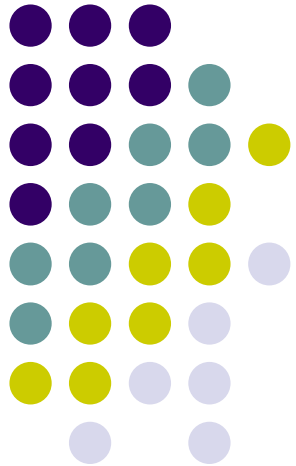
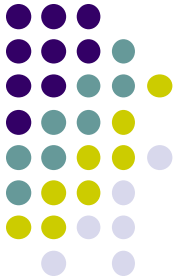
Practical Parallel Computing (実践的並列コンピューティング)

Part1: OpenMP (3)
May 18, 2020



Toshio Endo
School of Computing & GSIC
endo@is.titech.ac.jp

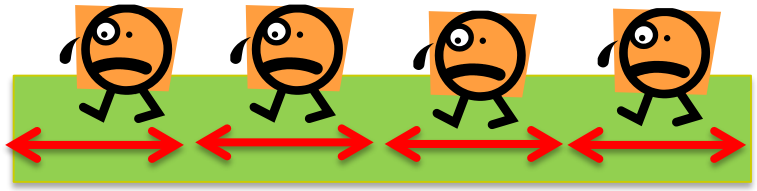
Overview of This Course



- Part 0: Introduction
  - 2 classes
- Part 1: OpenMP for shared memory programming
  - 4 classes ← We are here (3/4)
- Part 2: GPU programming
  - OpenACC and CUDA
  - 4 classes
- Part 3: MPI for distributed memory programming
  - 3 classes

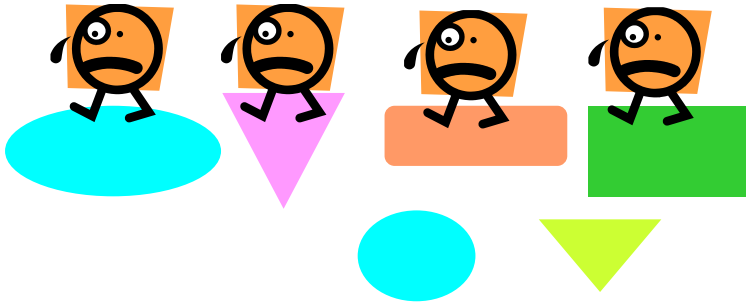
Today's Topic: Task Parallelism ~Comparison with Data Parallelism~

- Data Parallelism:
  - Every thread does uniform/similar tasks for different part of large data



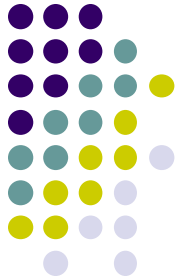
cf) mm, diffusion samples

- Task Parallelism:
  - Each thread does different tasks
    - Sometimes the number of tasks is unknown beforehand
    - Sometimes tasks are generated recursively



cf) fib, sort samples today

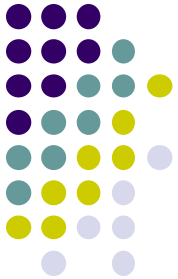
Data Parallelism/Task Parallelism in OpenMP

