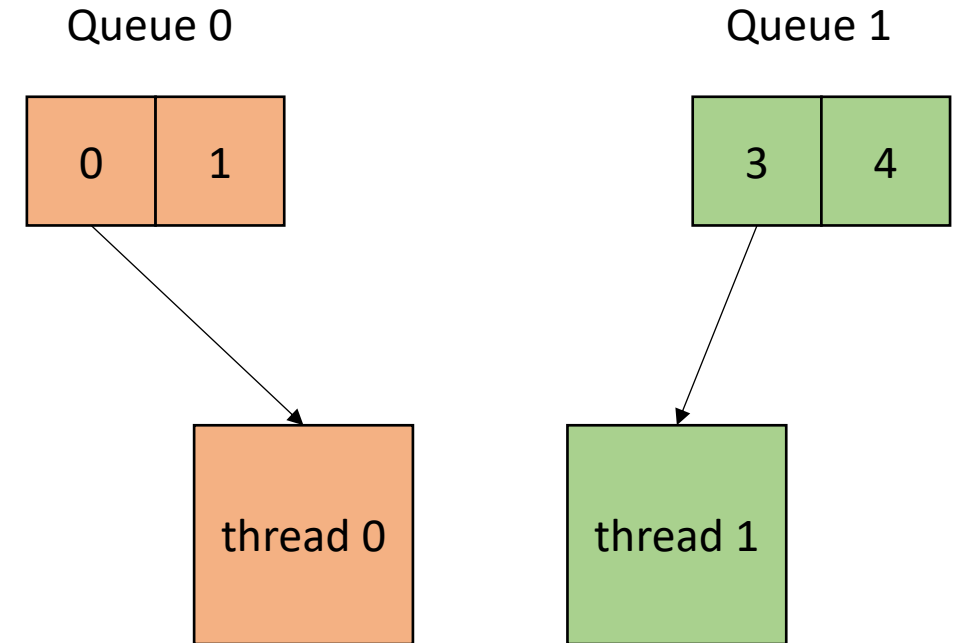


CSE113: Parallel Programming

- **Topics:**

- DOALL loops
- Static scheduling
- Workstealing



Announcements

- Midterm graded
- HW 1 is graded
- HW 2 graded this week.
- HW 3 due this week
 - You should be able to do part 2 after today's lecture.

Previous quiz + Review

Previous quiz + Review

Input/output queues use atomic increments and decrements to protect against threads that are trying to concurrently enqueue and dequeue

☐ True

☐ False

Implementation



Thread 0:
enq(6);

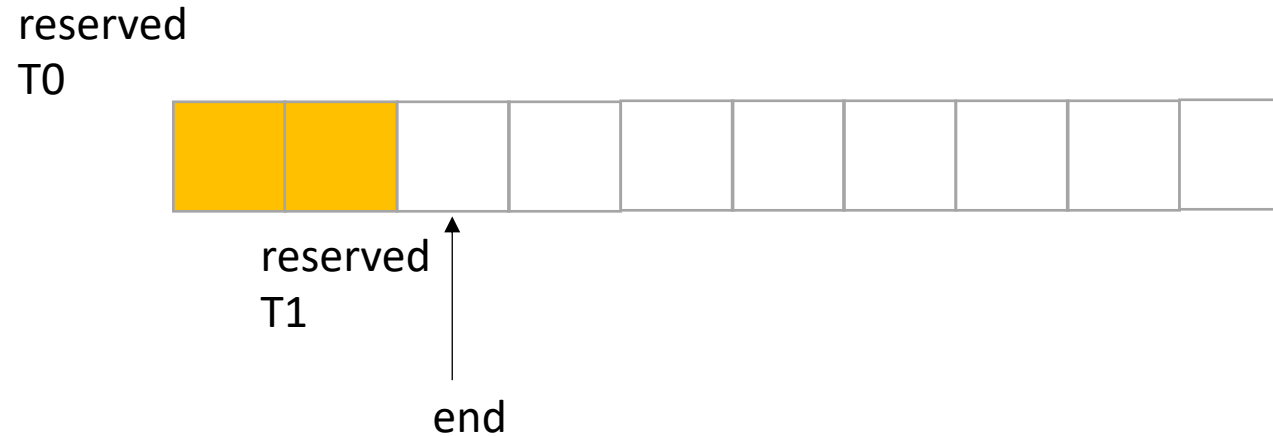
Thread 1:
enq(7);

What happens if a thread wants
to add an element?

Think concurrently:

```
reserved_index = atomic_fetch_add(&end, 1);
```

Implementation



Thread 0:
enq(6);

Thread 1:
enq(7);

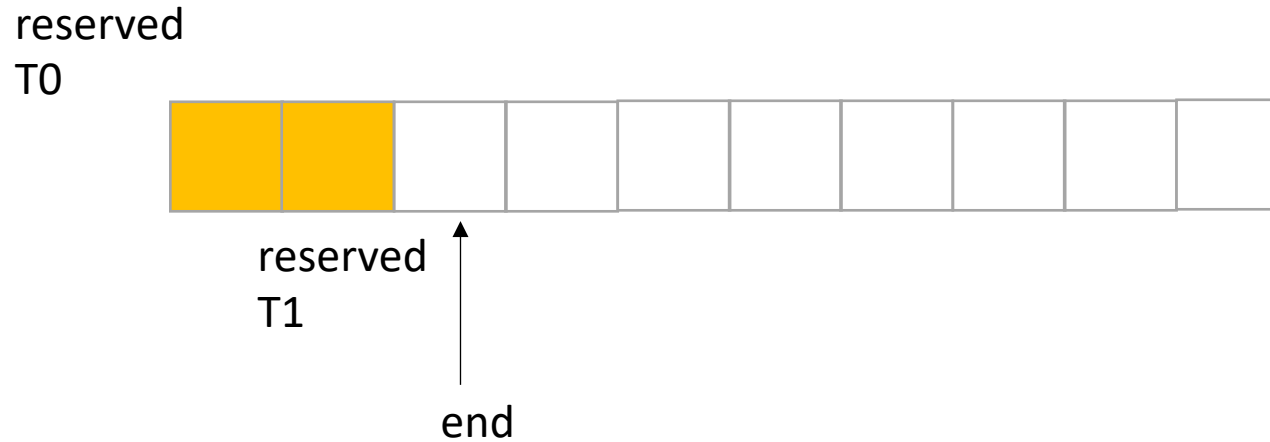
What happens if a thread wants to add an element?

Think concurrently:

```
reserved_index = atomic_fetch_add(&end, 1);
```

Implementation

*does it matter which order
threads add their data?*



Thread 0:
`enq(6);`

Thread 1:
`enq(7);`

What happens if a thread wants
to add an element?

Think concurrently:

```
reserved_index = atomic_fetch_add(&end, 1);
```

Implementation

*does it matter which order
threads add their data?*

reserved
T0



end

Thread 0:
enq(6);

Thread 1:
enq(7);

What happens if a thread wants
to add an element?

Think concurrently:

```
reserved_index = atomic_fetch_add(&end, 1);
```


Implementation

*does it matter which order
threads add their data? No!
Because there are no deqs!*

reserved
T0



end

Thread 0:
enq(6);

Thread 1:
enq(7);

What happens if a thread wants
to add an element?

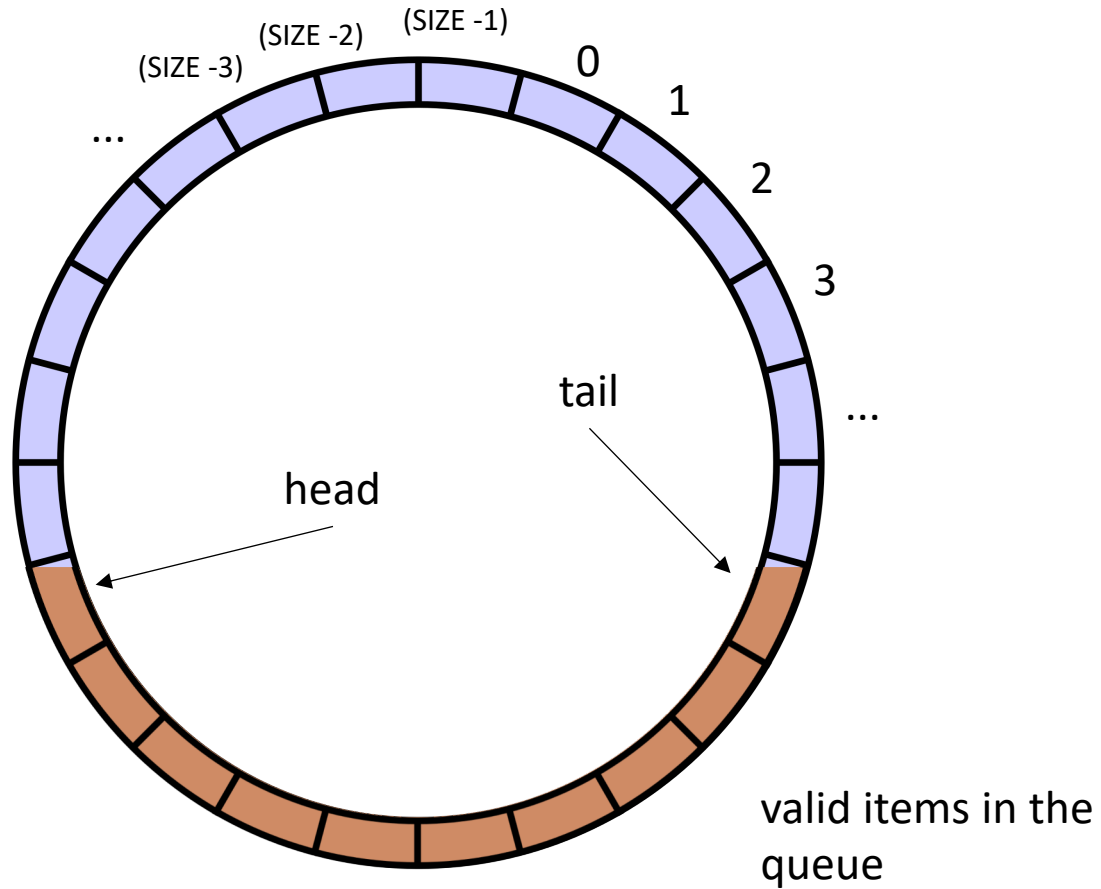
Think concurrently:

```
reserved_index = atomic_fetch_add(&end, 1);
```

Previous quiz + Review

Write a few questions about the pros and cons of using a specialized concurrent queue (e.g. an IO queue) and a fully general concurrent queue.

```
class InputOutputQueue {  
    private:  
        atomic_int front;  
        atomic_int end;  
        int list[SIZE];  
  
    public:  
        InputOutputQueue() {  
            front = end = 0;  
        }  
  
        void enq(int x) {  
            int reserved_index = atomic_fetch_add(&end, 1);  
            list[reserved_index] = x;  
        }  
  
        void deq() {  
            int reserved_index = atomic_fetch_add(&front, 1);  
            return list[reserved_index];  
        }  
  
        int size() {  
            return end.load() - front.load();  
        }  
}
```



```
class ProdConsQueue {
    private:
        atomic_int head;
        atomic_int tail;
        int buffer[SIZE];

    public:
        void enq(int x) {
            // wait for there to be room
            // store value at head
            // increment head
        }
        int deq() {
            // wait while queue is empty
            // get value at tail
            // increment tail
        }
}
```

Previous quiz + Review

The performance of an application using a producer-consumer queue depends most on:

- ☐ If the queue is implemented using mutex or not
- ☐ The rate at which the consumer enqueues elements
- ☐ The rate at which the producer enqueues elements

Previous quiz + Review

A circular buffer is:

-
- ☐ A useful data representation for fixed-length queues
-
- ☐ Part of the C++ standard library
-
- ☐ A special type of memory that is organized in circular patterns

Producer Consumer Queues

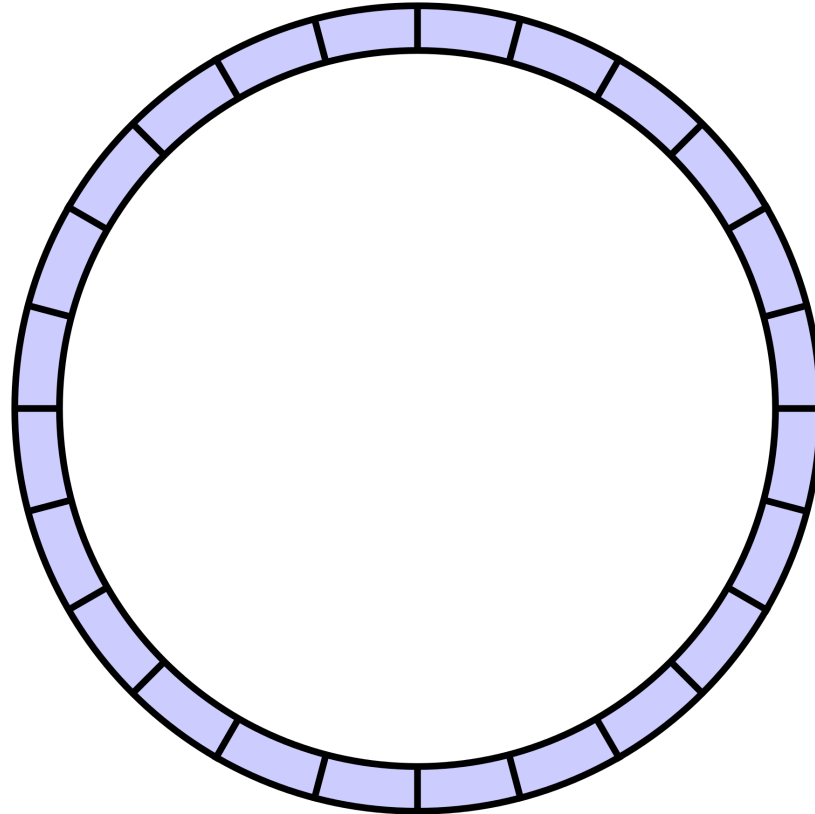
- Start with a fixed size array



We will use what is called a *circular buffer method*

Producer Consumer Queues

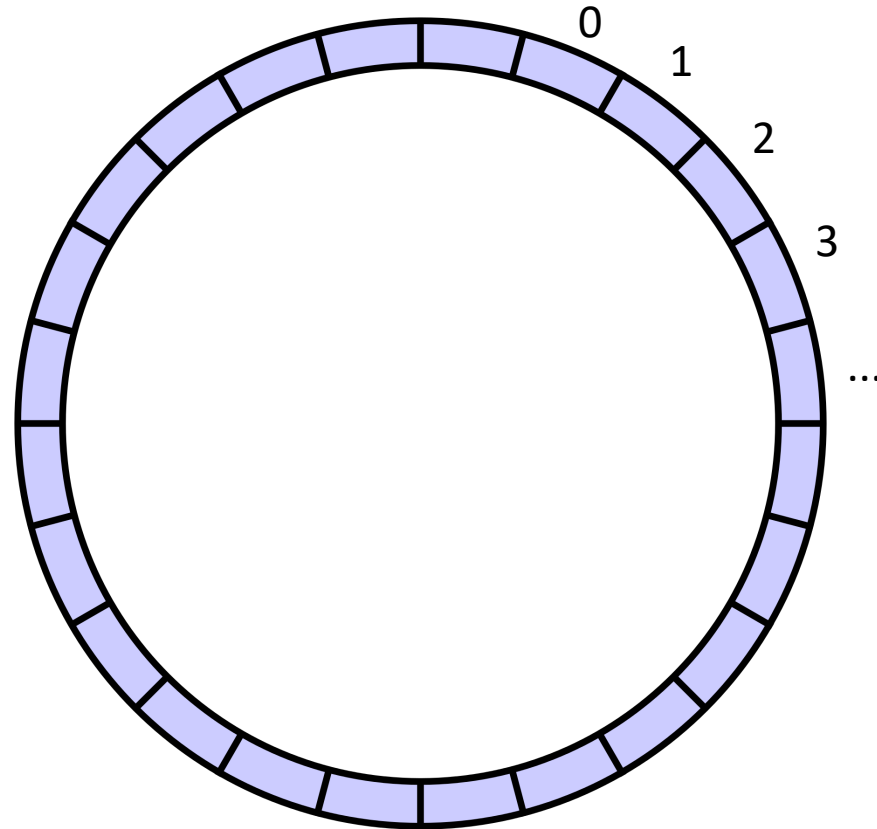
- Start with a fixed size array



conceptually it is a circle

Producer Consumer Queues

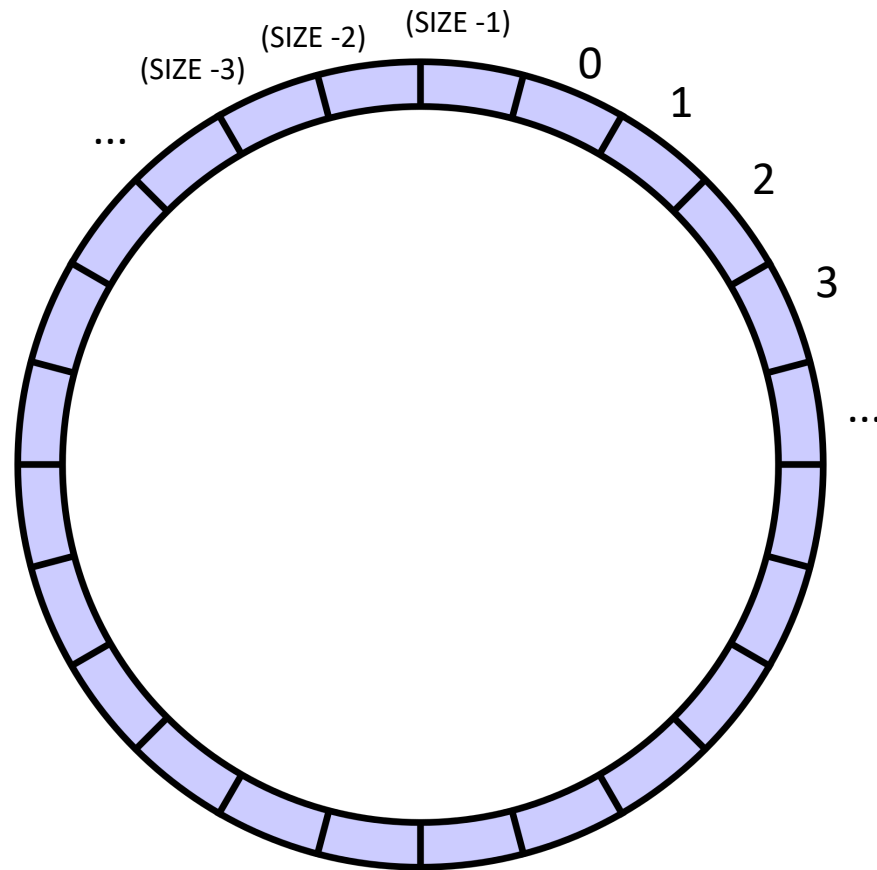
- Start with a fixed size array



conceptually it is a circle

Producer Consumer Queues

- Start with a fixed size array



indexes will
circulate in
order and
wrap around

conceptually it is a circle

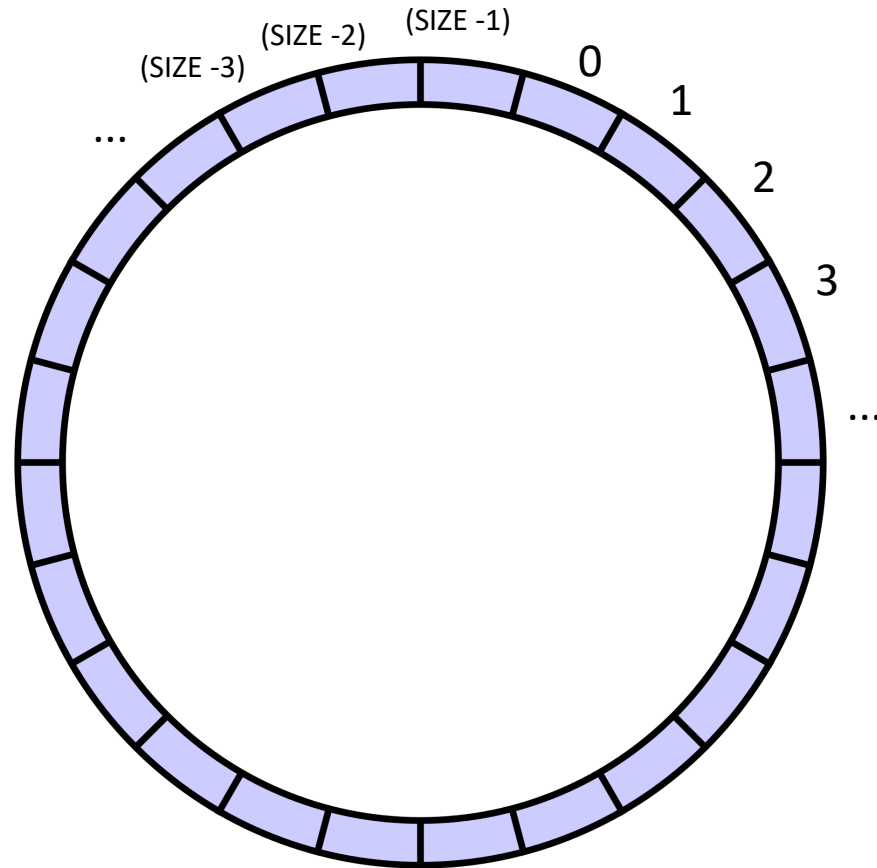
Producer Consumer Queues

- Start with a fixed size array

we will assume modular arithmetic:

