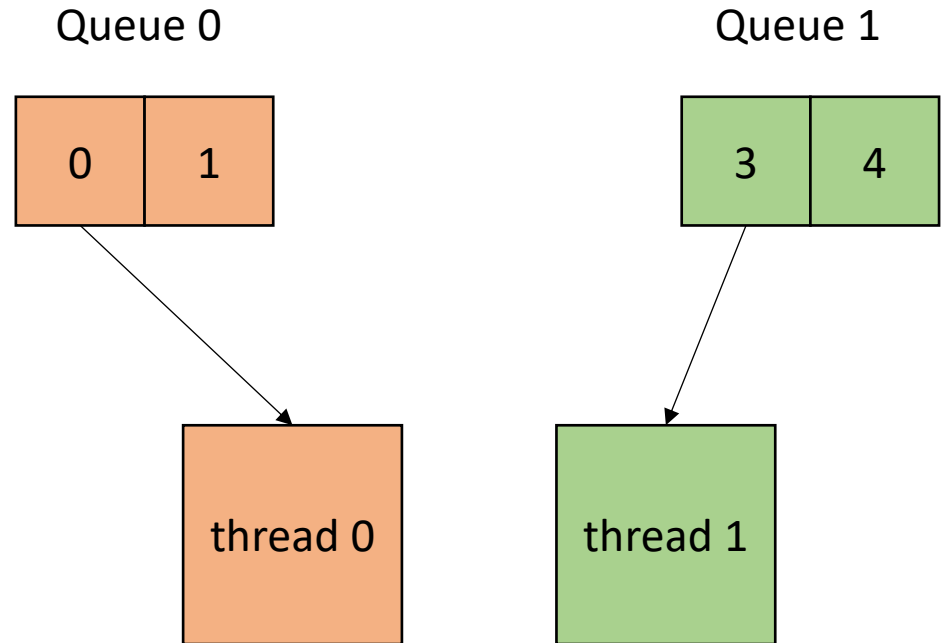


CSE113: Parallel Programming

Feb. 17, 2023

- **Topics:**

- Parallel schedules for DOALL loops
 - Static schedules
 - global workstealing
 - local workstealing



Announcements

- HW1 grades are out!
 - Please let us know if there are issues
- Homework 2 was due on Monday
 - We will start grading and try to get grades in soon
- Homework 3 is released
 - Should be able to do all parts by the end of today
 - Due Feb 23 + 4 days = Feb 27

Announcements

- Midterm out!
 - Due tonight at 6.
 - Open note, open internet (to a reasonable extent: no googling exact questions or asking questions on forums or ChatGPT)
 - do not discuss with classmates AT ALL while the test is active
 - **No late tests will be accepted.**
- You can ask clarifying questions about the midterm (**as private Piazza posts**). We will not comment on your answers or give any hints.

Previous quiz

A DOALL Loop must have:

-
- A loop variable that starts at 0 and is incremented by 1
 - loop iterations that are independent
 - be unrolled and interleaved
 - not access any memory locations

Previous quiz

A circular buffer is:

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

Previous quiz

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

-
- The rate at which the producer enqueues elements

 - The rate at which the consumer enqueues elements

 - If the queue is implemented using mutex or not

Previous quiz

Given what we've learned: what role do you believe the compiler should play in parallelizing DOALL loops?

For example, should it: (1) identify them? (2) parallelize them? (3) pick a parallel schedule?

There is no right or wrong answer here, but it is interesting to think about!

Review

Circular buffers in Producer/Consumer queues

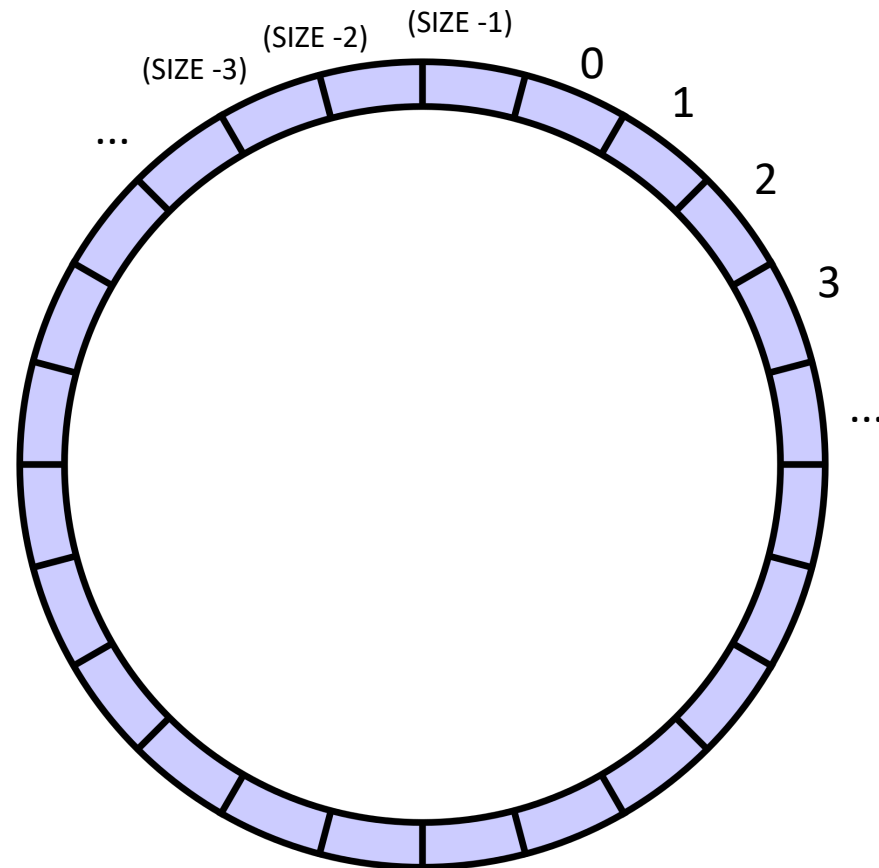
Producer Consumer Queues

- 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

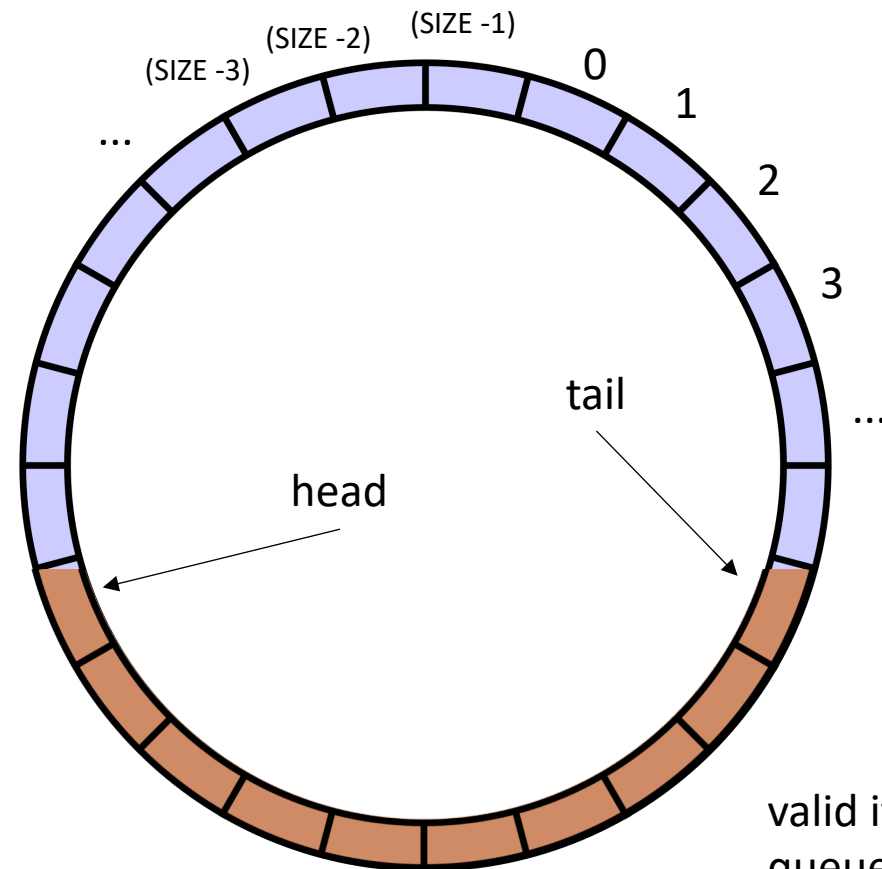
- Start with a fixed size array

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

head and tail:

enq to the head, deq from the tail

conceptually it is a circle



indexes will circulate in order and wrap around

valid items in the queue

Producer Consumer Queues

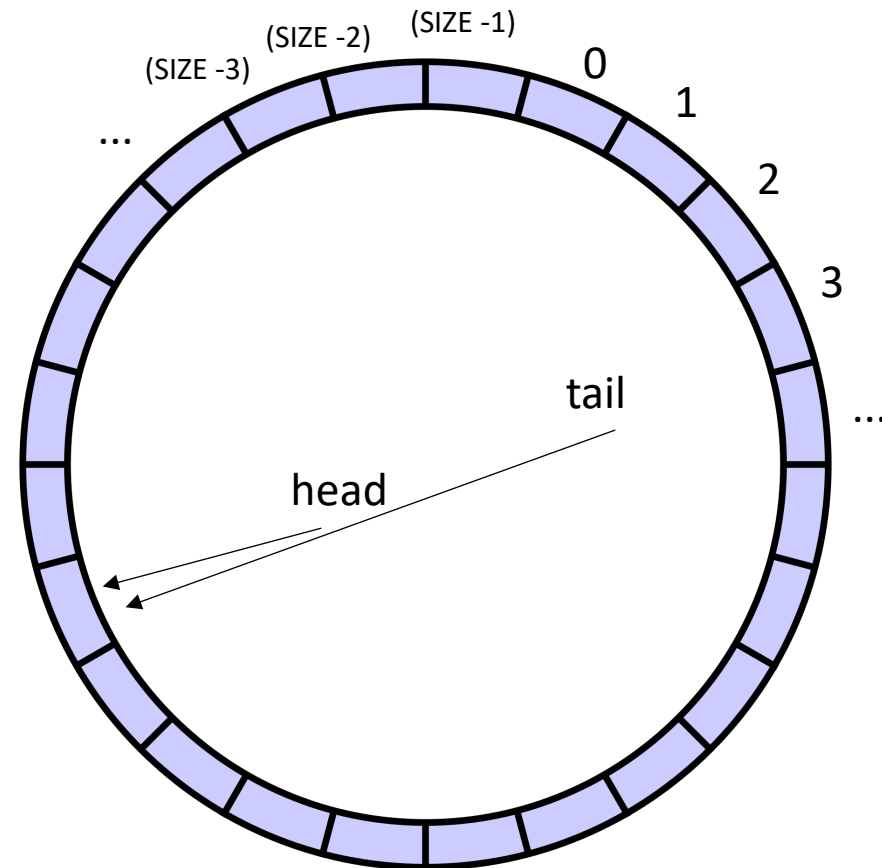
- Start with a fixed size array

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

head and tail

Empty queue is when
 $head == tail$

conceptually it is a circle



indexes will circulate in order and wrap around

Producer Consumer Queues

- Start with a fixed size array

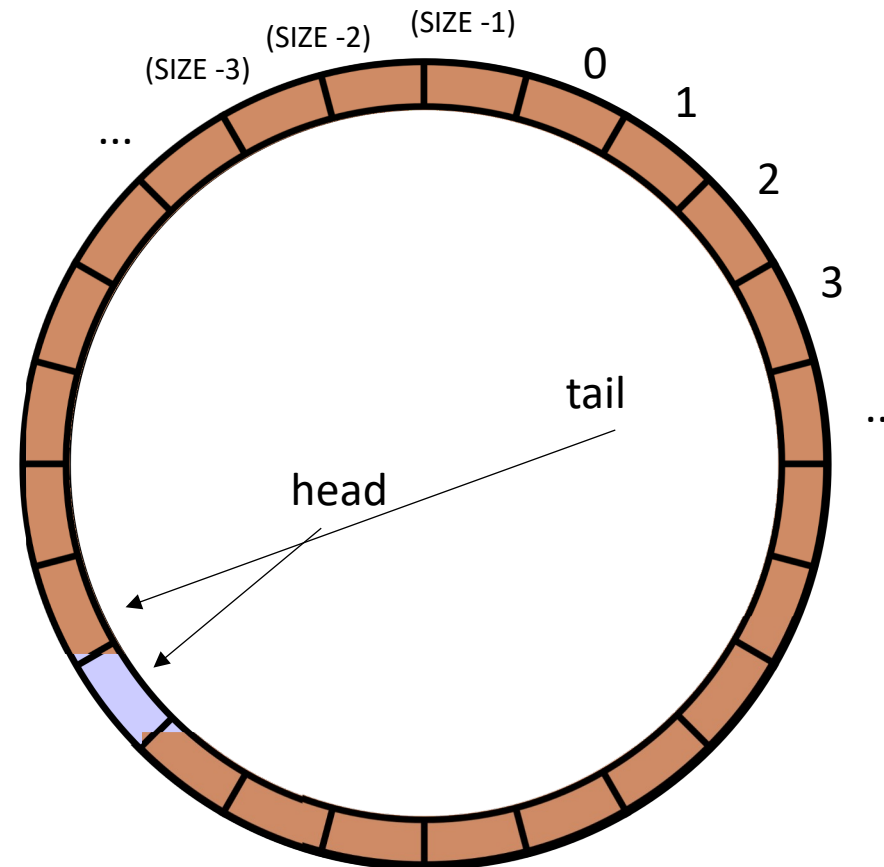
Two variables to keep track of where to deq and enq:

