Parallel Programming 101

https://github.com/igirotto/DSSC

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Synchronization

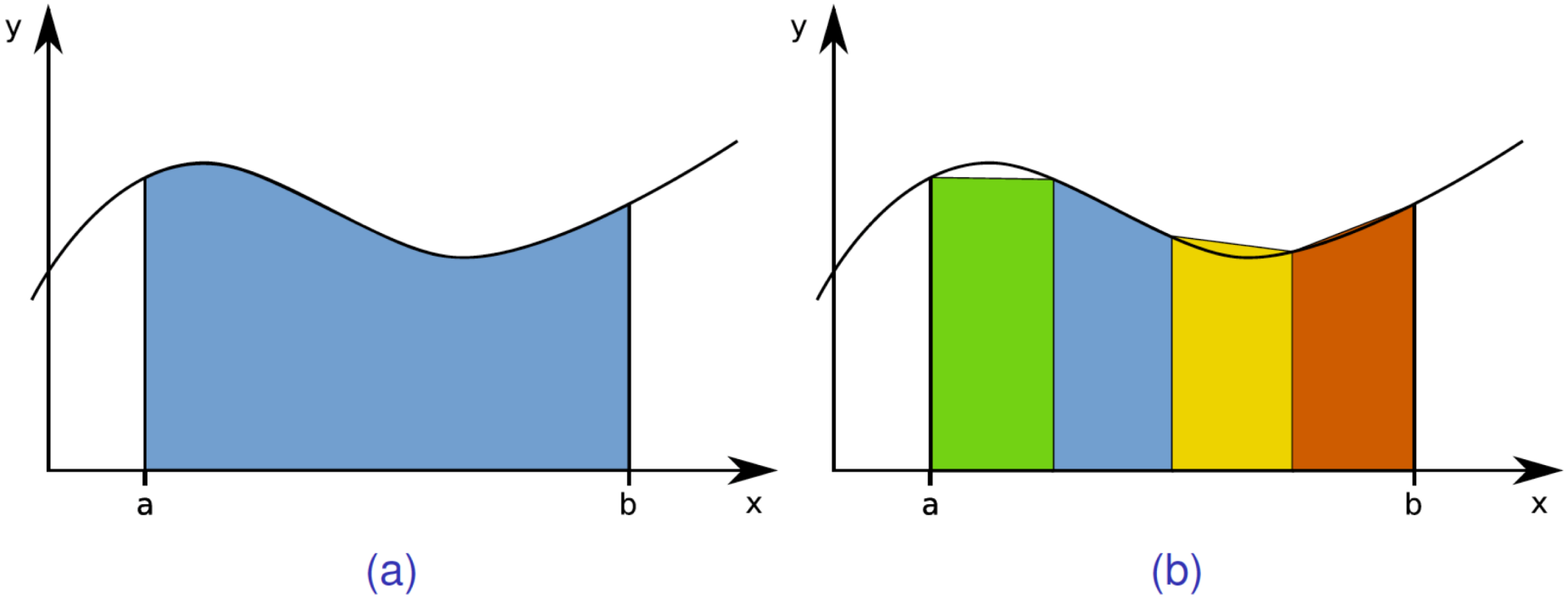


Figure: Approximating the area using the trapezoidal rule

Synchronization

$$\int_a^b f(x)\mathrm{d}x \approx \underbrace{\frac{(b-a)}{n}}_{h}\left[\frac{f(x_0)+f(x_1)}{2}+\frac{f(x_1)+f(x_2)}{2}+\ldots+\frac{f(x_{n-2})+f(x_{n-1})}{2}+\frac{f(x_{n-1})+f(x_n)}{2}\right]$$

$$\int_a^b f(x)\mathrm{d}x \approx \underbrace{\frac{(b-a)}{n}}_{h}\left[\frac{f(x_0)}{2}+f(x_1)+f(x_2)+\ldots+f(x_{n-1})+\frac{f(x_n)}{2}\right]$$

```
double h = (b - a) / n;
double approx = (f(a) + f(b)) / 2.0;

for(int i = 1; i <= n-1; ++i) {
    double x_i = a + i*h;
    approx += f(x_i);
}
approx = h * approx;
```