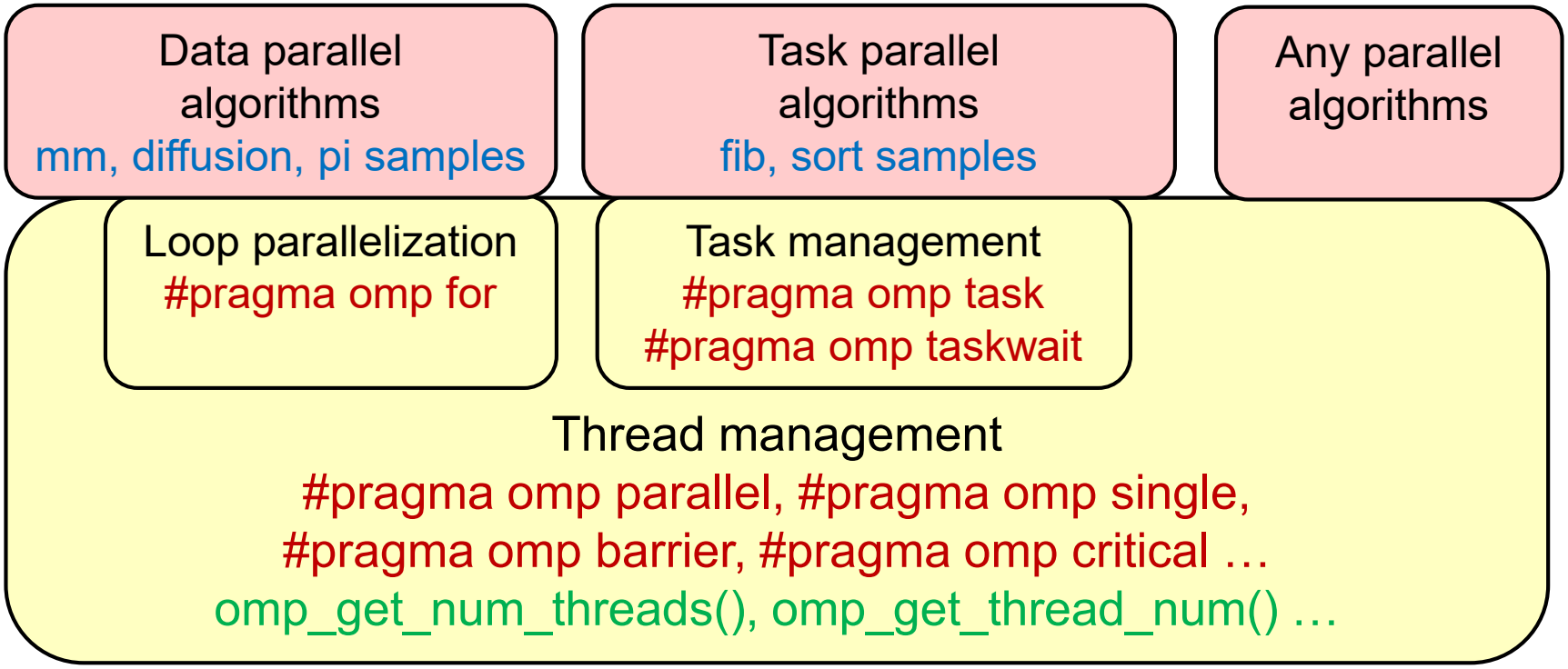


- #pragma omp for
  - Used for data parallelism (basically)
  - Number of tasks is known before starting for-loop
    - for (i = 0; i < n; i++) … → *n* tasks are divided among threads
- #pragma omp task
  - Used for task parallelism (basically)
  - Number of tasks may change during execution

※ You may write data parallel algorithm with “omp task” if you want, or vice versa

Relationship of OpenMP Syntaxes





※ This grouping is different from that in OpenMP official web (openmp.org/specifications/)

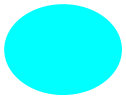
task/taskwait Syntaxes

See a sample at at /gs/hs1/tga-ppcomp/20/tasks-omp/

```
#pragma omp parallel
#pragma omp single
{
#pragma omp task
  {
    A;
  }

#pragma omp task
  B;

  C;
#pragma omp taskwait
}
```



"task" syntax generates a task that executes the following block/sentence

- A task is executed by one of threads who is idle (has nothing to do)
- New tasks and the original task may be executed in parallel
- Recursive task generation is ok
  - A parent task generates children tasks, and one of generates grandchildren…