if $x = (\text{SIZE} - 1)$ then
 $x + 1 == 0$;

conceptually it is a circle



indexes will
circulate in
order and
wrap around

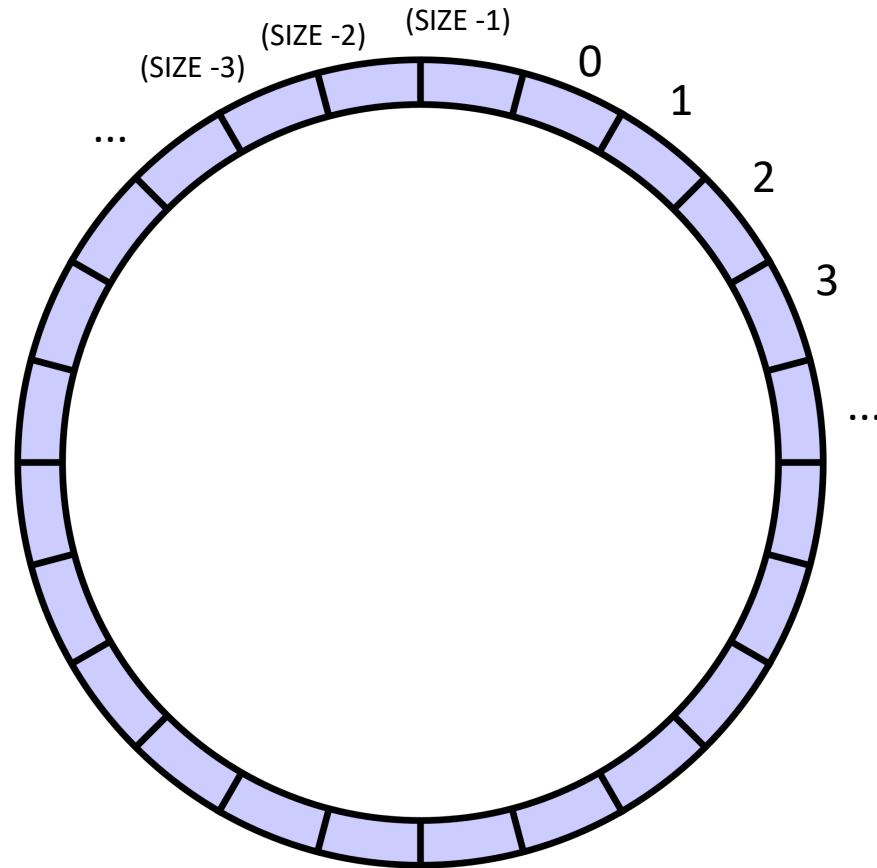
Producer Consumer Queues

- Start with a fixed size array

Two variables to keep track of
where to deq and enq:

head and tail

conceptually it is a circle



indexes will
circulate in
order and
wrap around

Producer Consumer Queues

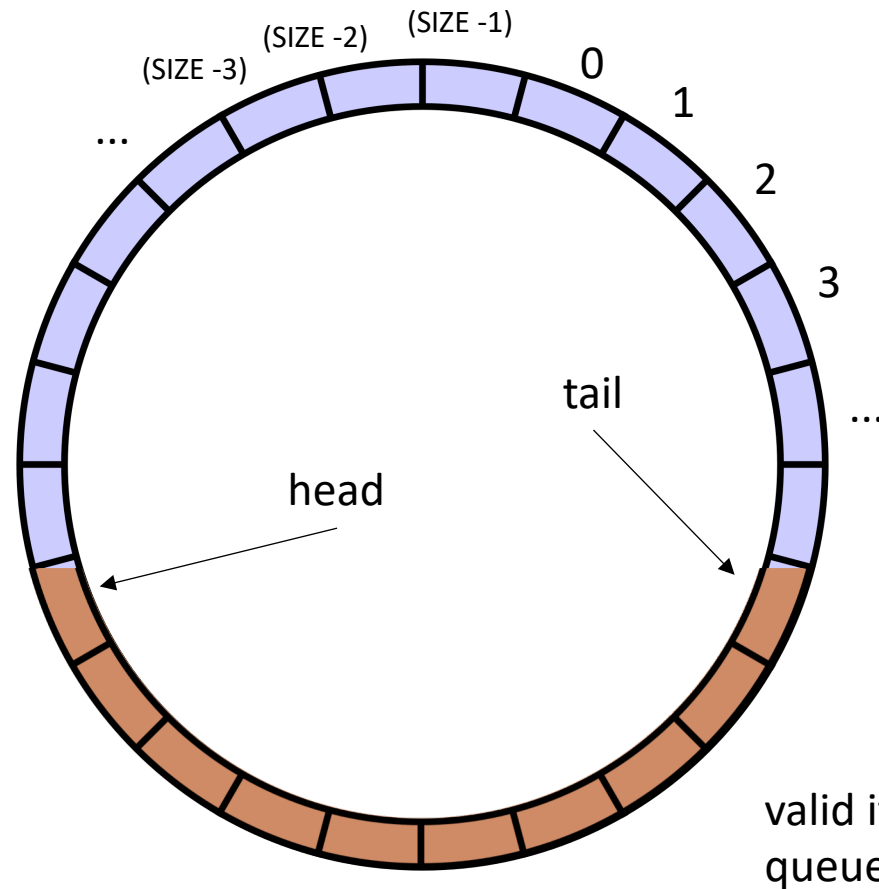
- Start with a fixed size array

Two variables to keep track of where to deq and enq:

head and tail:

enq to the head, deq from the tail

conceptually it is a circle



indexes will circulate in order and wrap around

Producer Consumer Queues

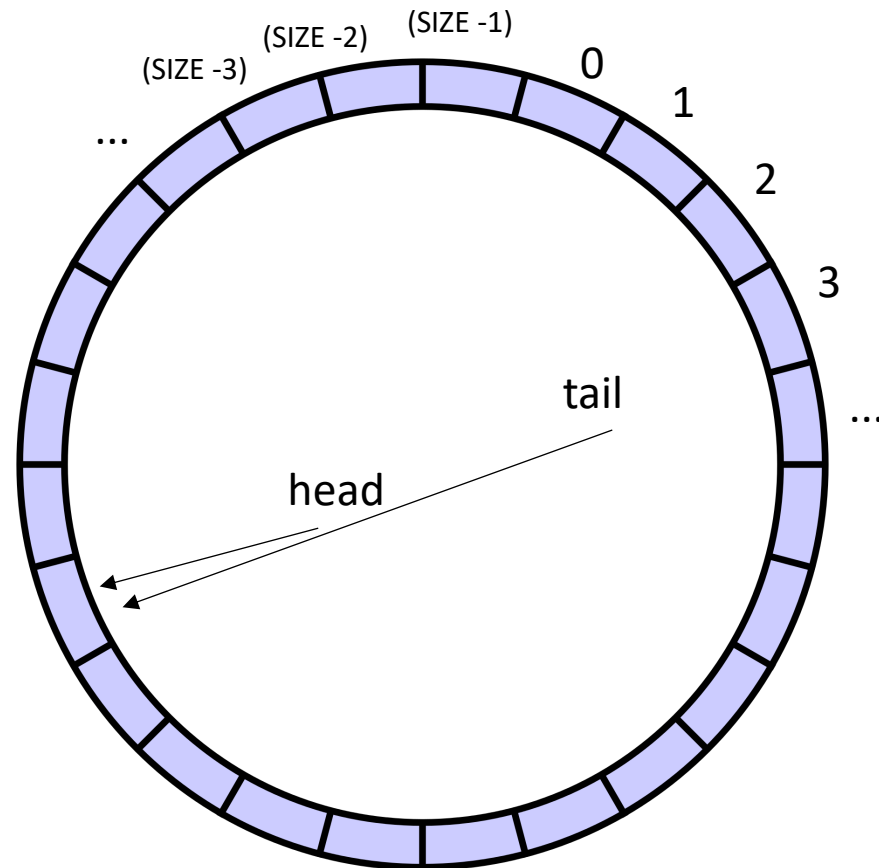
- Start with a fixed size array

Two variables to keep track of
where to deq and enq:

head and tail

Empty queue is when
 $\text{head} == \text{tail}$

conceptually it is a circle



indexes will
circulate in
order and
wrap around

Producer Consumer Queues

- Start with a fixed size array

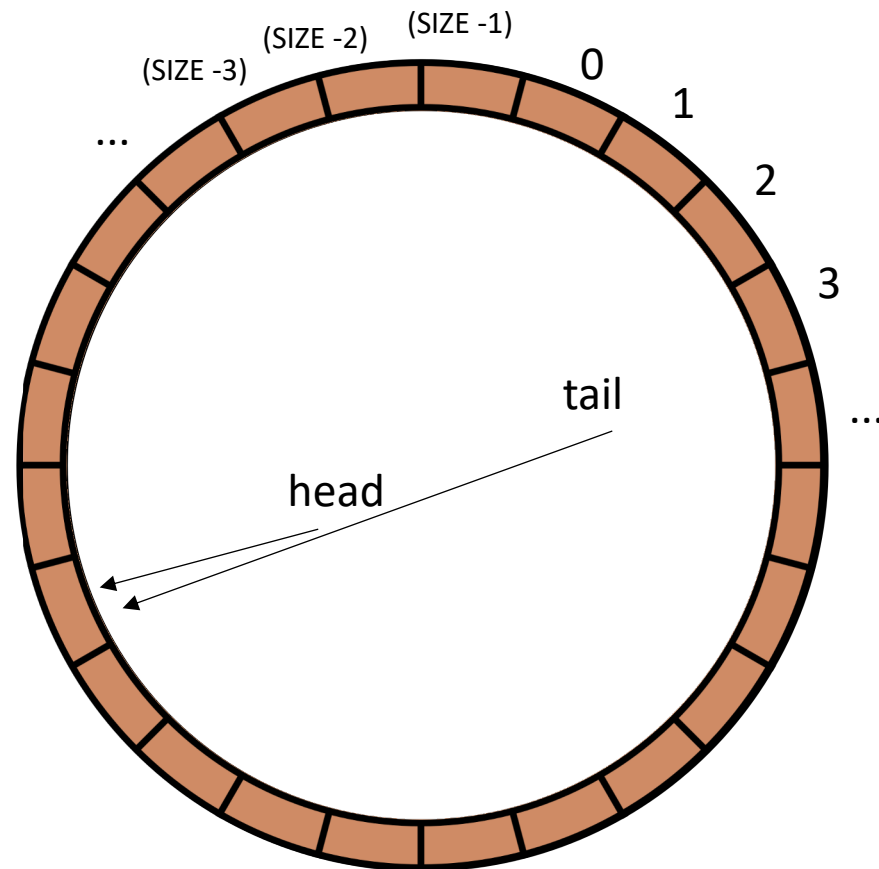
Two variables to keep track of where to deq and enq:

head and tail

Empty queue is when
 $\text{head} == \text{tail}$

Full queue is when
 $\text{head} == \text{tail}?$

conceptually it is a circle



indexes will
circulate in
order and
wrap around

Producer Consumer Queues

- Start with a fixed size array

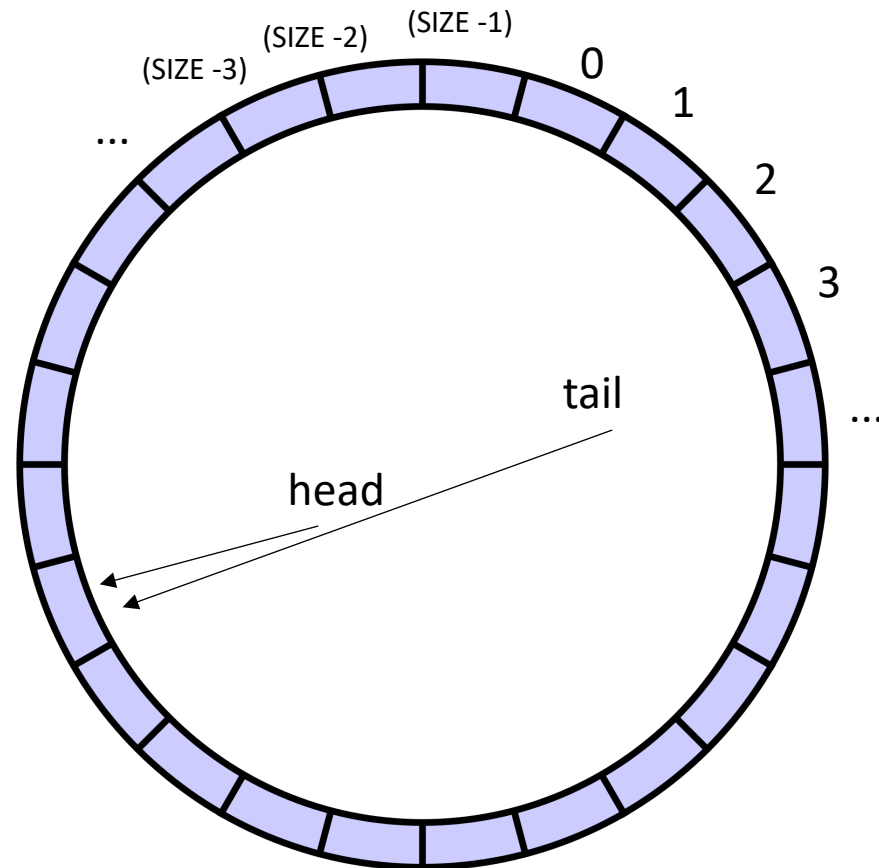
Two variables to keep track of where to deq and enq:

head and tail

Empty queue is when
 $\text{head} == \text{tail}$

Full queue is when
 $\text{head} == \text{tail}?$

conceptually it is a circle



indexes will
circulate in
order and
wrap around

but then
how to tell
full queue from
empty?

Producer Consumer Queues

- Start with a fixed size array

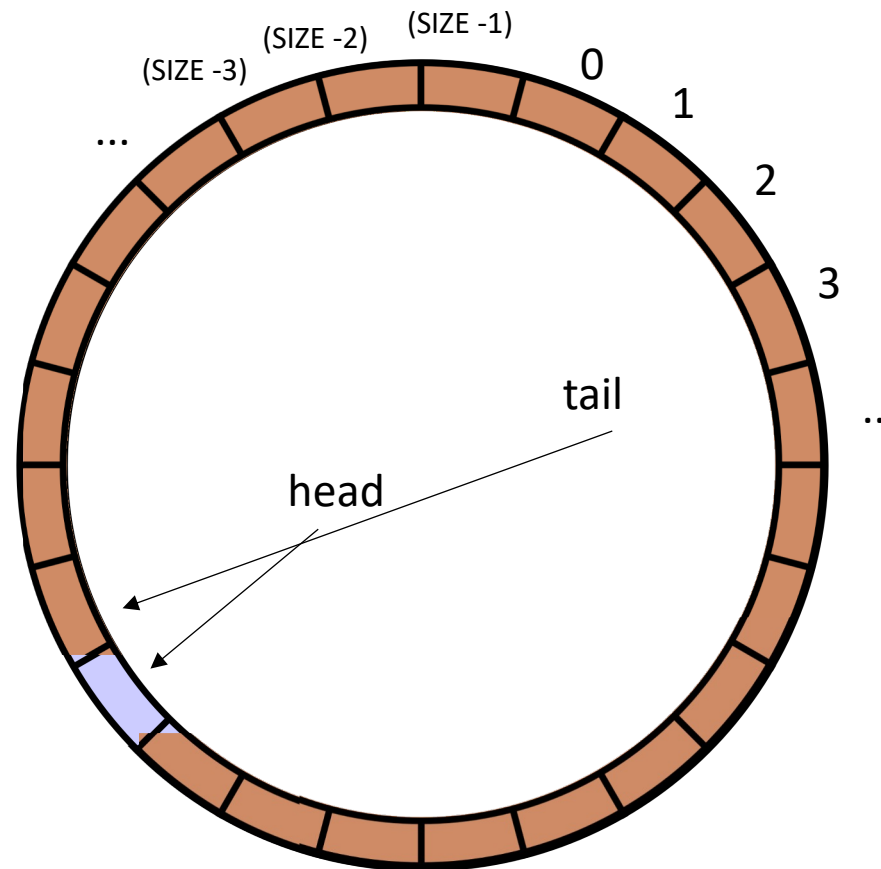
Two variables to keep track of where to deq and enq:

head and tail

Empty queue is when
 $\text{head} == \text{tail}$

Full queue is when
 $\text{head} + 1 == \text{tail}$

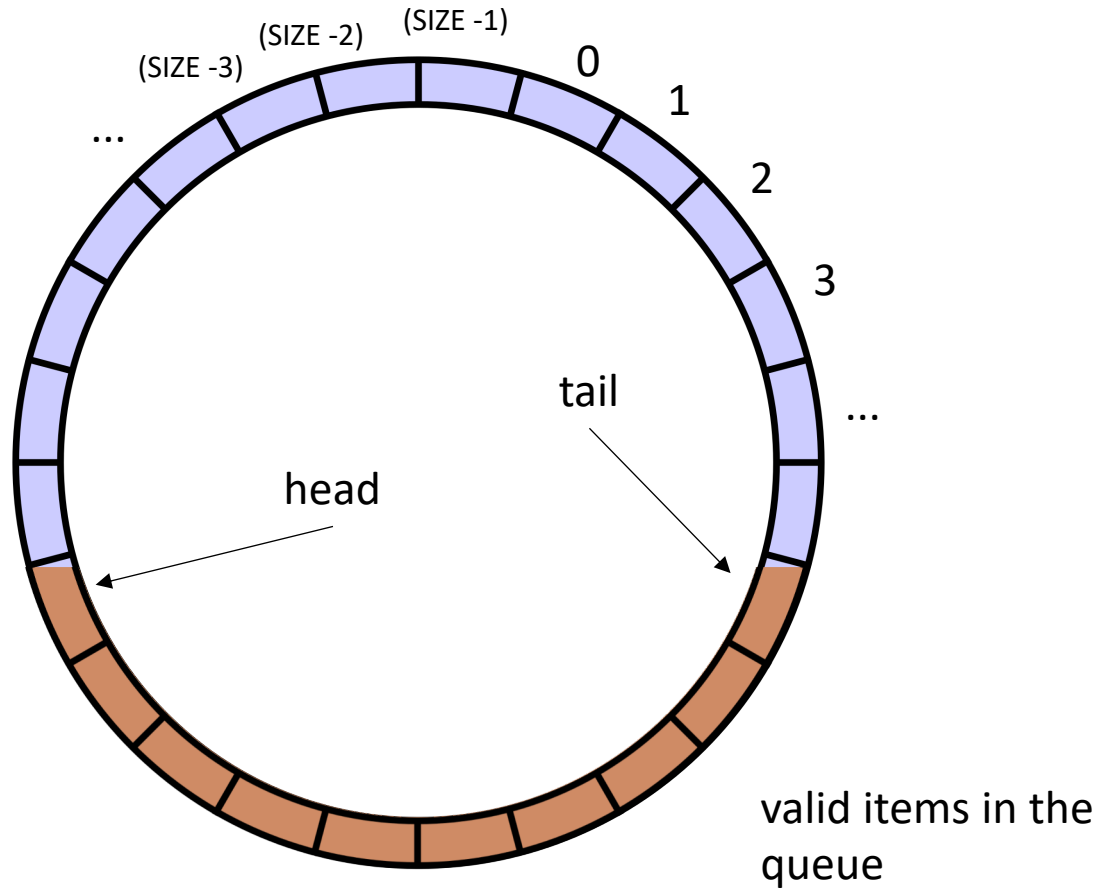
conceptually it is a circle



indexes will circulate in order and wrap around

wasting one location, but its okay...

review



```
class ProdConsQueue {  
    private:  
        atomic_int head;  
        atomic_int tail;  
        int buffer[SIZE];  
  
    public:  
        void enq(int x) {  
            // wait for there to be room  
            // store value at head  
            // increment head  
        }  
        int deq() {  
            // wait while queue is empty  
            // get value at tail  
            // increment tail  
        }  
}
```

On to new stuff!

