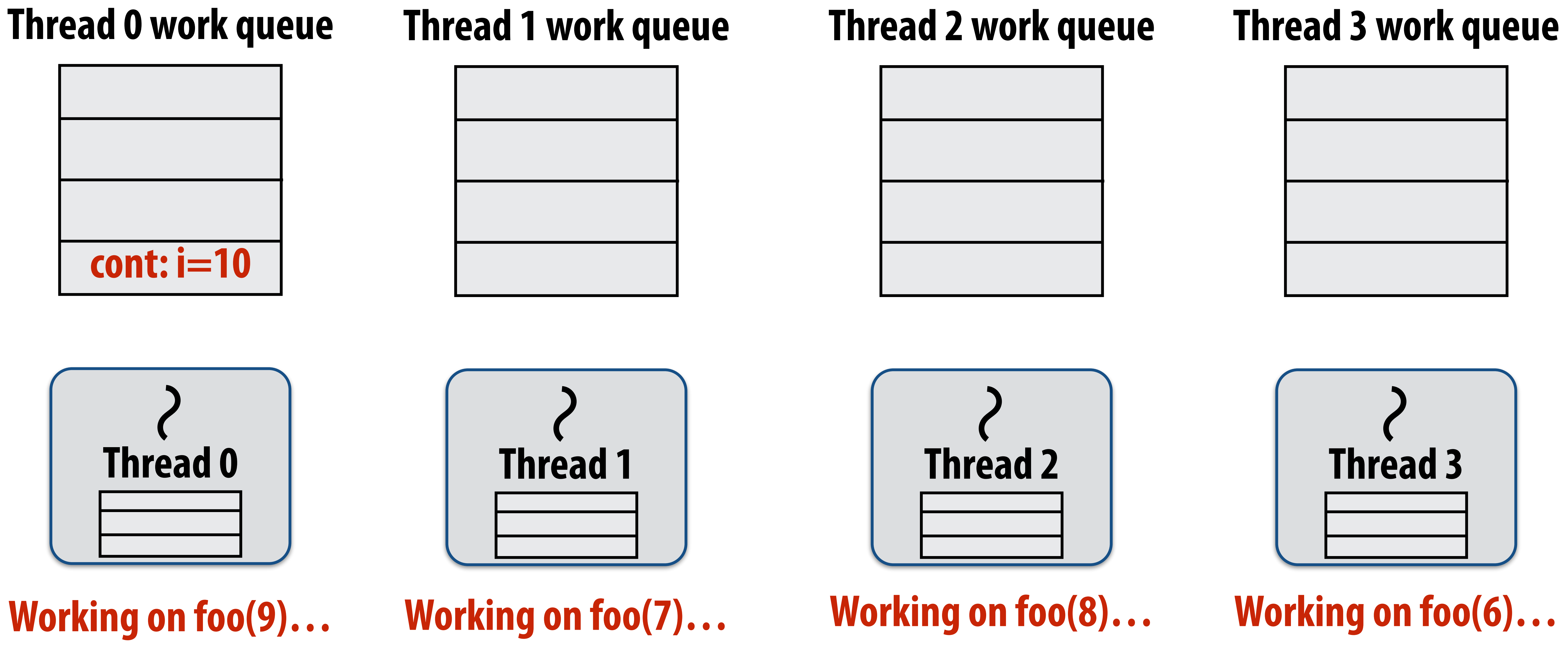


Code at right generates work in parallel, (code at left does not), so it more quickly fills up parallel machine

Implementing sync

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





Working on foo(9)…

Working on foo(7)…

Working on foo(8)…

Working on foo(6)…

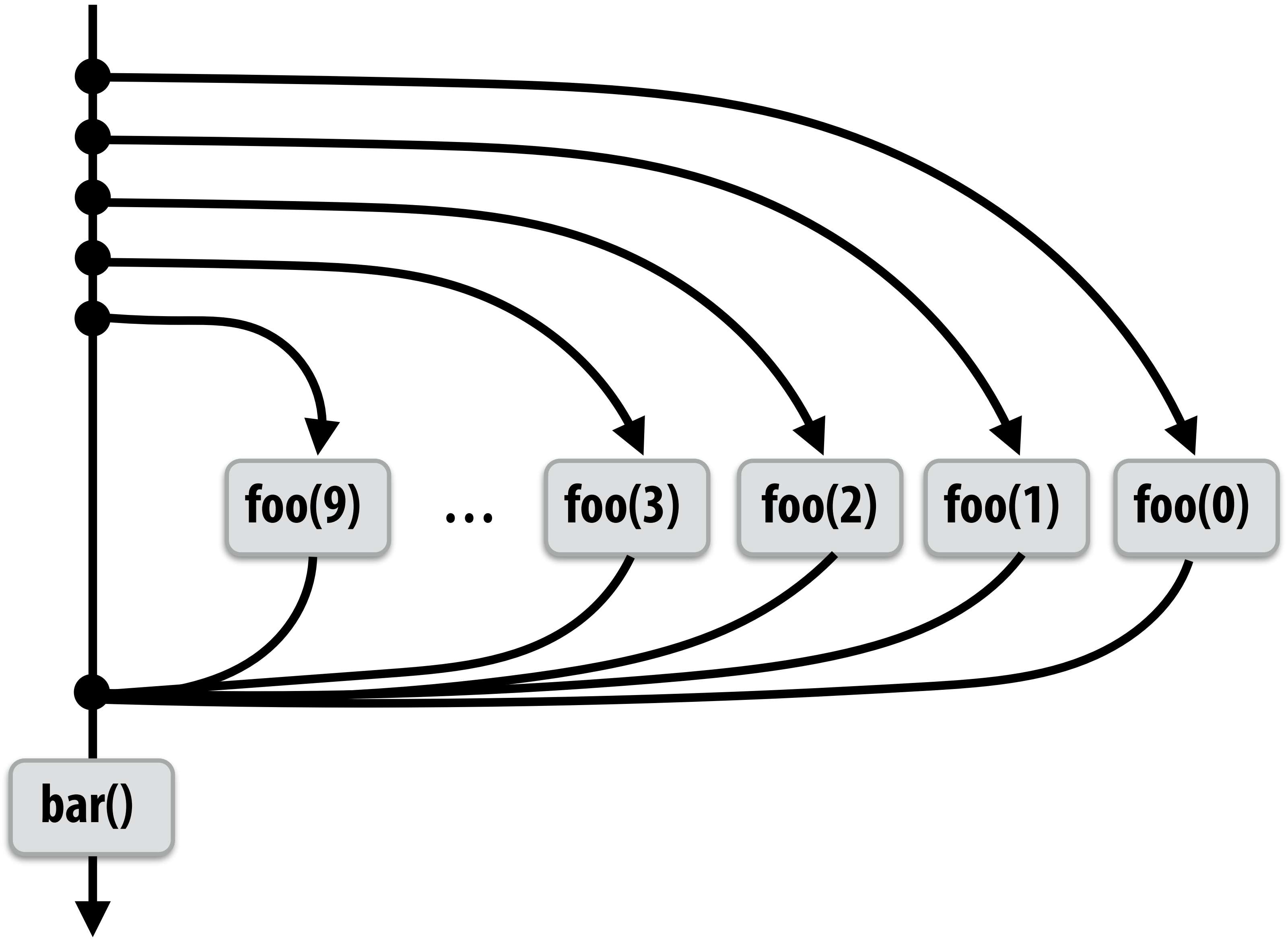
State of worker threads when all work from loop is nearly complete

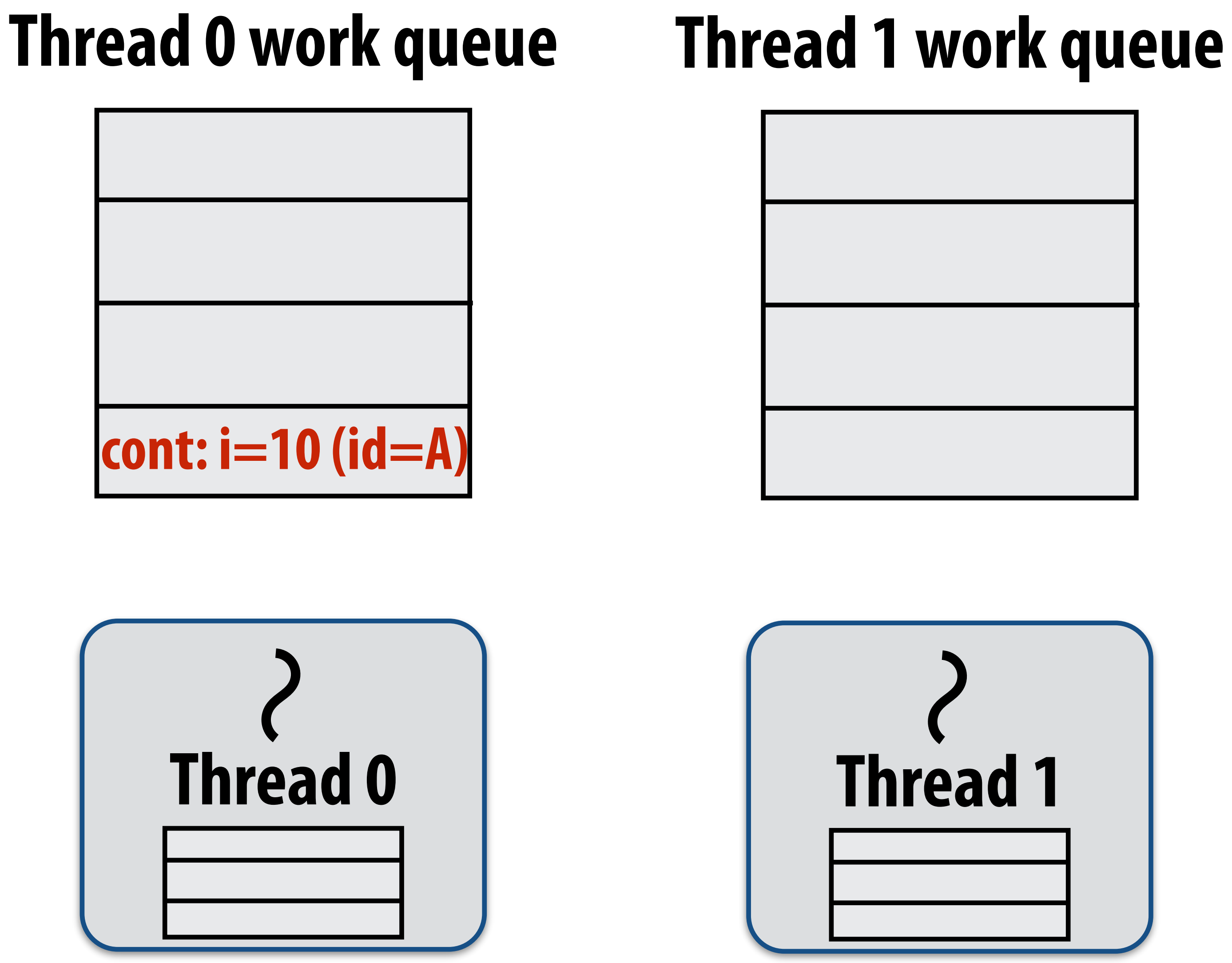
Implementing sync: no stealing case

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





cont: i=10 (id=A)

Working on foo(9), id=A…

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.