"taskwait" syntax waits end of all children tasks

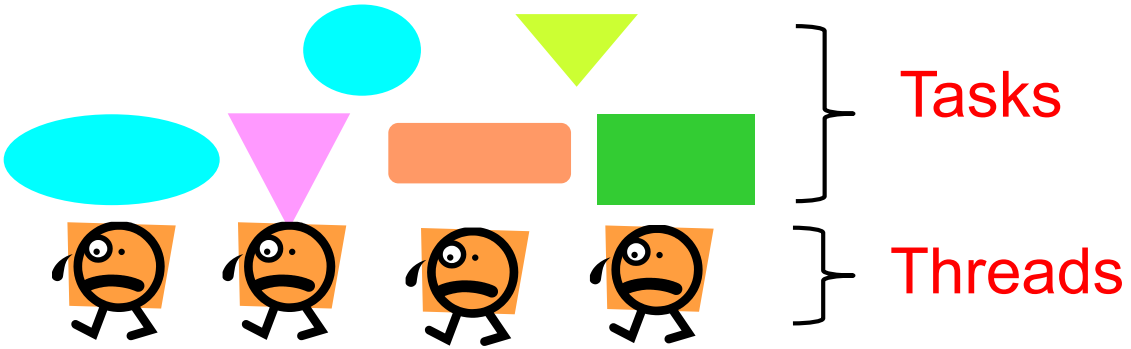
Differences between "Tasks" and "Threads"

Task A and task B are executed in parallel

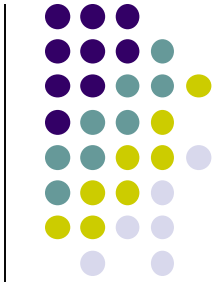
Thread A and thread B are executed in parallel

→ So, what is the difference?

- Number of threads is (basically) constant during a parallel region
  - OMP_NUM_THREADS, usually no more than number of processor cores
- Number of tasks may be changed frequently
  - may be >>number of processor cores
- When a thread becomes idle, it takes one of tasks and executes it



Note on Using “task” Syntax



- In OpenMP, tasks are taken and executed by idle threads

→ We need to prepare idle threads before creating tasks

```
#pragma omp parallel
#pragma omp single
 {

        :  (task generations)

 }
```

←Multiple threads start

←Only a single thread executes followings (other threads become idle)

←Parallel region finishes

[Q] What if we omit “omp parallel” & “omp single”?
→ There is 1 thread, which executes all tasks
→ No speed up! ☹

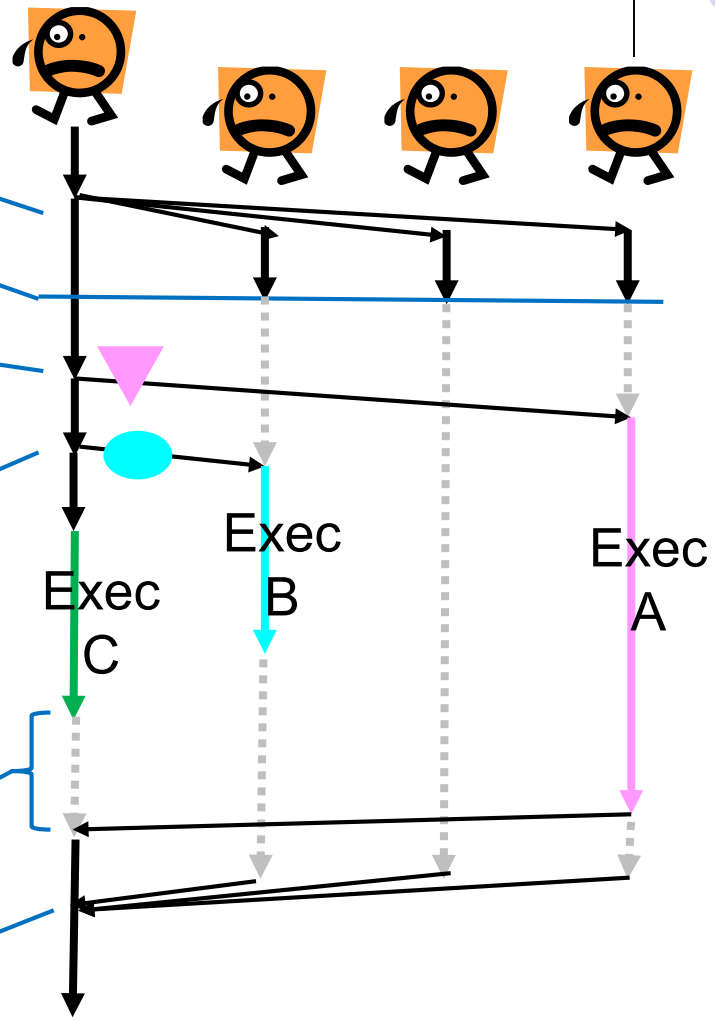
[Q] What if we omit only “omp single”?
→ Every thread execute all tasks redundantly
→ No speed up! ☹