- Work stealing

adds two arrays

```
for (int i = 0; i < SIZE; i++) {  
    a[i] = b[i] + c[i];  
}
```

adds elements with neighbors

```
for (int i = 0; i < SIZE; i++) {  
    a[i] += a[i+1]  
}
```

are they the same if you traverse them backwards?

adds two arrays

```
for (int i = 0; i < SIZE; i++) {  
    a[i] = b[i] + c[i];  
}
```

```
for (int i = SIZE-1; i >= 0; i--) {  
    a[i] = b[i] + c[i];  
}
```

adds elements with neighbors

```
for (int i = 0; i < SIZE; i++) {  
    a[i] += a[i+1]  
}
```

```
for (int i = SIZE-1; i >= 0; i--) {  
    a[i] += a[i+1]  
}
```

are they the same if you traverse them backwards?

adds two arrays

```
for (int i = 0; i < SIZE; i++) {  
    a[i] = b[i] + c[i];  
}
```

```
for (int i = SIZE-1; i >= 0; i--) {  
    a[i] = b[i] + c[i];  
}
```

adds elements with neighbors

```
for (int i = 0; i < SIZE; i++) {  
    a[i] += a[i+1]  
}
```

```
for (int i = SIZE-1; i >= 0; i--) {  
    a[i] += a[i+1]  
}
```

No!

adds two arrays

```
for (int i = 0; i < SIZE; i++) {  
    a[i] = b[i] + c[i];  
}
```

what about a random order?

```
for (pick i randomly) {  
    a[i] = b[i] + c[i];  
}
```

adds elements with neighbors

```
for (int i = 0; i < SIZE; i++) {  
    a[i] += a[i+1]  
}
```

```
for (pick i randomly) {  
    a[i] += a[i+1]  
}
```


adds two arrays

```
for (int i = 0; i < SIZE; i++) {  
    a[i] = b[i] + c[i];  
}
```

what about a random order?

```
for (pick i randomly) {  
    a[i] = b[i] + c[i];  
}
```

adds elements with neighbors

```
for (int i = 0; i < SIZE; i++) {  
    a[i] += a[i+1]  
}
```

```
for (pick i randomly) {  
    a[i] += a[i+1]  
}
```

No!

```
for (int i = 0; i < SIZE; i++) {  
    a[i] = b[i] + c[i];  
}
```

These are **DOALL** loops:

- Loop iterations are independent
- You can do them in ANY order and get the same results

```
for (int i = 0; i < SIZE; i++) {  
    a[i] = b[i] + c[i];  
}
```

These are **DOALL** loops:

- Loop iterations are independent
- You can do them in ANY order and get the same results
- Most importantly: you can do the iterations in parallel!
- Assign each thread a set of indices to compute

DOALL Loops

- Given a nest of For loops, can we make the outer-most loop parallel?
 - Safely
 - Efficiently

DOALL Loops

- We will consider a special type of for loop, common in scientific applications:
 - Operates on N dimensional arrays (only side-effects are array writes)
 - Array bases are disjoint and constant
 - Bounds, indexes are a function of loop variables, input variables and constants
 - Loops Increment by 1

```
for (int i = 0; i < dim1; i++) {  
    for (int j = 0; j < dim3; j++) {  
        for (int k = 0; k < dim2; k++) {  
            a[i][j] += b[i][k] * c[k][j];  
        }  
    }  
}
```

matrix multiplication
example

DOALL Loops

- We will consider a special type of for loop, common in scientific applications:
 - Operates on N dimensional arrays (only side-effects are array writes)
 - Array bases are disjoint and constant
 - Bounds, indexes are a function of loop variables, input variables and constants
 - Loops Increment by 1 (optional). Transform to 1.

DOALL Loops

- Given a nest of ***candidate*** For loops, determine if we can we make the outer-most loop parallel?
 - Safely
 - efficiently
- Criteria: every iteration of the outer-most loop must be *independent*
 - The loop can execute in any order, and produce the same result

Safety Criteria

- How do we check this?
 - If the property doesn't hold then there exists 2 iterations, such that if they are re-ordered, it causes different outcomes for the loop.
 - **Write-Write conflicts:** two distinct iterations write different values to the same location
 - **Read-Write conflicts:** two distinct iterations where one iteration reads from the location written to by another iteration.

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

```
for (i = 0; i < size; i++) {  
    a[index(i)] = loop(i);  
}
```

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

```
for (i = 0; i < size; i++) {  
    a[index(i)] = loop(i);  
}
```

index calculation based on the loop variable

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

```
for (i = 0; i < size; i++) {  
    a[index(i)] = loop(i);  
}
```

index calculation based on the loop variable
Computation to store in the memory location

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

```
for (i = 0; i < size; i++) {  
    a[index(i)] = loop(i);  
}
```

Write-write conflicts:

for two distinct iteration variables:

$i_x \neq i_y$

Check:

$\text{index}(i_x) \neq \text{index}(i_y)$

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

```
for (i = 0; i < size; i++) {  
    a[index(i)] = loop(i);  
}
```

Write-write conflicts:

for two distinct iteration variables:

$i_x \neq i_y$

Check:

$\text{index}(i_x) \neq \text{index}(i_y)$

Why?

Because if

$\text{index}(i_x) == \text{index}(i_y)$

then:

$a[\text{index}(i_x)]$ will equal
either $\text{loop}(i_x)$ or $\text{loop}(i_y)$
depending on the order

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*

```
for (i = 0; i < size; i++) {  
    a[write_index(i)] = a[read_index(i)] + loop(i);  
}
```

Read-write conflicts:

for two distinct iteration variables:

$i_x \neq i_y$

Check:

$\text{write_index}(i_x) \neq \text{read_index}(i_y)$

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*

```
for (i = 0; i < size; i++) {  
    a[write_index(i)] = a[read_index(i)] + loop(i);  
}
```

Read-write conflicts:

for two distinct iteration variables:

$i_x \neq i_y$

Check:

$\text{write_index}(i_x) \neq \text{read_index}(i_y)$

Why?

if i_x iteration happens first, then
iteration i_y reads an updated value.

if i_y happens first, then it reads the
original value

Examples:

```
for (i = 0; i < 128; i++) {  
    a[i] = a[i]*2;  
}
```


Examples:

```
for (i = 0; i < 128; i++) {  
    a[i] = a[i]*2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i] = a[0]*2;  
}
```

Examples:

```
for (i = 0; i < 128; i++) {  
    a[i] = a[i]*2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i] = a[0]*2;  
}
```

```
for (i = 1; i < 128; i++) {  
    a[i] = a[0]*2;  
}
```

Examples:

```
for (i = 0; i < 128; i++) {  
    a[i] = a[i] * 2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i] = a[0] * 2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i%64] = a[i] * 2;  
}
```

```
for (i = 1; i < 128; i++) {  
    a[i] = a[0] * 2;  
}
```

Examples:

```
for (i = 0; i < 128; i++) {  
    a[i] = a[i] * 2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i] = a[0] * 2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i%64] = a[i] * 2;  
}
```

```
for (i = 1; i < 128; i++) {  
    a[i] = a[0] * 2;  
}
```

i1 = 0, i2 = 1 both writing to 0

Examples:

```
for (i = 0; i < 128; i++) {  
    a[i] = a[i] * 2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i] = a[0] * 2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i%64] = a[i] * 2;  
}
```

```
for (i = 1; i < 128; i++) {  
    a[i] = a[0] * 2;  
}
```

```
for (i = 0; i < 128; i++) {  
    a[i%64] = a[i+64] * 2;  
}
```

Parallel Schedules

- Consider the following program:

There are 3 arrays: a , b , c .

We want to compute:

```
for (int i = 0; i < SIZE; i++) {  
    c[i] = a[i] + b[i];  
}
```

Is this a DOALL loop?

Parallel Schedules

- Consider the following program:

There are 3 arrays: a , b , c .

We want to compute:

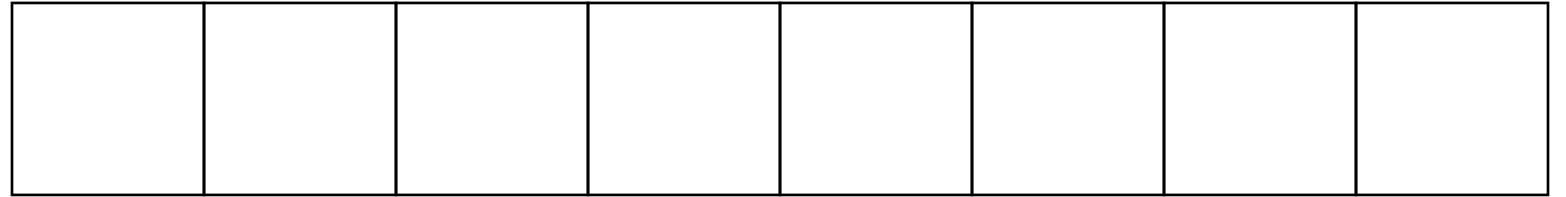
```
for (int i = 0; i < SIZE; i++) {  
    c[i] = a[i] + b[i];  
}
```

Is this a DOALL loop?

How should we parallelize it?

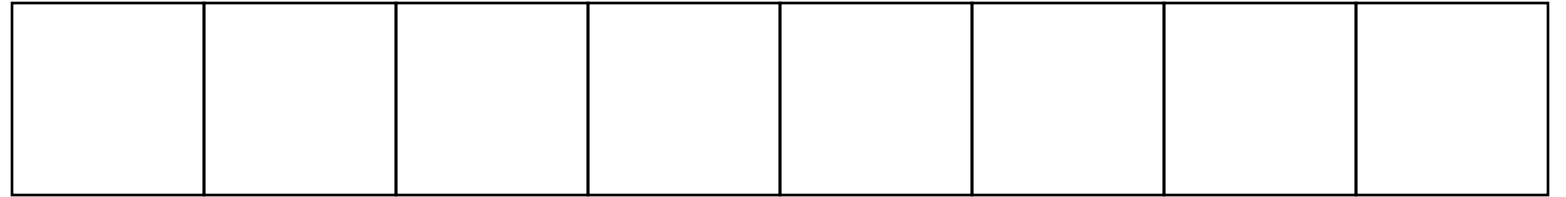
Parallel Schedules

array a



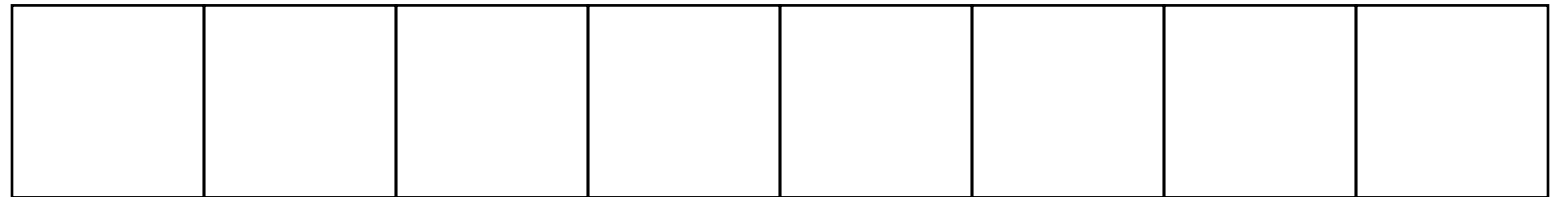
+ + + + + + + +

array b



= = = = = = = =

array c



Parallel Schedules

Computation
can easily be
divided into
threads

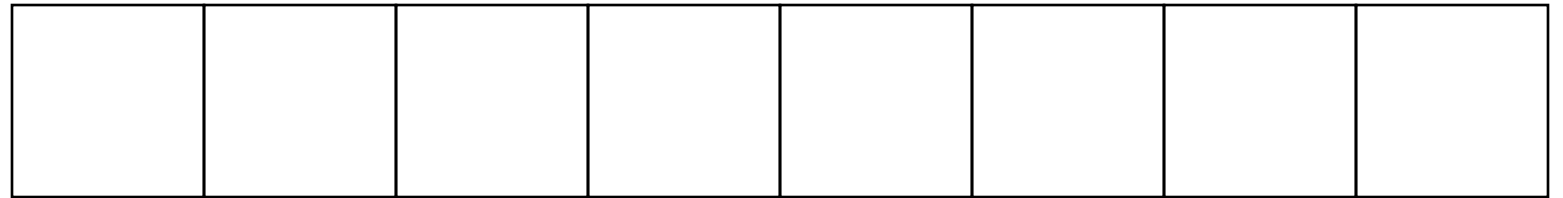
Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

array a



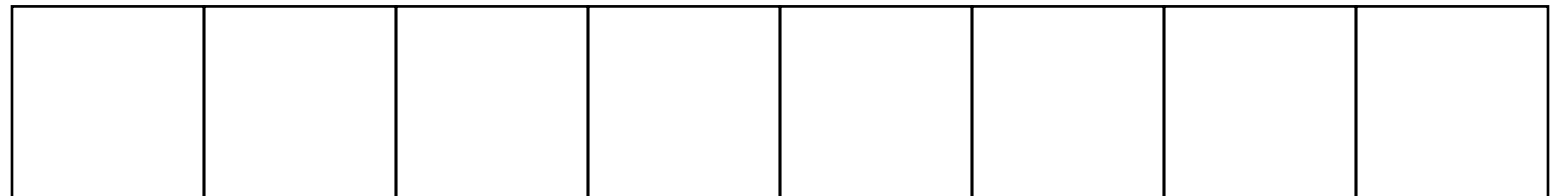
+ + + + + + + +

array b



= = = = = = = =

array c

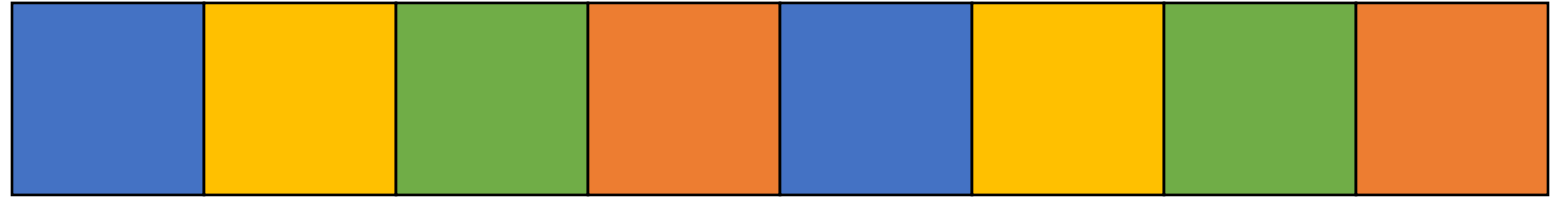


Parallel Schedules

Computation
can easily be
divided into
threads

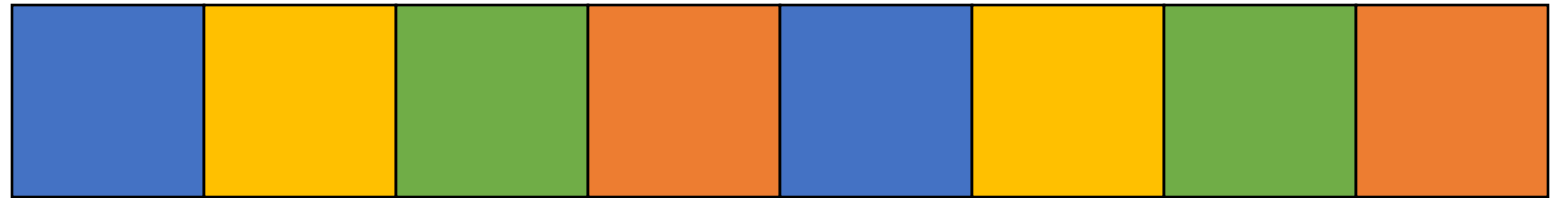
Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

array a



+ + + + + + + +

array b



= = = = = = = =

array c

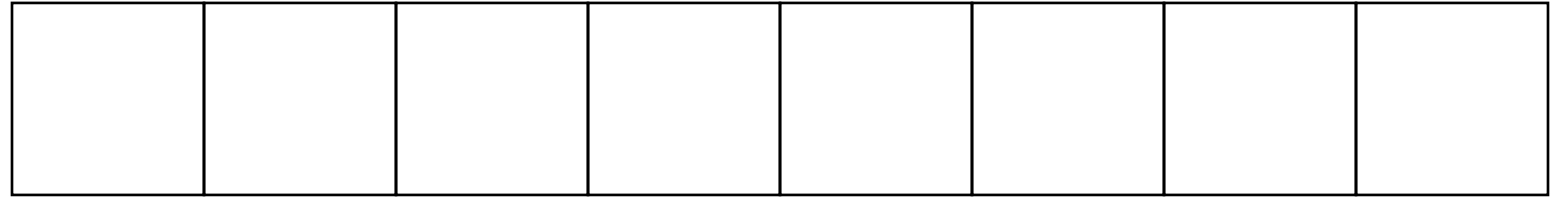


Parallel Schedules

Computation
can easily be
divided into
threads

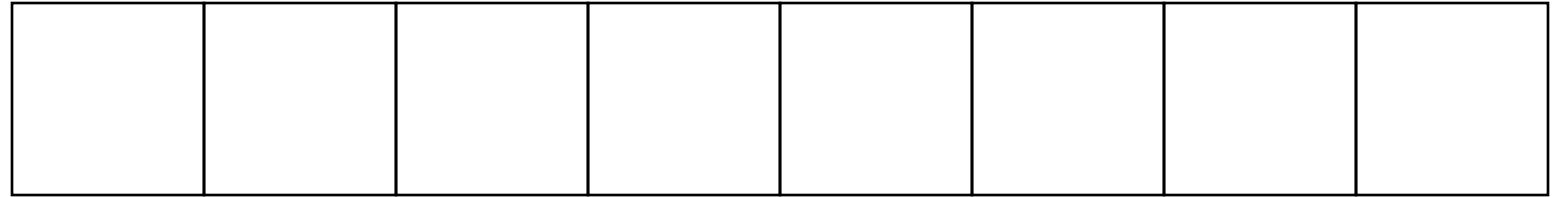
Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

array a



+ + + + + + + +

array b



= = = = = = = =

array c



Parallel Schedules

array a



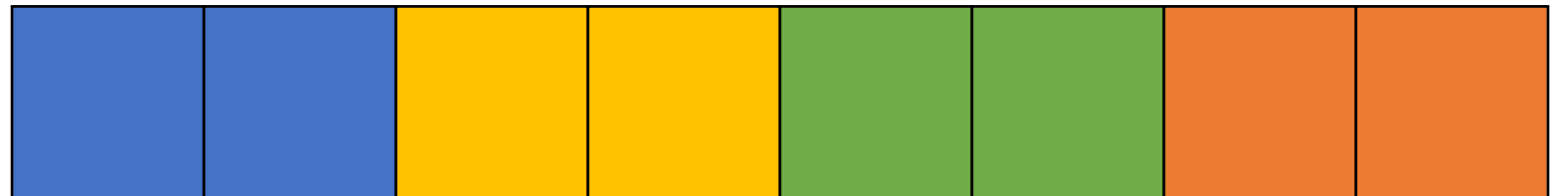
+ + + + + + + +

array b



= = = = = = = =

array c



Parallel Schedules

- Which one is more efficient?

Parallel Schedules

- Which one is more efficient? Avoid false sharing.

Parallel Schedules

- Which one is more efficient?
- These are called Parallel Schedules for DOALL Loops
- We will discuss several of them.