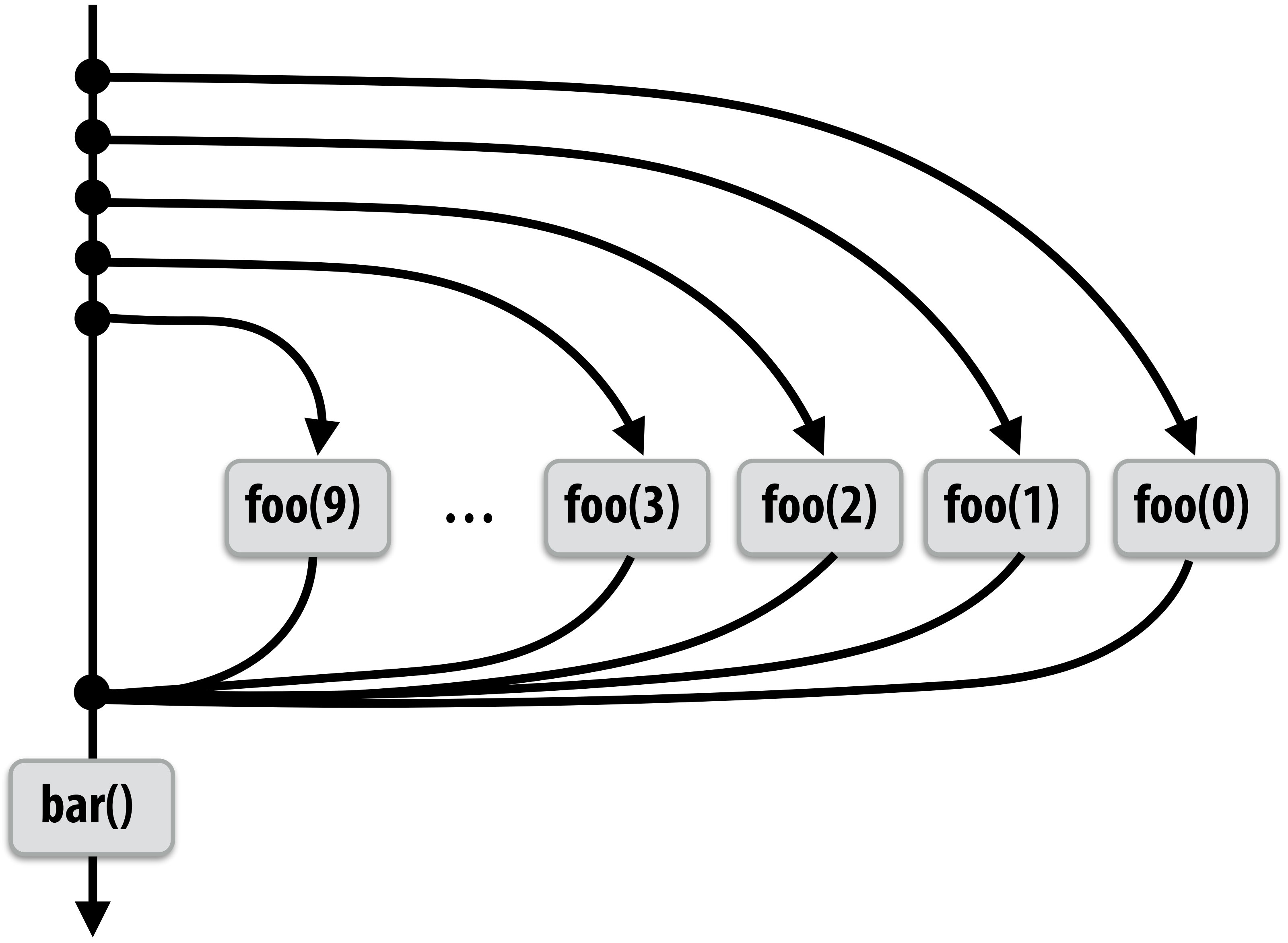
Implementing sync: stealing case

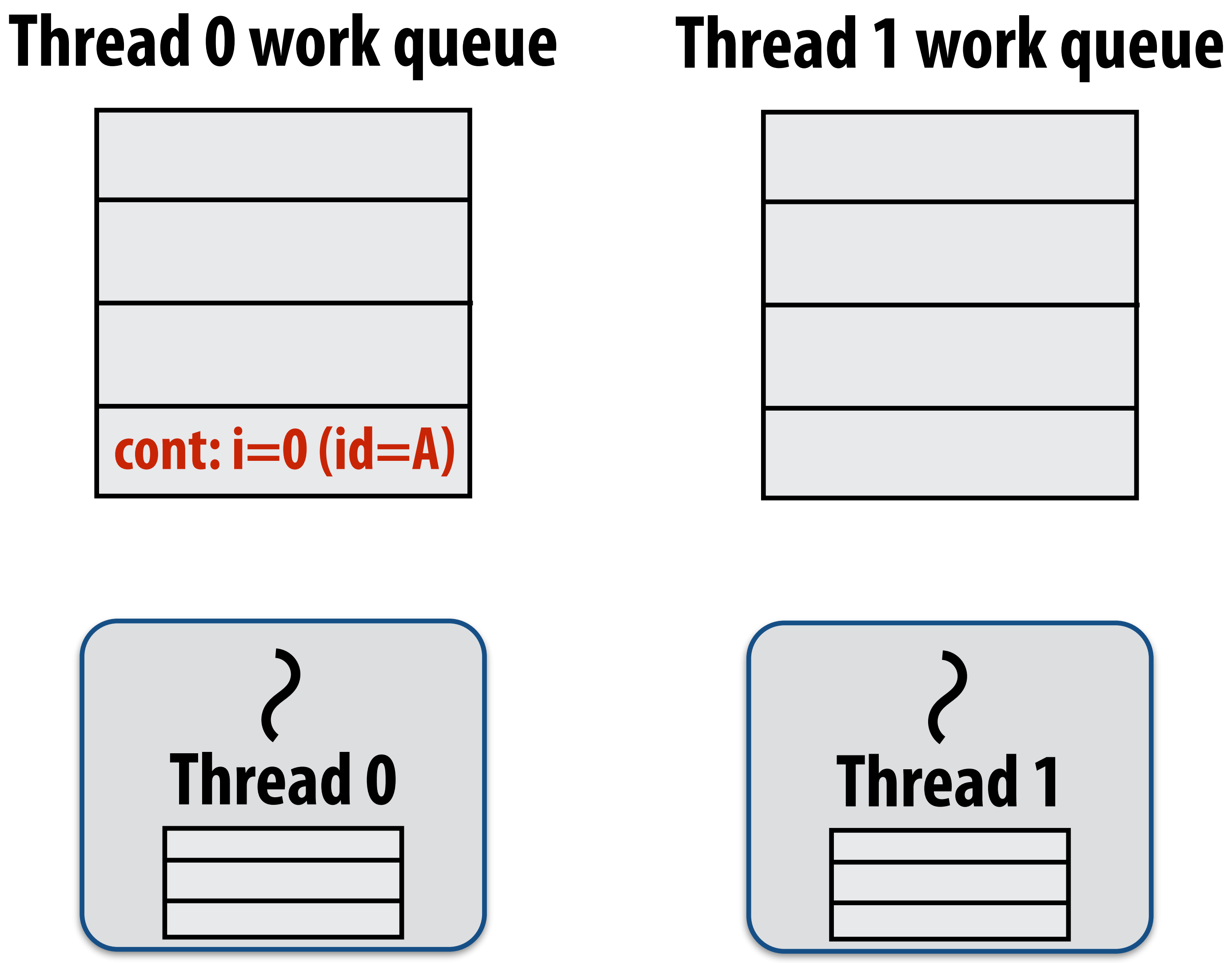
block (id: A)

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

Sync for all calls spawned within block A

```
bar();
```





Thread 0 work queue

cont: i=0 (id=A)