Threads Executes Tasks
(see “tasks-omp” sample)

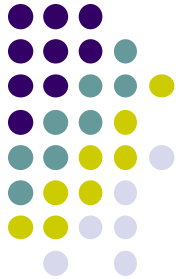
```
#pragma omp parallel
#pragma omp single
{
#pragma omp task
  {
    A;
  }

#pragma omp task
  B;

  C;
#pragma omp taskwait
}  (end of parallel region)
```



Number of Tasks



- In the tasks-omp sample, there are 3 tasks in the world
  → No speed up with ≧ 4 threads

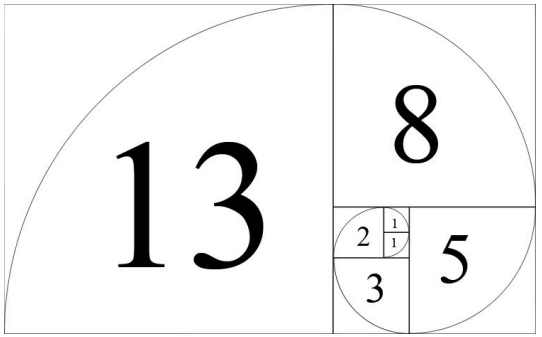
  “Too less tasks are bad ☹”

- To use threads (CPU cores) effectively, the number of tasks should be ≧ OMP_NUM_THREADS

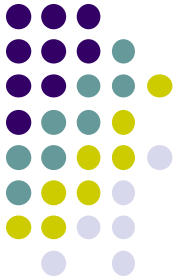
  ➔Next, we try a sample program with recursive function calls to generate plenty of tasks

“fib” Sample Program

- Available at /gs/hs1/tga-ppcomp/20/fib/
- Calculates the Fibonacci number
  - fib(n) = fib(n-1) + fib(n-2)
  - 1, 1, 2, 3, 5, 8, 13…
- Execution: ./fib [n]
  - ./fib 40 → outputs 40th Fibonacci number
- Recursive function call is used
  - It uses an inefficient algorithm as a sample
- Computational complexity: O(fib(n)) ≒ O(1.618^n)



OpenMP Version of fib (version 1)



```
long fib_r(int n)
{
  long f1, f2;
  if (n <= 1) return n;

#pragma omp task shared(f1)
  f1 = fib_r(n-1);

#pragma omp task shared(f2)
  f2 = fib_r(n-2);

#pragma omp taskwait

  return f1+f2;
}
```