head and tail

Empty queue is when
 $head == tail$

Full queue is when
 $head + 1 == tail$

conceptually it is a circle

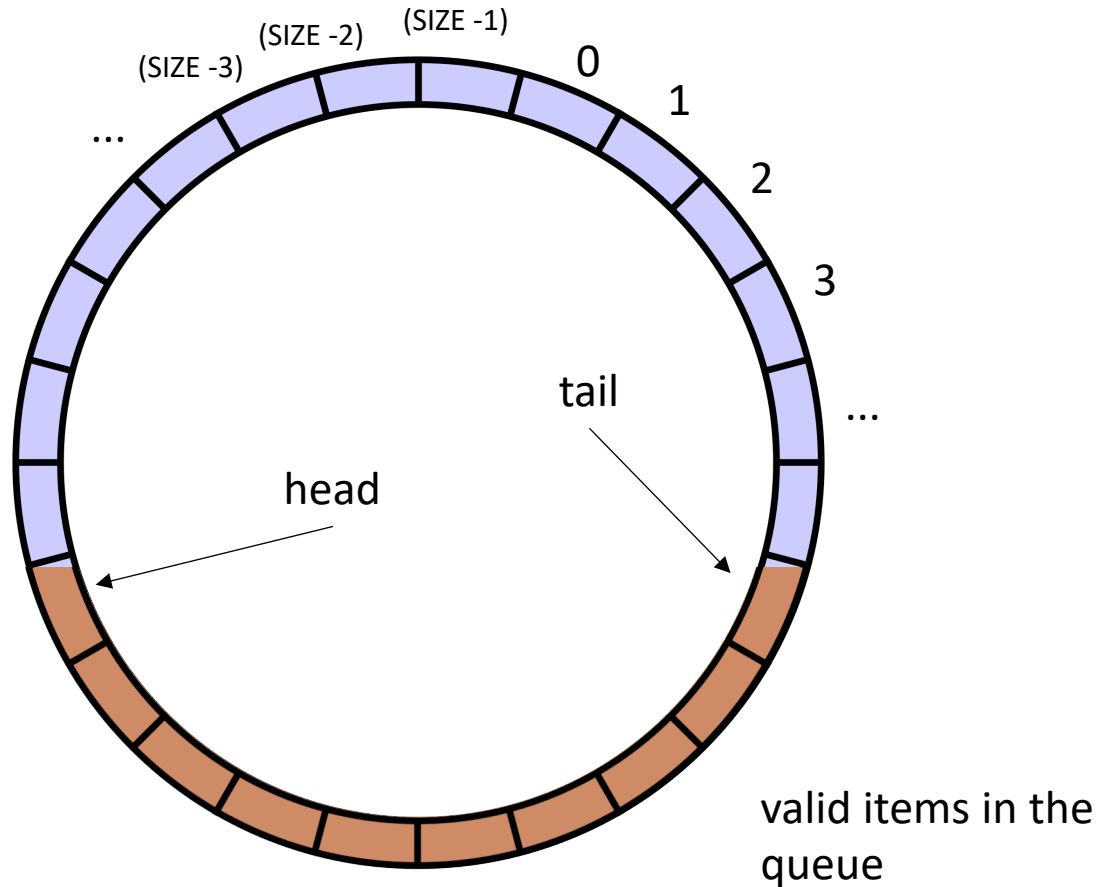


indexes will circulate in order and wrap around

wasting one location, but its okay...

Other questions:

Do these need to be atomic RMWs?



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

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

DOALL Loops

```
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

Examples:

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

Examples:

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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;  
}
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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;  
}
```

Schedule

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

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

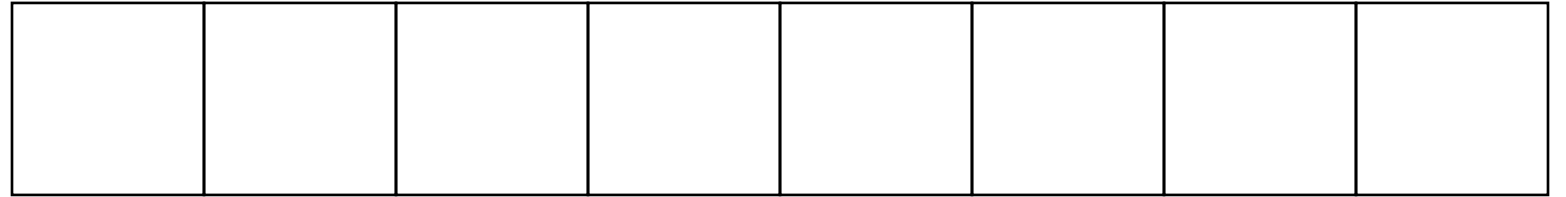
```
for (int i = 0; i < SIZE; i++) {  
    c[i] = a[i] + b[i];  
}
```

Is this a DOALL loop?

How should we parallelize it?

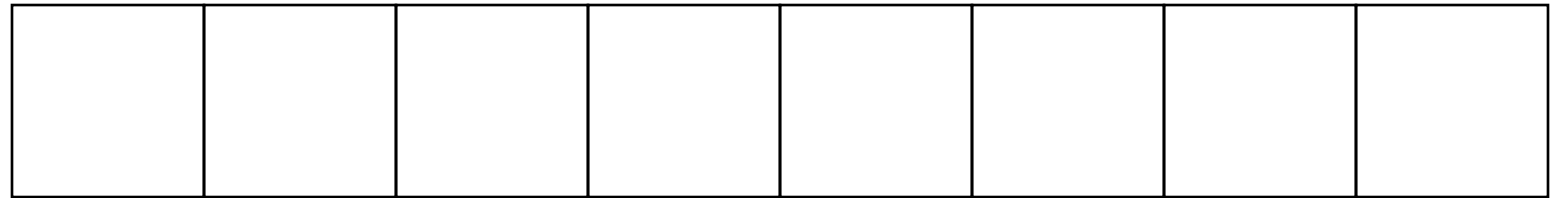
Parallel Schedules

array a



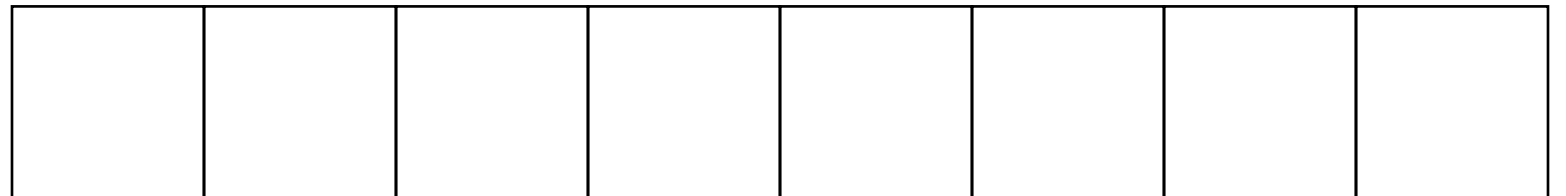
+ + + + + + + +

array b



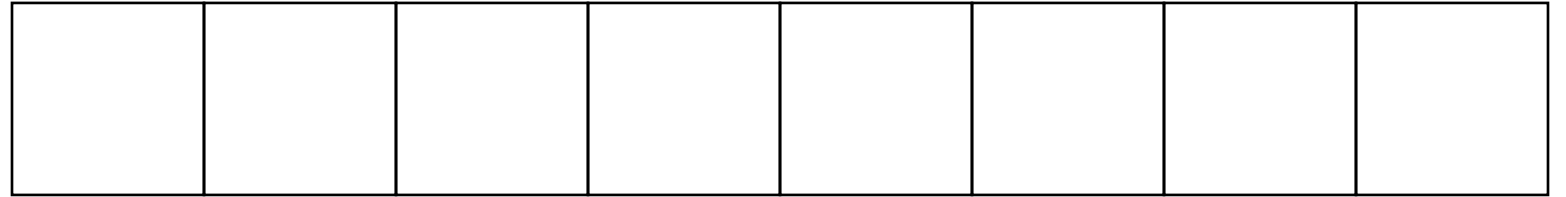
= = = = = = = =

array c



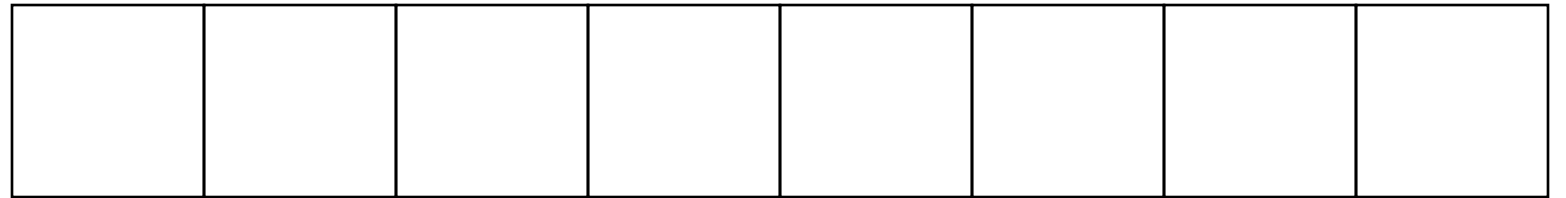
Parallel Schedules

array a



+ + + + + + + +

array b



= = = = = = = =

array c



Computation
can easily be
divided into
threads

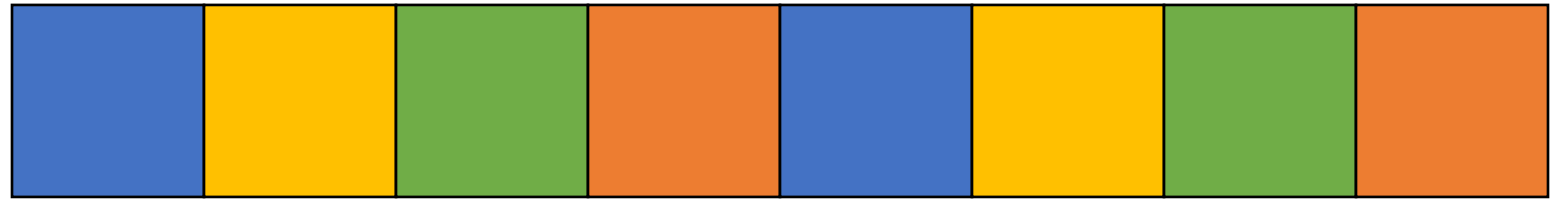
- Thread 0 - Blue
- Thread 1 - Yellow
- Thread 2 - Green
- Thread 3 - Orange

Parallel Schedules

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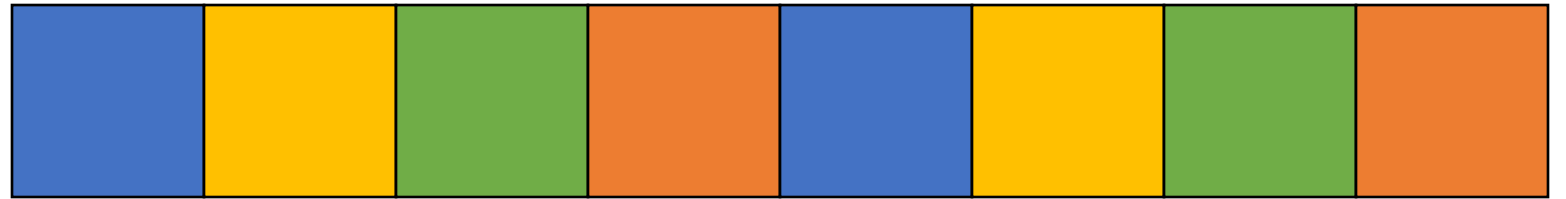
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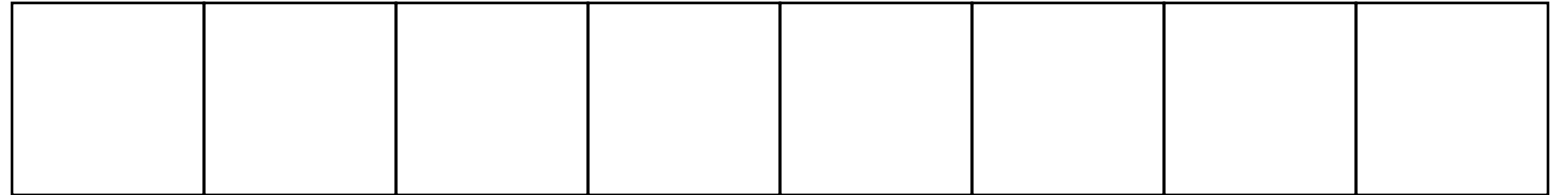


Parallel Schedules

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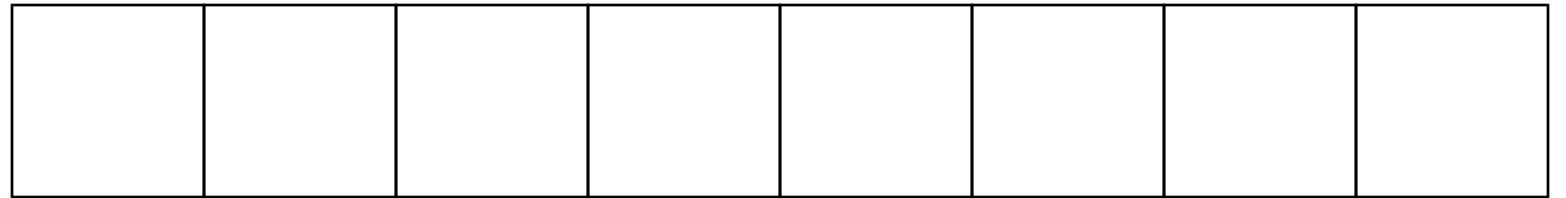
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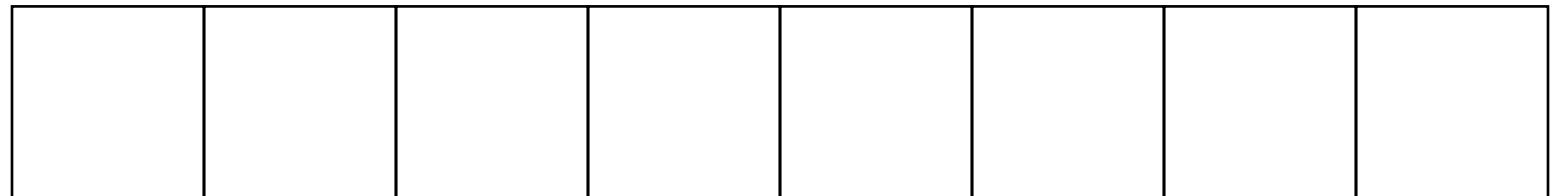
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Parallel Schedules

array a



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threads

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- Thread 3 - Orange

Parallel Schedules

- Which one is more efficient?