Thread 1 work queue

Working on foo(0), id=A…

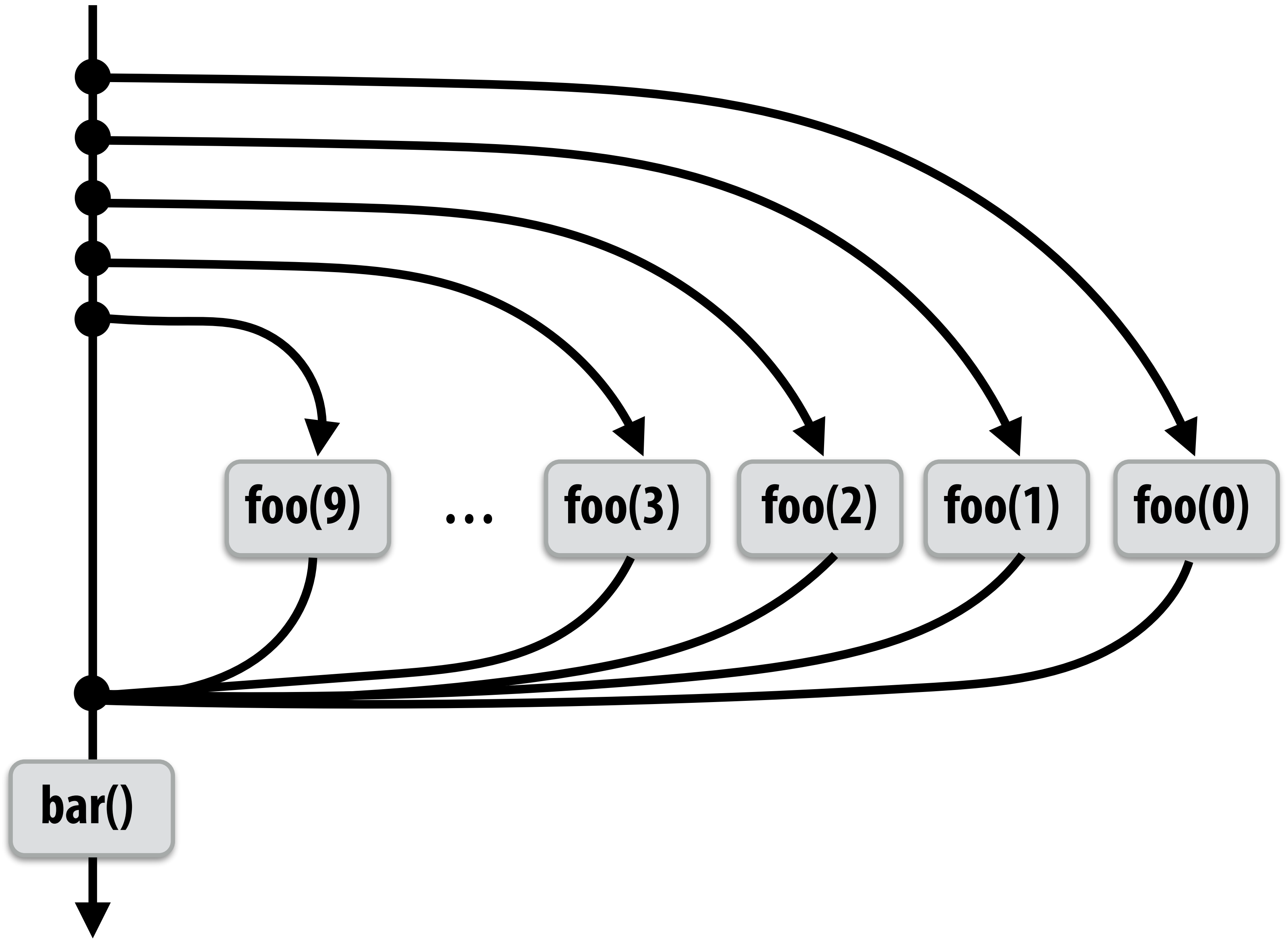
Implementing sync: stealing case

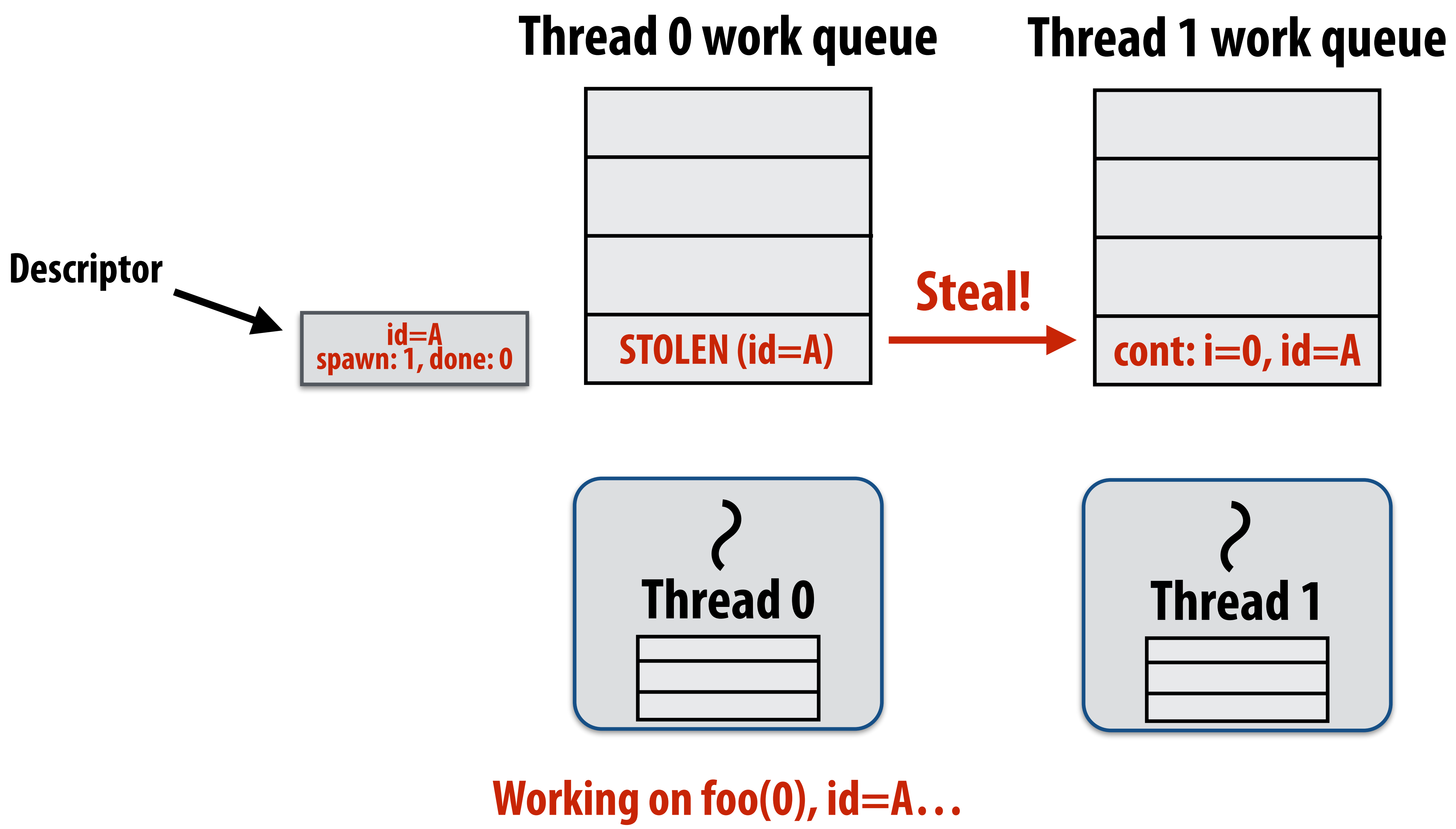
block (id: A)

```
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

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.

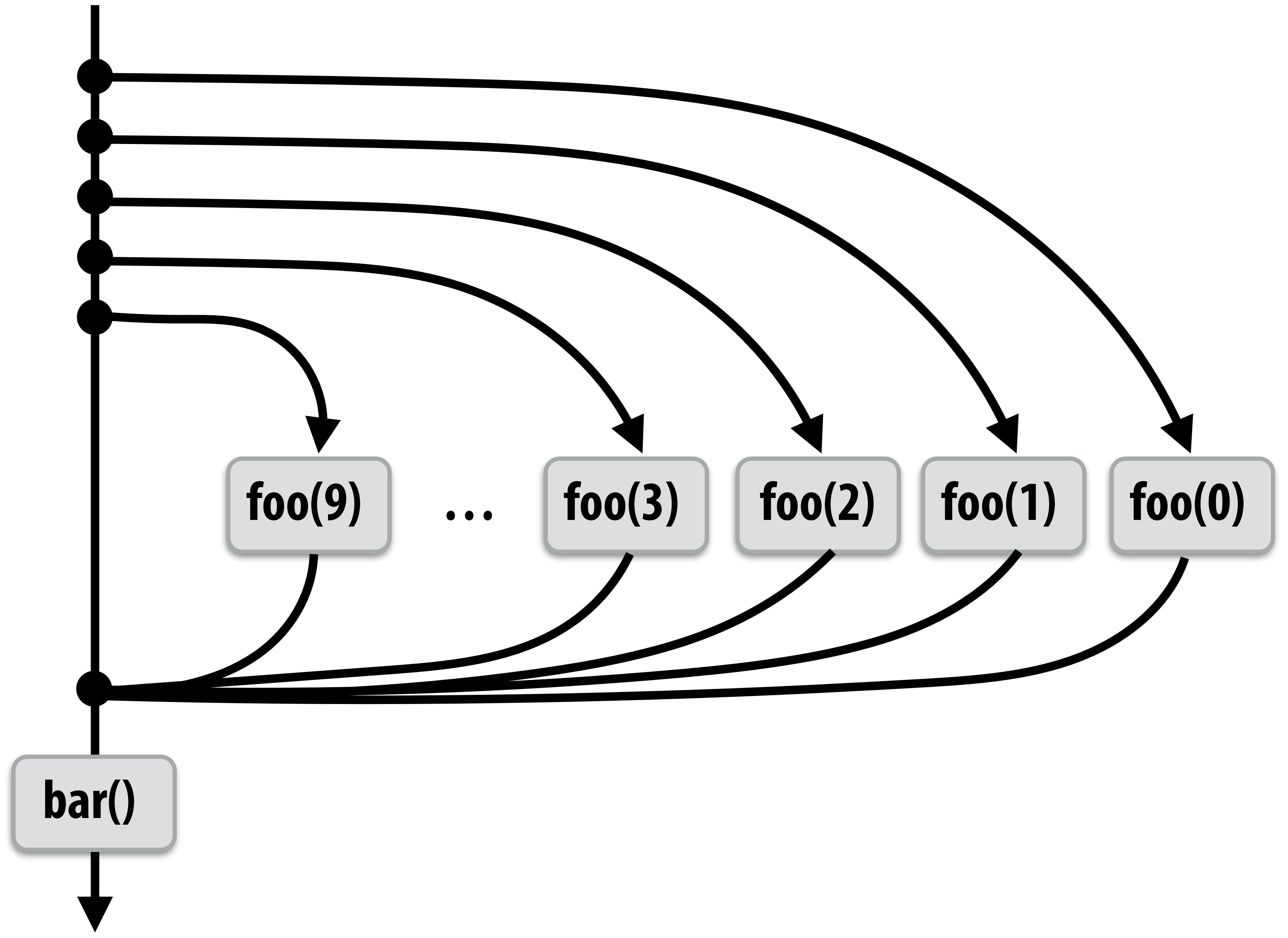
The 1 spawn tracked by the descriptor corresponds to foo(0) being run by thread 0. (Since the continuation is now owned by thread 1 after the steal.)

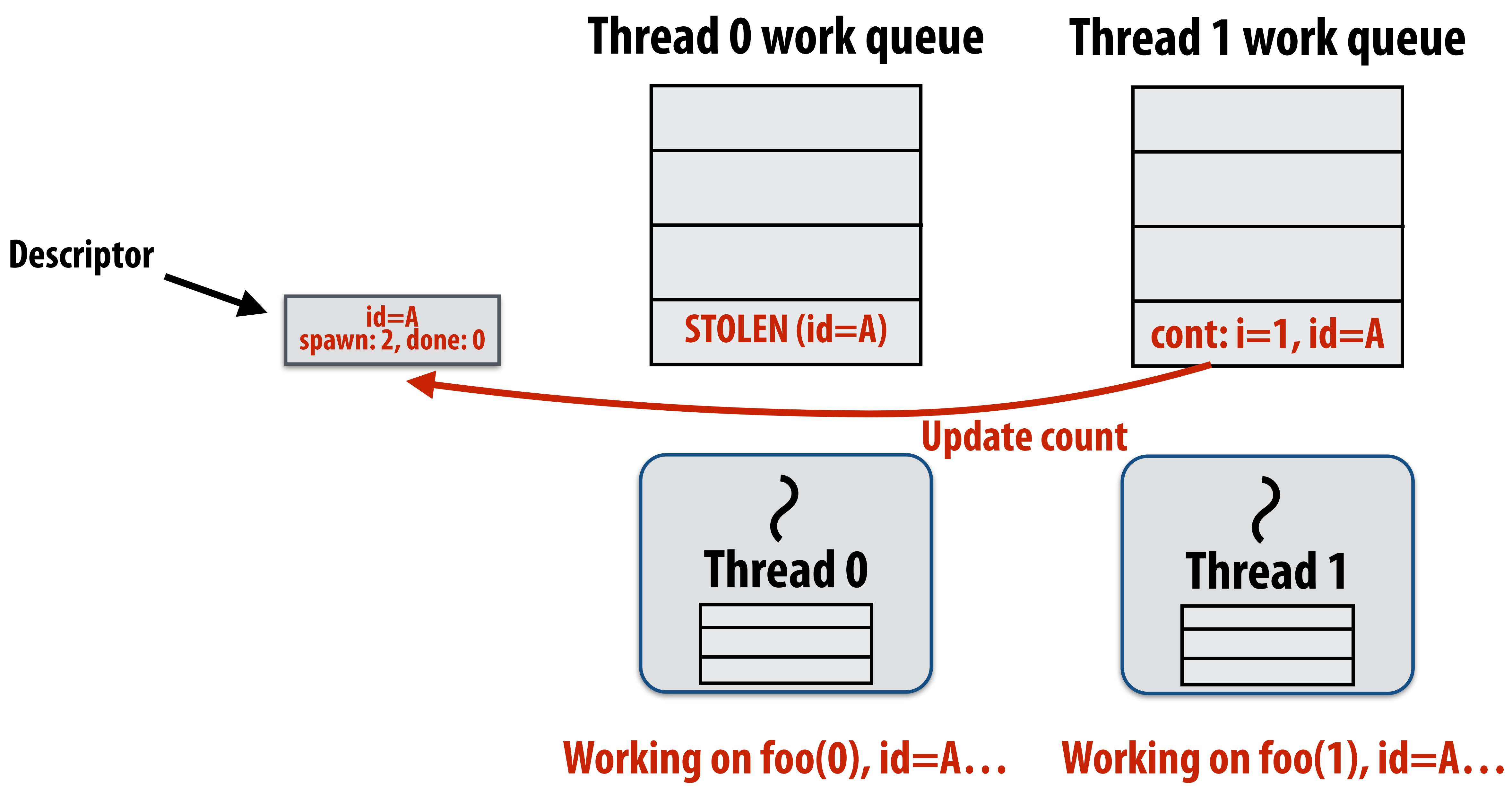
Implementing sync: stealing case