Schedule

- DOALL Loops
- **Parallel Schedules:**
 - **Static**
 - Global Worklists
 - Local Worklists

Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
    ...  
    for (int x = 0; x < SIZE; x++) {  
        // Each iteration takes roughly  
        // equal time  
    }  
    ...  
}
```

0	1	2	3	4	5	6	7		SIZE -1
---	---	---	---	---	---	---	---	--	---------

Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
    ...  
    for (int x = 0; x < SIZE; x++) {  
        // Each iteration takes roughly  
        // equal time  
    }  
    ...  
}
```

say $SIZE / NUM_THREADS = 4$

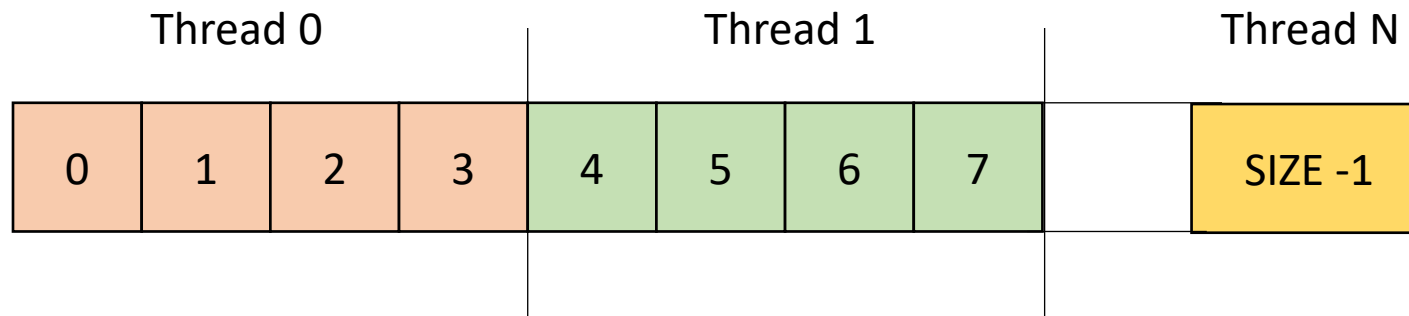
0	1	2	3	4	5	6	7		SIZE - 1
---	---	---	---	---	---	---	---	--	----------

Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
    ...  
    for (int x = 0; x < SIZE; x++) {  
        // Each iteration takes roughly  
        // equal time  
    }  
    ...  
}
```

say $SIZE / NUM_THREADS = 4$



Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
    ...  
    for (int x = 0; x < SIZE; x++) {  
        // Each iteration takes roughly  
        // equal time  
    }  
    ...  
}
```

make a new function with the for loop inside. Pass all needed variables as arguments. Take an extra argument for a thread id

Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
    ...  
    for (int x = 0; x < SIZE; x++) {  
    // Each iteration takes roughly  
    // equal time  
    }  
    ...  
}
```

```
void parallel_loop(..., int tid, int num_threads)  
{  
      
    for (int x = 0; x < SIZE; x++) {  
        // work based on x  
    }  
}
```

make a new function with the for loop inside. Pass all needed variables as arguments. Take an extra argument for a thread id

Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
    ...  
    for (int x = 0; x < SIZE; x++) {  
    // Each iteration takes roughly  
    // equal time  
    }  
    ...  
}
```

```
void parallel_loop(..., int tid, int num_threads)  
{  
  
    int chunk_size = SIZE / NUM_THREADS;  
    for (int x = 0; x < SIZE; x++) {  
        // work based on x  
    }  
}
```

determine chunk size in new function

Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
    ...  
    for (int x = 0; x < SIZE; x++) {  
    // Each iteration takes roughly  
    // equal time  
    }  
    ...  
}
```

```
void parallel_loop(..., int tid, int num_threads)  
{  
  
    int chunk_size = SIZE / NUM_THREADS;  
    int start = chunk_size * tid;  
    int end = start + chunk_size;  
    for (int x = start; x < end; x++) {  
        // work based on x  
    }  
}
```

Set new loop bounds

Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
    ...  
    for (int t = 0; t < NUM_THREADS; t++) {  
        spawn(parallel_loop(..., t, NUM_THREADS))  
    }  
    join();  
    ...  
}
```

```
void parallel_loop(..., int tid, int num_threads)  
{  
  
    int chunk_size = SIZE / NUM_THREADS;  
    int start = chunk_size * tid;  
    int end = start + chunk_size;  
    for (int x = start; x < end; x++) {  
        // work based on x  
    }  
}
```

You will need to adapt the thread spawn, join
to C++

Spawn threads

Static schedule

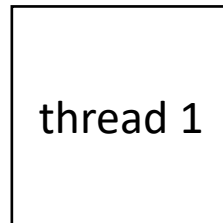
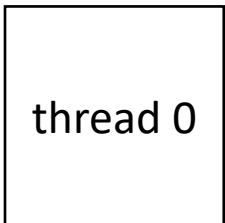
- Example, 2 threads/cores, array of size 8

0	1	2	3	4	5	6	7
---	---	---	---	---	---	---	---

chunk_size = ?

0: start = ? 1: start = ?

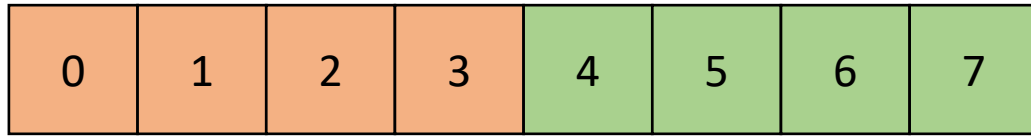
0: end = ? 1: end = ?



```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

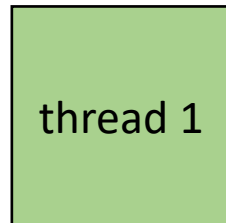
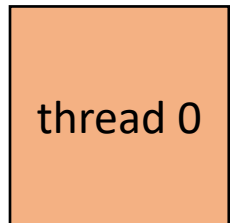
- Example, 2 threads/cores, array of size 8



chunk_size = 4

0: start = 0 1: start = 4

0: end = 4 1: end = 8



```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

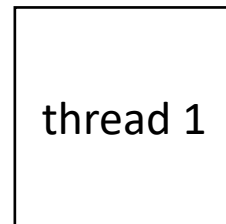
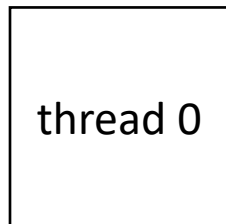
- Example, 2 threads/cores, array of size 9

0	1	2	3	4	5	6	7	8
---	---	---	---	---	---	---	---	---

chunk_size = ?

0: start = ? 1: start = ?

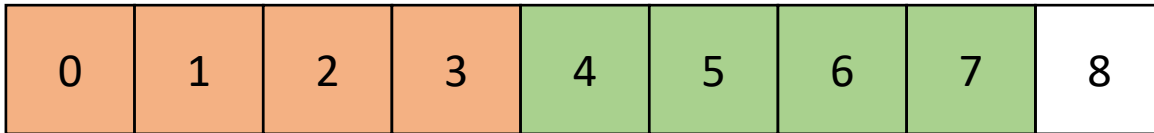
0: end = ? 1: end = ?



```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

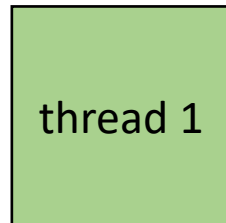
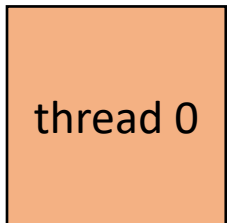
- Example, 2 threads/cores, array of size 9



chunk_size = 4

0: start = 0 1: start = 4

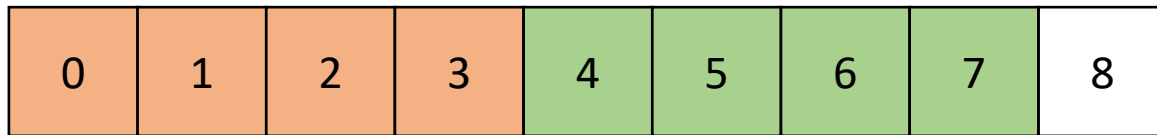
0: end = 4 1: end = 8



```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

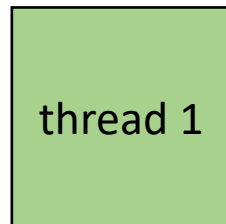
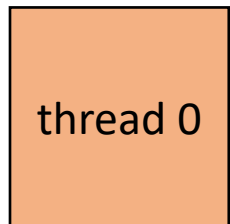
- Example, 2 threads/cores, array of size 9



chunk_size = 4

0: start = 0 1: start = 4

0: end = 4 1: end = 8

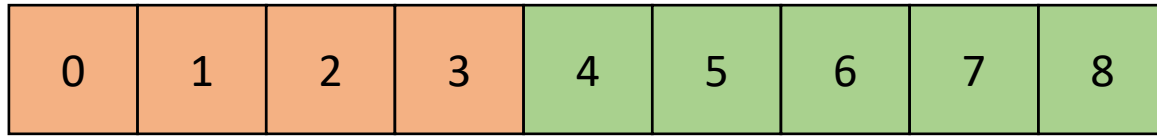


```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    if (tid == num_threads - 1) {
        end = SIZE;
    }
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

last thread gets more work

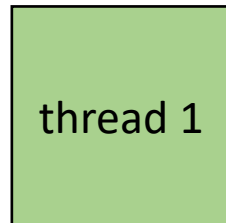
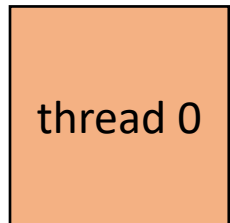
- Example, 2 threads/cores, array of size 9



chunk_size = 4

0: start = 0 1: start = 4

0: end = 4 1: end = ?



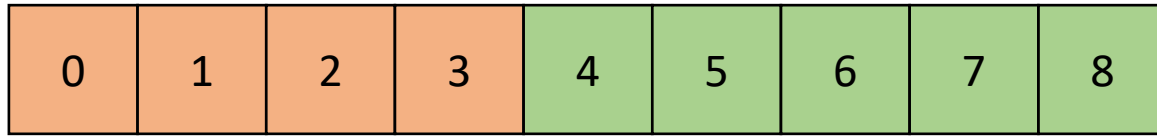
```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    if (tid == num_threads - 1) {
        end = SIZE;
    }
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

- Example, 2 threads/cores, array of size 9

last thread gets more work

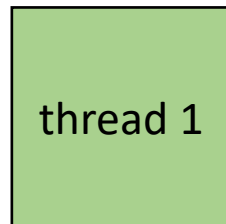
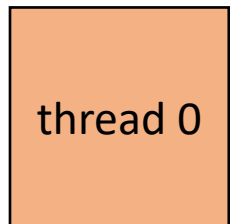
What is the worst case?



chunk_size = 4

0: start = 0 1: start = 4

0: end = 4 1: end = 9



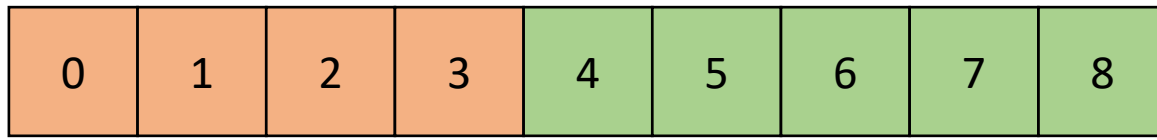
```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    if (tid == num_threads - 1) {
        end = SIZE;
    }
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

- Example, 2 threads/cores, array of size 9

last thread gets more work

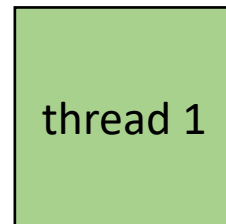
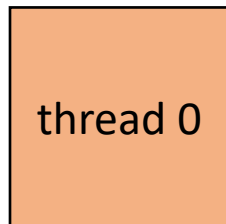
What is the worst case?
3 items



chunk_size = 4

0: start = 0 1: start = 4

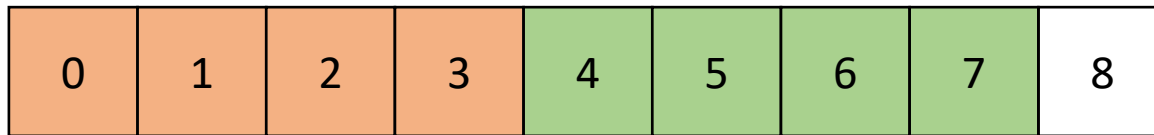
0: end = 4 1: end = 9



```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    if (tid == num_threads - 1) {
        end = SIZE;
    }
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```


Static schedule

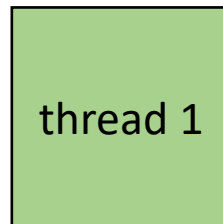
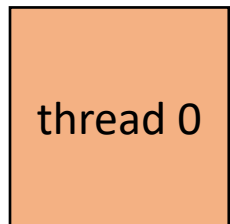
- Example, 2 threads/cores, array of size 9



chunk_size = 4

0: start = 0 1: start = 4

0: end = 4 1: end = 8

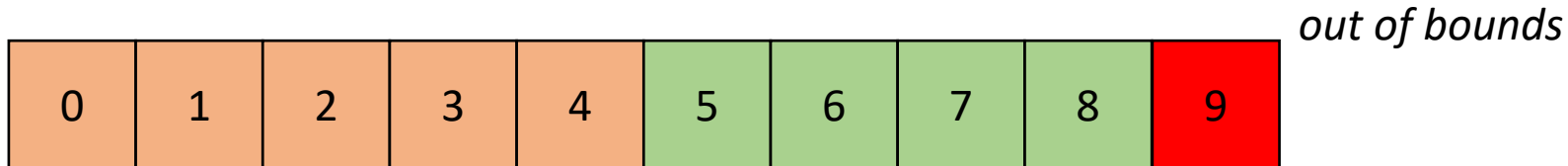


ceiling division, this will distribute uneven work in the last thread to all other threads

```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size =
        (SIZE + (NUM_THREADS - 1)) / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

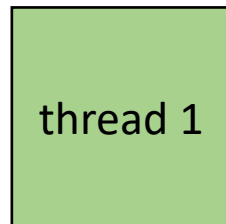
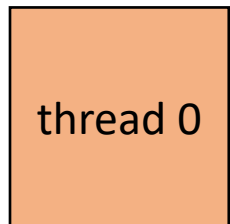
- Example, 2 threads/cores, array of size 9



chunk_size = 5

0: start = 0 1: start = 5

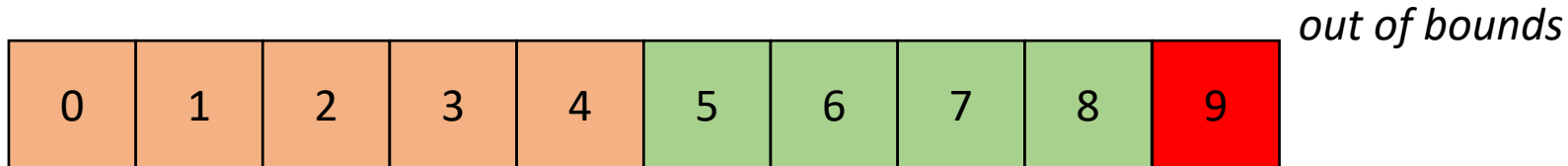
0: end = 5 1: end = 10



```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size =
        (SIZE+(NUM_THREADS-1))/NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

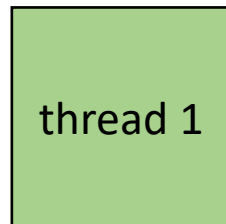
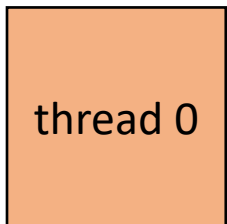
- Example, 2 threads/cores, array of size 9



chunk_size = 5

0: start = 0 1: start = 5

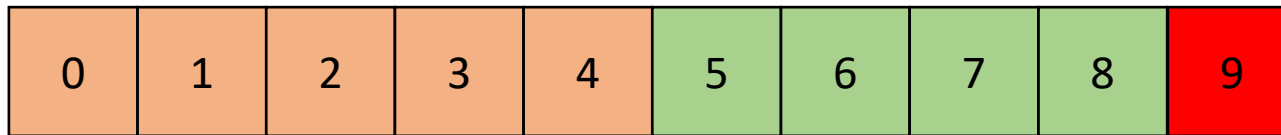
0: end = 5 1: end = 10



```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size =
        (SIZE + (NUM_THREADS - 1)) / NUM_THREADS;
    int start = chunk_size * tid;
    int end =
        min(start + chunk_size, SIZE)
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Static schedule

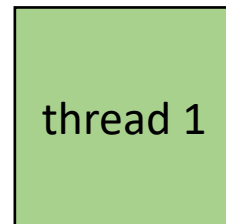
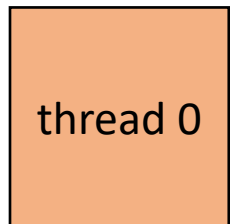
- Example, 2 threads/cores, array of size 9



chunk_size = 5

0: start = 0 1: start = 5

0: end = 5 1: end = 9



most threads do equal amounts of work, last thread may do less.

Which one is better/worse?

Approach 1:

Max slowdown for last thread does all the extra work? 3 items

Approach 2: (with ceiling)

Max slowdown is 1 item.

```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size =
        (SIZE + (NUM_THREADS - 1)) / NUM_THREADS;
    int start = chunk_size * tid;
    int end =
        min(start + chunk_size, SIZE)
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```

Schedule

- DOALL Loops
- **Parallel Schedules:**
 - Static
 - **Global Worklists**
 - Local Worklists

Irregular parallelism in loops

- Tasks are not balanced
- Appears in lots of emerging workloads

Irregular parallelism in loops

- Tasks are not balanced
- Appears in lots of emerging workloads

social network analytics where threads are parallel across users



Irregular parallelism in loops

- Independent iterations have different amount of work to compute
- Threads with longer tasks take longer to compute.
- Threads with shorter tasks are under utilized.

```
for (x = 0; x < SIZE; x++) {  
    for (y = x; y < SIZE; y++) {  
        a[x,y] = b[x,y] + c[x,y];  
    }  
}
```

irregular (or unbalanced) parallelism:
each x iteration performs different
amount of work.

Irregular parallelism in loops

- Calculate imbalance cost if x is chunked:
 - Thread 1 takes iterations $0 - \text{SIZE}/2$
 - Thread 2 takes iterations $\text{SIZE}/2 - \text{SIZE}$

```
for (x = 0; x < SIZE; x++) {  
    for (y = x; y < SIZE; y++) {  
        a[x,y] = b[x,y] + c[x,y];  
    }  
}
```

Irregular parallelism in loops

- Calculate imbalance cost if x is chunked:
 - Thread 1 takes iterations 0 - SIZE/2
 - Thread 2 takes iterations SIZE/2 - SIZE

Calculate how much total work:

$$\text{total_work} = \sum_{n=0}^{\text{SIZE}} n$$

```
for (x = 0; x < SIZE; x++) {  
    for (y = x; y < SIZE; y++) {  
        a[x,y] = b[x,y] + c[x,y];  
    }  
}
```

Irregular parallelism in loops

- Calculate imbalance cost if x is chunked:
 - Thread 1 takes iterations 0 - SIZE/2
 - Thread 2 takes iterations SIZE/2 - SIZE

```
for (x = 0; x < SIZE; x++) {  
    for (y = x; y < SIZE; y++) {  
        a[x,y] = b[x,y] + c[x,y];  
    }  
}
```

Calculate how much total work:

$$\text{total_work} = \sum_{n=0}^{\text{SIZE}} n$$

Calculate work done by first thread:

$$\text{t1_work} = \sum_{n=0}^{\text{SIZE}/2} n$$

Irregular parallelism in loops

- Calculate imbalance cost if x is chunked:
 - Thread 1 takes iterations 0 - SIZE/2
 - Thread 2 takes iterations SIZE/2 - SIZE

```
for (x = 0; x < SIZE; x++) {  
    for (y = x; y < SIZE; y++) {  
        a[x,y] = b[x,y] + c[x,y];  
    }  
}
```

Calculate how much total work:

$$\text{total_work} = \sum_{n=0}^{\text{SIZE}} n$$

Calculate work done by first thread:

$$\text{t1_work} = \sum_{n=0}^{\text{SIZE}/2} n$$

Calculate work done by second thread:

$$\text{t2_work} = \text{total_work} - \text{t1_work}$$

Irregular parallelism in loops

Example: SIZE = 64

total_work = 2016

t2_work = 496

t1_work = 1520

t1 does ~3x more work than t2

Only provides ~1.3x speedup

Potential solution:

Have T1 do only ¼ of the iterations

Gives a better speedup of 1.77x

Not a feasible solution because often times load imbalance is not given by a static equation on loop bounds!

Calculate how much total work:

$$\text{total_work} = \sum_{n=0}^{\text{SIZE}} n$$

Calculate work done by first thread:

$$\text{t1_work} = \sum_{n=0}^{\text{SIZE}/2} n$$

Calculate work done by second thread:

$$\text{t2_work} = \text{total_work} - \text{t1_work}$$

Work stealing

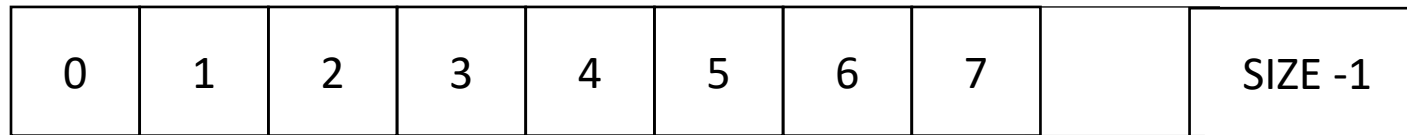
- Tasks are dynamically assigned to threads.