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  
    }  
    ...  
}
```



Static schedule

- Works well when loop iterations take similar amounts of time

```
void foo() {  
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    }  
    ...  
}
```

say $SIZE / NUM_THREADS = 4$

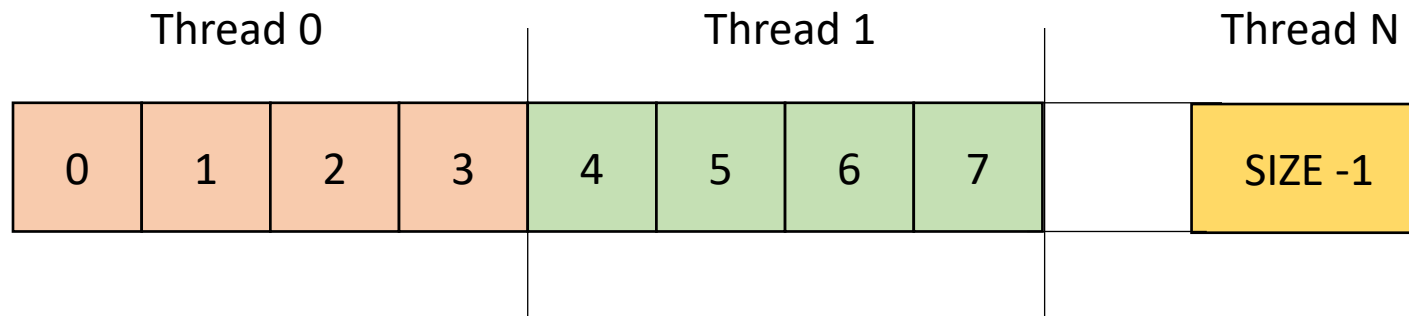


Static schedule

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

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    ...  
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```

```
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

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void foo() {  
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    // 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  
    }  
}
```

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();  
    ...  
}
```

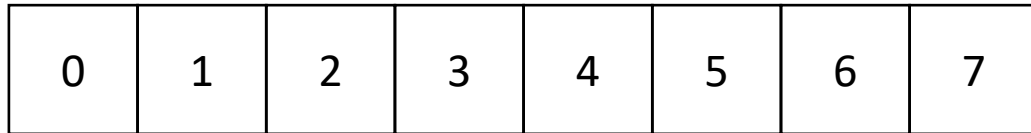
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void parallel_loop(..., int tid, int num_threads)  
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    int end = start + chunk_size;  
    for (int x = start; x < end; x++) {  
        // work based on x  
    }  
}
```

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

Spawn threads

Static schedule

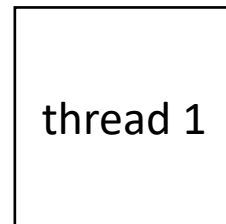
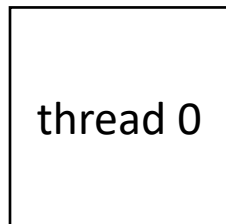
- Example, 2 threads/cores, array of size 8



chunk_size = ?

0: start = ? 1: start = ?

0: end = ? 1: end = ?



```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
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Static schedule

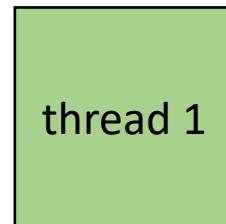
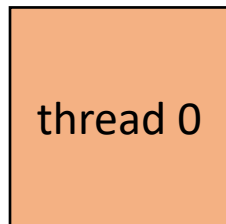
- Example, 2 threads/cores, array of size 8



`chunk_size = 4`

0: start = 0 1: start = 4

0: end = 4 1: end = 8

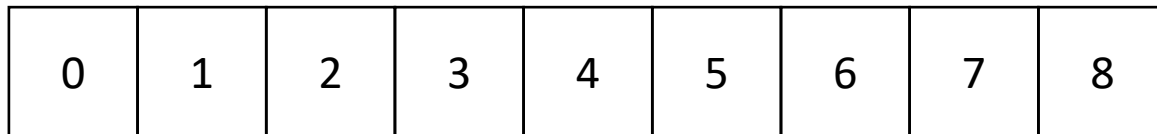


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}
```

End example

Static schedule

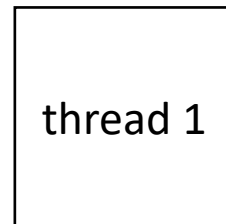
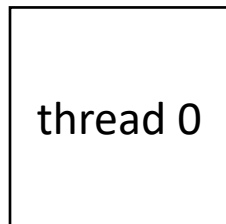
- Example, 2 threads/cores, array of size 9



chunk_size = ?

0: start = ? 1: start = ?

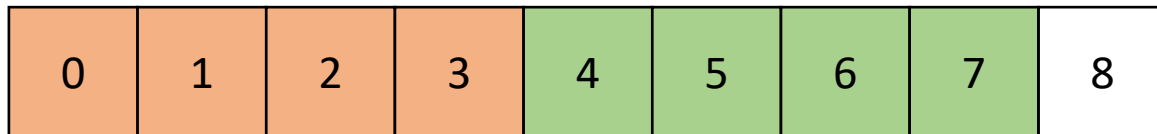
0: end = ? 1: end = ?



```
void parallel_loop(..., int tid, int num_threads)
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}
```

Static schedule

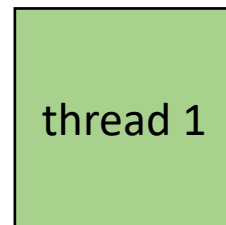
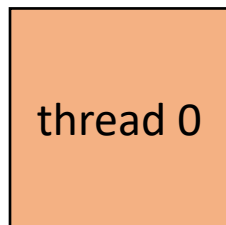
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`chunk_size = 4`

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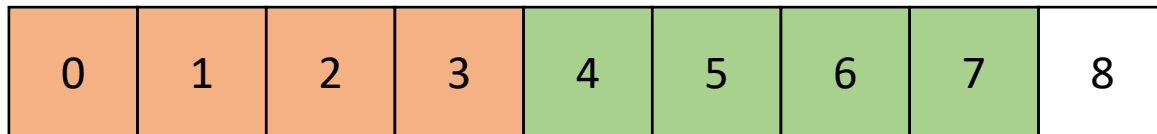
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```

Static schedule

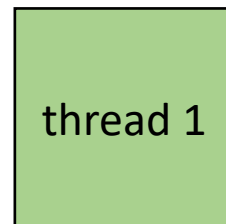
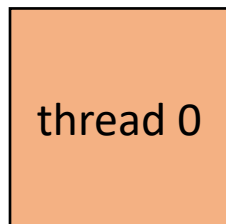
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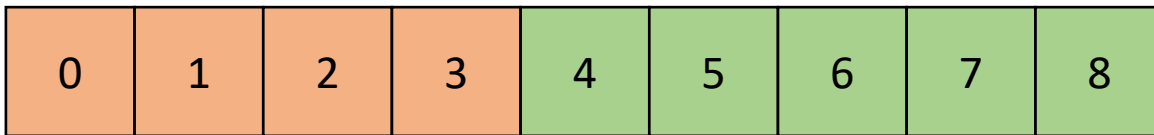


```
void parallel_loop(..., int tid, int num_threads)
{
    int chunk_size = SIZE / NUM_THREADS;
    int start = chunk_size * tid;
    int end = start + chunk_size;
    if (tid == num_threads - 1) {
        end = SIZE;
    }
    for (int x = start; x < end; x++) {
        // work based on x
    }
}
```


Static schedule

last thread gets more work

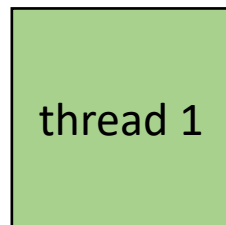
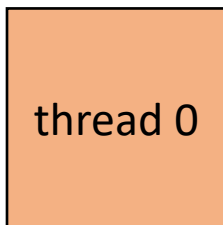
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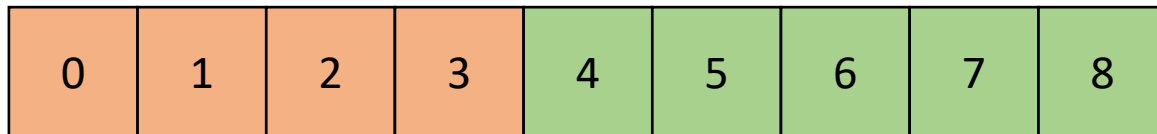
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```
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```

Static schedule

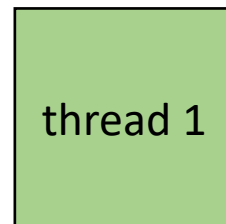
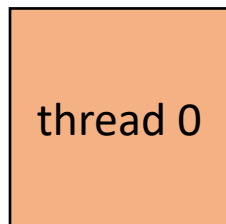
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last thread gets more work

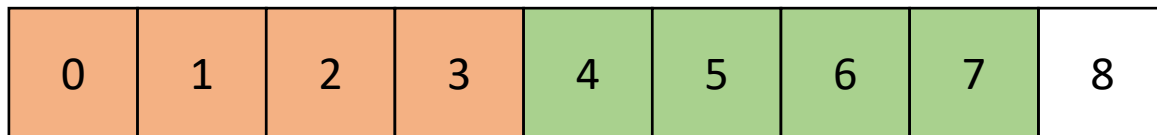
What is the worst case?

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

End example

Static schedule

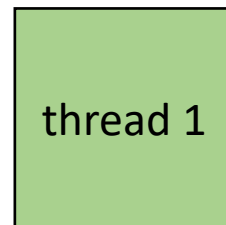
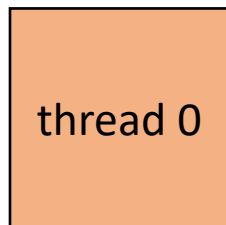
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0: start = 0 1: start = 4

0: end = 4 1: end = 8

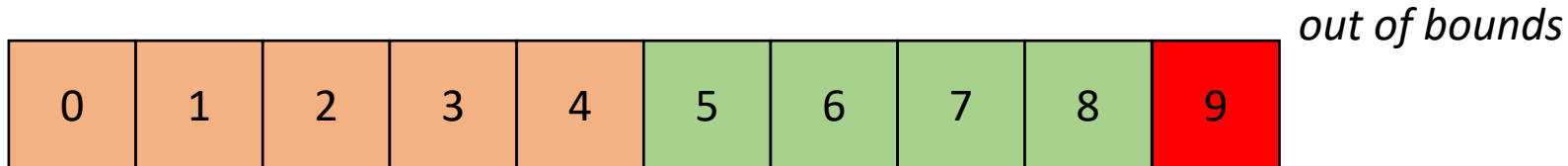


ceiling division, this will distribute uneven work in the last thread to all other threads

```
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

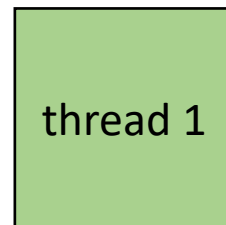
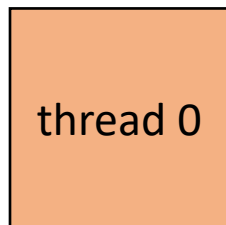
- Example, 2 threads/cores, array of size 9



chunk_size = 5

0: start = 0 1: start = 5

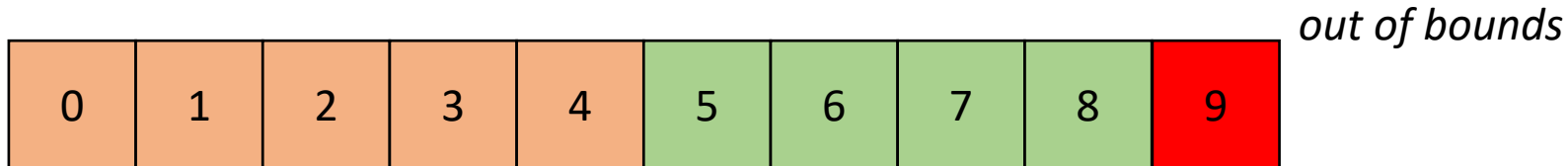
0: end = 5 1: end = 10



```
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

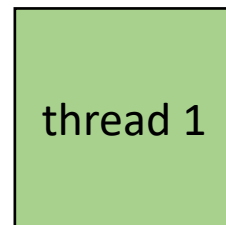
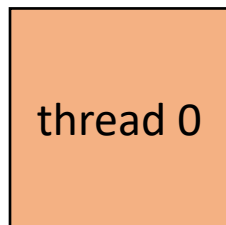
- Example, 2 threads/cores, array of size 9



chunk_size = 5

0: start = 0 1: start = 5

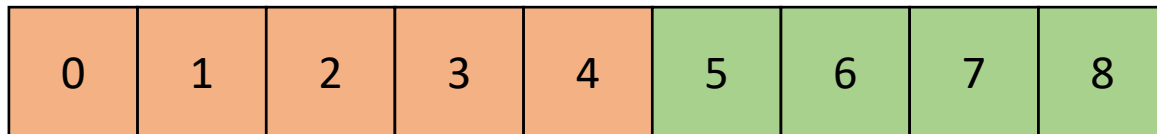
0: end = 5 1: end = 10



```
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

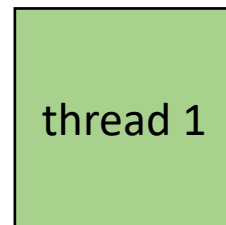
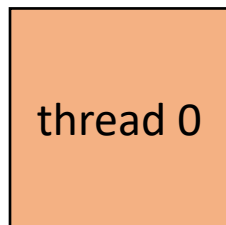
- Example, 2 threads/cores, array of size 9



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?

Max slowdown for last thread does all the extra work?

