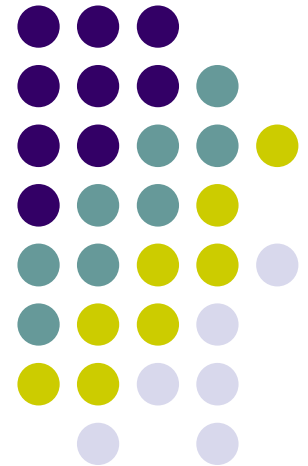
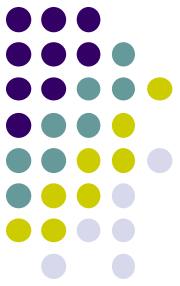


Practical Parallel Computing (実践的並列コンピューティング)

Part1: OpenMP (1)
May 11, 2020

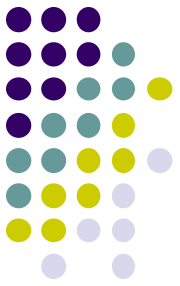
Toshio Endo
School of Computing & GSIC
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Overview of This Course

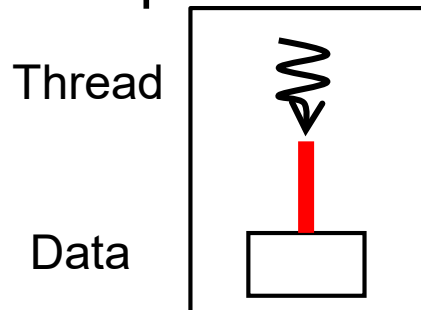
- Part 0: Introduction
 - 2 classes
- Part 1: **OpenMP** for shared memory programming
 - 4 classes ← We are here (1/4)
- Part 2: **GPU** programming
 - OpenACC and CUDA
 - 4 classes
- Part 3: **MPI** for distributed memory programming
 - 3 classes



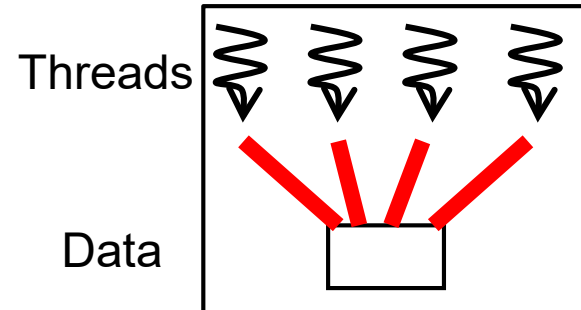
What is OpenMP?

- One of programming APIs based on **shared-memory** parallel model
 - Multiple threads work cooperatively
 - Threads can share data

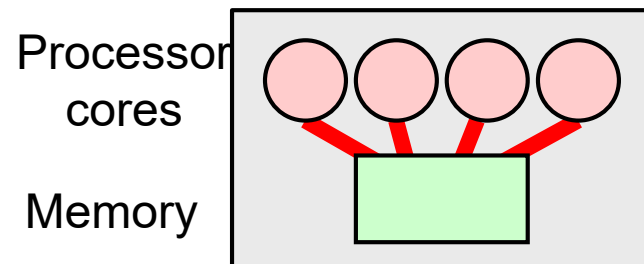
Simple C software



OpenMP software



Hardware





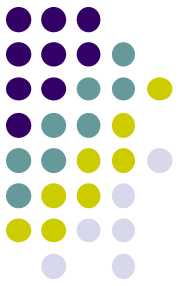
OpenMP Programs Look Like

- OpenMP defines extensions to C/C++/Fortran
- Directive syntaxes & library functions
 - Directives look like: `#pragma omp` ~~

```
int a[100], b[100], c[100];
int i;
#pragma omp parallel for
for (i = 0; i < 100; i++) {
    a[i] = b[i]+c[i];
}
```

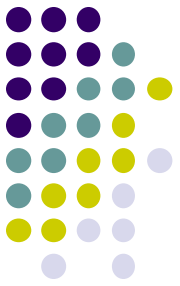
An example of OpenMP
directive

In this case, a directive has
an effect on the following
block/sentence



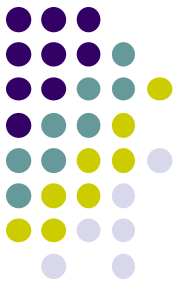
Sample Programs

- [/gs/hs1/tga-ppcomp/20/](#) directory
 - You have to be a member of [tga-ppcomp](#) group
 - There are sub-directories per sample
- Samples related to today's class
 - [hello-omp](#)
 - matrix multiplication
 - [mm](#): sequential version
 - [mm-omp](#): OpenMP version