Available at

/gs/hs1/tga-ppcomp/20/fib-slow-omp/

- In this version,

  a task = recursive call

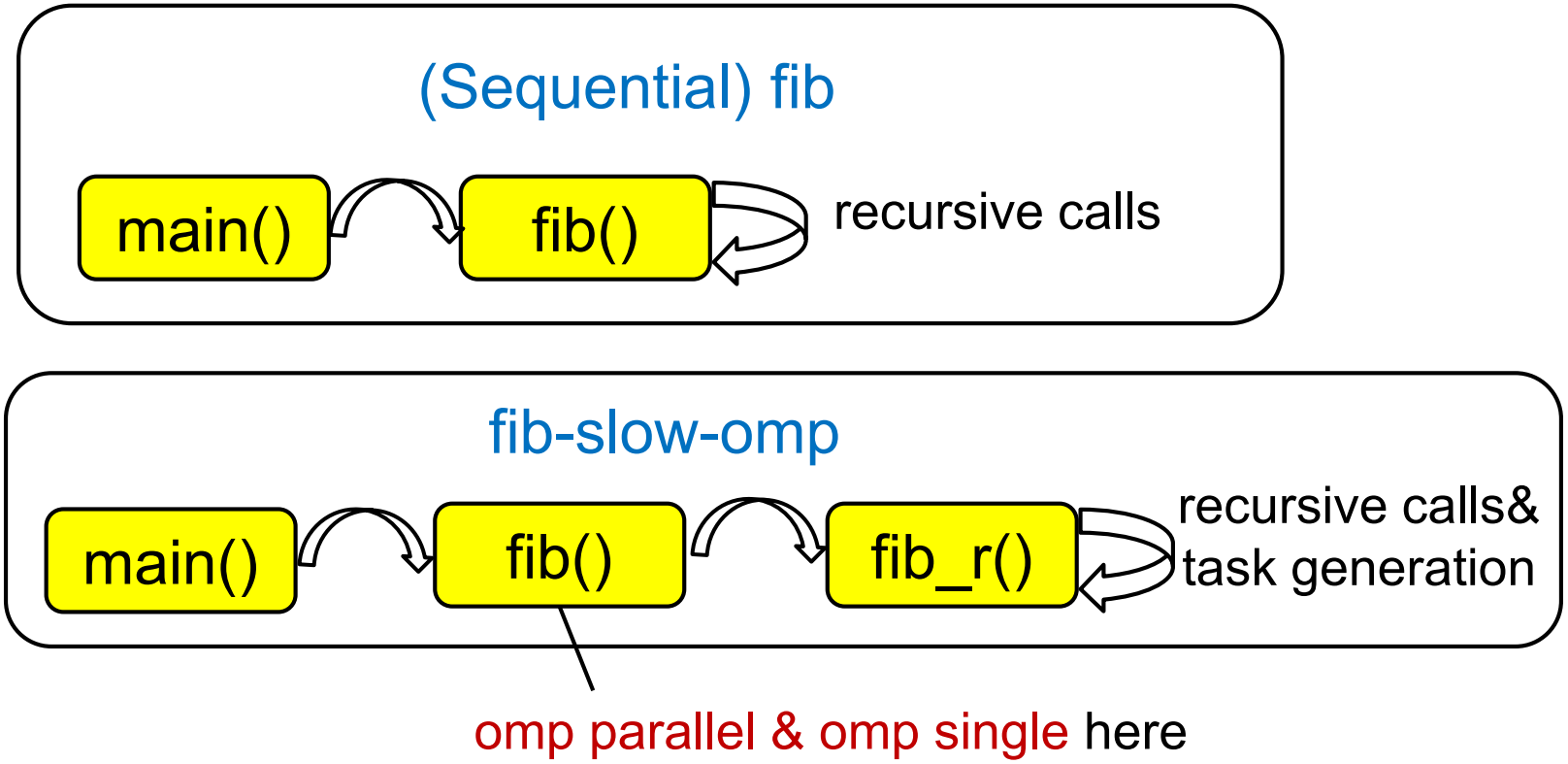
Tasks are generated

We wait for completion of the above 2 tasks

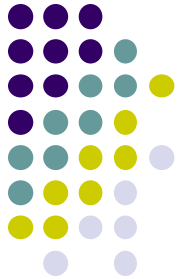
Don’t forget “omp taskwait”

Note on omp parallel → omp single

- We need “omp parallel & omp single” only once, but where?



Rules about Variables



In default, *copies* of variables are created for each child task

- The value of "*n*" is brought from parent to a child task
  → OK ☺
- But a child has a only copy → update to "f1" or "f2" is not visible to parent. NG! ☹

"shared(var)" option makes the variable "var" be shared between parent and the child

- Using it, update to "f1" or "f2" is visible to parent

The First Version is Too Slow

Execution time of ./fib 40

- On a TSUBAME3.0 node

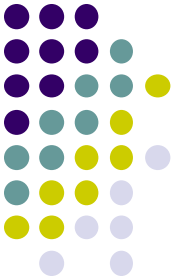
fib	1	threads
	0.60	seconds

fib-slow -omp	1	2	4	8	threads
	33	~300	~360	~480	seconds

- OpenMP version is much slower than original fib
  - With 1 thread, 40x slower
- Also it is much slower with multi-threads

→ How can we improve?