Max slowdown for ceiling?

```
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
    }
}
```

End example

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 $0 - \text{SIZE}/2$
 - 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];  
    }  
}
```

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

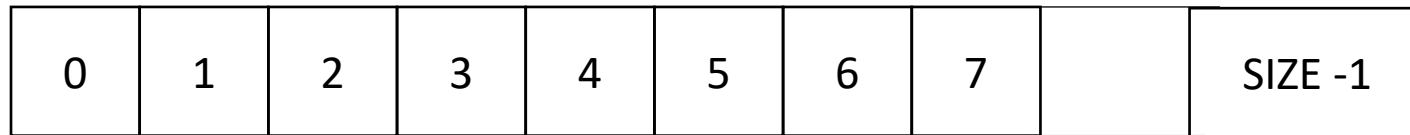
- Tasks are dynamically assigned to threads.

Work stealing - global implicit worklist

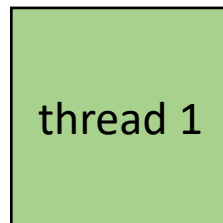
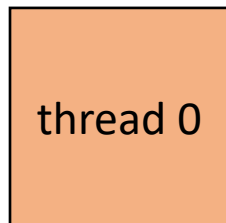
- Pros
 - Simple to implement
- Cons:
 - High contention on global counter
 - Potentially bad memory locality.

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

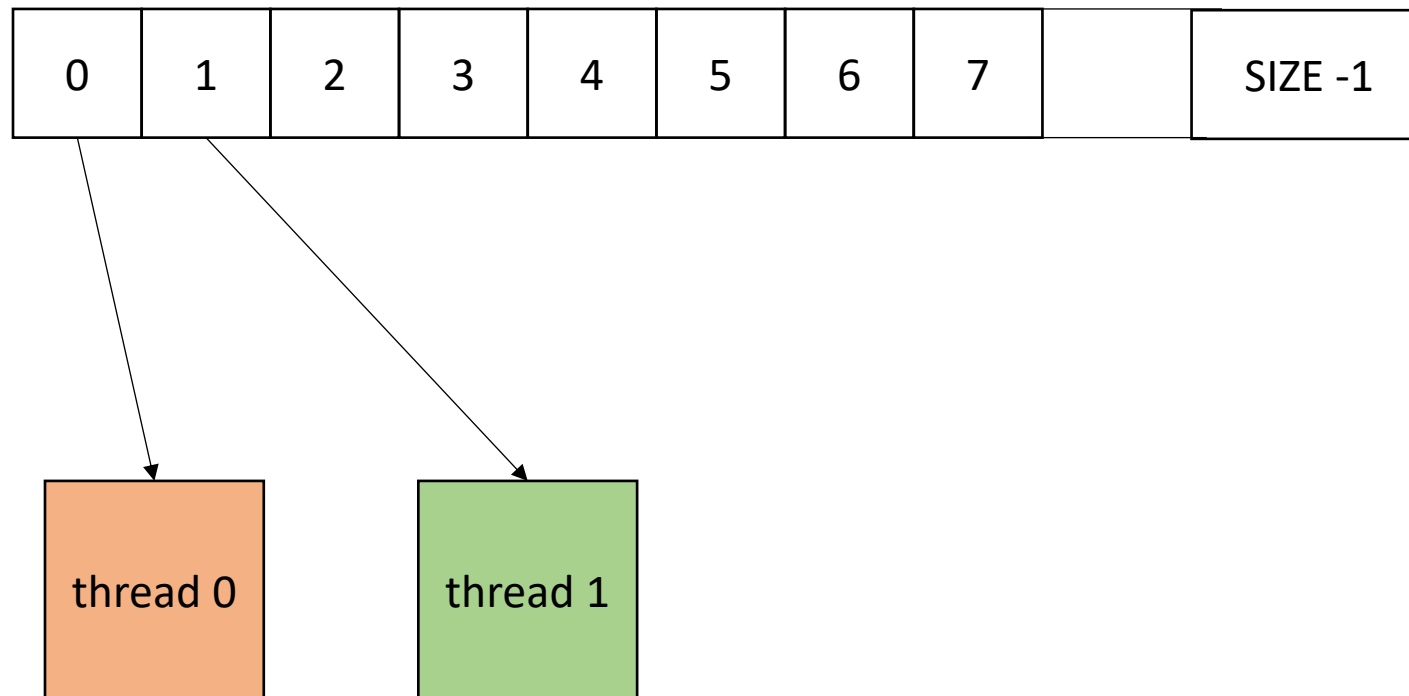


cannot color initially!



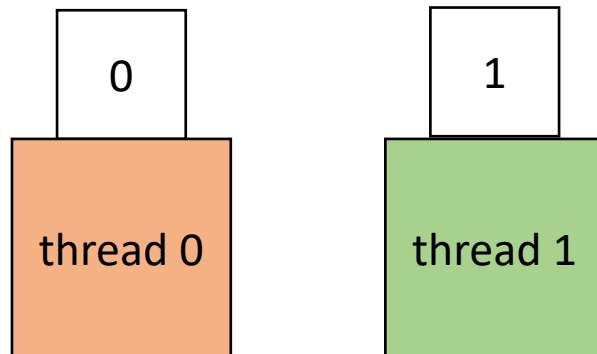
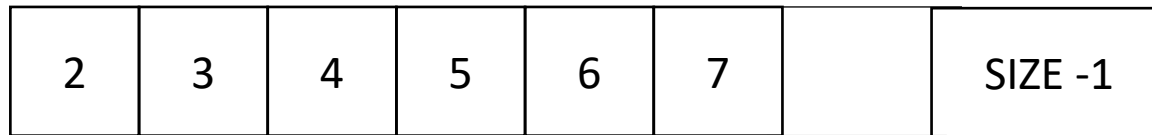
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



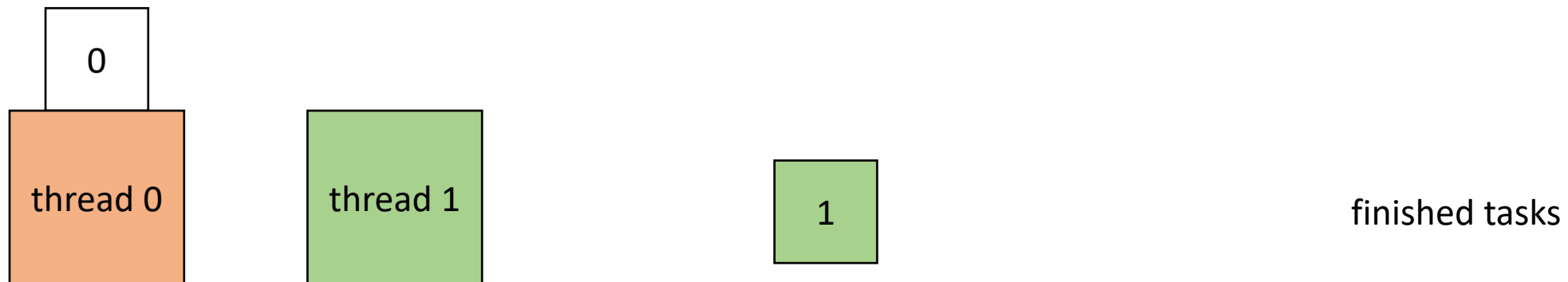
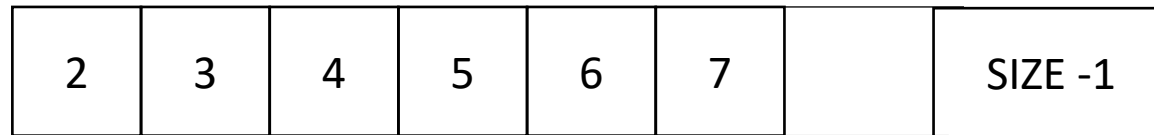
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



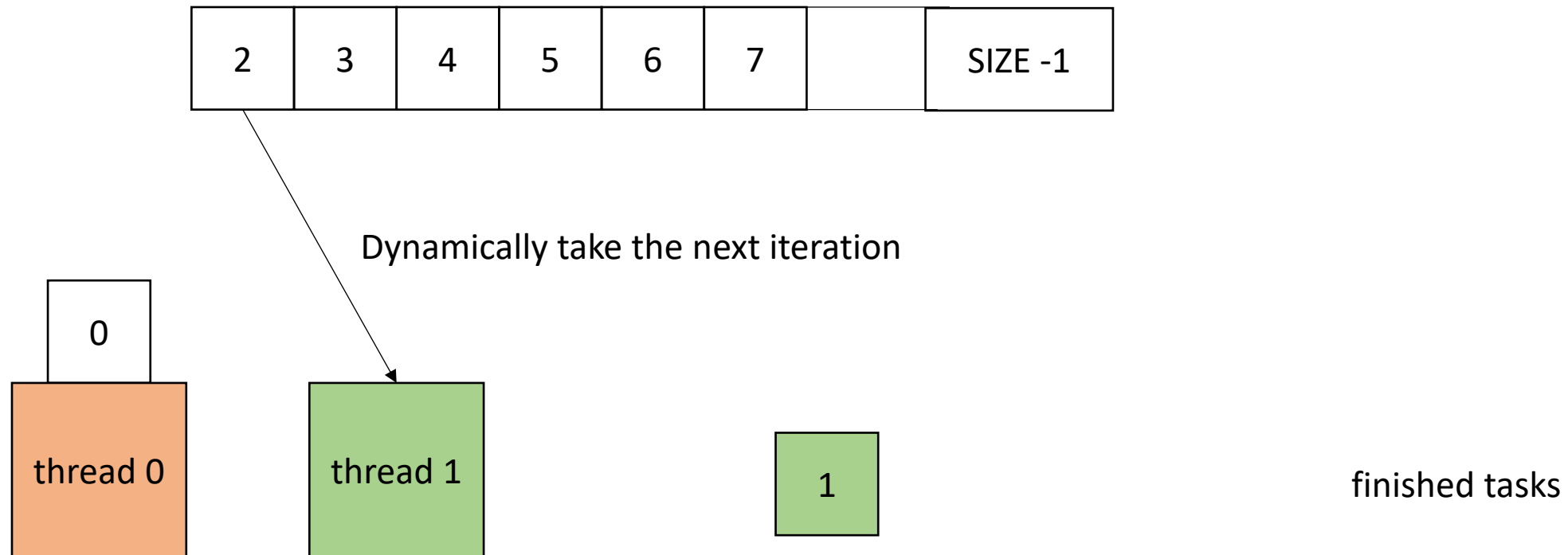
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



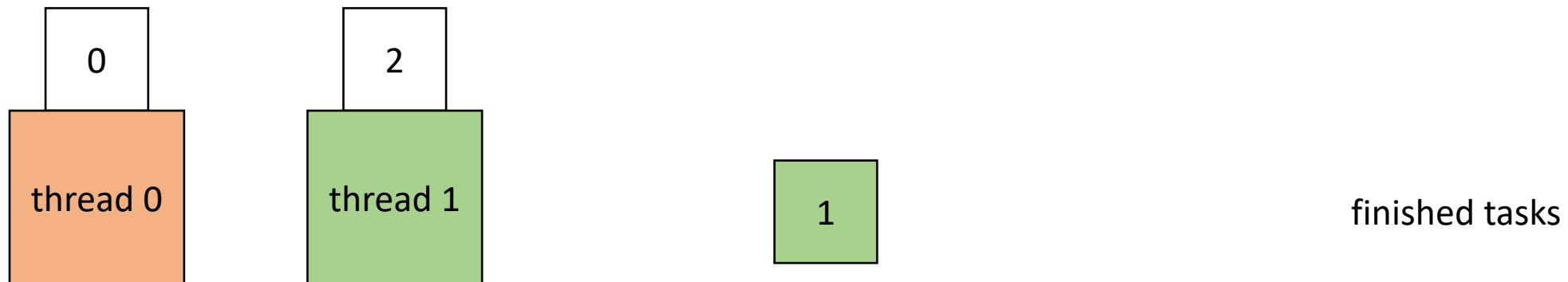
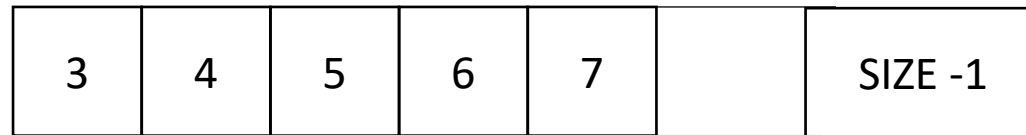
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



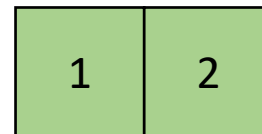
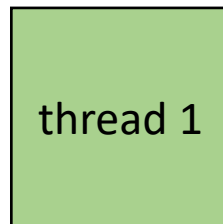
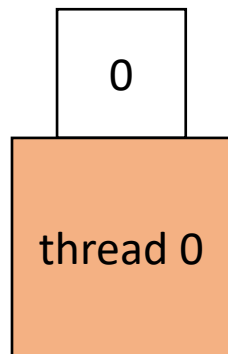
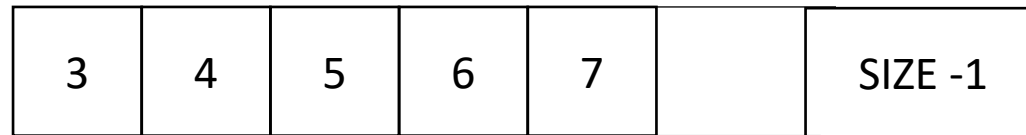
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



Work stealing - global implicit worklist

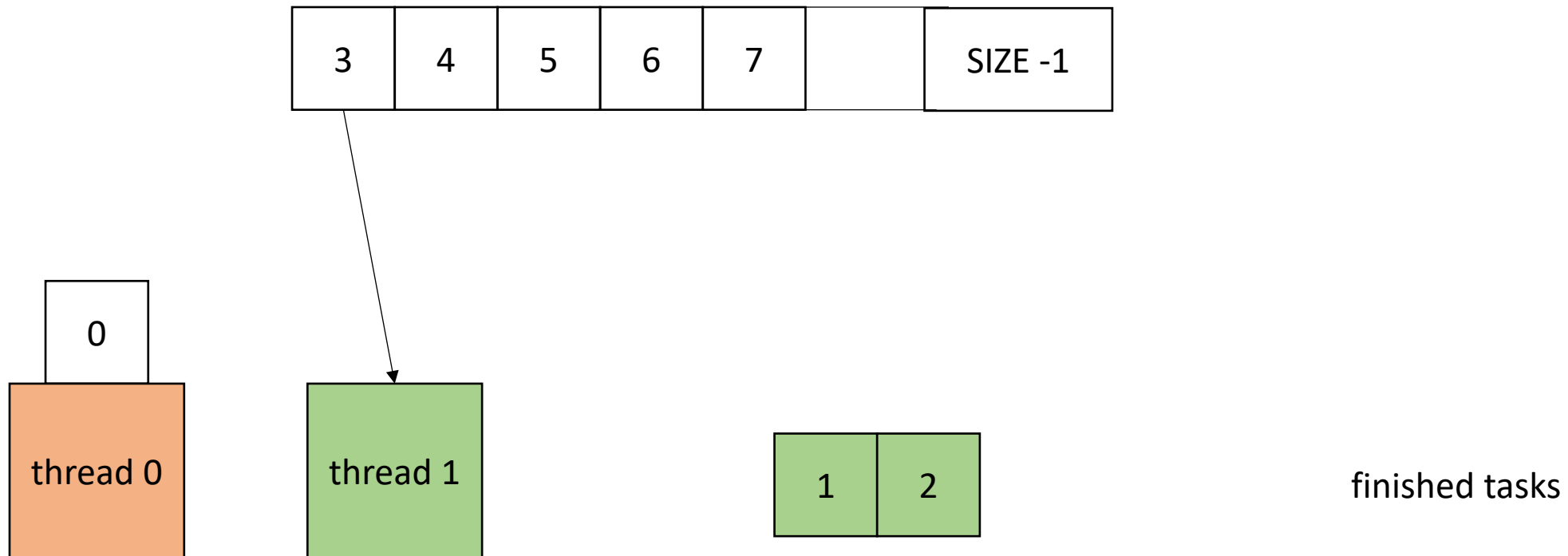
- Global worklist: threads take tasks (iterations) dynamically



finished tasks

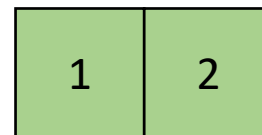
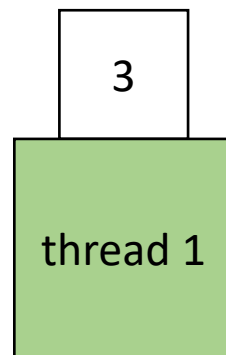
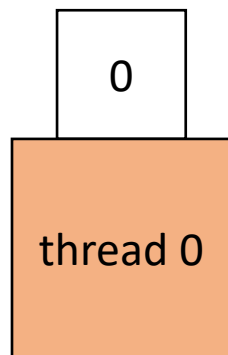
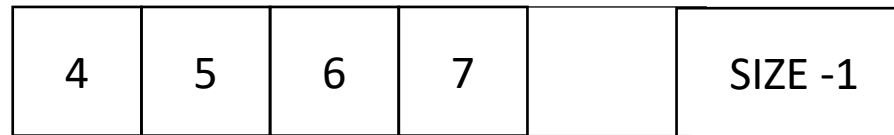
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



Work stealing - global implicit worklist

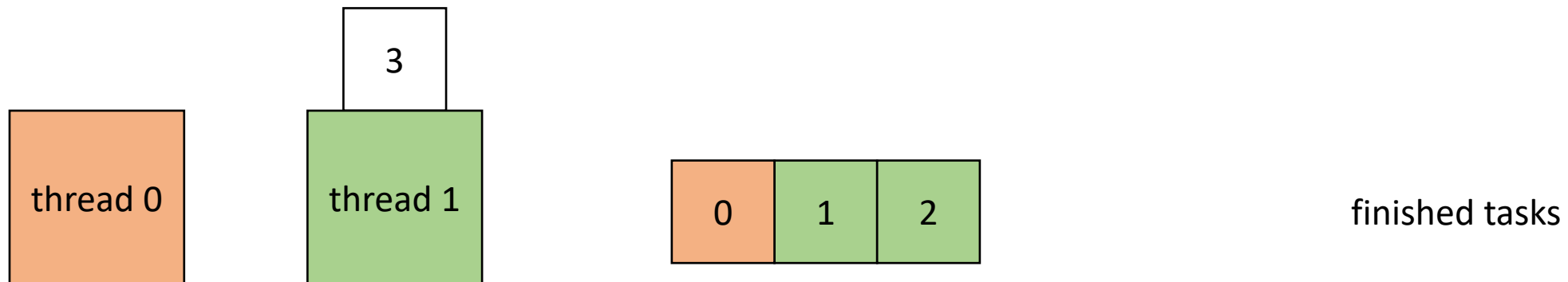
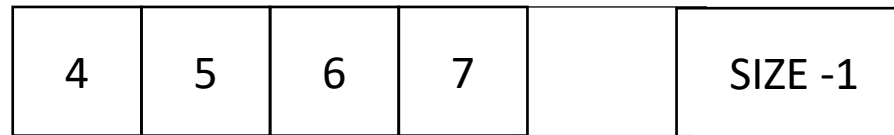
- Global worklist: threads take tasks (iterations) dynamically



finished tasks

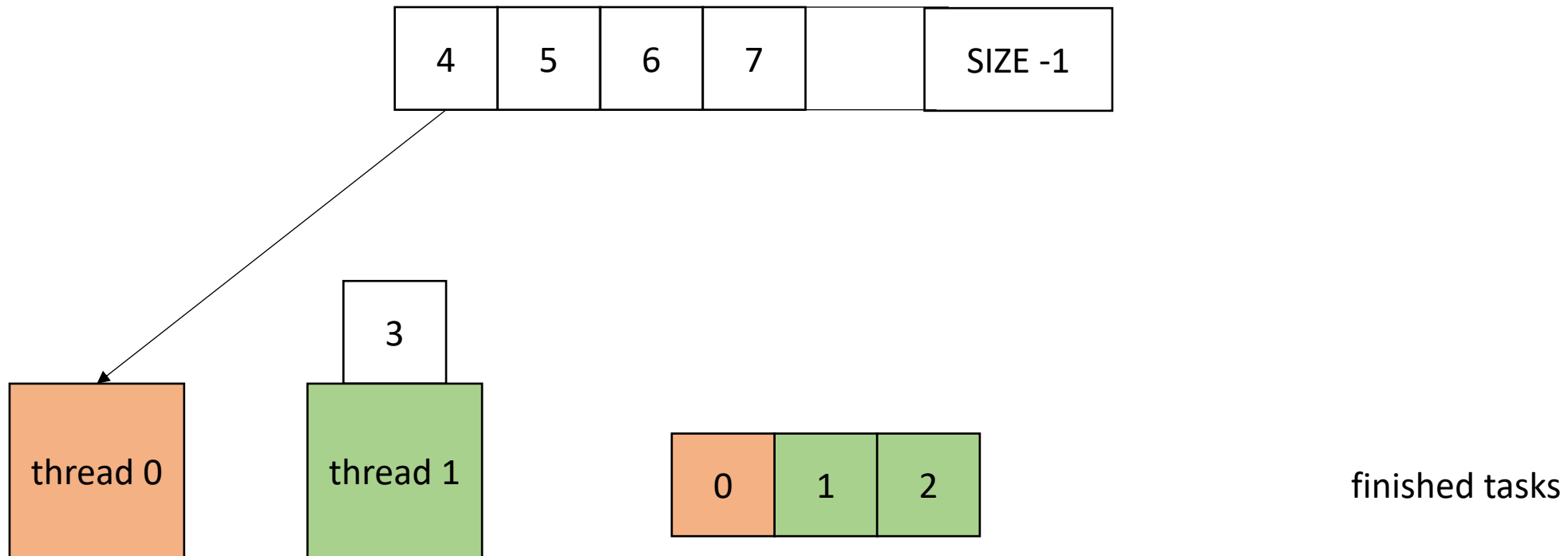
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



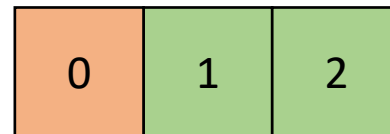
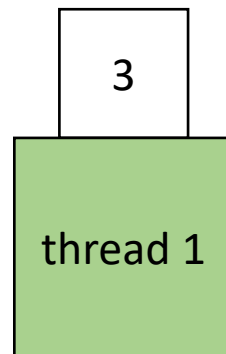
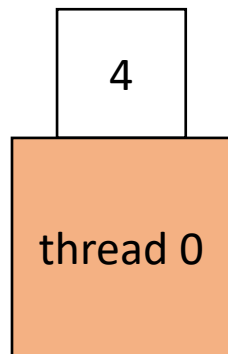
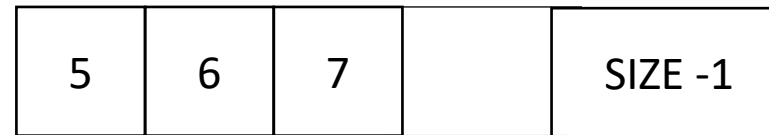
Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



finished tasks

End example

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();  
    ...  
}
```