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 work queue

STOLEN (id=A)

Thread 1 work queue

cont: i=1, id=A

Descriptor

id=A
spawn: 2, done: 0

Update count

Thread 0

Thread 1

Working on foo(0), id=A…

Working on foo(1), id=A…

Thread 1 is now running foo(1)

Note: spawn count is now 2

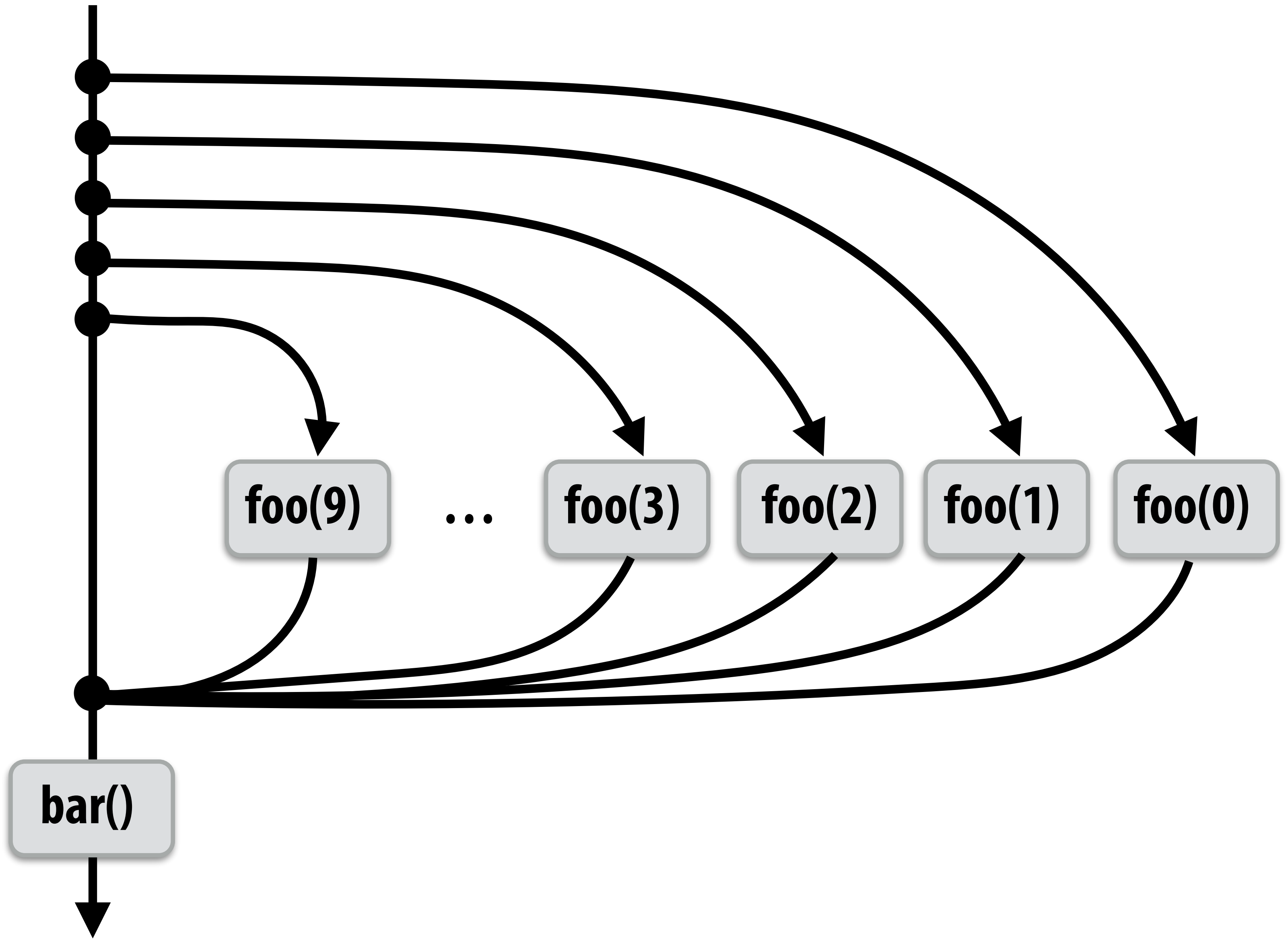
Implementing sync: stealing case

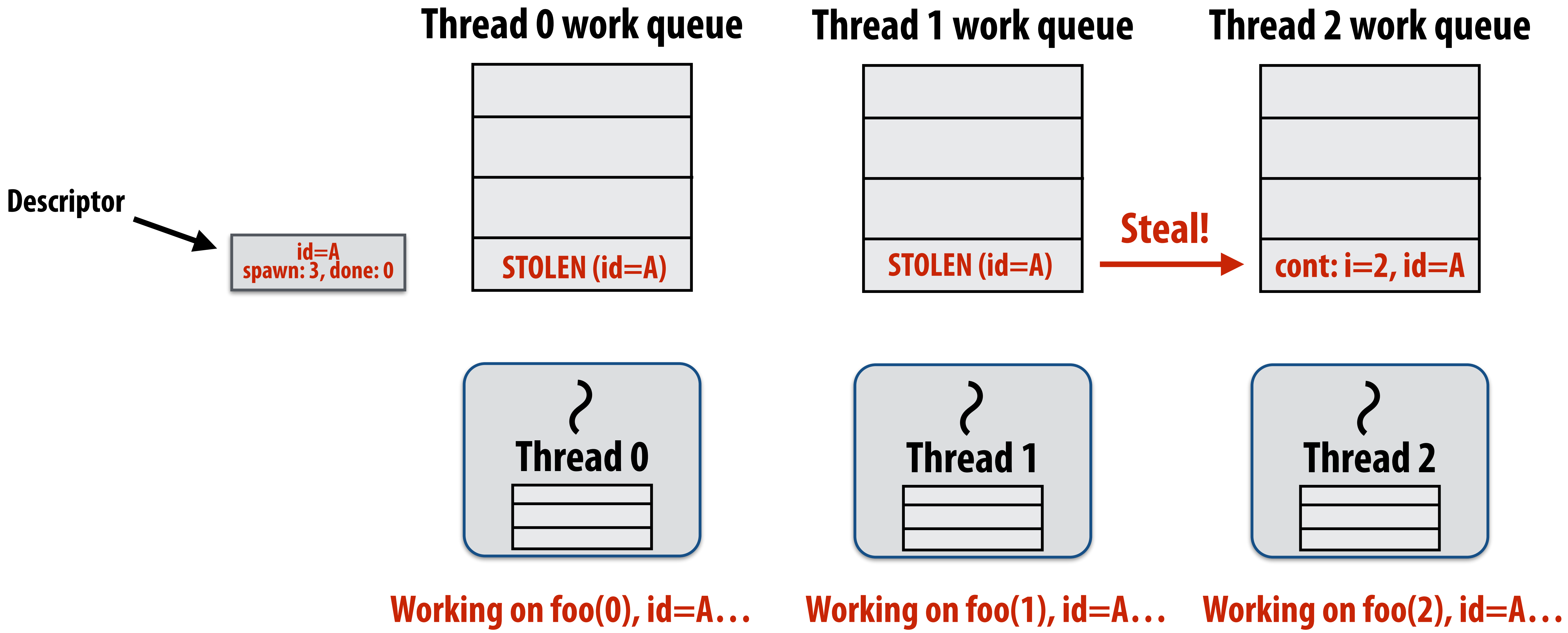
block (id: A)

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

Sync for all calls spawned within block A