Work stealing - global implicit worklist

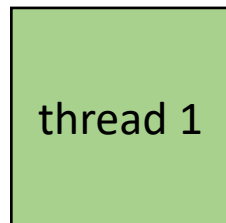
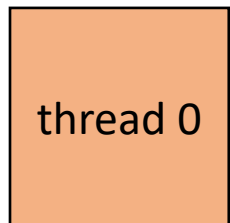
- Pros
 - Simple to implement
- Cons:
 - High contention on global counter
 - Potentially bad memory locality.

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

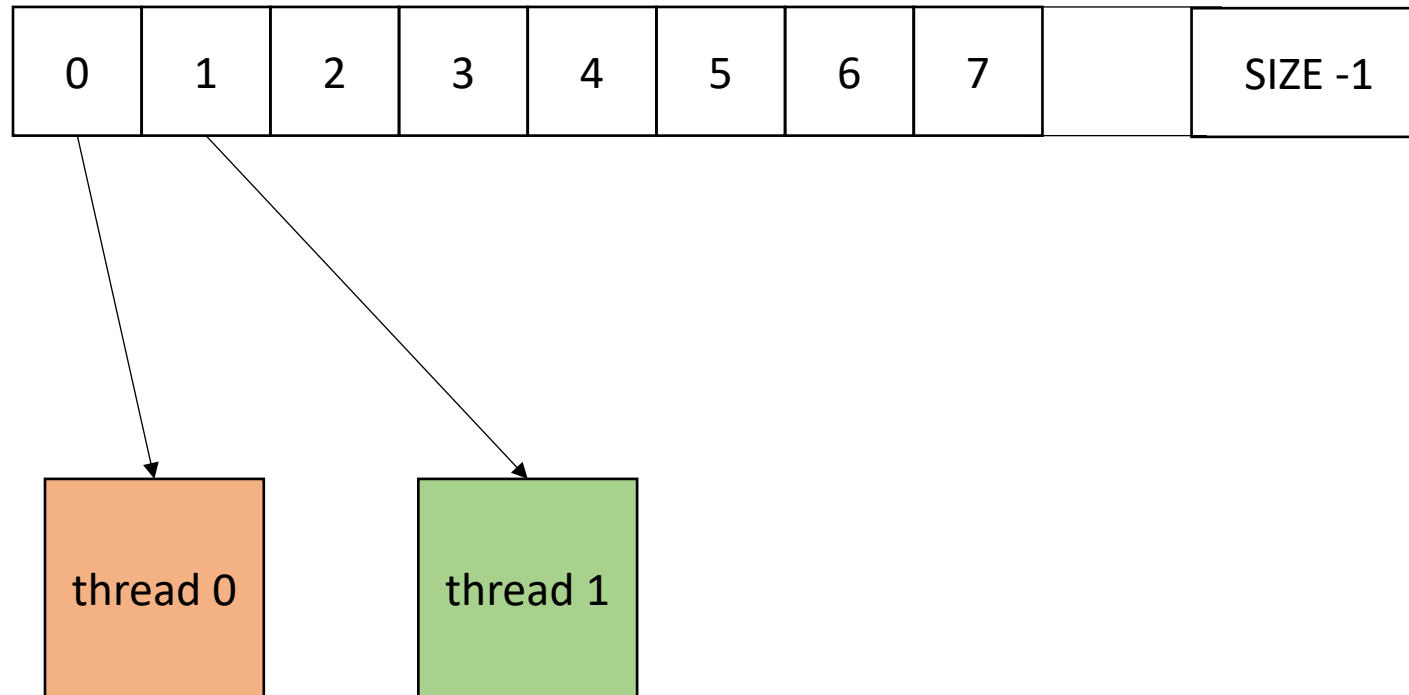


cannot color initially!



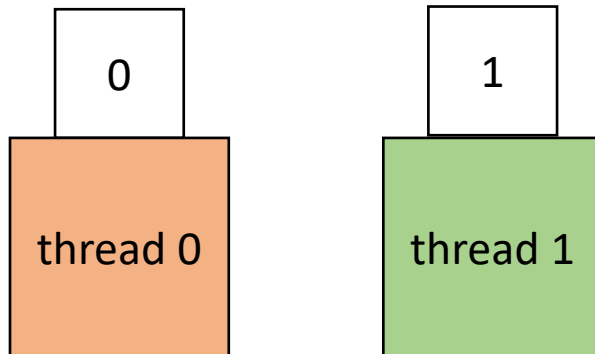
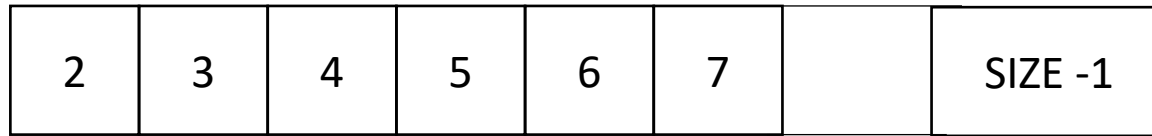
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



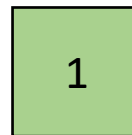
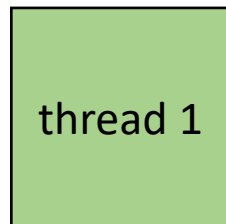
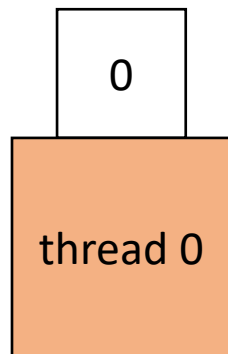
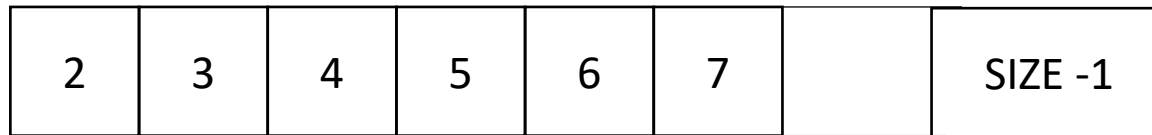
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



Work stealing - global implicit worklist

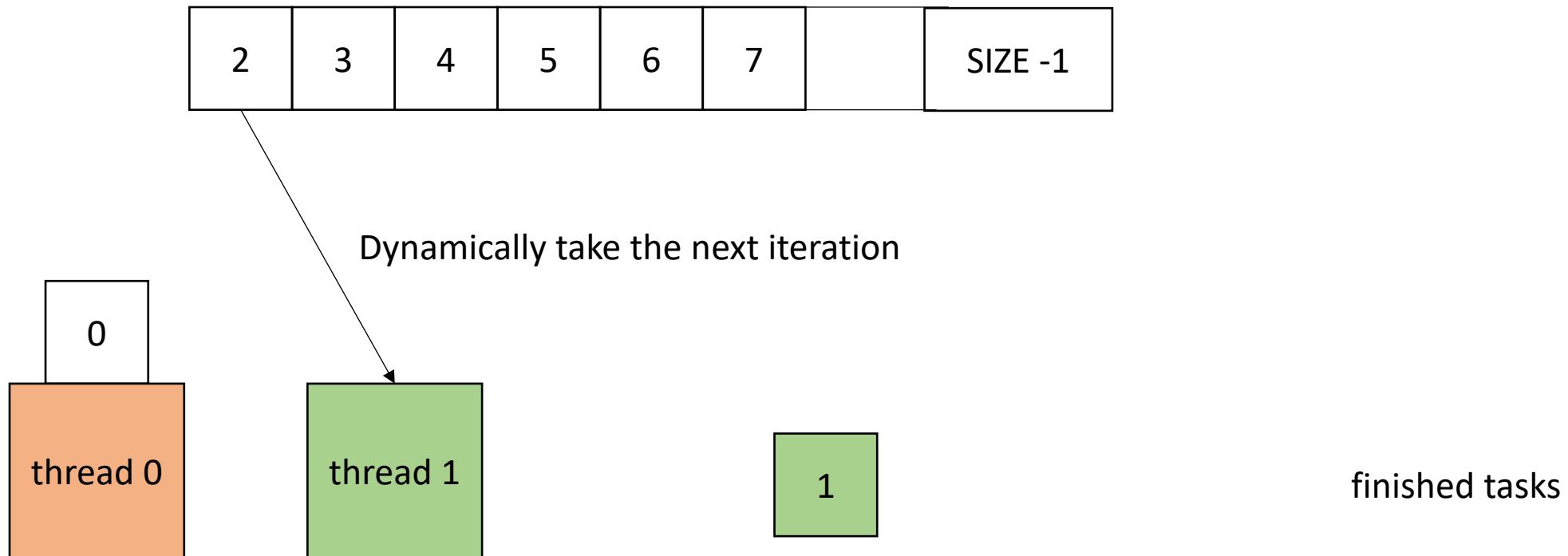
- Global worklist: threads take tasks (iterations) dynamically



finished tasks

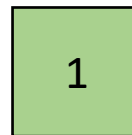
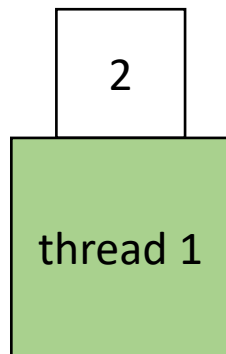
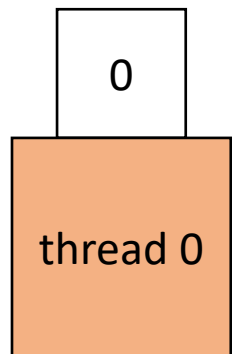
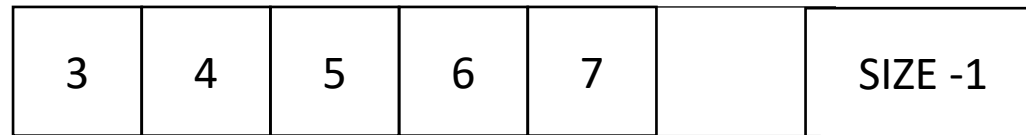
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



Work stealing - global implicit worklist

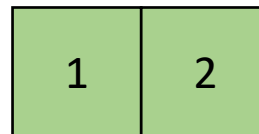
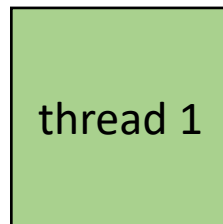
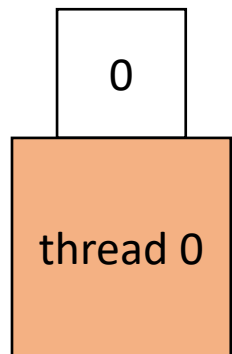
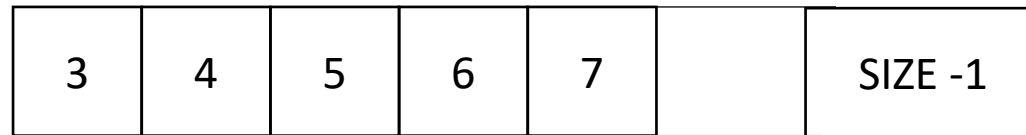
- Global worklist: threads take tasks (iterations) dynamically



finished tasks

Work stealing - global implicit worklist

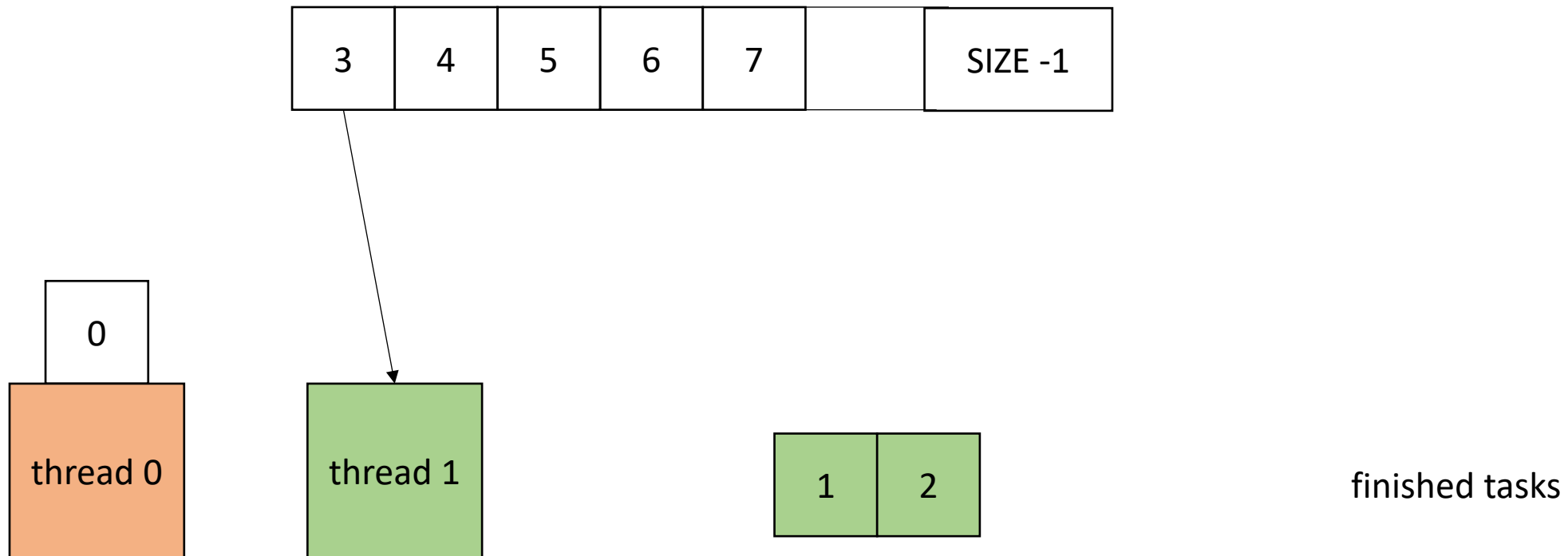
- Global worklist: threads take tasks (iterations) dynamically



finished tasks

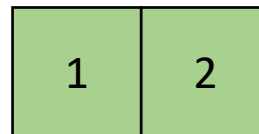
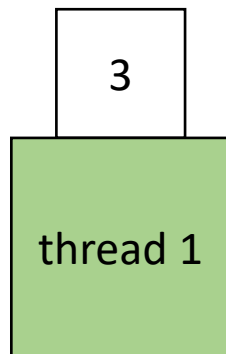
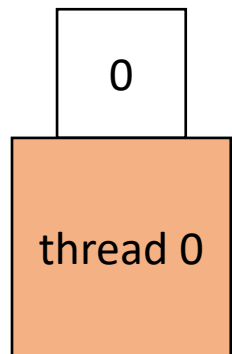
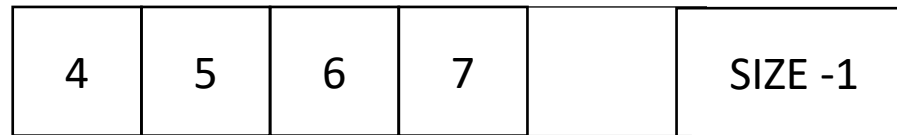
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



Work stealing - global implicit worklist

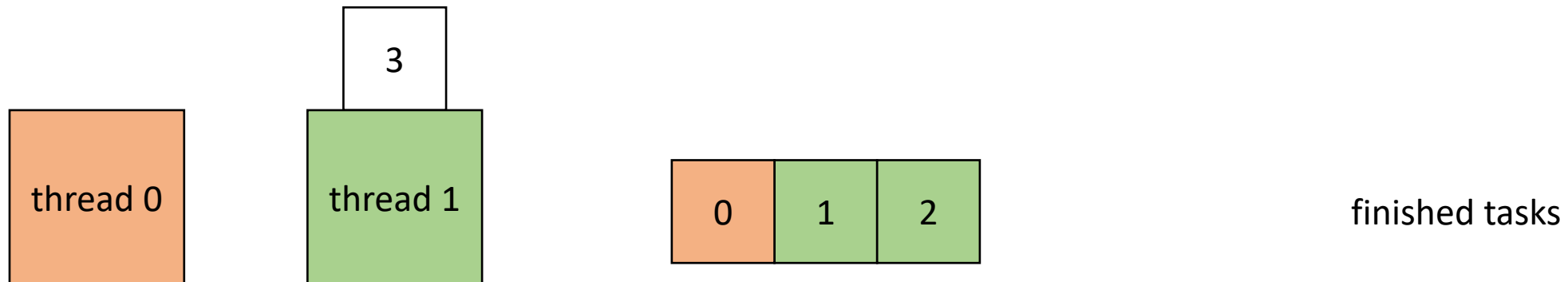
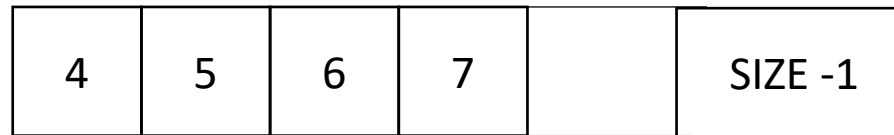
- Global worklist: threads take tasks (iterations) dynamically



finished tasks

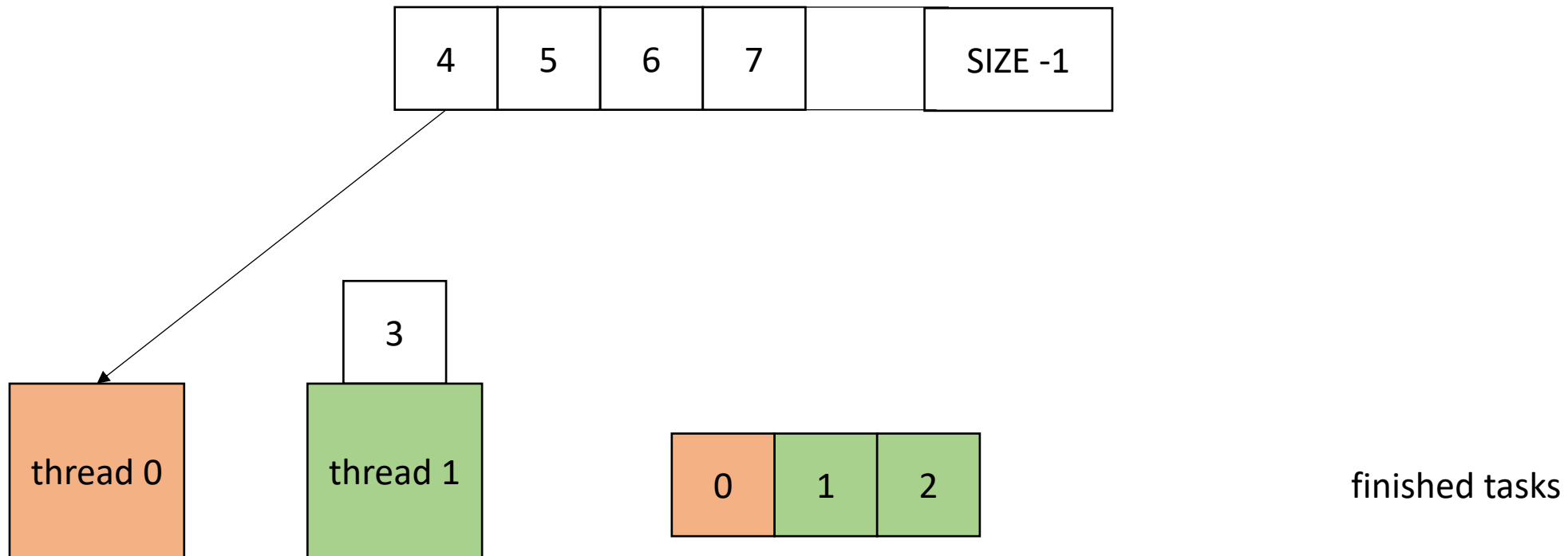
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



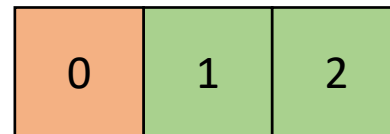
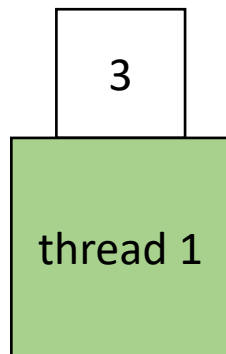
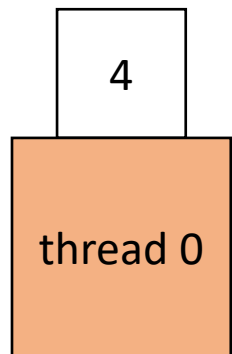
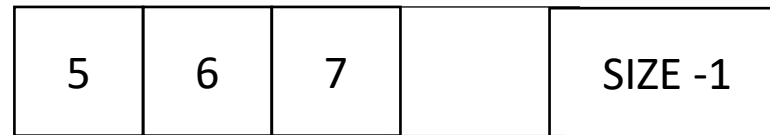
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



finished tasks

Work stealing - global implicit worklist

- How to implement

```
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
    ...  
}
```

Work stealing - global implicit worklist

- How to implement

```
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
    // dynamic work based on x  
    }  
    ...  
}
```

```
void parallel_loop(...) {  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
}
```

Replicate code in a new function. Pass all needed variables as arguments.