Synchronization

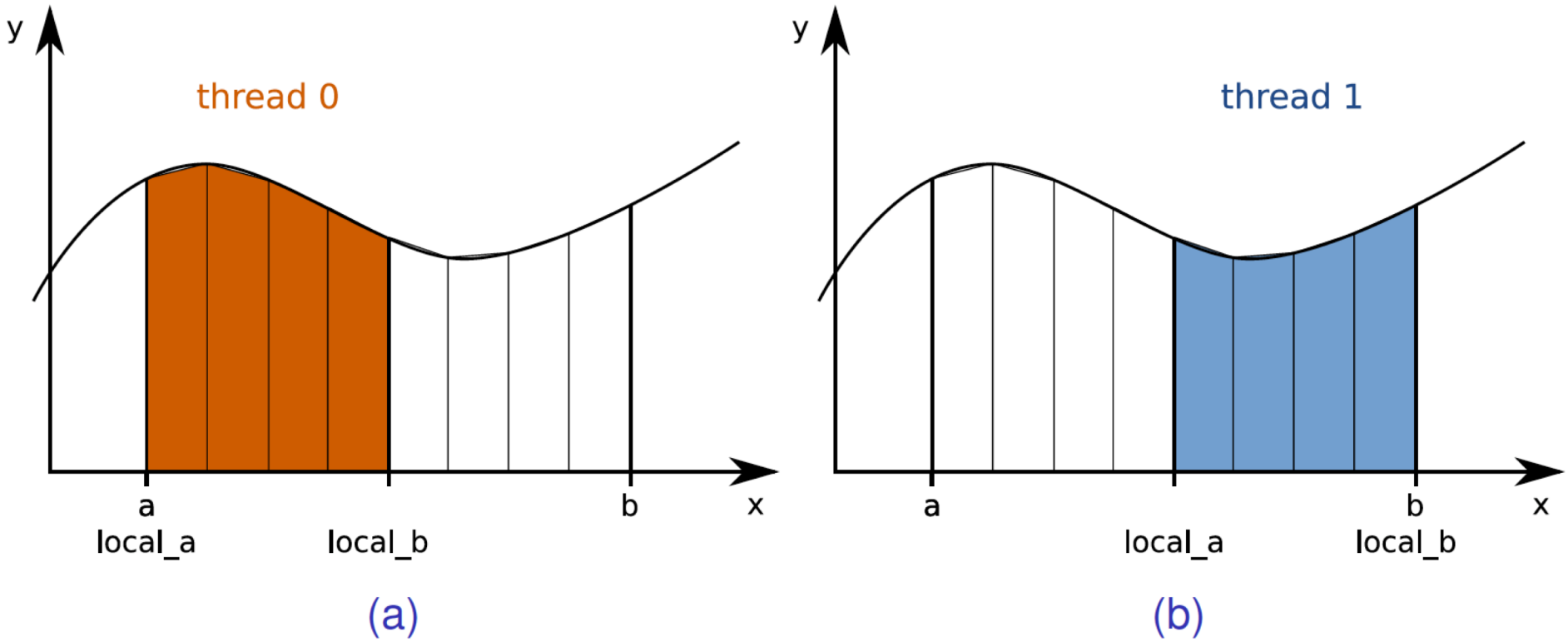
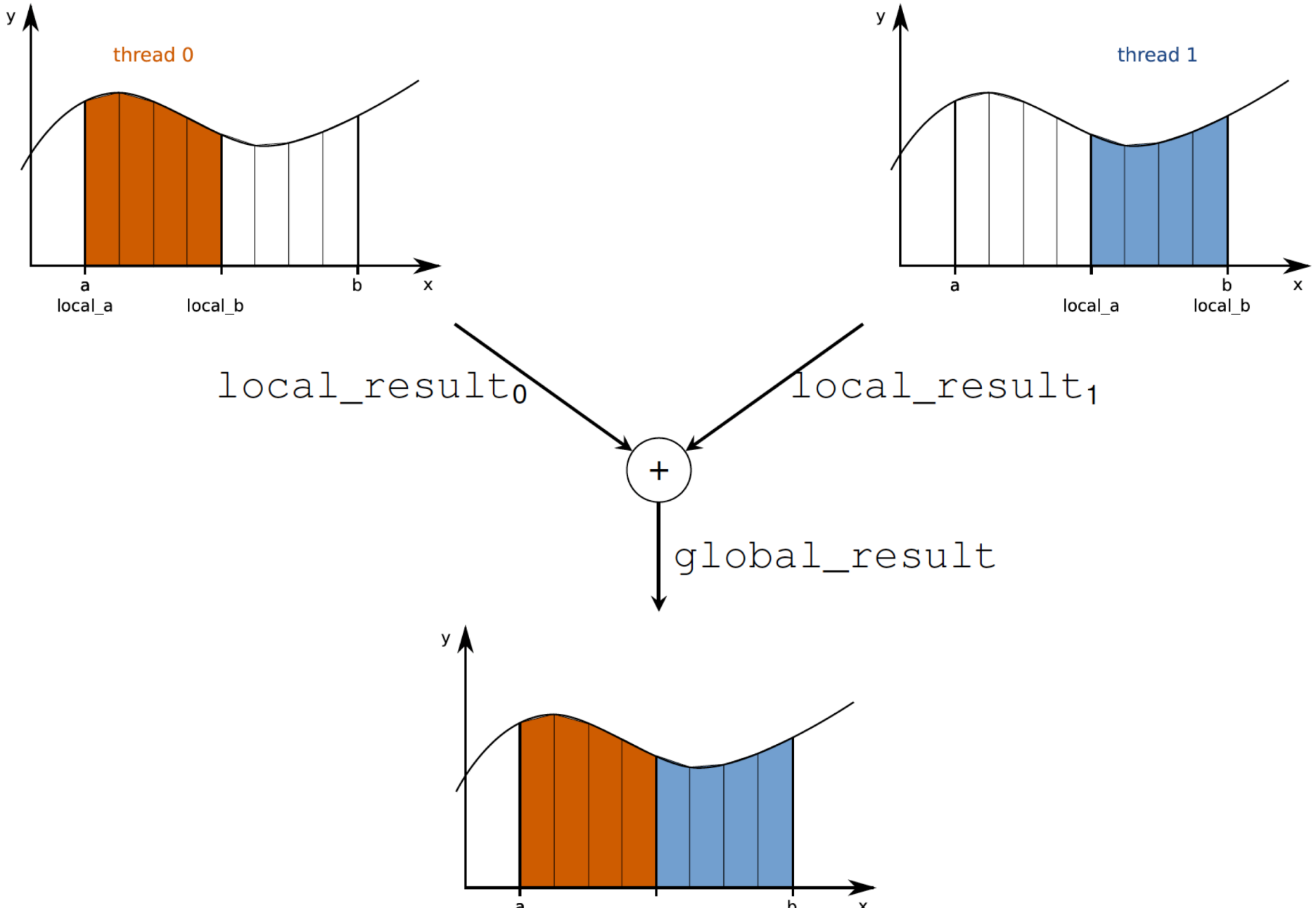