```
bar();
```





Thread 0 work queue

Thread 1 work queue

Thread 2 work queue

Descriptor

id=A
spawn: 3, done: 0

STOLEN (id=A)

STOLEN (id=A)

Steal!

cont: i=2, id=A

Working on foo(0), id=A…

Working on foo(1), id=A…

Working on foo(2), id=A…

Thread 2 now running foo(2)

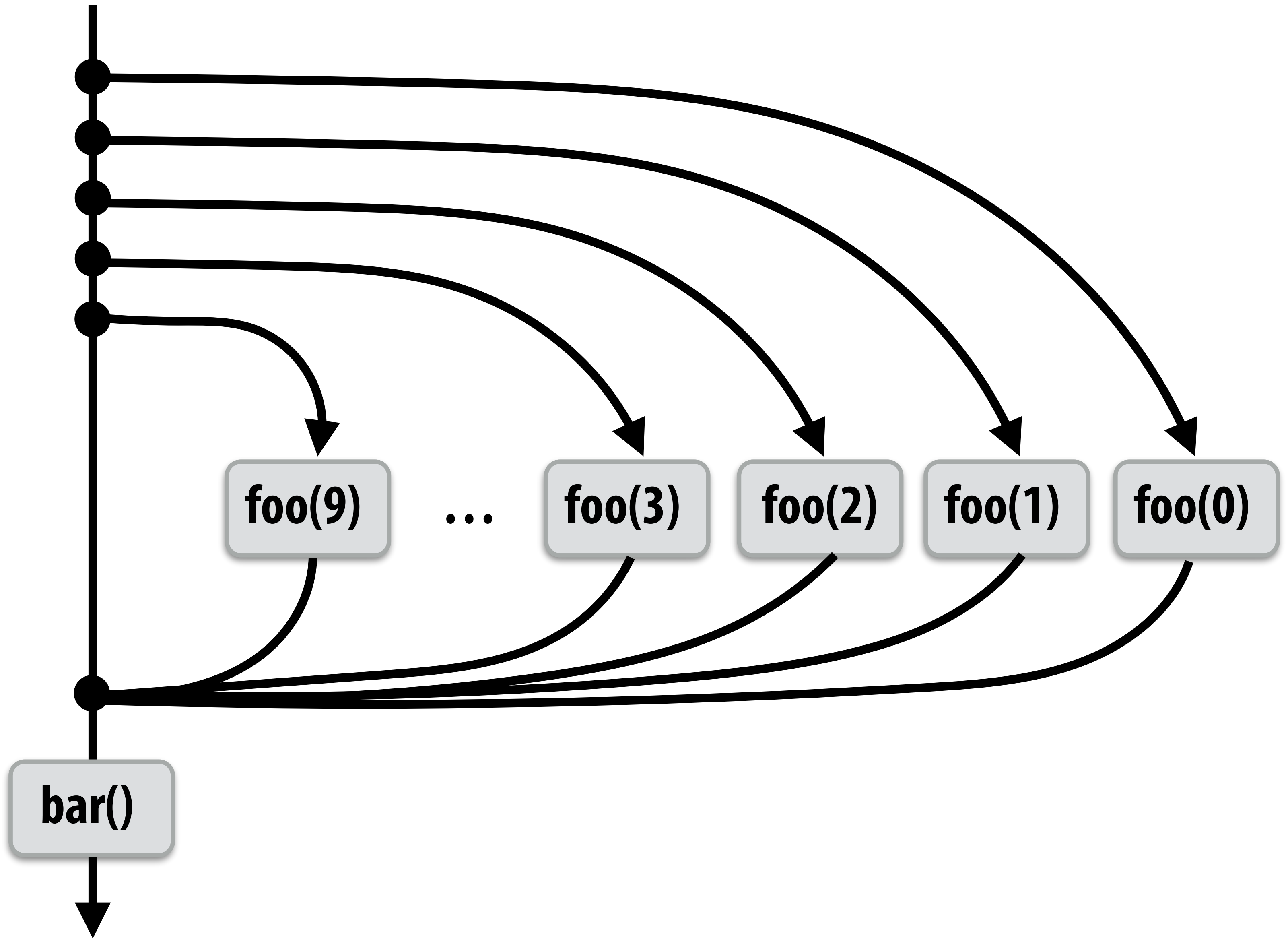
Implementing sync: stealing case

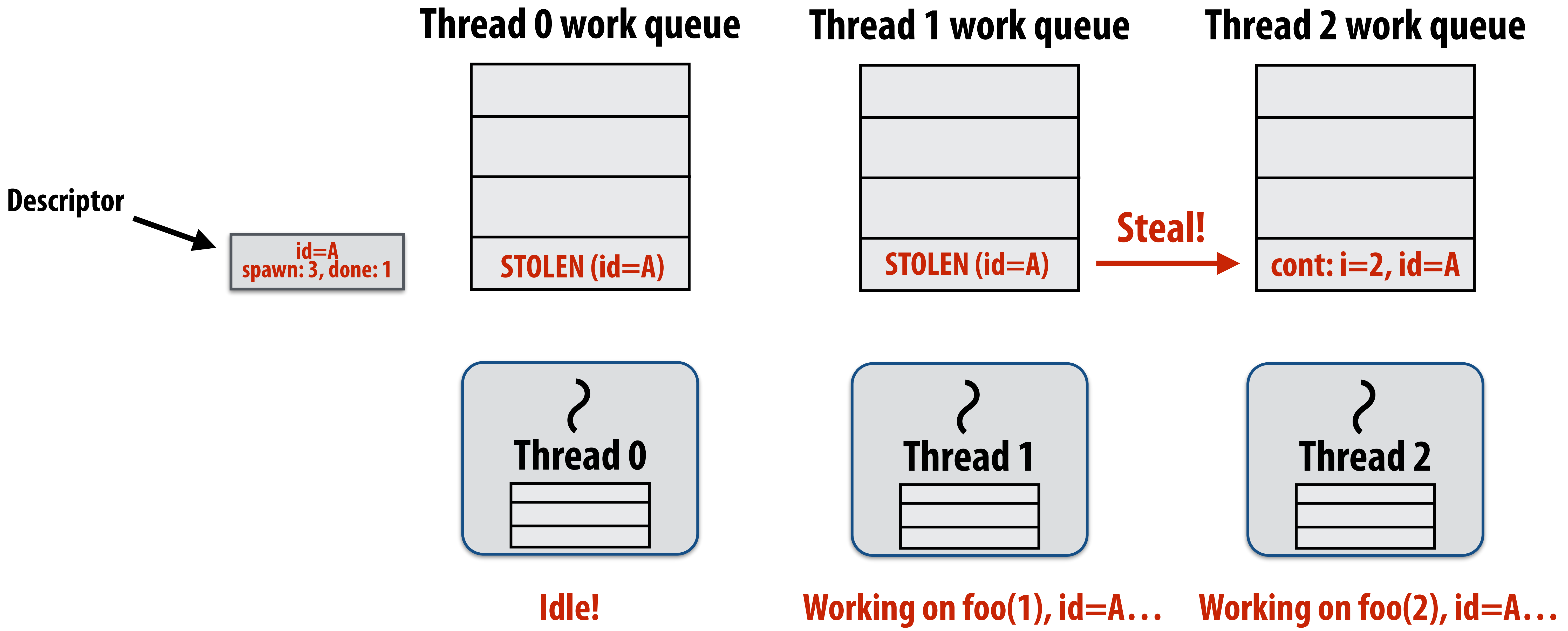
block (id: A)

```
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)