Work stealing - global implicit worklist

- How to implement

```
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
    // dynamic work based on x  
    }  
    ...  
}
```

```
atomic_int x(0);  
void parallel_loop(...) {  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
}
```

move loop variable to be a global atomic variable

Work stealing - global implicit worklist

- How to implement

```
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
    // dynamic work based on x  
    }  
    ...  
}
```

```
atomic_int x(0);  
void parallel_loop(...) {  
    for (int local_x = ??  
        local_x < SIZE;  
        local_x = ??) {  
        // dynamic work based on x  
    }  
}
```

change loop bounds in new function to use a local variable using global variable.

Work stealing - global implicit worklist

- How to implement

*These must be
atomic updates!*

```
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
    // dynamic work based on x  
    }  
    ...  
}
```

```
atomic_int x(0);  
void parallel_loop(...) {  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
        // dynamic work based on x  
    }  
}
```

change loop bounds in new function to use a local variable using global variable.

Work stealing - global implicit worklist

- How to implement

```
void foo() {  
    ...  
    for (t = 0; x < THREADS; t++) {  
        spawn(parallel_loop);  
    }  
    join();  
    ...  
}
```

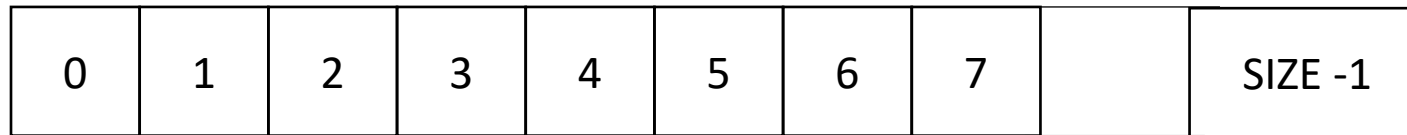
```
atomic_int x(0);  
void parallel_loop(...) {  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
        // dynamic work based on x  
    }  
}
```

Spawn threads in original function and join them afterwards

You will have to change to C++ syntax for the homework!

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



x: 0

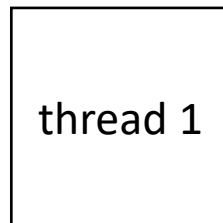
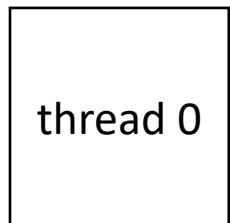
0 - local_x - UNDEF

1 - local_x - UNDEF

```
atomic_int x(0);
void parallel_loop(...) {

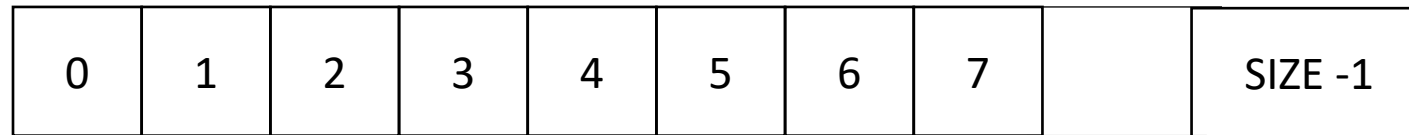
    for (int local_x = atomic_fetch_add(&x,1);
         local_x < SIZE;
         local_x = atomic_fetch_add(&x,1)) {

        // dynamic work based on x
    }
}
```



Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

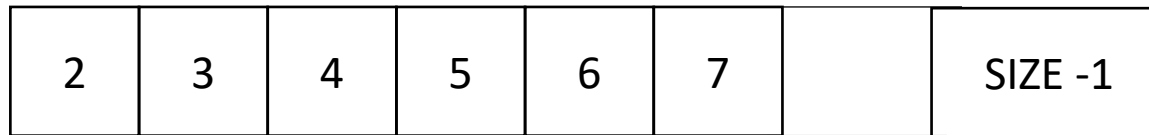


x: 2
0 - local_x - 0
1 - local_x - 1

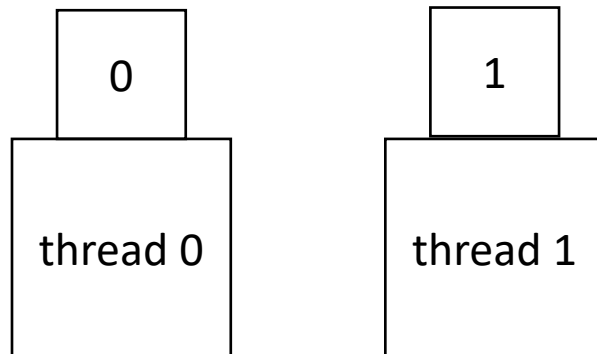
```
atomic_int x(0);  
void parallel_loop(...) {  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



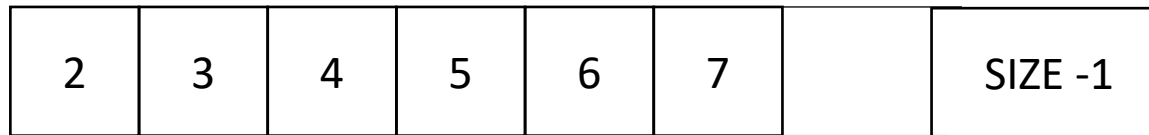
x: 2
0 - local_x - 0
1 - local_x - 1



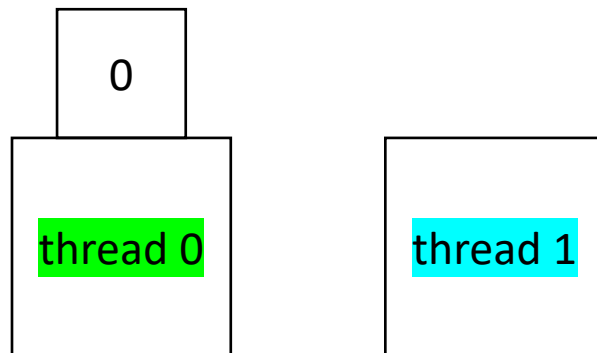
```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



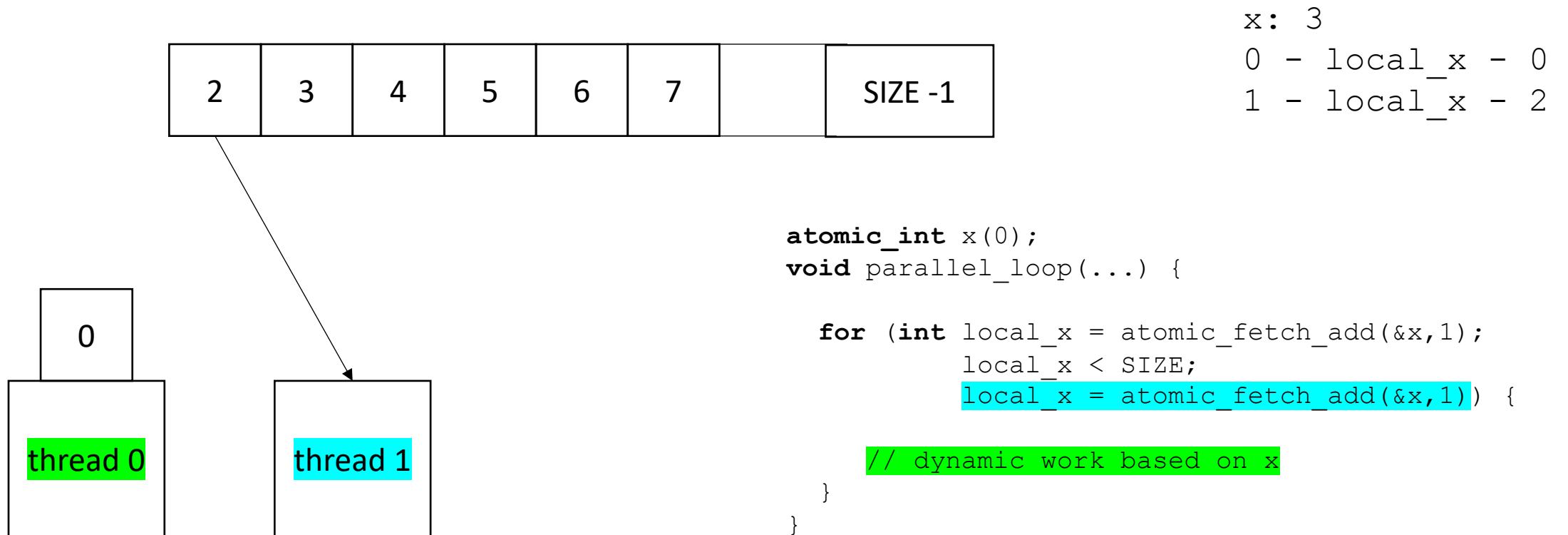
x: 2
0 - local_x - 0
1 - local_x - 1



```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

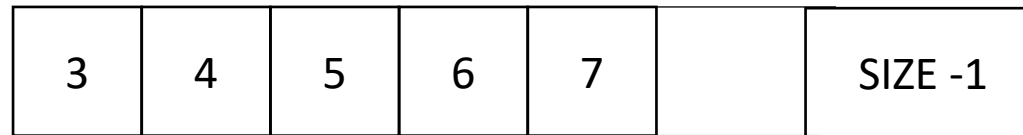
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

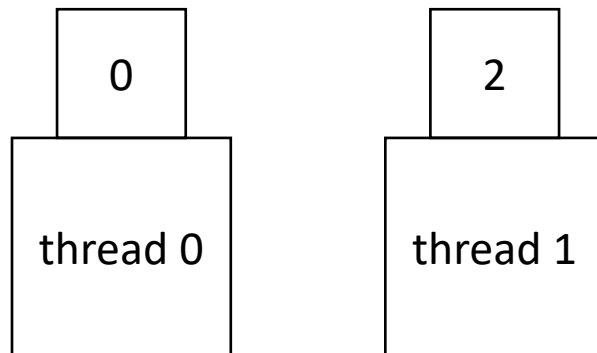


Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



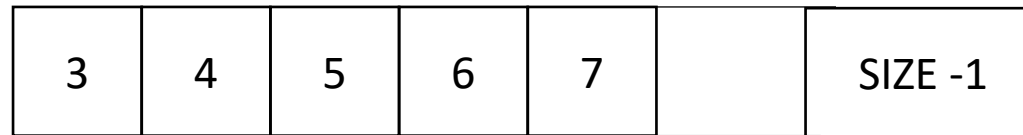
x: 3
0 - local_x - 0
1 - local_x - 2



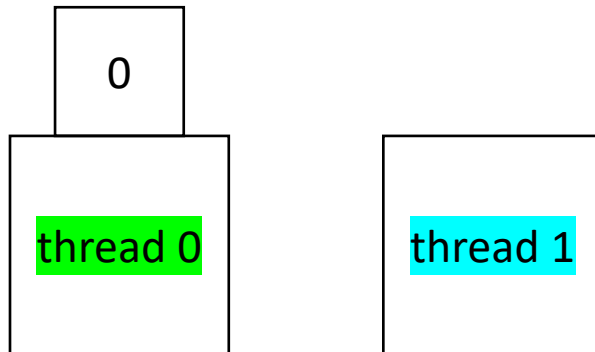
```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



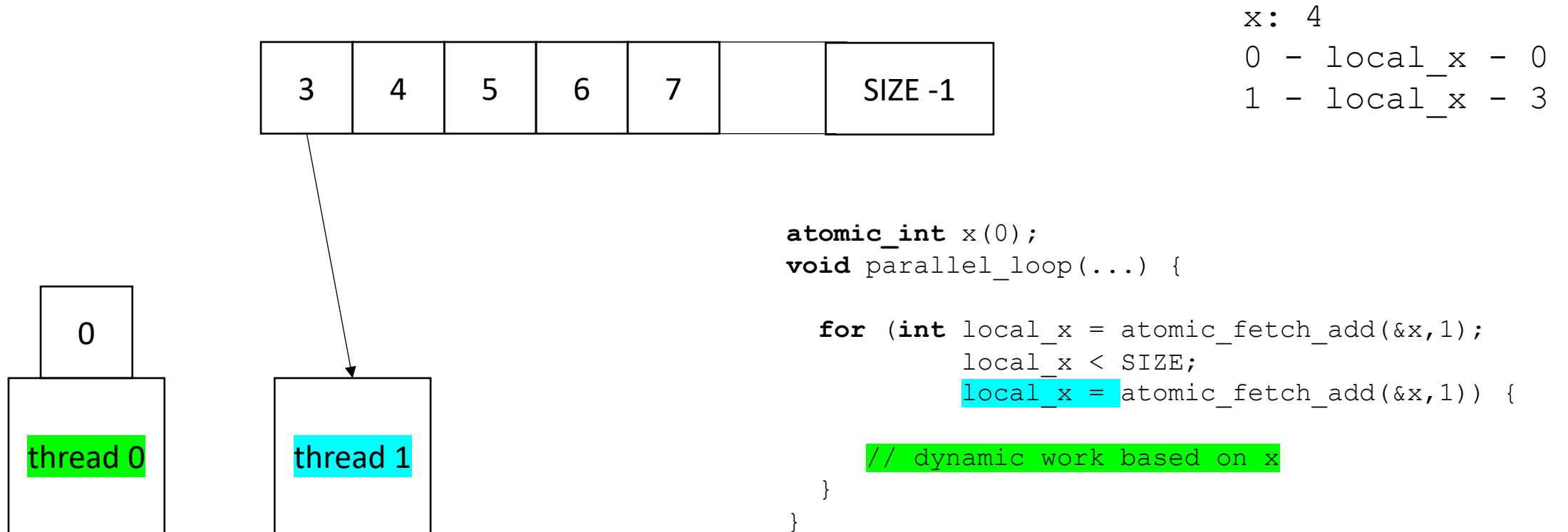
x: 3
0 - local_x - 0
1 - local_x - 2



```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

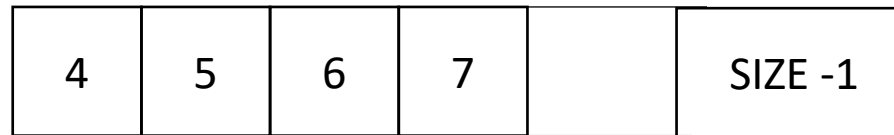

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

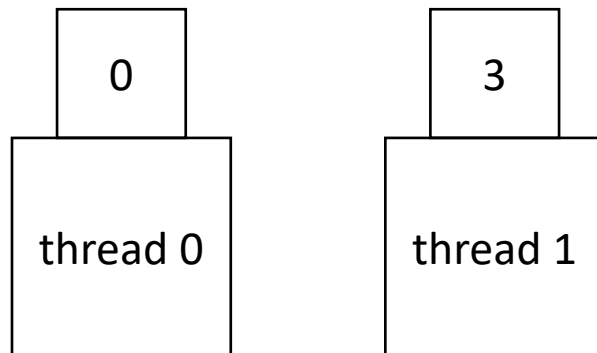


Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



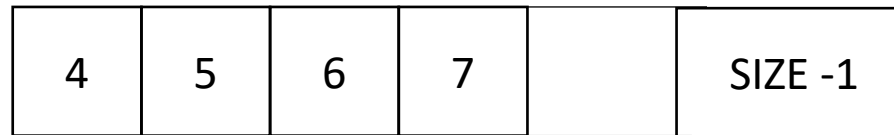
x: 4
0 - local_x - 0
1 - local_x - 3



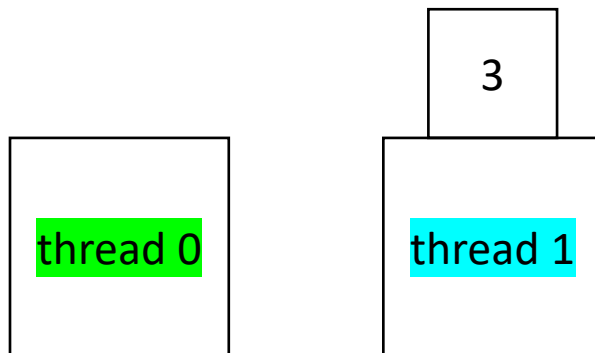
```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



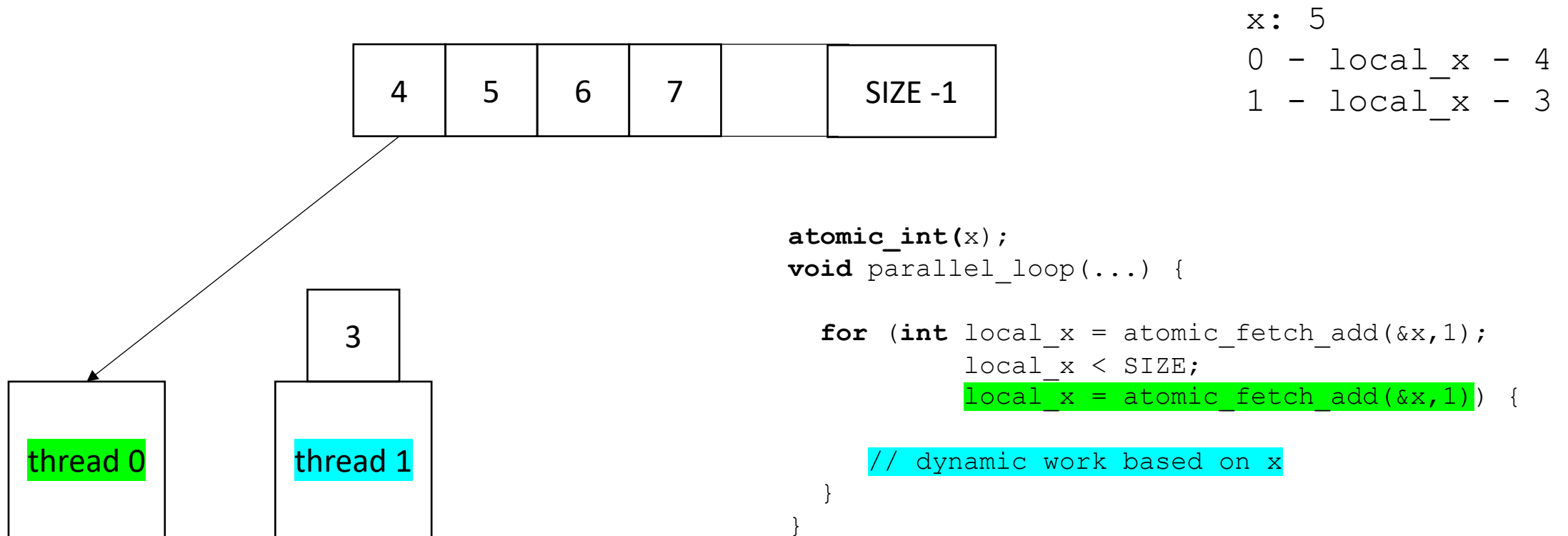
x: 4
0 - local_x - 0
1 - local_x - 3



```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

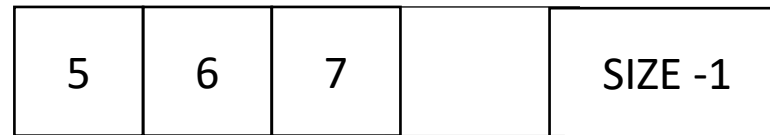
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



Work stealing - global implicit worklist

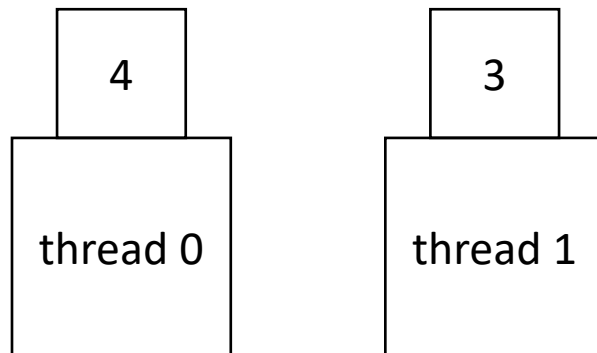
- Global worklist: threads take tasks (iterations) dynamically



x: 5

0 - local_x - 4

1 - local_x - 3