Figure: Splitting the work between two threads

Synchronization



```
double global_result = 0.0;

#pragma omp parallel
{
    double h = (b - a) / n;
    int    local_n = ...
    double local_a = ...
    double local_b = ...

    double local_result = (f(local_a) + f(local_b)) / 2.0;
    for(int i = 1; i <= local_n-1; ++i) {
        double x_i = local_a + i*h;
        local_result += f(x_i);
    }
    local_result = h * local_result;

    ...
}
```

Race Condition

A race condition exists when the following is true:

1. one or more threads read the same data location
2. at least one of them is writing that data location

A block of code that causes a race condition is called a **critical section**.

Synchronization: `critical` directive

- ensures that threads have mutually-exclusive access to a block of code
- only one thread can enter a critical section
- effectively serializes execution of this block of code
- **all unnamed critical blocks in the same parallel block are treated as one**
- **expensive!**

```
#pragma omp critical
global_result += local_result;
```

```
#pragma omp critical
{
    global_result += local_result;
}
```

Synchronization: Named `critical` blocks

- Non overlapping critical sections can run in parallel
- Useful to minimize blocking if not needed

```
if(...) {
    // threads that go this way...
    #pragma omp critical(a)
    {
        // modify shared resource a
    }
} else {
    // ... don't block threads that
    // go this way.
    #pragma omp critical(b)
    {
        // modify shared resource b
    }
}
```

Synchronization: `atomic` directive

- atomic enables mutual exclusion for some simple operations
- these are converted into special hardware instructions if supported
- however, it only protects the read/update of the target location

```
#pragma omp parallel
{
    // compute my_result

    #pragma omp atomic
    x += my_result;
}
```

acceptable operations

- `x++`
- `x--`
- `++x`
- `--x`
- `x binop= expr`
- `x = x binop expr`
- `x = expr binop x`

where `binop` is one of

`+ * - / & ^ | << >>`

```
#pragma omp parallel
{
    #pragma omp atomic
    x += func(); // warning func() is not atomic!
}
```