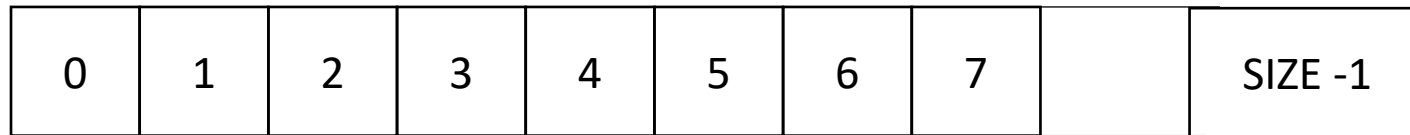
```
atomic_int x(0);  
void parallel_loop(...) {  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
        // dynamic work based on x  
    }  
}
```

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

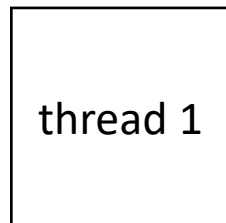
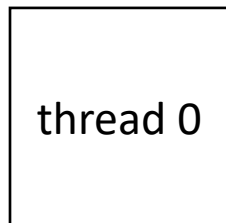


x: 0

0 - local_x - UNDEF

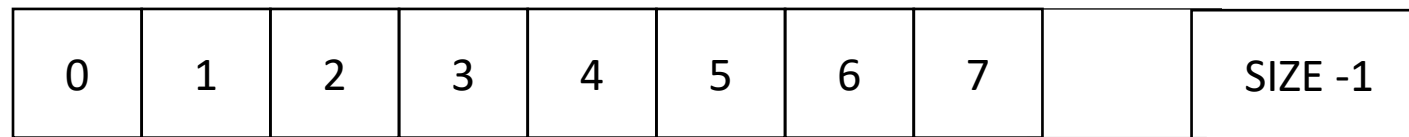
1 - local_x - UNDEF

```
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

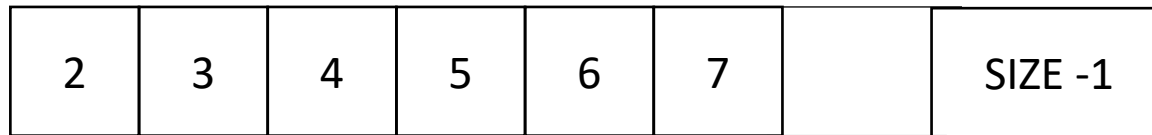
0 - local_x - 0

1 - local_x - 1

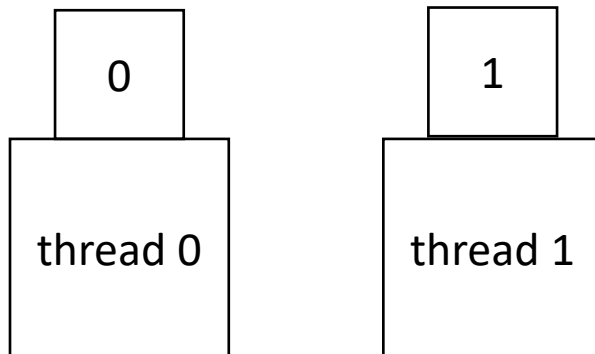
```
atomic_int x(0);
void parallel_loop(...) {
    for (int local_x = atomic_fetch_add(&x,1);
         local_x < SIZE;
         local_x = atomic_fetch_add(&x,1)) {
        // dynamic work based on x
    }
}
```


Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



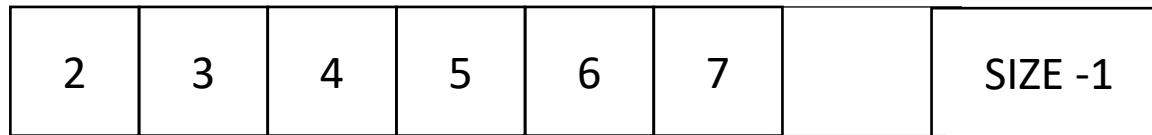
x: 2
0 - local_x - 0
1 - local_x - 1



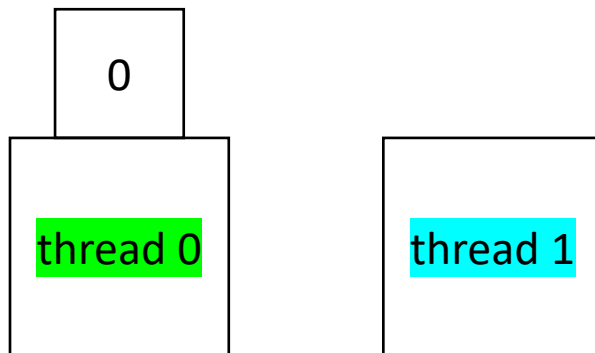
```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



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

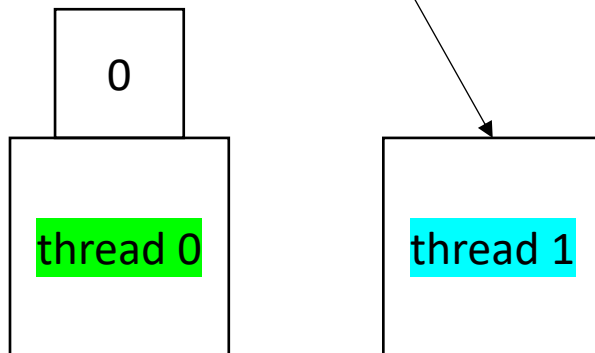
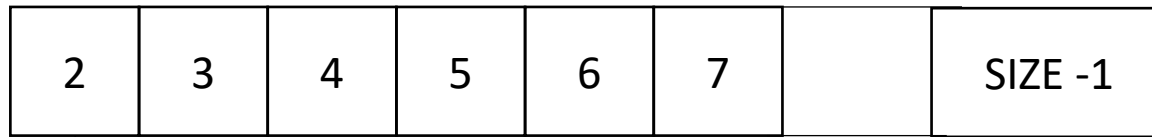


```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

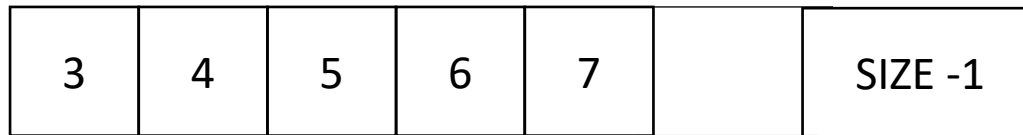
x: 3
0 - local_x - 0
1 - local_x - 2