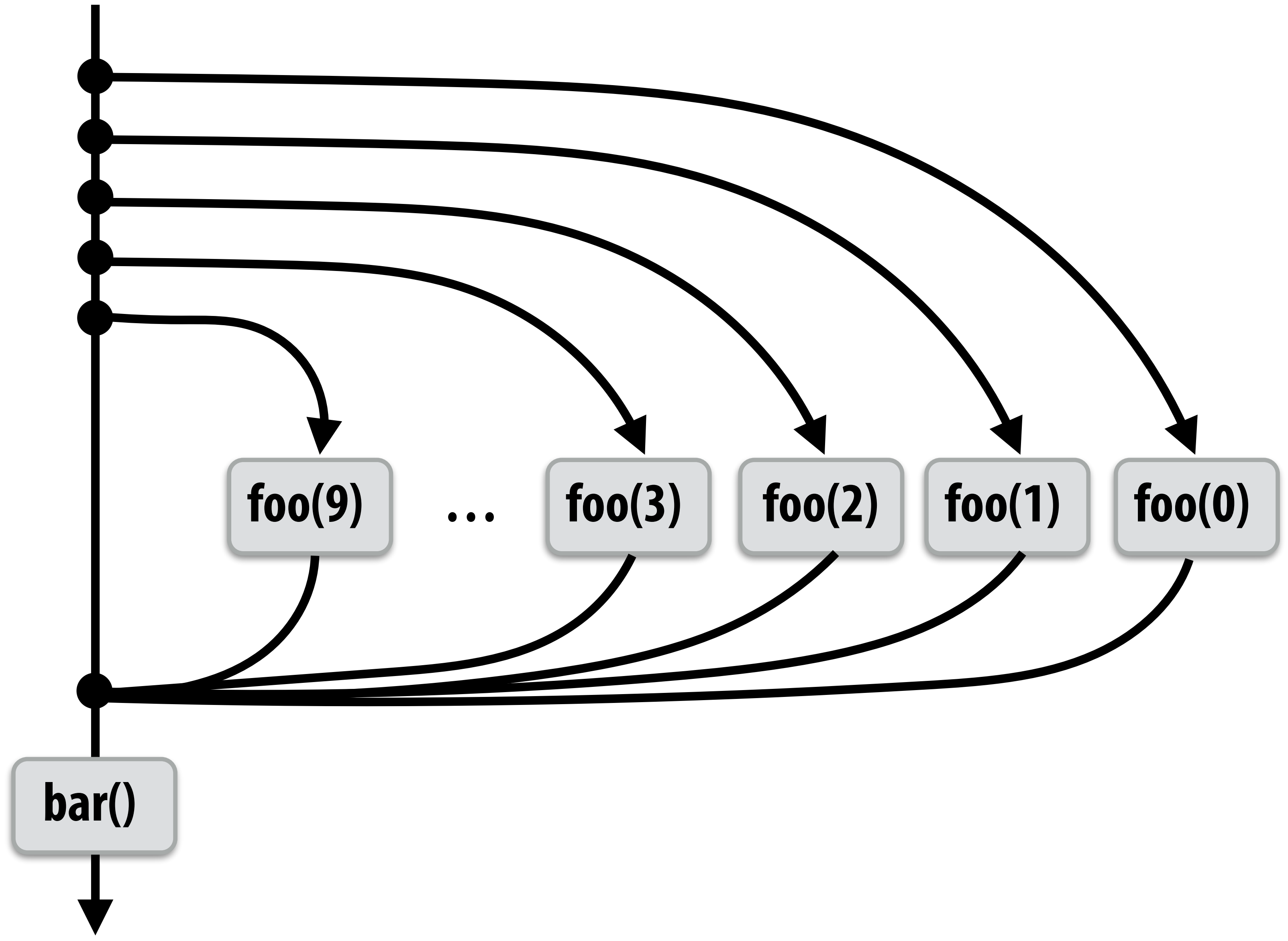
Implementing sync: stealing case

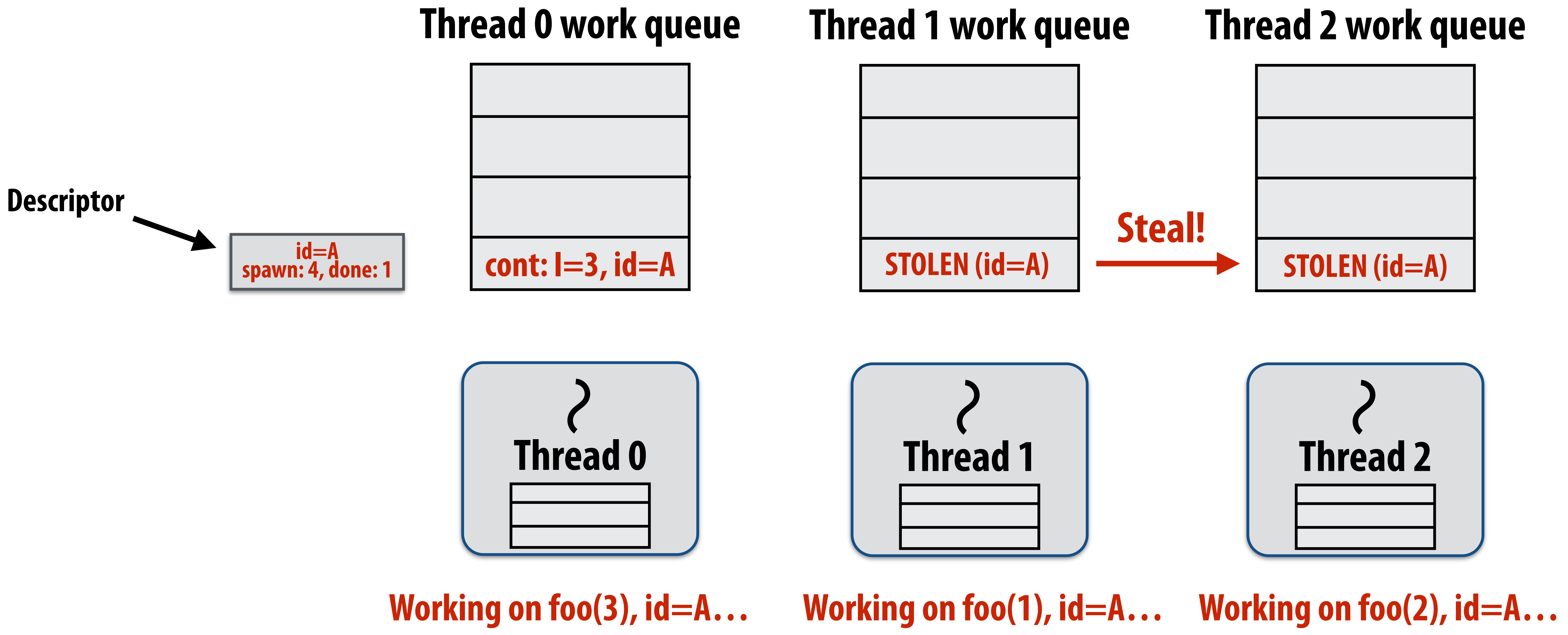
block (id: A)

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

Sync for all calls spawned within block A

```
bar();
```





Thread 0 work queue

Thread 1 work queue

Thread 2 work queue

Descriptor

id=A
spawn: 4, done: 1

cont: I=3, id=A

STOLEN (id=A)

Steal!

STOLEN (id=A)