Synchronization: `barrier` directive

This directive synchronizes the threads in a team by causing them to wait until all of the other threads have reached this point in the code.

```
#pragma omp parallel
{
    // do something in parallel using your team of threads

    #pragma omp barrier
    // wait until all threads reach this point

    // continue computation in parallel
}
```

Timing

```
double tstart = omp_get_wtime();
// do work
double duration = omp_get_wtime() - tstart;
```

```
#pragma omp parallel
{
    double tstart = omp_get_wtime();
    // do part 1

    #pragma omp barrier

    double part1_duration = omp_get_wtime() - tstart;

    // continue with part 2
}
```

Timing

```
double tstart = omp_get_wtime();
// do work
double duration = omp_get_wtime() - tstart;
```

```
#pragma omp parallel
{
    double tstart = omp_get_wtime();
    // do part 1

    #pragma omp barrier

    double part1_duration = omp_get_wtime() - tstart;

    // continue with part 2
}
```

Parallel Integral

Define a function which does the local sum in range [$local_a$, $local_b$]

```
double local_sum(double local_a, double local_b, int local_n, double h) {
    double local_result = (f(local_a) + f(local_b)) / 2.0;
    for(int i = 1; i <= local_n-1; ++i) {
        double x_i = local_a + i*h;
        local_result += f(x_i);
    }
    local_result = h * local_result;
    return local_result;
}
```

Parallel Integral

```
double global_result = 0.0;

#pragma omp parallel
{
    double h = (b - a) / n;

    int tid = omp_get_thread_num();
    int nthreads = omp_get_num_threads();

    int local_n = n / nthreads;
    double local_a = a + tid * local_n * h;
    double local_b = local_a + local_n * h;

    // what is wrong with this code?
    #pragma omp critical
    global_result += local_sum(local_a, local_b, local_n, h);
}
```

Parallel Integral

```
double global_result = 0.0;

#pragma omp parallel
{
    double h = (b - a) / n;

    int tid = omp_get_thread_num();
    int nthreads = omp_get_num_threads();

    int local_n = n / nthreads;
    double local_a = a + tid * local_n * h;
    double local_b = local_a + local_n * h;

    double local_result = local_sum(local_a, local_b, local_n, h);

    #pragma omp atomic
    global_result += local_result;
}
```

Synchronization: `reduction` clause

- creates a private variable for each thread
- each thread works on private copy
- finally all thread results are accumulated using operator
- allowed operators: `+, -, *, &, |, ^, &&, ||, min, max`
- each operator has a default initialization value (e.g. 0 for addition, 1 for multiplication)

```
double global_result = 0.0;

#pragma omp parallel reduction(+:global_result)
{
    double h = (b - a) / n;
    int tid = omp_get_thread_num();
    int nthreads = omp_get_num_threads();
    int local_n = n / nthreads;
    double local_a = a + tid * local_n * h;
    double local_b = local_a + local_n * h;

    global_result += local_sum(local_a, local_b, local_n, h);
}
```

Synchronization: `nowait` clause

Work sharing constructs have a implict barrier at their end. With nowait you can allow them to continue after they finish their part.

```
#pragma omp parallel
{
    #pragma omp for
    for(...) {
    }
    // implicit barrier

    #pragma omp for
    for(...) {
    }
}
```

```
#pragma omp parallel
{
    #pragma omp for nowait
    for(...) {
    }
    // threads can continue

    #pragma omp for
    for(...) {
    }
}
```

Synchronization: `master` clause

```
#pragma omp parallel
{
    #pragma omp master
    {
        // only master thread should execute this
        // useful for I/O or initialization
        // there is NO implicit barrier!
    }

    // add explicit barrier if needed
    #pragma omp barrier
    ...
}
```

Synchronization: `single` clause

```
#pragma omp parallel
{
    #pragma omp single
    {
       // only one thread will execute this block
       // all others wait until it completes
       // implicit barrier!
    }
}
```

```
#pragma omp parallel
{
    #pragma omp single nowait
    {
       // only one thread will execute this block
       // others will go right past it
    }
}
```

Resources

https://computing.llnl.gov/tutorials/openMP/