```
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

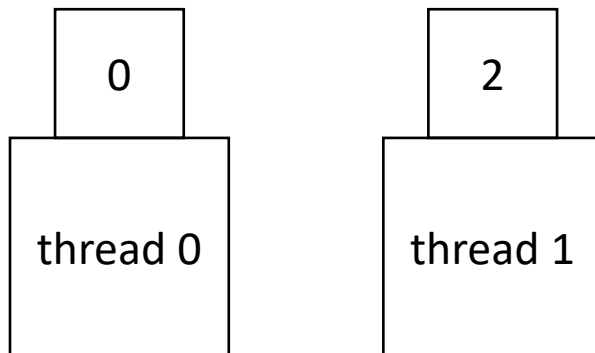
- Global worklist: threads take tasks (iterations) dynamically



x: 3

0 - local_x - 0

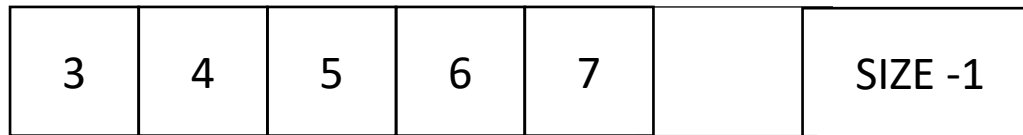
1 - local_x - 2



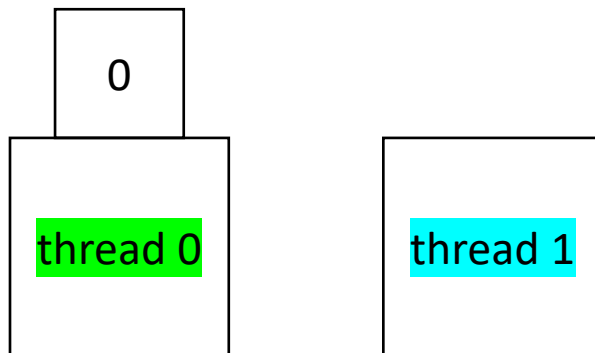
```
atomic_int x(0);
void parallel_loop(...) {
    for (int local_x = atomic_fetch_add(&x,1);
         local_x < SIZE;
         local_x = atomic_fetch_add(&x,1)) {
        // dynamic work based on x
    }
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



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

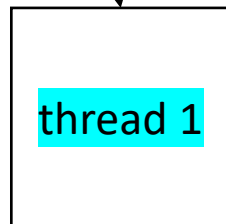
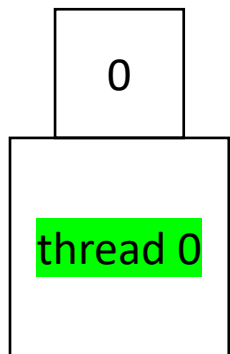
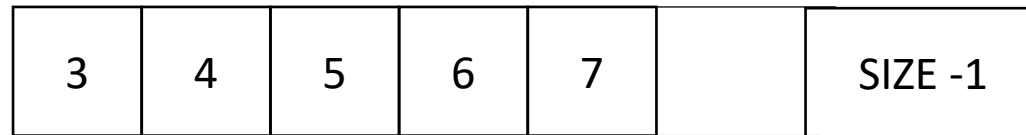


```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

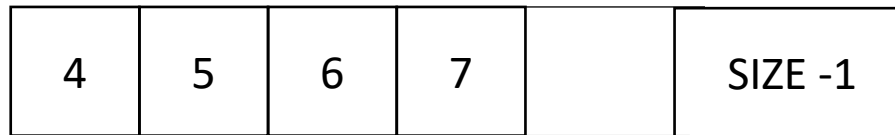
x: 4
0 - local_x - 0
1 - local_x - 3



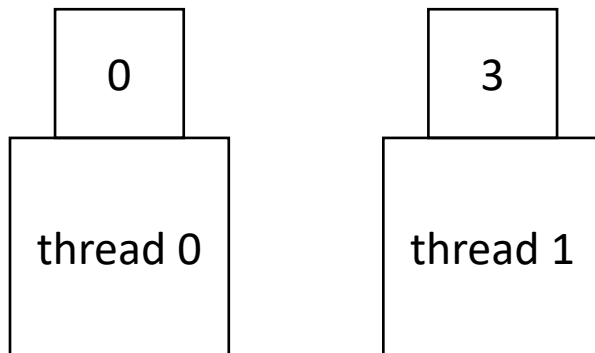
```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



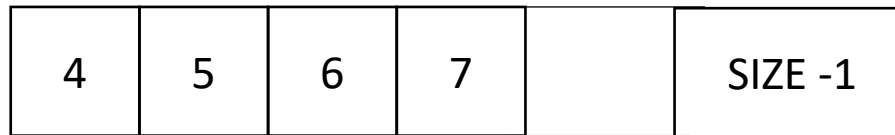
x: 4
0 - local_x - 0
1 - local_x - 3



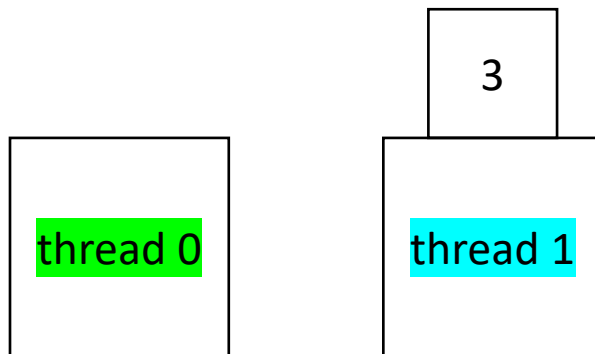
```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



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

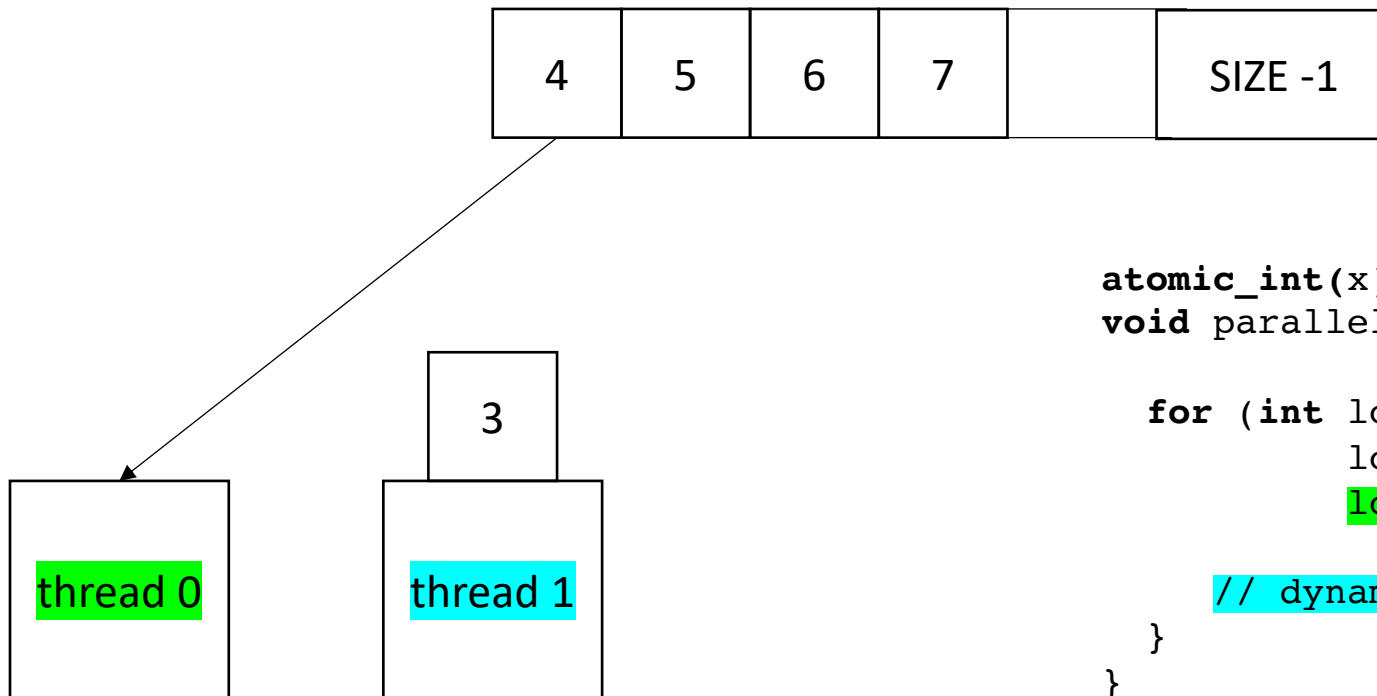


```
atomic_int x(0);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```


Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically

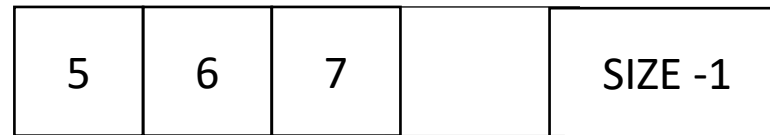
x: 5
0 - local_x - 4
1 - local_x - 3



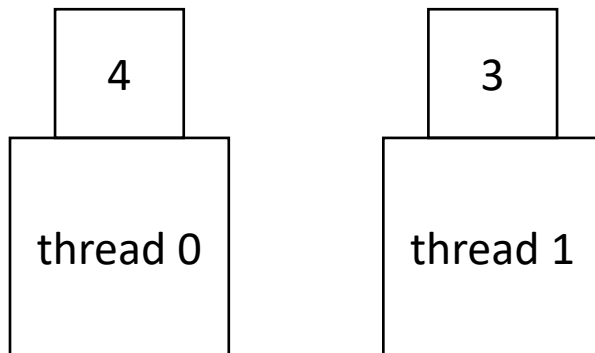
```
atomic_int(x);  
void parallel_loop(...) {  
  
    for (int local_x = atomic_fetch_add(&x,1);  
         local_x < SIZE;  
         local_x = atomic_fetch_add(&x,1)) {  
  
        // dynamic work based on x  
    }  
}
```

Work stealing - global implicit worklist

- Global worklist: threads take tasks (iterations) dynamically



x: 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

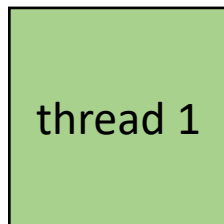
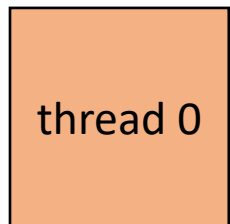
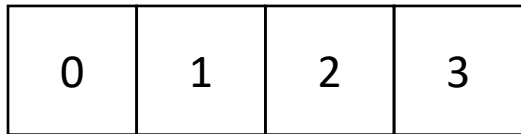
- DOALL Loops
- **Parallel Schedules:**
 - Static
 - Global Worklists
 - **Local Worklists**

Work stealing - local worklists

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

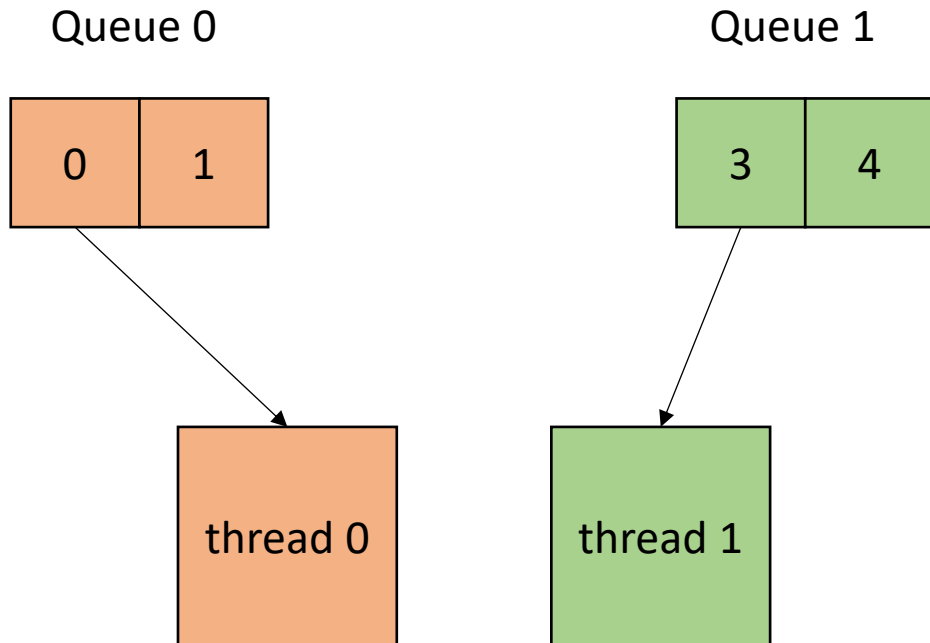
Work stealing - local worklists

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



Work stealing - local worklists

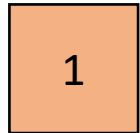
- local worklists: divide tasks into different worklists for each thread



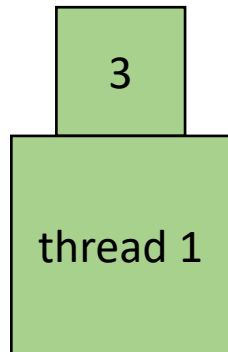
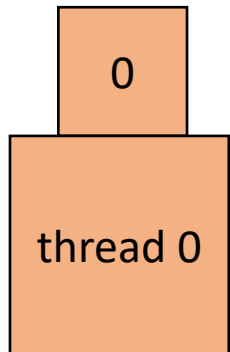
Work stealing - local worklists

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

Queue 0



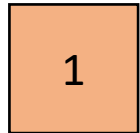
Queue 1



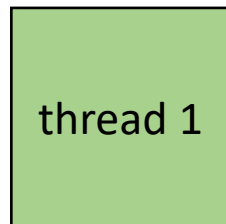
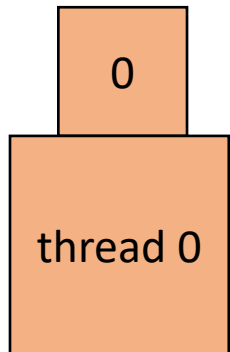
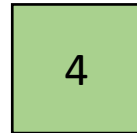
Work stealing - local worklists

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

Queue 0

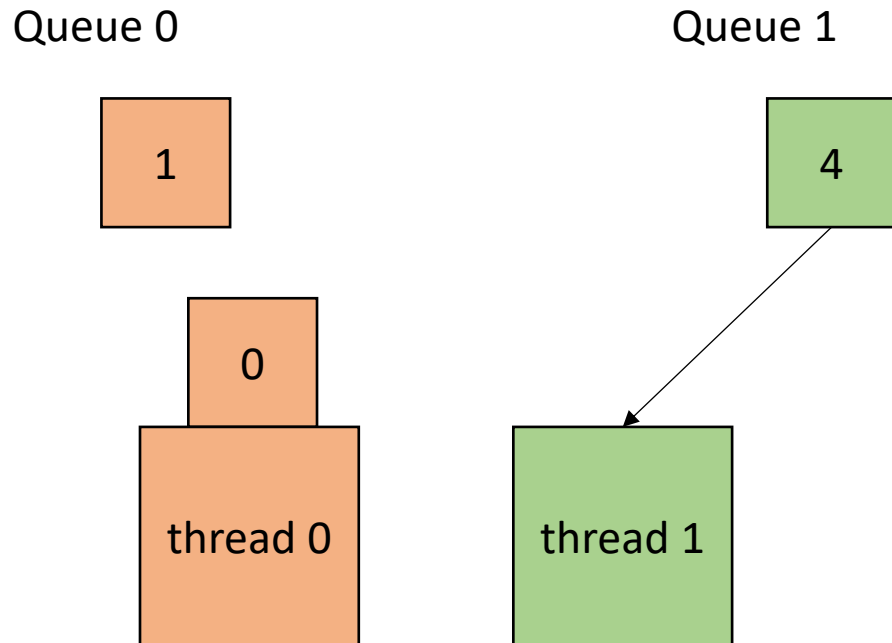


Queue 1



Work stealing - local worklists

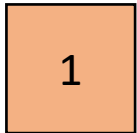
- local worklists: divide tasks into different worklists for each thread



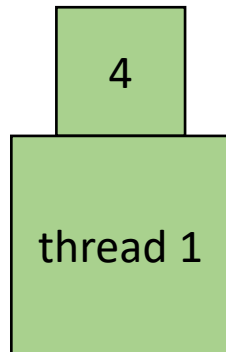
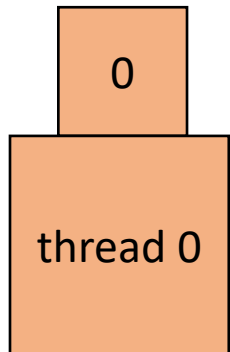
Work stealing - local worklists

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

Queue 0



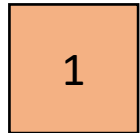
Queue 1



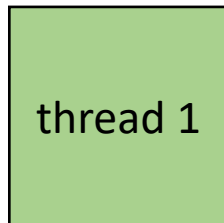
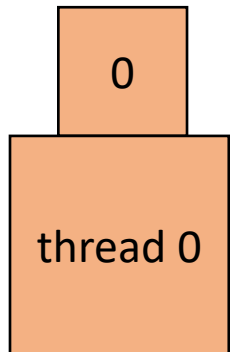
Work stealing - local worklists

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

Queue 0

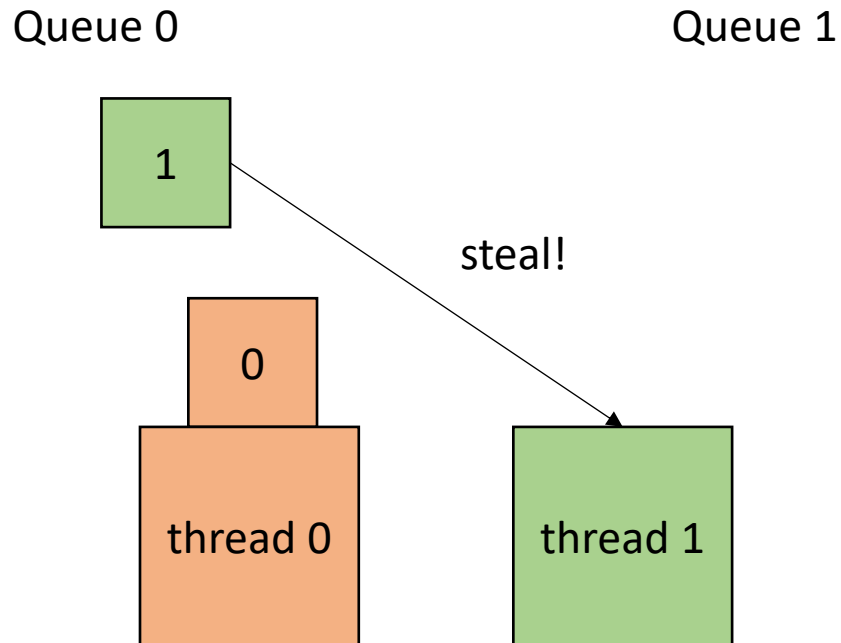


Queue 1



Work stealing - local worklists

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

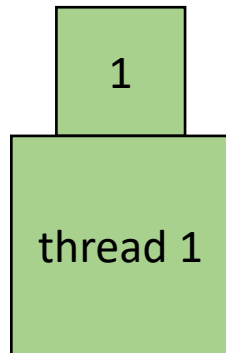
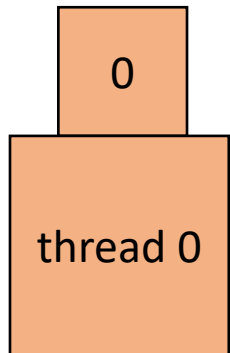


Work stealing - local worklists

- 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_queues 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_queues 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_queues 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  
    }  
}
```