Thread 0

Thread 1

Thread 2

Working on foo(3), id=A…

Working on foo(1), id=A…

Working on foo(2), id=A…

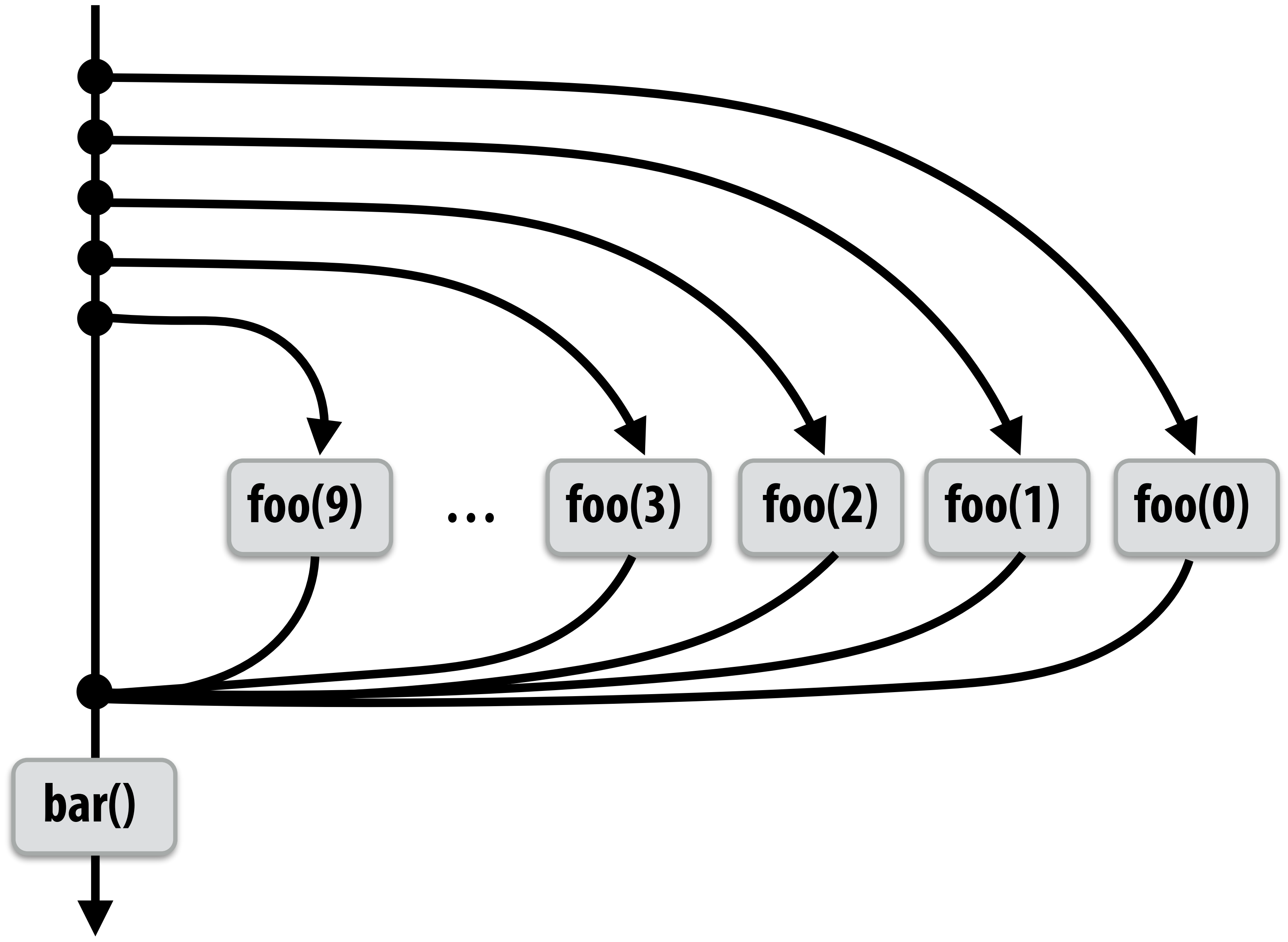
Thread 0 steals more work

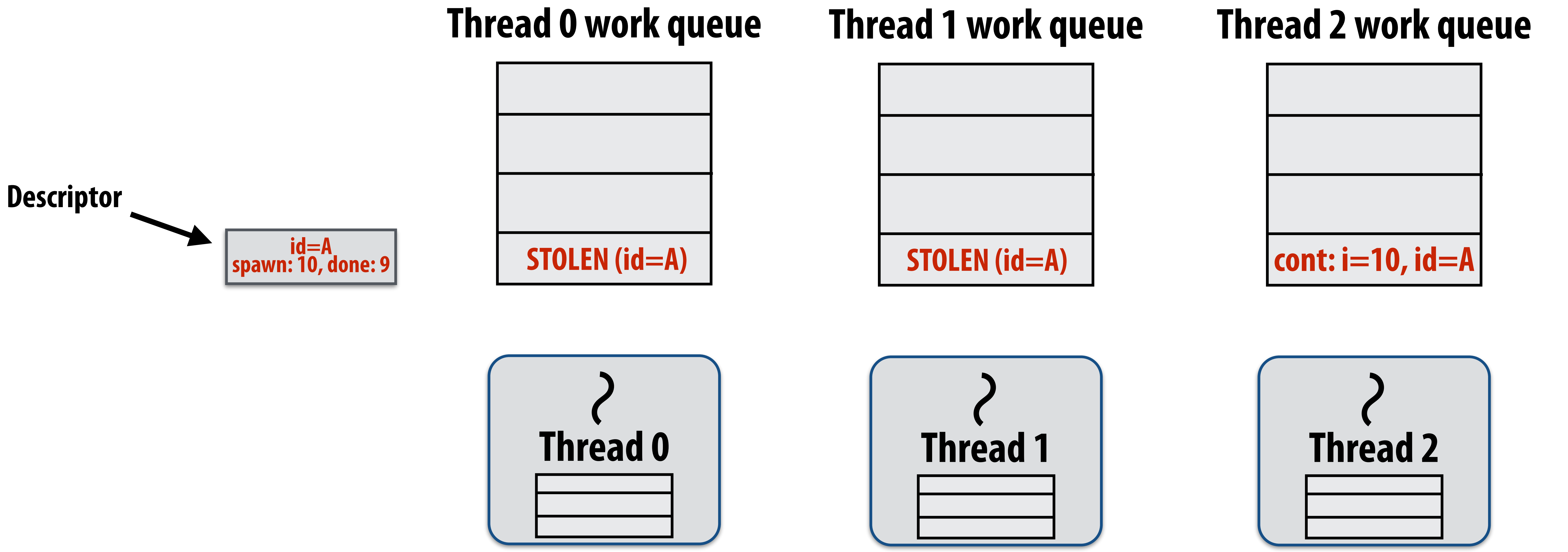
Implementing sync: stealing case

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





id=A
spawn: 10, done: 9

Thread 0 work queue	Thread 1 work queue	Thread 2 work queue
STOLEN (id=A)	STOLEN (id=A)	cont: i=10, id=A
Idle!	Idle!	Working on foo(9), id=A…

Computation nearing end…

Only foo(9) remains to be completed.

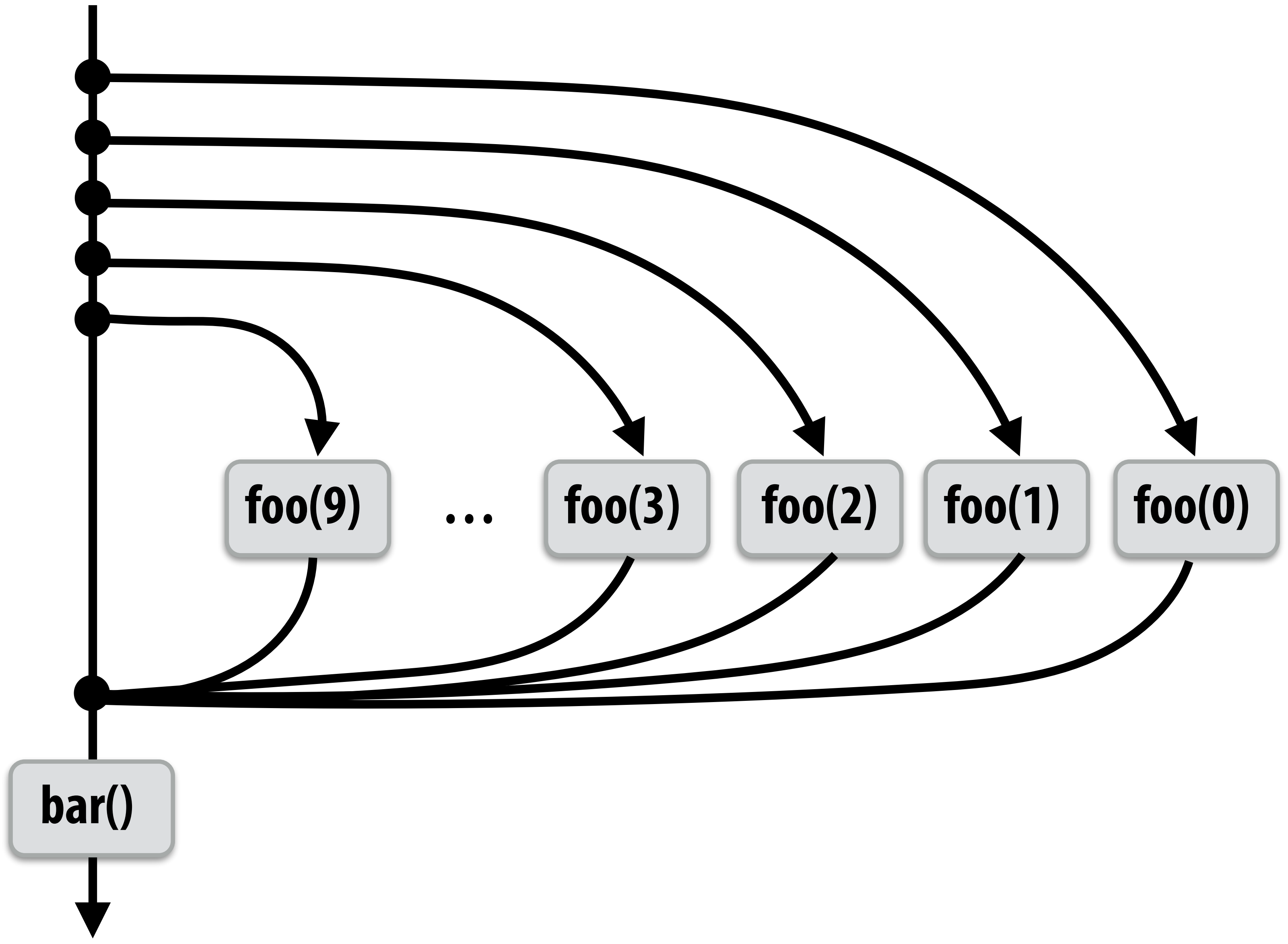
Implementing sync: stealing case

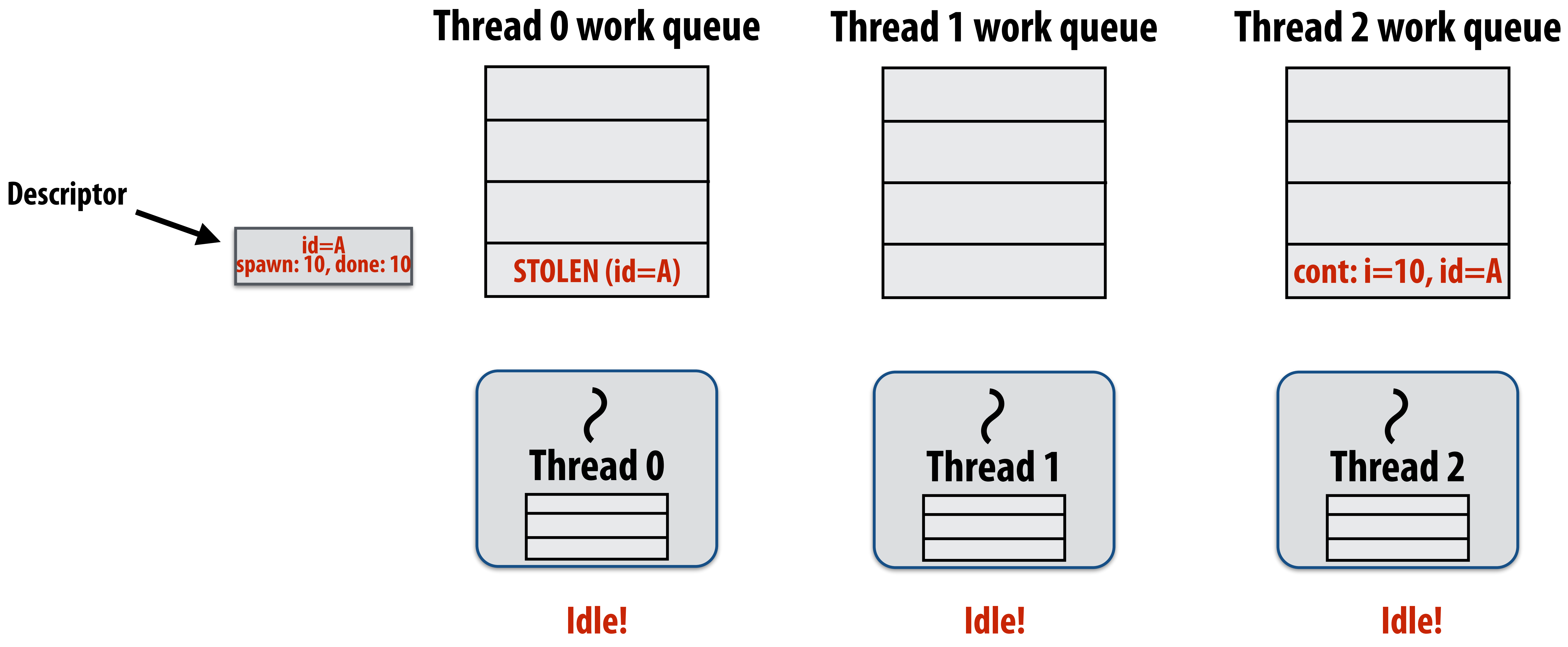
block (id: A)