Pitfall in “task” Syntax



- While OpenMP allows to generate many tasks, task generation cost is not negligible

Rough comparison:

Function call cost << Task generation cost

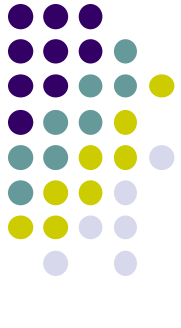
<< Thread generation cost

- In version 1, “./fib n” generates O(fib(n)) tasks

→ Too much tasks are bad!

- How can we reduce the number of tasks?

OpenMP Version of fib (version 2)



```
long fib_r(int n)
{
  long f1, f2;
  if (n <= 1) return n;

  if (n <= 30) {
    f1 = fib_r(n-1);
    f2 = fib_r(n-2);
  }
  else {
#pragma omp task shared(f1)
    f1 = fib_r(n-1);
#pragma omp task shared(f2)
    f2 = fib_r(n-2);
#pragma omp taskwait
  }
  return f1+f2;
}
```

if *n* is "sufficiently" small, we do not generate tasks

Available at
/gs/hs1/tga-ppcomp/20/fib-omp/

- To avoid generating too many tasks, we check n
  - Changing threshold (=30) would affect performance
- If n is large, we generate tasks
- If n is small, we do not generate

Performance of Version 2

Execution time of ./fib 40

fib

1	threads
0.6	seconds

fib-slow -omp

1	2	4	8	threads
33	~300	~360	~480	seconds

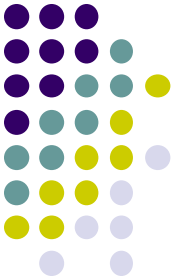
fib-omp

1	2	4	8	threads
0.75	0.46	0.29	0.21	seconds

- Performance of Version 2 is largely improved and more stable
  - With 1 thread, still 25% slower than sequential fib

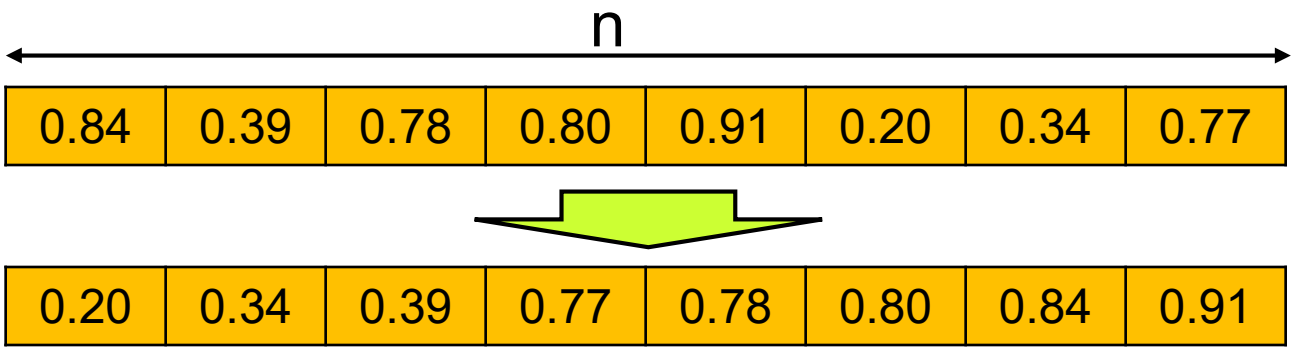
→ Restricting task generation is important for speed

“sort” Sample Program Related to Assignment [O2]