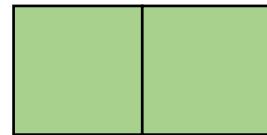
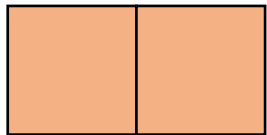
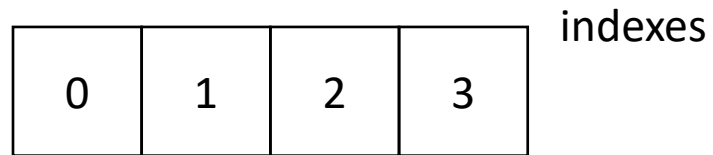
What type of queues?

We're going to use InputOutput Queues!

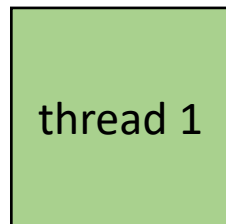
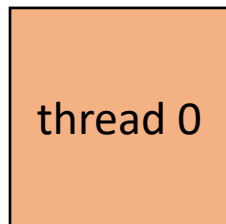
Make a global array of concurrent queues

Work stealing - local worklists

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

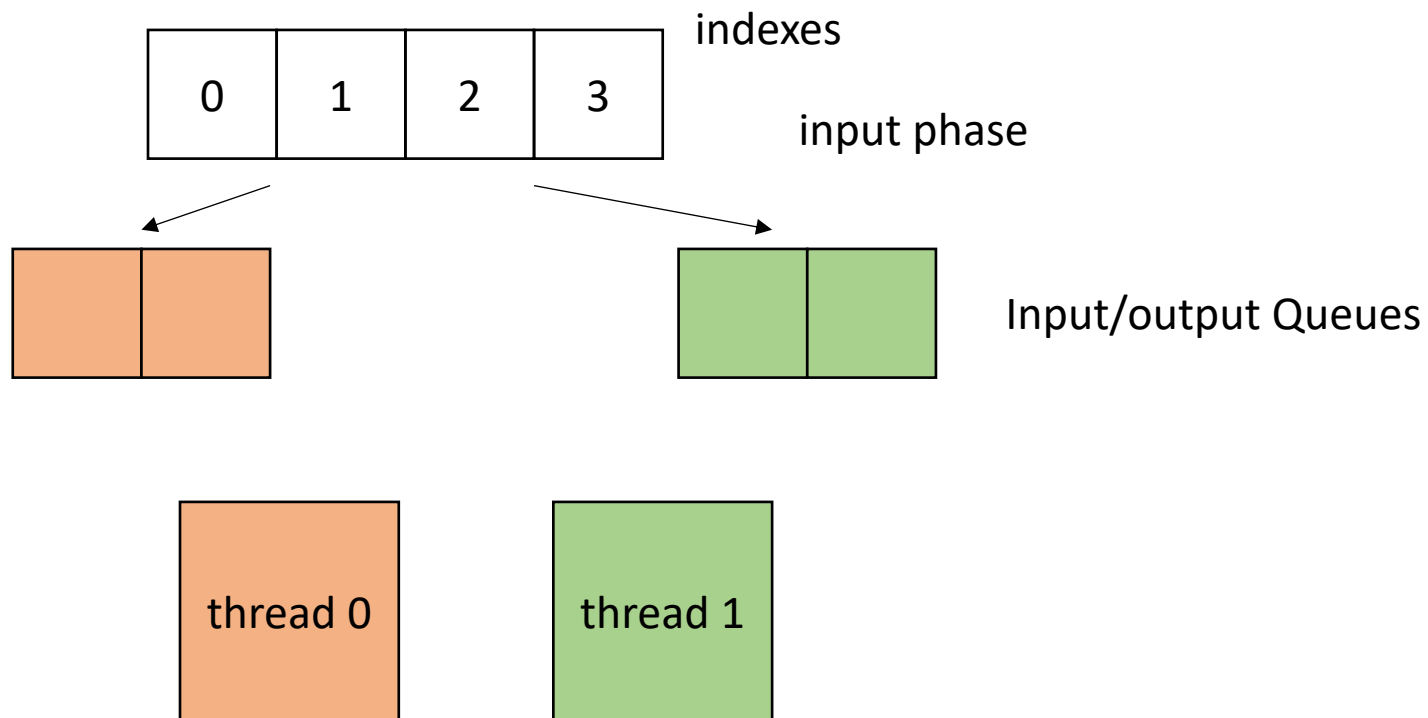


Input/output Queues



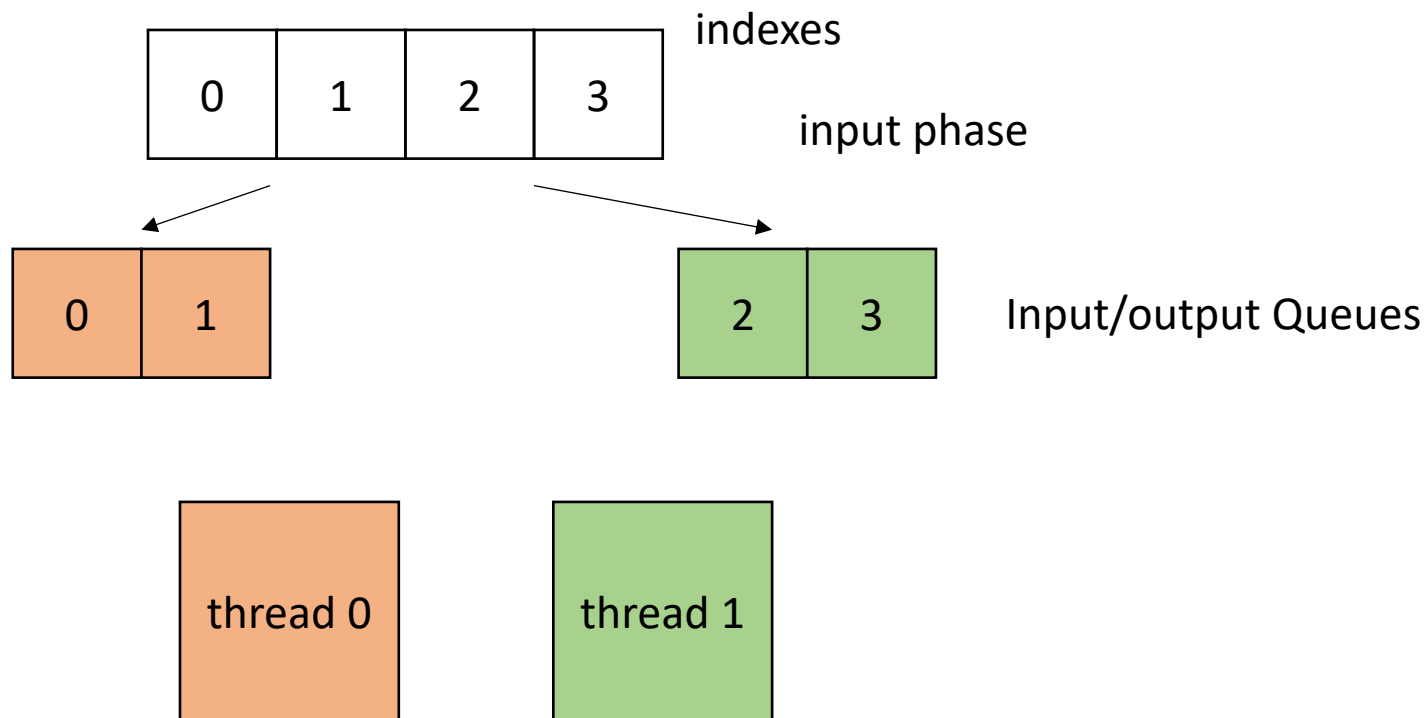
Work stealing - local worklists

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



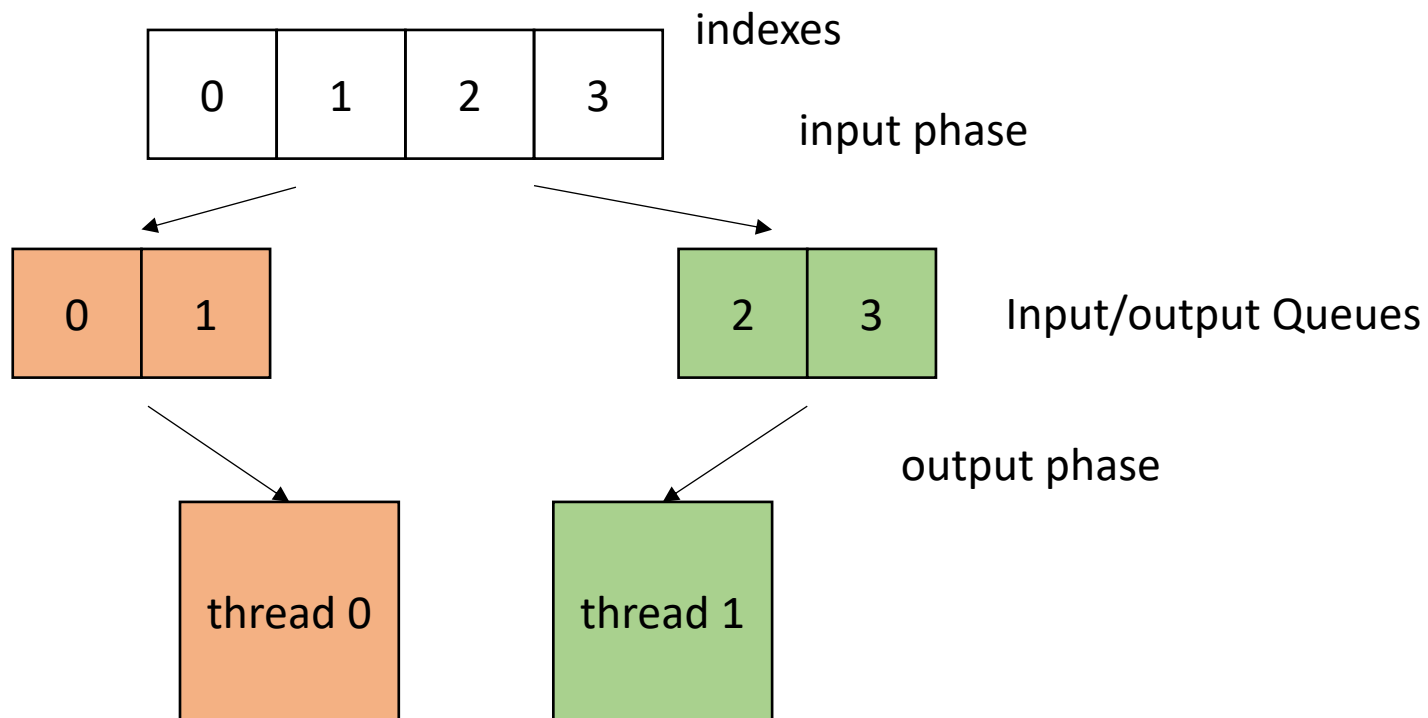
Work stealing - local worklists

- 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

```
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

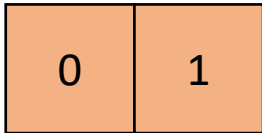
```
concurrent_queues cq[NUM_THREADS];  
void foo() {  
    ...  
    // initialize queues  
    // join threads  
  