Using hello-omp Sample

```
[make sure that you are at a interactive node (r7i7nX) ]  
cd ~/t3workspace [Example in web-only route]  
cp -r /gs/hs1/tga-ppcomp/20/hello-omp .  
cd hello-omp  
make  
[this creates an executable file "hello"]  
./hello
```



Compiling OpenMP Programs

All famous compilers support OpenMP (fortunately☺), but require different options (unfortunately☹)

- gcc
 - `-fopenmp` option in compiling and linking
- PGI compiler
 - `module load pgi`, and then use `pgcc`
 - `-mp` option in compiling and linking
- Intel compiler
 - `module load intel`, and then use `icc`
 - `-openmp` option in compiling and linking

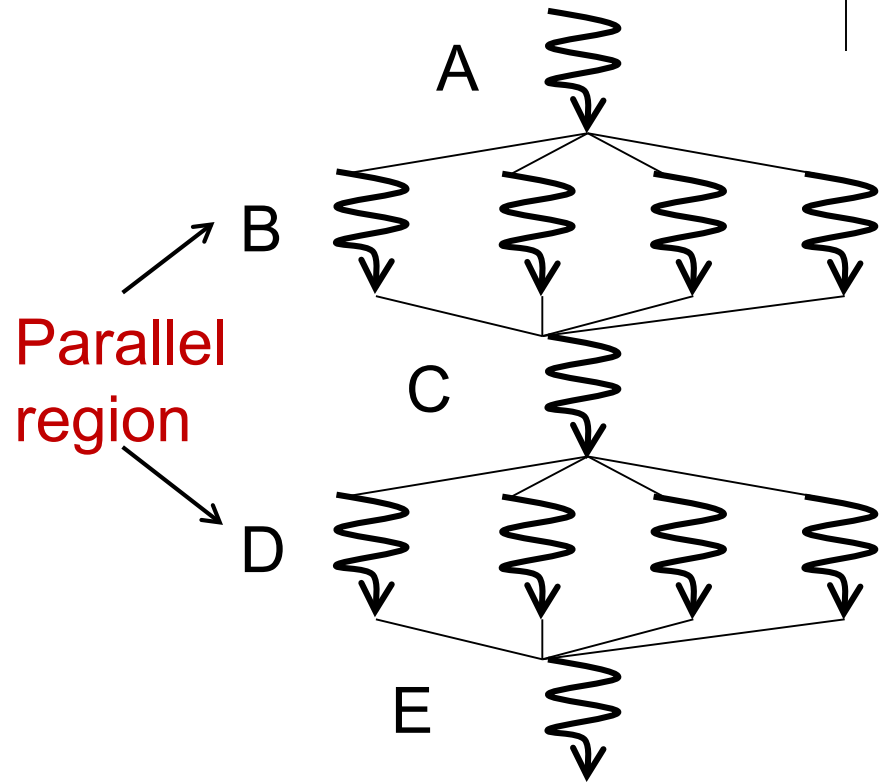
Also see outputs of “make” in OpenMP sample directory

Basic Parallelism in OpenMP: Parallel Region



```
#include <omp.h>

int main()
{
    A;
    #pragma omp parallel
    {
        B;
    }
    C;
    #pragma omp parallel
    {
        D;
        E;
    }
}
```



Sentence/block immediately after **#pragma omp parallel** is called **parallel region**, executed by multiple threads

- Here a “block” is a region surrounded by braces { }
- Functions called from parallel region are also in parallel region



Number of Threads

- Specify number of threads by **OMP_NUM_THREADS** environment variable (this is done out of program)
 - cf) export OMP_NUM_THREADS=4
in command line
 - In default, number of cores (including HyperThreads) are used. On an interactive node, $7 \times 2 = 14$
- Obtain number of threads
 - cf) `n = omp_get_num_threads();`
- Obtain “my ID” of calling thread
 - cf) `id = omp_get_thread_num();`
 - $0 \leq id < n$ (total number)



Outputs of hello-omp

Before the parallel region

```
Hello OpenMP World
I'm 8-th thread out of 14 threads
I'm 6-th thread out of 14 threads
I'm 9-th thread out of 14 threads
I'm 1-th thread out of 14 threads
I'm 0-th thread out of 14 threads
I'm 7-th thread out of 14 threads
:
Good Bye OpenMP World
```