```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Schedule

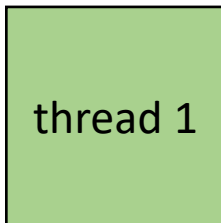
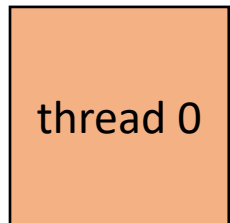
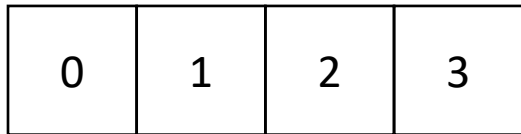
- DOALL Loops
- **Parallel Schedules:**
 - Static
 - Global Worklists
 - **Local Worklists**

Work stealing - local worklists

- More difficult to implement
- low contention on local data-structures
- potentially better cache locality

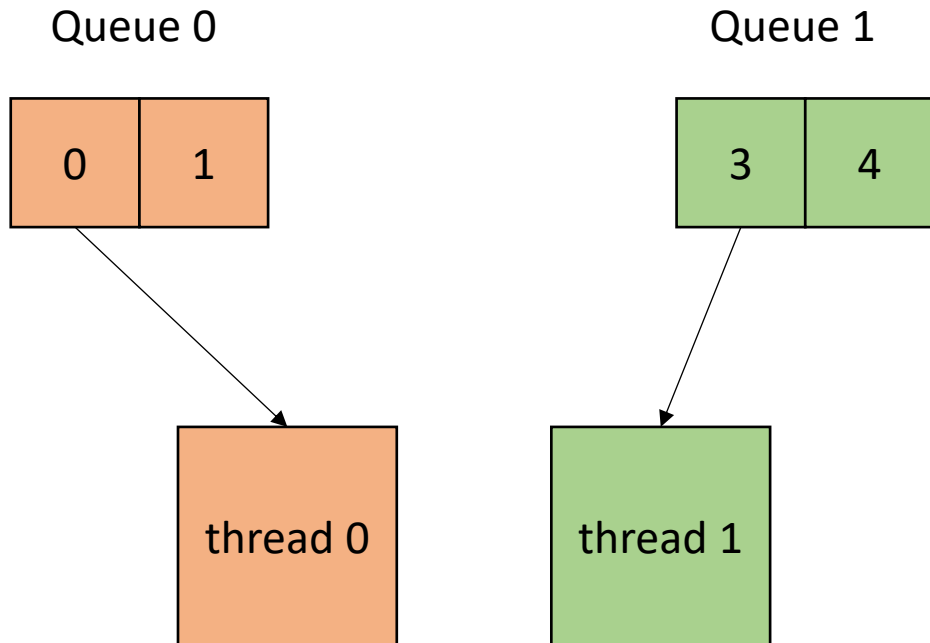
Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread



Work stealing - local worklists

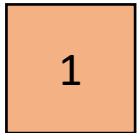
- local worklists: divide tasks into different worklists for each thread



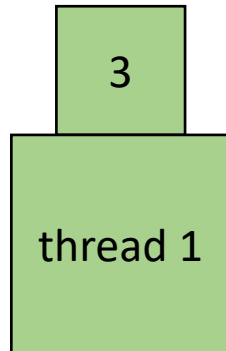
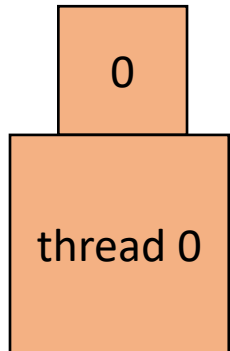
Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread

Queue 0



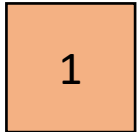
Queue 1



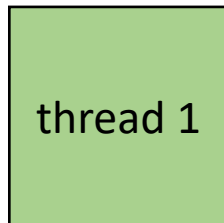
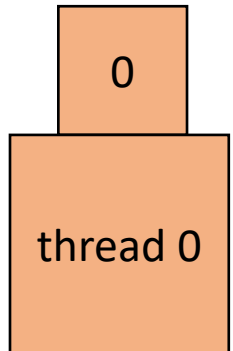
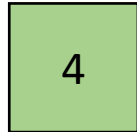
Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread

Queue 0

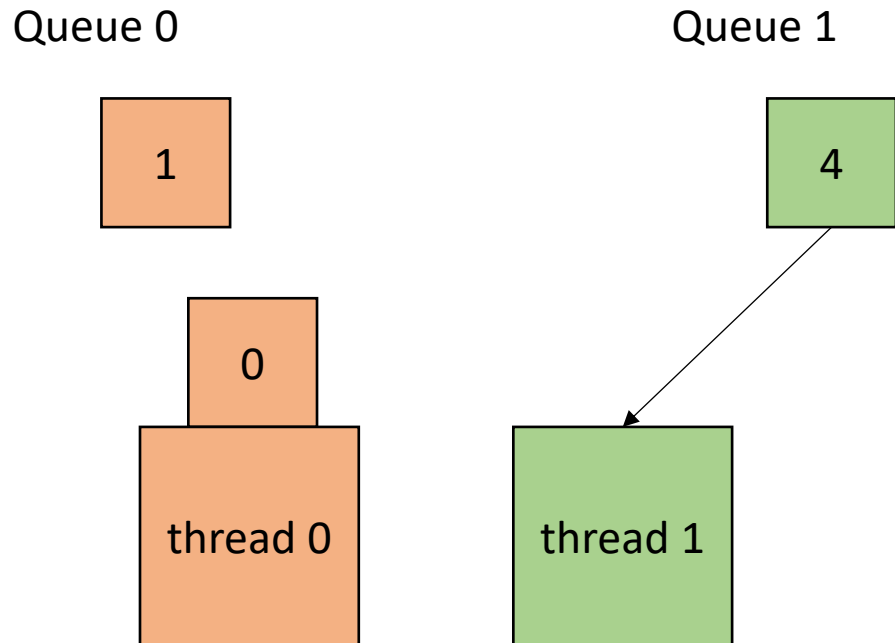


Queue 1



Work stealing - local worklists

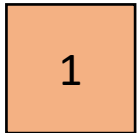
- local worklists: divide tasks into different worklists for each thread



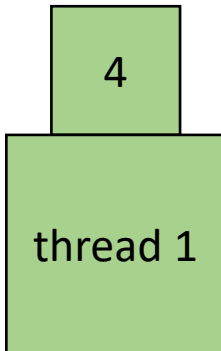
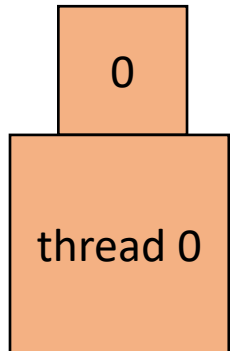
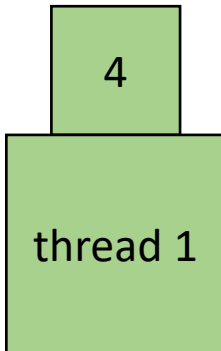
Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread

Queue 0



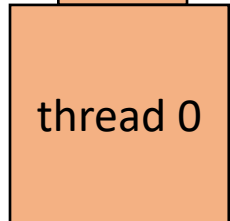
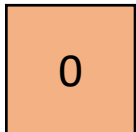
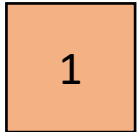
Queue 1



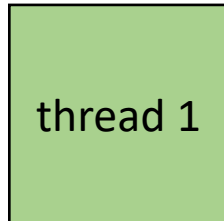
Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread

Queue 0

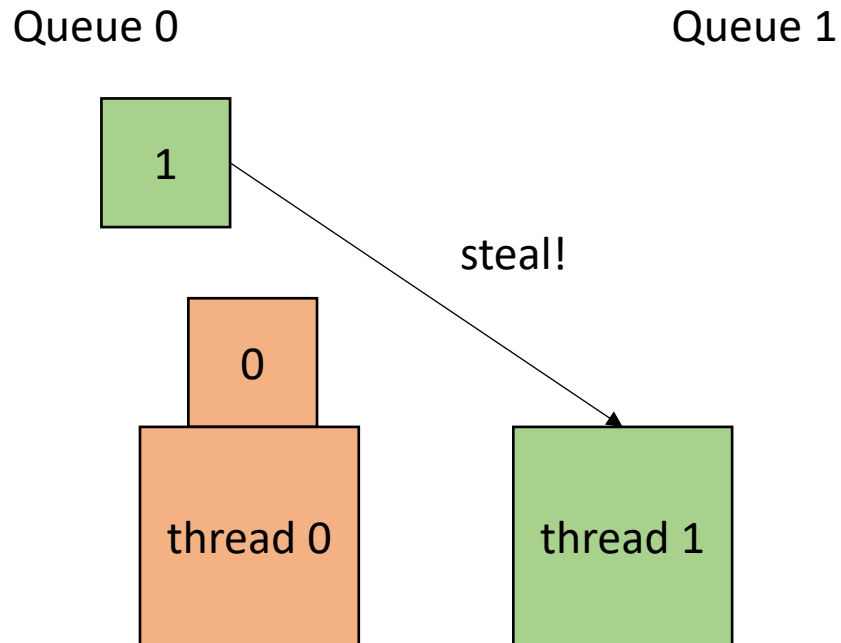


Queue 1



Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread

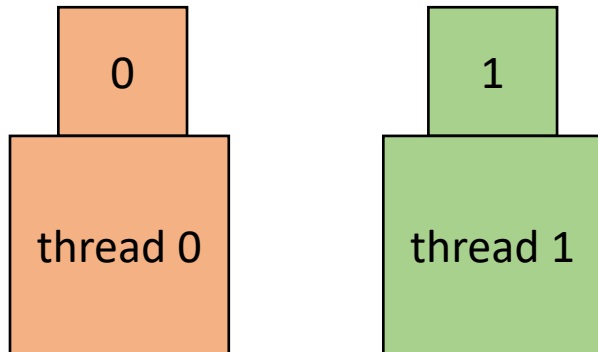


Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread

Queue 0

Queue 1



Work stealing - local worklists

- How to implement:

```
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
    ...  
}
```

Work stealing - local worklists

- How to implement:

```
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
    // dynamic work based on x  
    }  
    ...  
}
```

```
void parallel_loop(..., int tid) {  
  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
}
```

Make a new function, taking any variables used in loop body as args. Additionally take in a thread id

Work stealing - local worklists

- How to implement:

```
concurrent_queue cq[NUM_THREADS];  
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
    // dynamic work based on x  
    }  
    ...  
}
```

```
void parallel_loop(..., int tid) {  
  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
}
```

Make a global array of concurrent queues

Work stealing - local worklists

- How to implement:

```
concurrent_queue cq[NUM_THREADS];  
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
    // dynamic work based on x  
    }  
    ...  
}
```

```
void parallel_loop(..., int tid) {  
  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
}
```

What type of queues?

Make a global array of concurrent queues

Work stealing - local worklists

- How to implement:

```
concurrent_queue cq[NUM_THREADS];  
void foo() {  
    ...  
    for (x = 0; x < SIZE; x++) {  
    // dynamic work based on x  
    }  
    ...  
}
```

Make a global array of concurrent queues

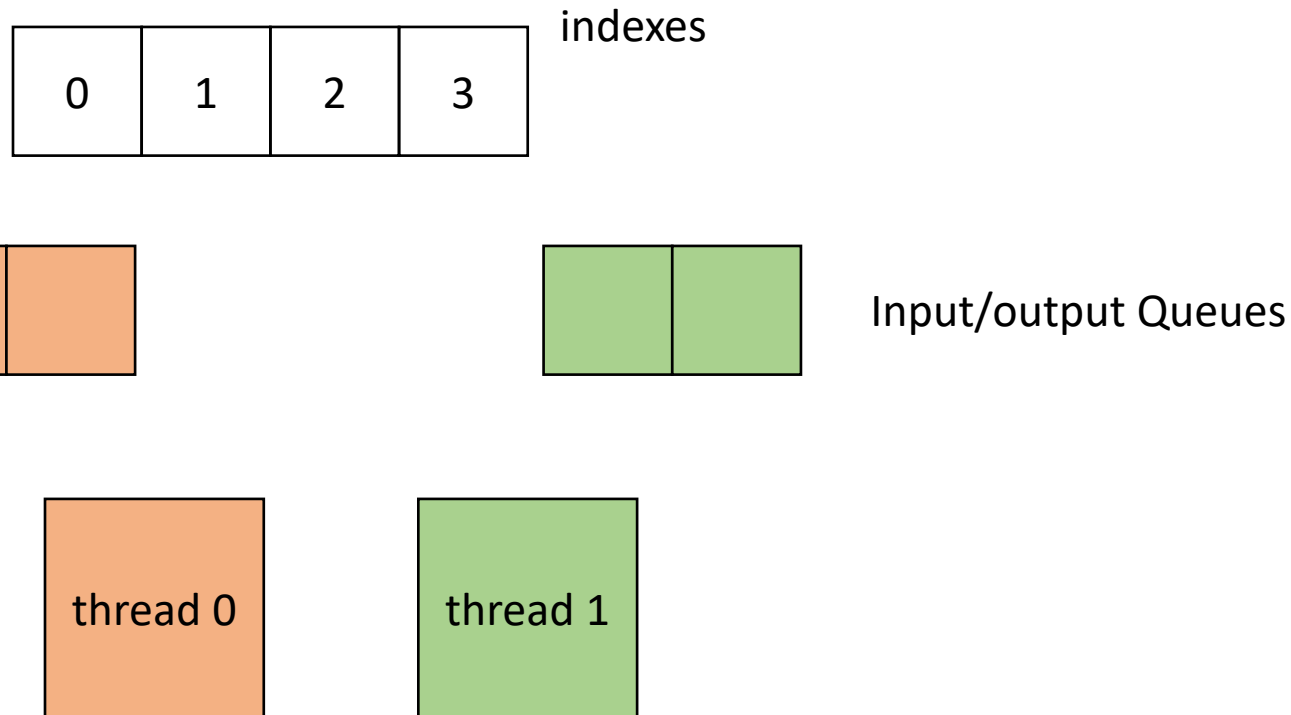
```
void parallel_loop(..., int tid) {  
  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
}
```

What type of queues?

We're going to use InputOutput Queues!

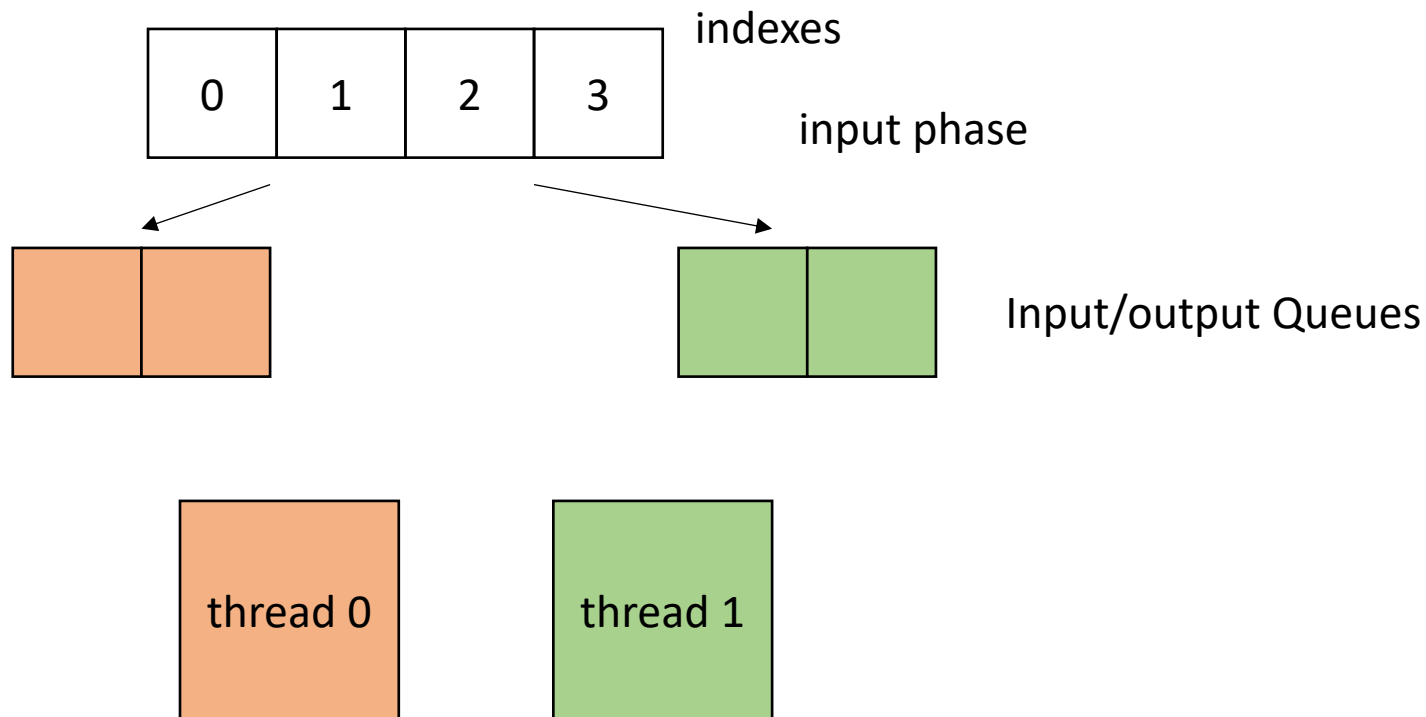
Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread



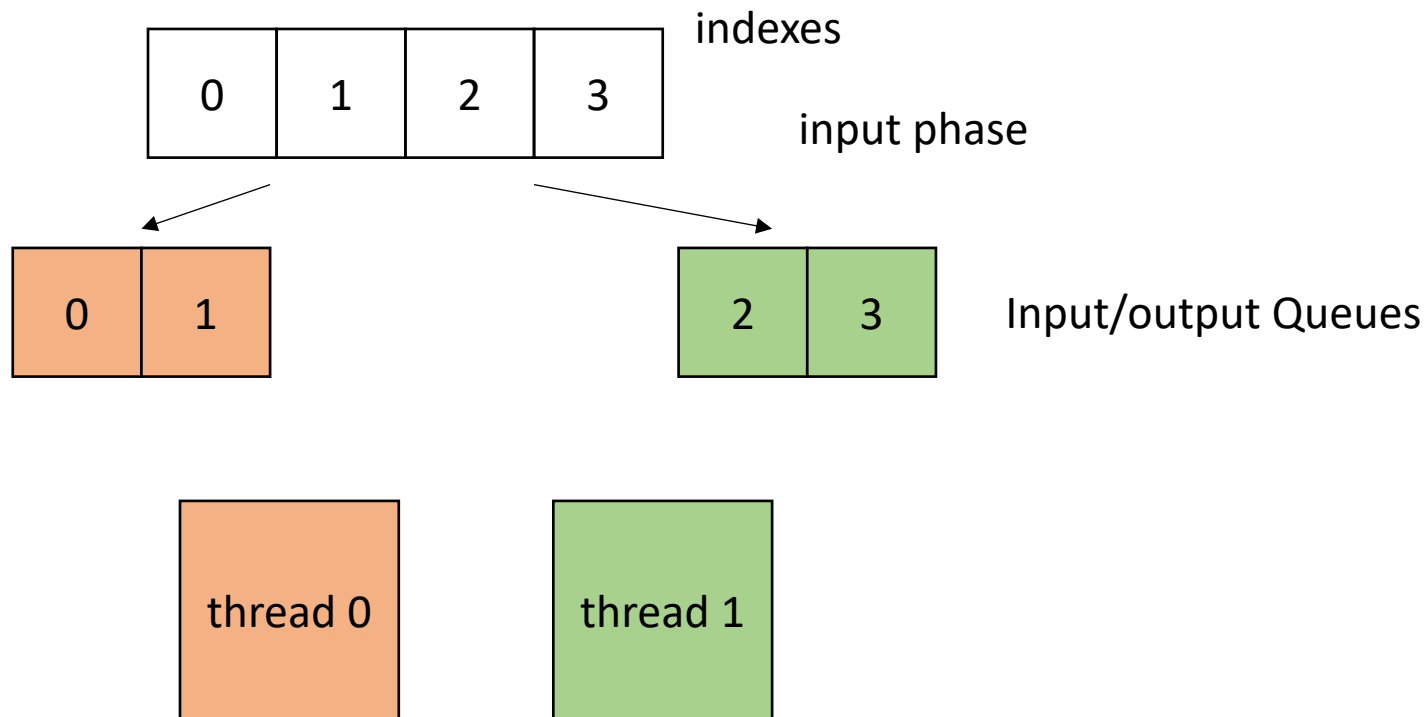
Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread



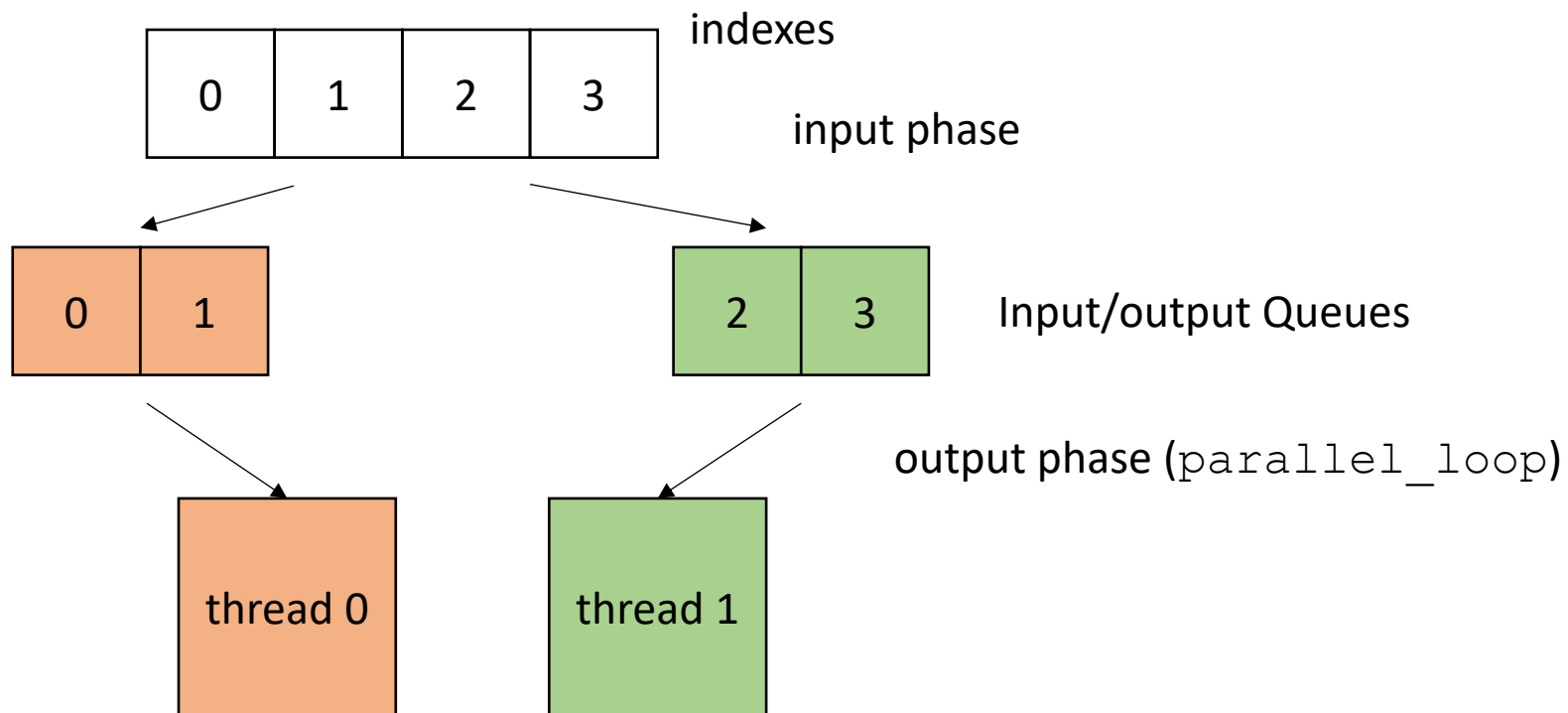
Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread



Work stealing - local worklists

- local worklists: divide tasks into different worklists for each thread



Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
  
    ...  
}
```

First we need to initialize the queues

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // Spawn threads to initialize  
    // join initializing threads  
  
    ...  
}
```

```
void parallel_enq(..., int tid, int num_threads)  
{  
  
    int chunk_size = SIZE / NUM_THREADS;  
    int start = chunk_size * tid;  
    int end = start + chunk_size;  
    for (int x = start; x < end; x++) {  
        cq[tid].enq(x);  
    }  
}
```

Just like the static schedule, except we are enqueueing

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // Spawn threads to initialize  
    // join initializing threads  
    ...  
}
```

Make sure to account for boundary conditions!

```
void parallel_enq(..., int tid, int num_threads)  
{  
  
    int chunk_size = SIZE / NUM_THREADS;  
    int start = chunk_size * tid;  
    int end = start + chunk_size;  
    for (int x = start; x < end; x++) {  
        cq[tid].enq(x);  
    }  
}
```

Just like the static schedule, except we are enqueueing

Work stealing - local worklists

- How to implement in a compiler:

```
NUM_THREADS = 2;  
SIZE = 4;  
CHUNK = 2;
```

x	0	1	2	3
tid	0	0	1	1

Make sure to account for boundary conditions!

```
void parallel_enq(..., int tid, int num_threads)  
{  
  
    int chunk_size = SIZE / NUM_THREADS;  
    int start = chunk_size * tid;  
    int end = start + chunk_size;  
    for (int x = start; x < end; x++) {  
        cq[tid].enq(x);  
    }  
}
```

Just like the static schedule, except we are enqueueing

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    ...  
}
```

```
void parallel_loop(..., int tid, int num_threads) {  
    for (x = 0; x < SIZE; x++) {  
        // dynamic work based on x  
    }  
}
```

How do we modify the parallel loop?

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    ...  
}
```

```
void parallel_loop(..., int tid, int num_threads) {  
  
    int task = 0;  
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())  
    {  
        // dynamic work based on task  
    }  
}
```

loop until the queue is empty

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    ...  
}
```

```
void parallel_loop(..., int tid, int num_threads) {  
  
    int task = 0;  
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())  
    {  
        // dynamic work based on task  
    }  
}
```

loop until the queue is empty
Are we finished?

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    ...  
}
```

```
atomic_int finished_threads(0);  
void parallel_loop(..., int tid, int num_threads) {  
  
    int task = 0;  
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())  
    {  
        // dynamic work based on task  
    }  
    atomic_fetch_add(&finished_threads, 1);  
}
```

Track how many threads are finished

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    ...  
}
```

```
atomic_int finished_threads(0);  
void parallel_loop(..., int tid, int num_threads) {  
  
    int task = 0;  
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())  
    {  
        // dynamic work based on task  
    }  
    atomic_fetch_add(&finished_threads,1);  
    while (finished_threads.load() != num_threads) {  
  
    }  
}
```

While there are threads that are still working

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    ...  
}
```

```
atomic_int finished_threads(0);  
void parallel_loop(..., int tid, int num_threads) {  
  
    int task = 0;  
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())  
    {  
        // dynamic work based on task  
    }  
    atomic_fetch_add(&finished_threads,1);  
    while (finished_threads.load() != num_threads) {  
        int target = // pick a thread to steal from  
        int task = cq[target].deq();  
    }  
}
```

pick a random target and steal a task

Work stealing - local worklists

```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    // join loop threads  
    ...  
}
```

```
atomic_int finished_threads(0);  
void parallel_loop(..., int tid, int num_threads) {  
  
    int task = 0;  
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())  
    {  
        // dynamic work based on task  
    }  
    atomic_fetch_add(&finished_threads,1);  
    while (finished_threads.load() != num_threads) {  
        int target = // pick a thread to steal from  
        int task = cq[target].deq();  
        if (task != -1) {  
            // perform task  
        }  
    }  
}
```

Work stealing - local worklists

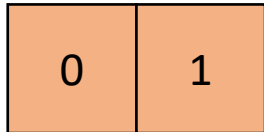
```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    // join loop threads  
    ...  
}
```

join the threads

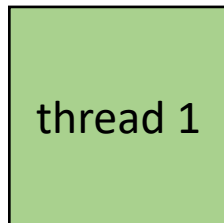
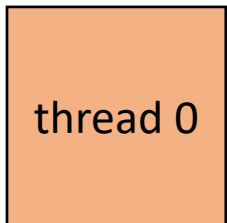
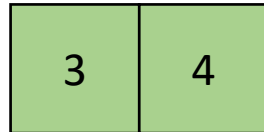
```
atomic_int finished_threads(0);  
void parallel_loop(..., int tid, int num_threads) {  
  
    int task = 0;  
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())  
    {  
        // dynamic work based on task  
    }  
    atomic_fetch_add(&finished_threads,1);  
    while (finished_threads.load() != num_threads) {  
        int target = // pick a thread to steal from  
        int task = cq[target].deq();  
        if (task != -1) {  
            // perform task  
        }  
    }  
}
```

Work stealing - local worklists

IOQueue 0



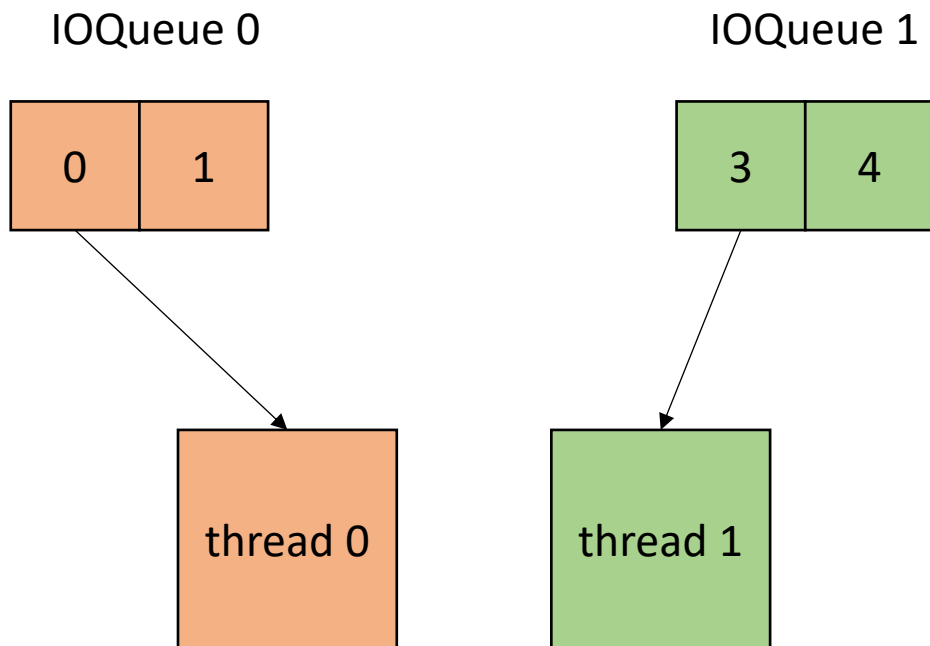
IOQueue 1



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Work stealing - local worklists

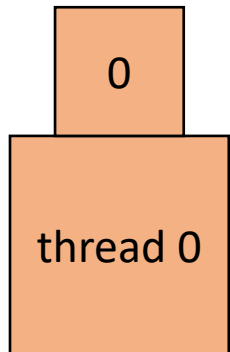
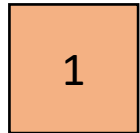


```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

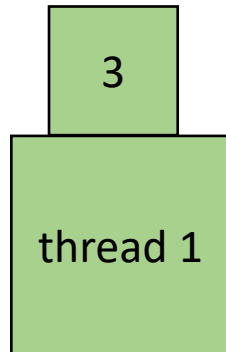
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Work stealing - local worklists

IOQueue 0



IOQueue 1

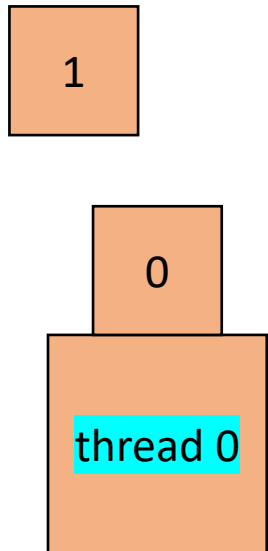


```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

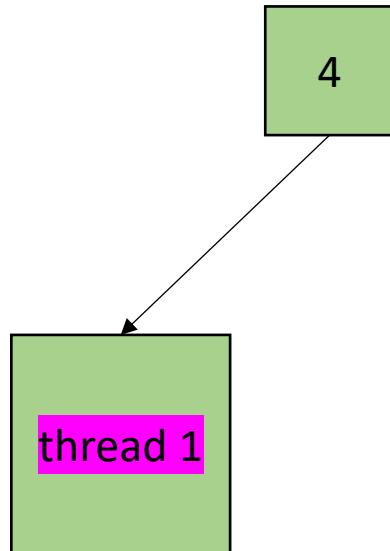
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```


Work stealing - local worklists

IOQueue 0



IOQueue 1

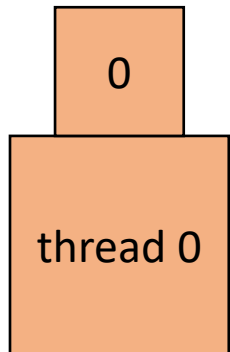
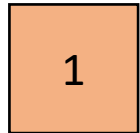


```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

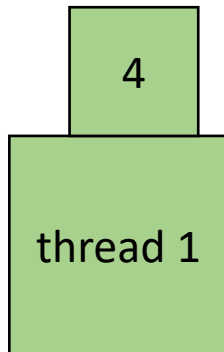
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Work stealing - local worklists

IOQueue 0



IOQueue 1

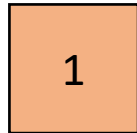


```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

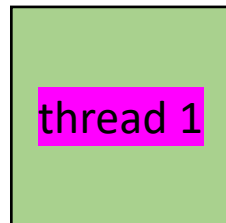
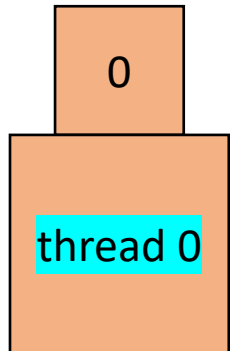
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Work stealing - local worklists

IOQueue 0



IOQueue 1



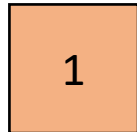
```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

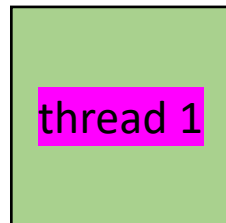
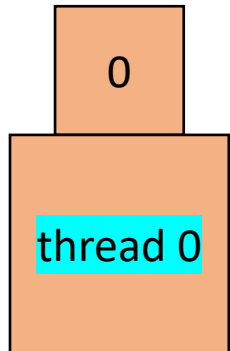
Work stealing - local worklists

finished_threads: 1

IOQueue 0



IOQueue 1



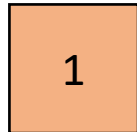
```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

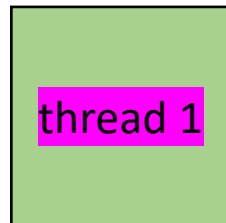
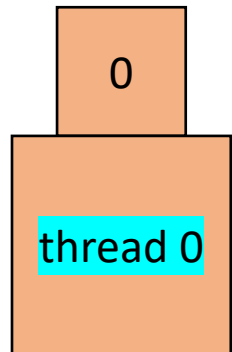
Work stealing - local worklists

finished_threads: 1

IOQueue 0



IOQueue 1



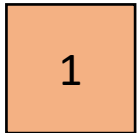
```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

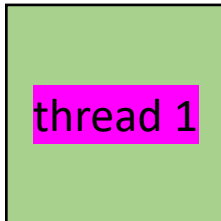
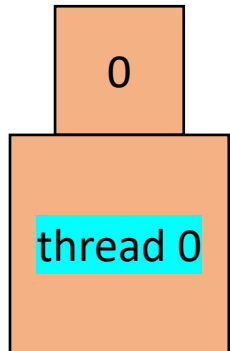
Work stealing - local worklists

finished_threads: 1

IOQueue 0



IOQueue 1



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

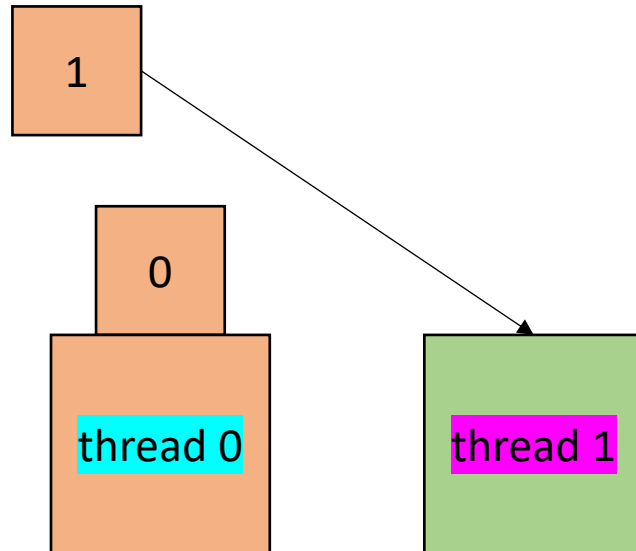
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Work stealing - local worklists

finished_threads: 1

IOQueue 0

IOQueue 1



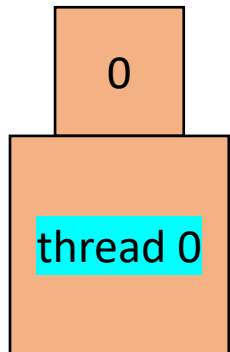
```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

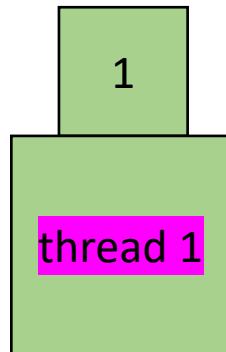
Work stealing - local worklists

finished_threads: 1

IOQueue 0



IOQueue 1



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

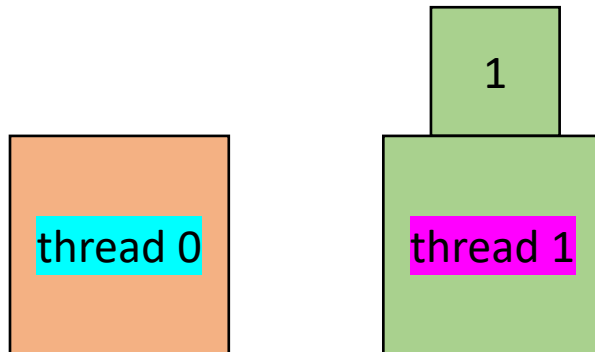
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```


Work stealing - local worklists

finished_threads: 1

IOQueue 0

IOQueue 1



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

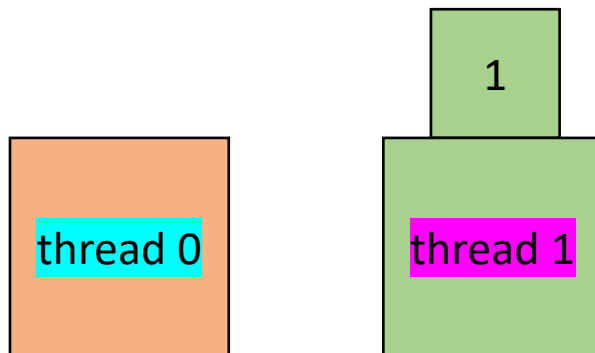
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

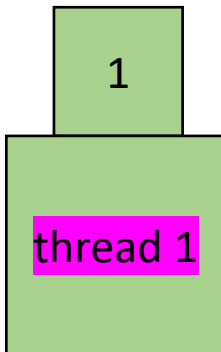
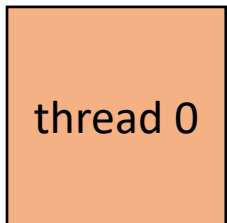
Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1

finished!



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

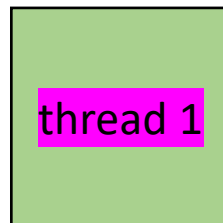
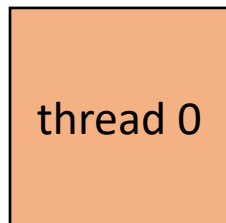
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

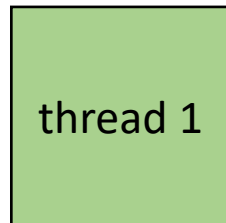
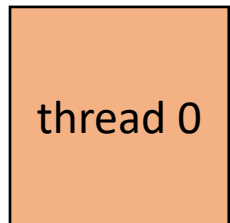
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1



```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

Open mp

- Code examples

Next topic

- General concurrent set