    // launch loop function  
    // join loop threads  
    ...  
}
```

join the threads

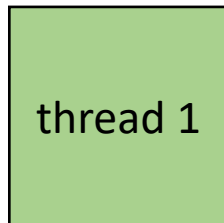
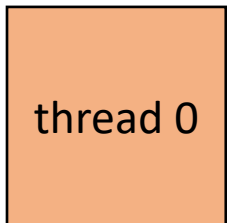
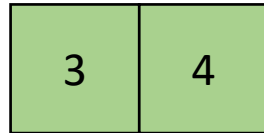
```
atomic_int finished_threads(0);  
void parallel_loop(..., int tid, int num_threads) {  
  
    int task = 0;  
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())  
    {  
        // dynamic work based on task  
    }  
    atomic_fetch_add(&finished_threads,1);  
    while (finished_threads.load()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



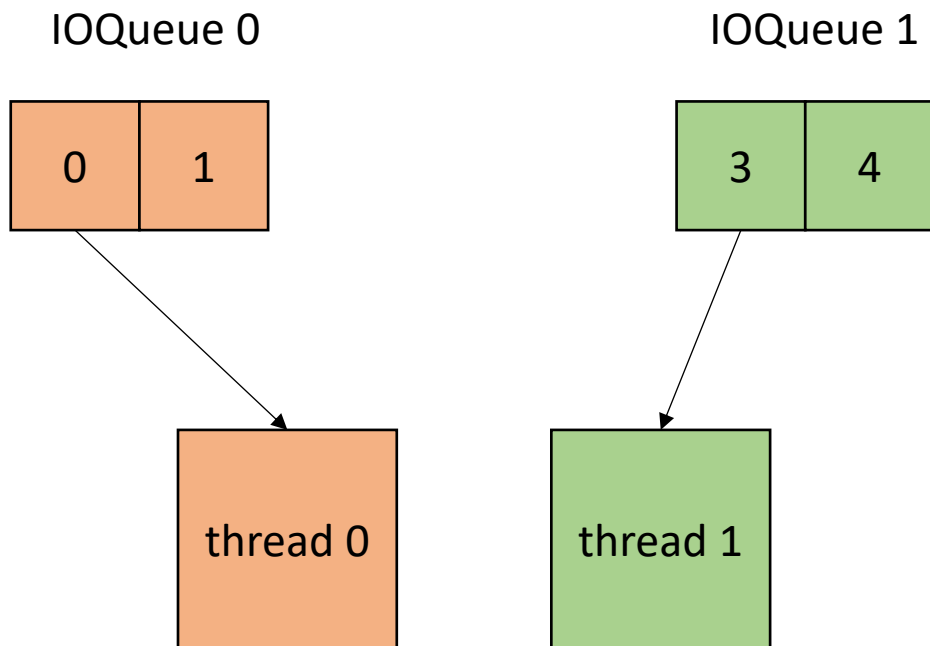
IOQueue 1



```
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

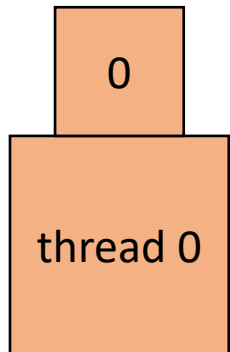
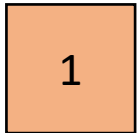


```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

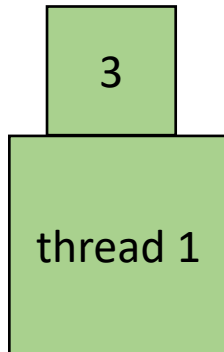
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();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

Work stealing - local worklists

IOQueue 0



IOQueue 1

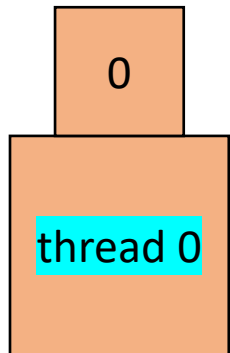
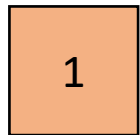


```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

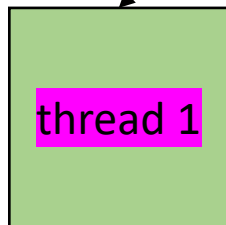
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
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        if (task != -1) {
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     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

Work stealing - local worklists

IOQueue 0



IOQueue 1

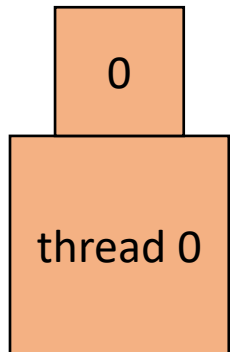
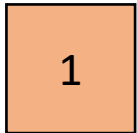


```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

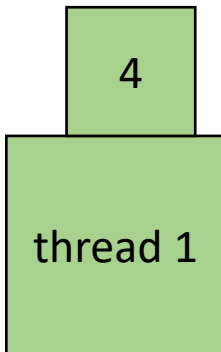
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
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        int target = // pick a thread to steal from
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        if (task != -1) {
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        }
    }
}
```

Work stealing - local worklists

IOQueue 0



IOQueue 1

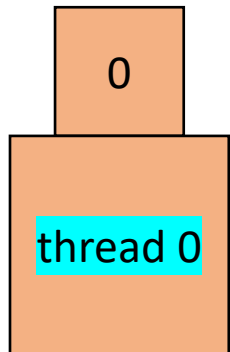
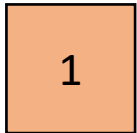


```
atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

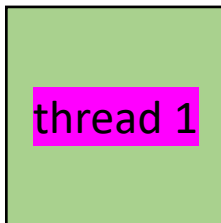
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();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

Work stealing - local worklists

IOQueue 0



IOQueue 1



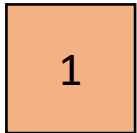
```
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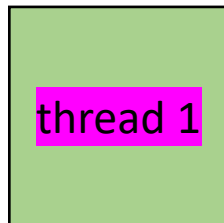
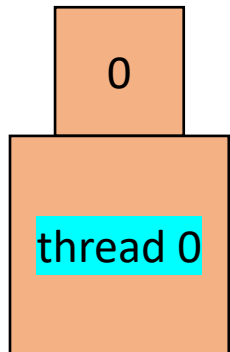

Work stealing - local worklists

finished_threads: 1

IOQueue 0



IOQueue 1



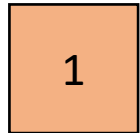
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atomic_int finished_threads(0);
void parallel_loop(..., int tid, int num_threads) {

    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
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        if (task != -1) {
            // perform task
        }
    }
}
```

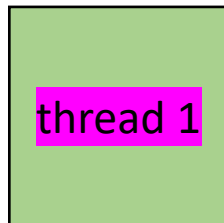
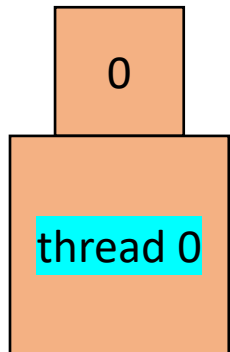
Work stealing - local worklists

finished_threads: 1

IOQueue 0



IOQueue 1



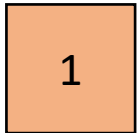
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        int target = // pick a thread to steal from
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        if (task != -1) {
            // perform task
        }
    }
}
```

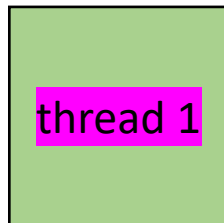
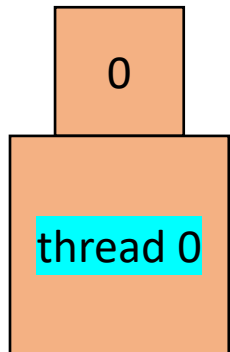
Work stealing - local worklists

finished_threads: 1

IOQueue 0



IOQueue 1



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

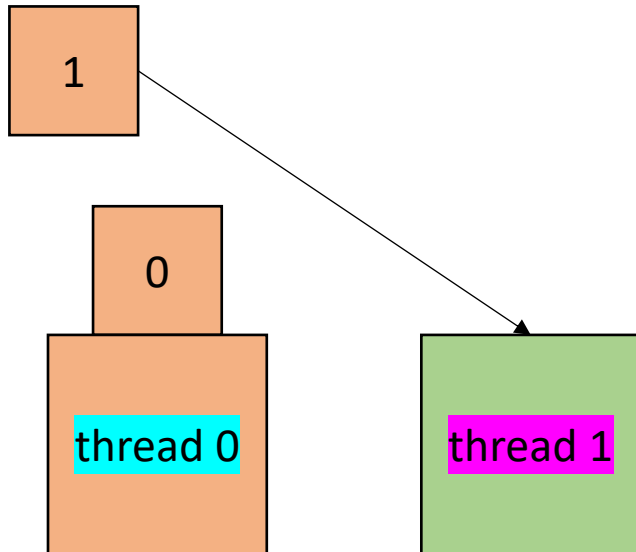
    int task = 0;
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        if (task != -1) {
            // perform task
        }
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```

Work stealing - local worklists

finished_threads: 1

IOQueue 0

IOQueue 1



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

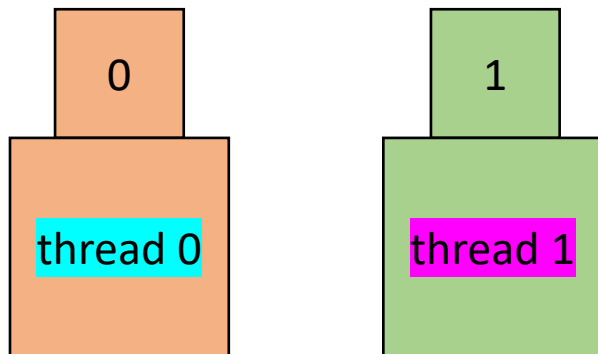
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
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        int task = cq[target].deq();
        if (task != -1) {
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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

Work stealing - local worklists

finished_threads: 1

IOQueue 0

IOQueue 1



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

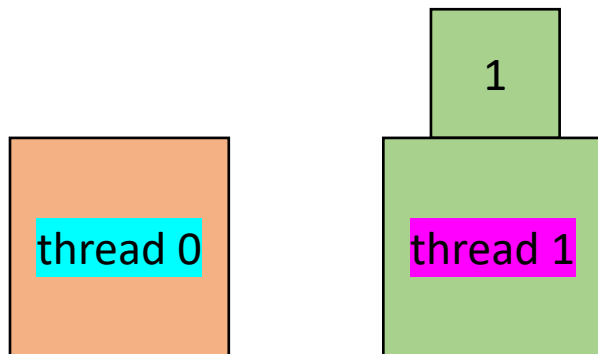
    int task = 0;
    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
    {
        // dynamic work based on task
    }
    atomic_fetch_add(&finished_threads,1);
    while (finished_threads.load() != num_threads) {
        int target = // pick a thread to steal from
        int task = cq[target].deq();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

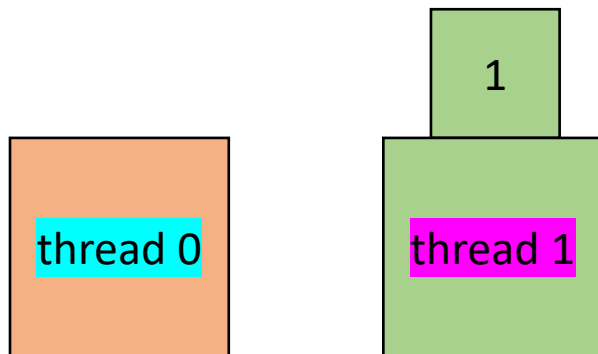
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        int task = cq[target].deq();
        if (task != -1) {
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        }
    }
}
```

Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1



```
atomic_int finished_threads(0);
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    for (x = cq[tid].deq(); x != -1; x = cq[tid].deq())
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    }
    atomic_fetch_add(&finished_threads, 1);
    while (finished_threads.load() != num_threads) {
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        int task = cq[target].deq();
        if (task != -1) {
            // perform task
        }
    }
}
```

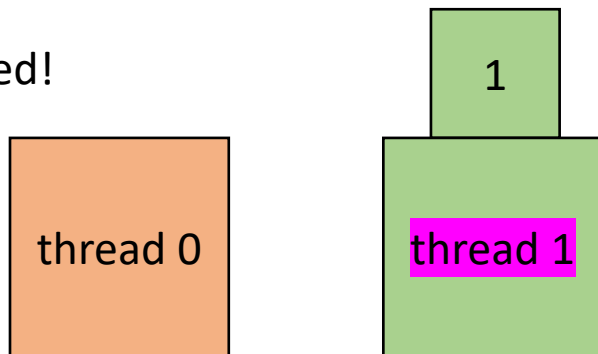
Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1

finished!



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

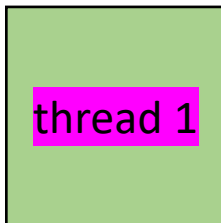
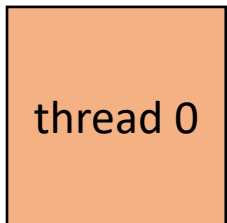
    int task = 0;
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    atomic_fetch_add(&finished_threads,1);
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    }
}
```


Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1



```
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void parallel_loop(..., int tid, int num_threads) {

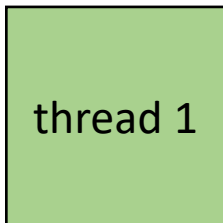
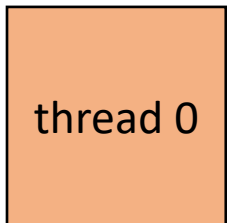
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Work stealing - local worklists

finished_threads: 2

IOQueue 0

IOQueue 1



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        }
    }
}
```

Next week

- generalized concurrent objects
- Get midterm turned in
- Get started on HW 3
- See you on Wednesday