Inside the parallel region,
each thread prints a message
for several (5) times

omp_get_num_threads()

omp_get_thread_num()

After the parallel region

Executing a Sample with Various Number of Threads



[make sure that there is an executable file “hello”]

```
export OMP_NUM_THREADS=1  
./hello
```

```
export OMP_NUM_THREADS=4  
./hello
```

```
export OMP_NUM_THREADS=7  
./hello
```

```
export OMP_NUM_THREADS=14  
./hello
```

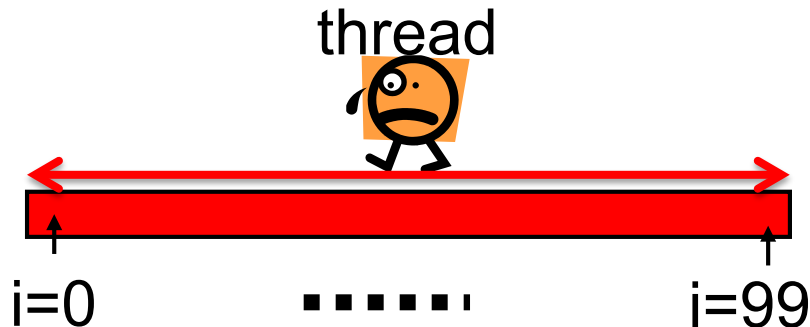
How Can We Make a Program Faster?



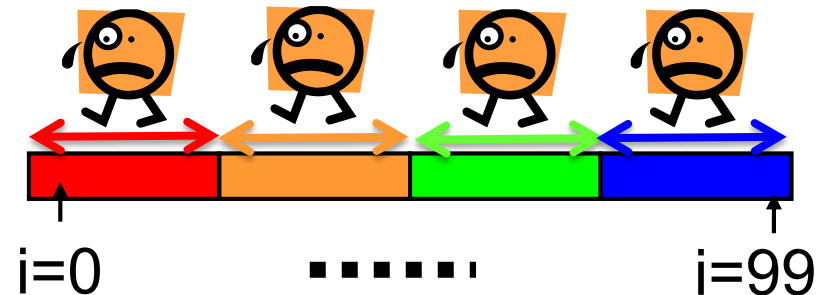
```
for (i = 0; i < 100; i++) { some computation; }
```

assumption: 100 tasks are independent with each other

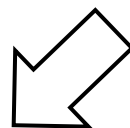
Only with one thread



With 4 threads



thread 0: for ($i = 0$; $i < 25$; ...
thread 1: for ($i = 25$; $i < 50$; ...
thread 2: for ($i = 50$; $i < 75$; ...
thread 3: for ($i = 75$; $i < 100$; ...



OpenMP has a syntax to do this smarter

#pragma omp for for Easy Parallel Programming



“for” loop with simple forms can parallelized easily

```
{  
#pragma omp parallel  
{  
    int i;  
#pragma omp for  
    for (i = 0; i < 100; i++) {  
        a[i] = b[i]+c[i];  
    }  
}  
}
```

#pragma omp for must be

- inside a parallel region
- right before a “for” loop

→ Computations in the loop are distributed among threads (work distribution)

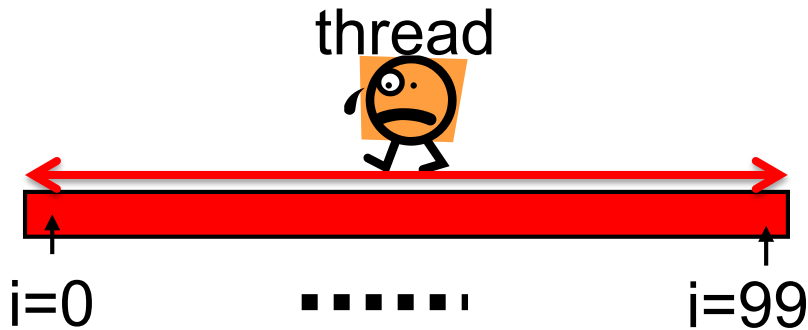
- With 4 threads, each thread take $100/4=25$ iterations → speed up!!
 - Indivisible cases are ok, such as 7 threads