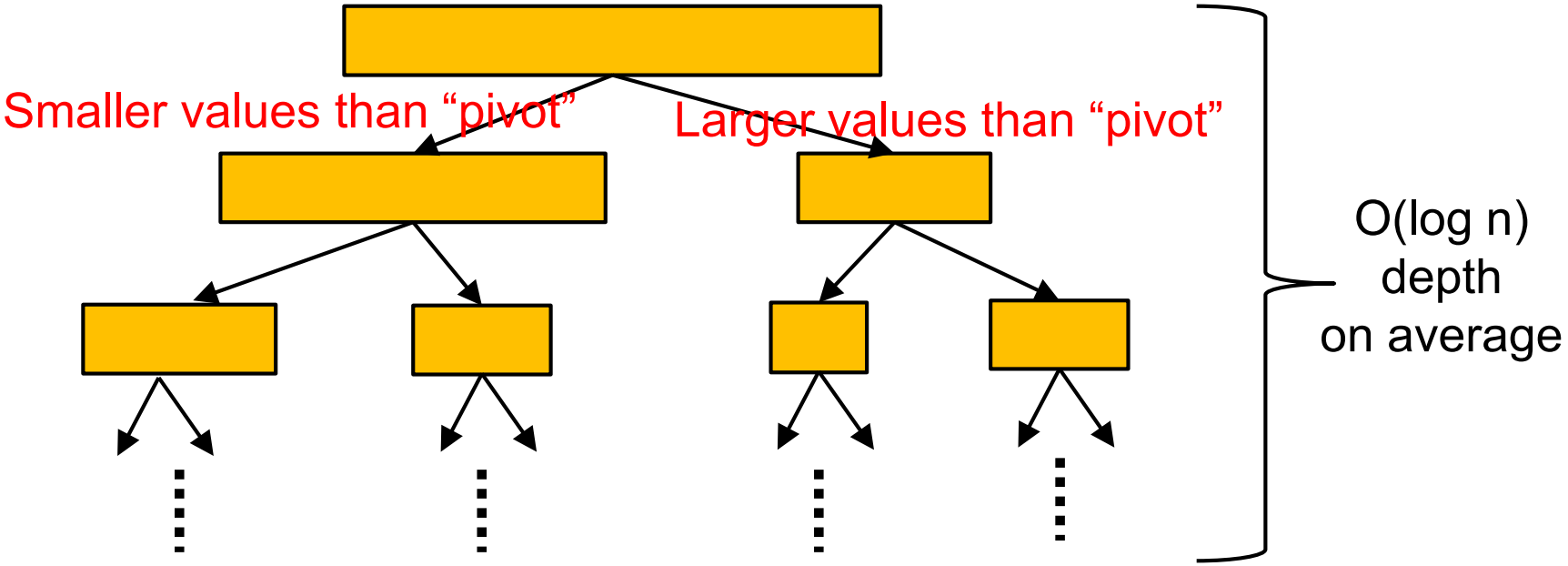
Available at /gs/hs1/tga-ppcomp/20/sort/

- Execution: ./sort [n]
- It sorts an array of length *n* by the quick sort algorithm
  - Array elements have double type
- Compute Complexity: O(n log n) on average
  - More efficient than $O(n^2)$ algorithm such as bubble sort

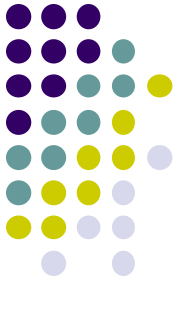


Quick Sort

- A recursive algorithm
  - Take a value, called “pivot” from the array
  - Partition array into two parts, “small” and “large”
  - “small” part and “large” part are sorted recursively



Structure of sort Sample

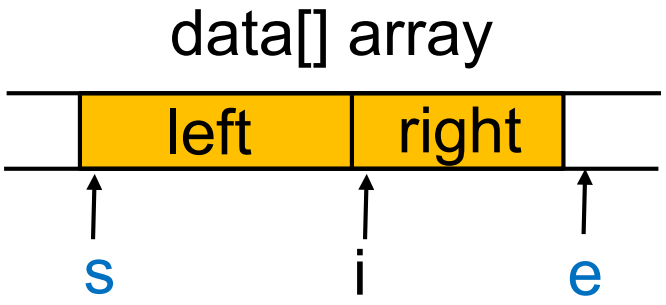


```
int sort(double *data, int s, int e)
{
  int i, j;
  double pivot;
  if (e-s <= 1)  return 0;

  /* pivot selection */
       :

  /* partition data[] into 2 parts */
       :
  /* Here "i" is boundary of 2 parts */

  sort(data, s, i);   /* Sort left part recursively*/
  sort(data, i, e);  /* Sort right part recursively */
}
```

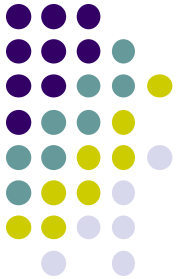


Harder to parallelize

Generating 2 tasks would be a good idea

[Q] Should we restrict too much task generation? And how?