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

Sync for all calls spawned within block A

```
bar();
```





Descriptor: id=A, spawn: 10, done: 10

Thread 0 work queue	Thread 1 work queue	Thread 2 work queue
STOLEN (id=A)		cont: i=10, id=A

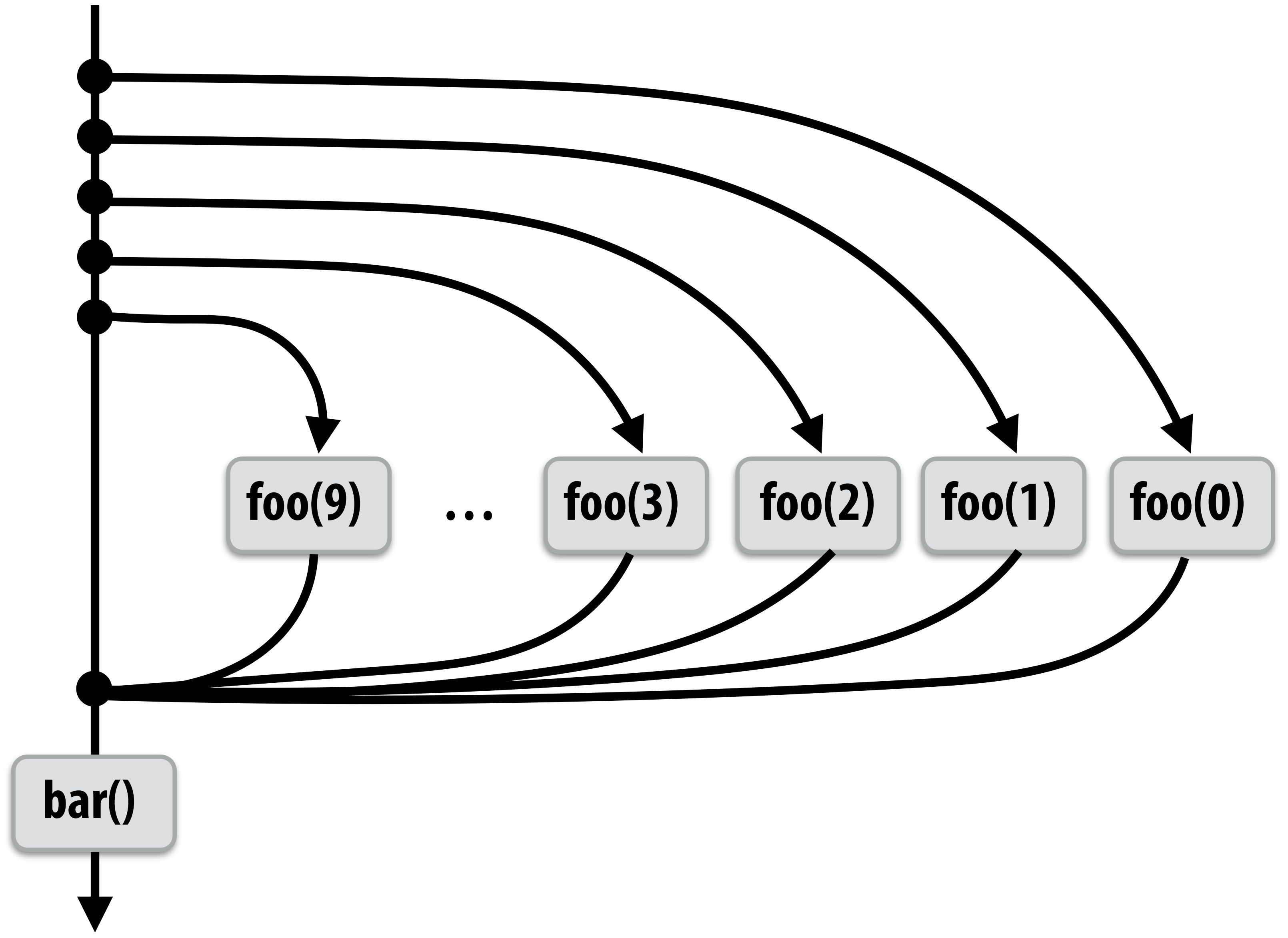
Last spawn completes.

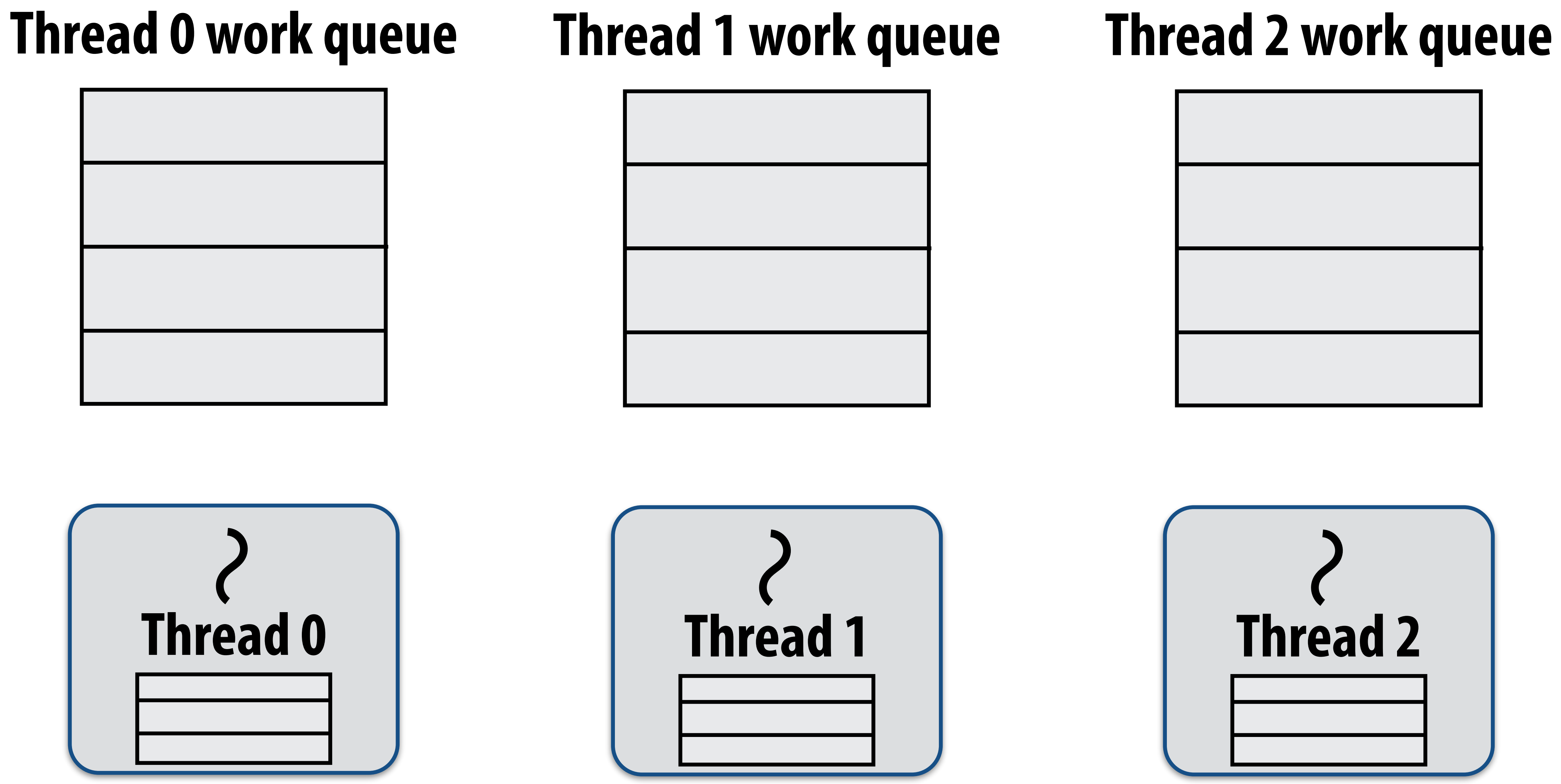
Implementing sync: stealing case

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 work queue

Thread 1 work queue

Thread 2 work queue

Thread 0

Thread 1

Thread 2

Idle!

Idle!

Working on bar()…

Thread 2 now resumes continuation and executes 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
  - Threads only go idle if there is no work to steal in the 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

Cilk summary

- **Fork-join parallelism: a natural way to express divide-and-conquer algorithms**
  - Discussed Cilk Plus, but many other systems also have fork/join primitives (e.g., OpenMP)

- **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)