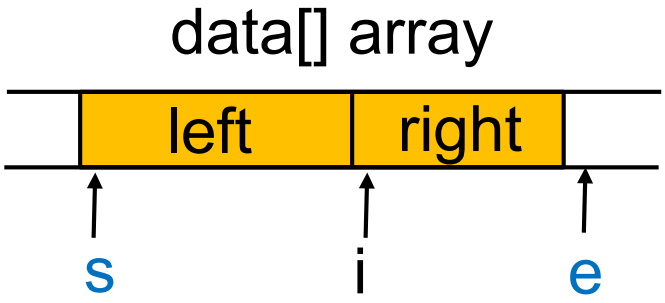
Is it Correct to Parallelize Recursive Calls in sort?



C1
C2

```
:
sort(data, s, i);  /* Sort left part recursively*/
sort(data, i, e);  /* Sort right part recursively */
```

- Let us discuss why computations C1 and C2 can be parallelized
  - Analyze read-set R and write-set W of each

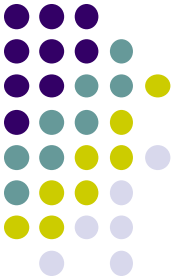


- R(C1) = W(C1) = {data[s], data[s+1], … data[i-1]}
- R(C2) = W(C2) = {data[i], data[i+1], … data[e-1]}

Disjoint
➔ independent!

Even with recursive task generations, this discussion can be applied

[Revisited] When We Can Use “omp for”



- Loops with some (complex) forms cannot be supported, unfortunately ☹
- The target loop must be in the following form

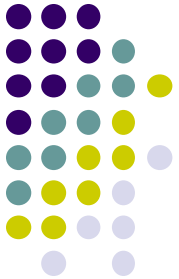
```
#pragma omp for
  for (i = value; i op value; incr-part)
    body
```

“*op*” : <, >, <=, >=, etc.
“*incr-part*” : i++, i--, i+=c, i-=c, etc.

```
OK ☺:  for (x = n; x >= 0; x-=4)
NG ☹:  for (i = 0; test(i); i++)
NG ☹:  for (p = head; p != NULL; p = p->next)
```

⇨ *Instead, we can parallelize it with “task” syntax*

Parallelize Irregular Loops with "task" Syntax



- In list search, number of iterations cannot be known before execution → we can use "task"

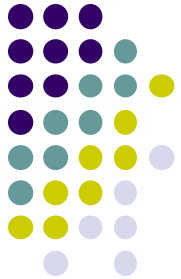
```
#pragma omp parallel
#pragma omp single
  {
     for (p = head; p != NULL;
          p = p->next) {
#pragma omp task
        [Do something with p]
     }
#pragma omp taskwait
  }
```

- A task for one list node = one OpenMP task

Note:
- The number of generated tasks = List length.

→ Task generation costs may be large

Assignments in OpenMP Part (Abstract)



Choose one of [O1]—[O3], and submit a report

Due date: June 4 (Thu)

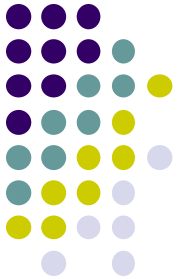
[O1] Parallelize “diffusion” sample program by OpenMP.
(/gs/hs1/tga-ppcomp/20/diffusion/ on TSUBAME)

[O2] Parallelize “sort” sample program by OpenMP.
(/gs/hs1/tga-ppcomp/20/sort/ on TSUBAME)

[O3] (Freestyle) Parallelize *any* program by OpenMP.

For more detail, please see OpenMP (1) slides on May 14

Next Class:



- OpenMP(4)
  - Mutual exclusion
  - Bottlenecks in parallel programs
  - Job submission on TSUBAME