- Abbreviation: omp parallel + omp for = omp parallel for

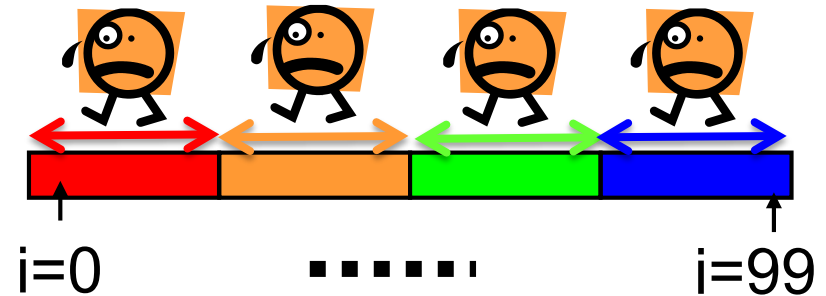
Why “omp for” Reduces Execution Time



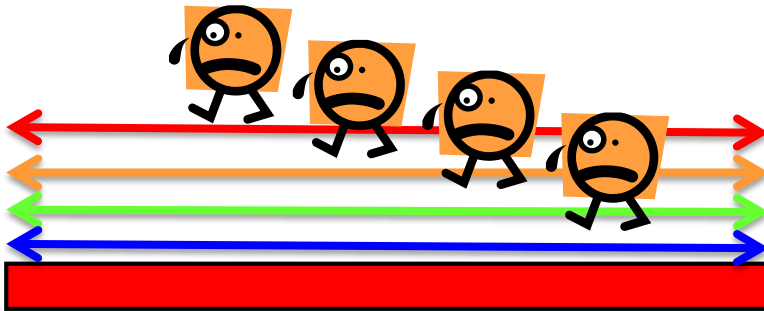
Only with one thread



With several threads



- What if we use “omp parallel”, but **forget** to write “omp for”?

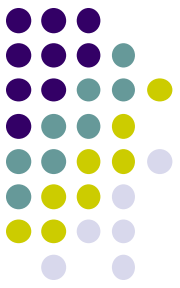


Every thread would work for all iterations

→ No speed up ☹️

→ Answer will be wrong ☹️

“mm” sample: Matrix Multiply



Available at </gs/hs1/tga-ppcomp/20/mm/>

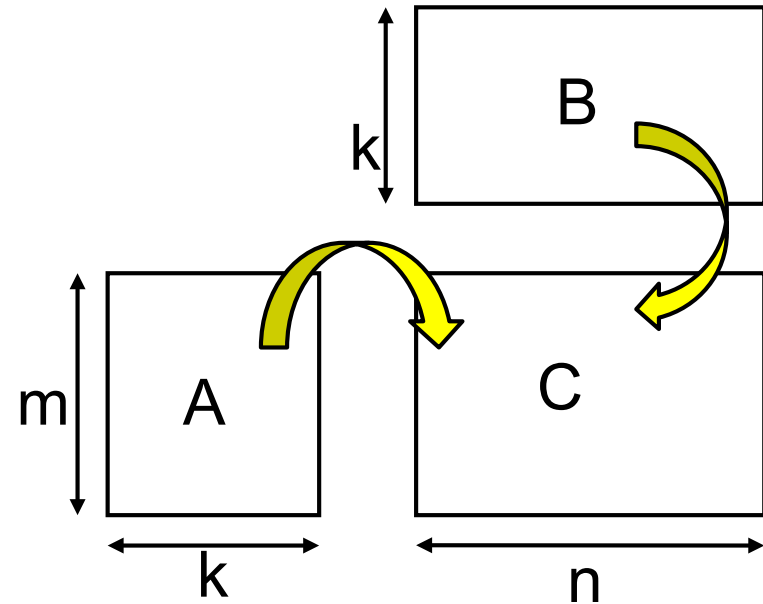
A: a $(m \times k)$ matrix

B: a $(k \times n)$ matrix

C: a $(m \times n)$ matrix

$C \leftarrow A \ B$

- This sample supports variable matrix sizes
- Execution: `./mm [m] [n] [k]`



```
for (j = 0; j < n; j++) {  
    for (l = 0; l < k; l++) {  
        for (i = 0; i < m; i++) {  
            C[i+j*ldc] += A[i+l*lda] * B[l+j*ldb];  
        } } }  
}
```

OpenMP Version of mm (mm-omp)



- There are 3 loops. Here, j loop is parallelized

```
#pragma omp parallel private(i,l)
#pragma omp for                ← j loop is parallelized
for (j = 0; j < n; j++) {
    for (l = 0; l < k; l++) {
        for (i = 0; i < m; i++) {
            C[i+j*ldc] += A[i+l*lda] * B[l+j*ldb];
        } } }
```

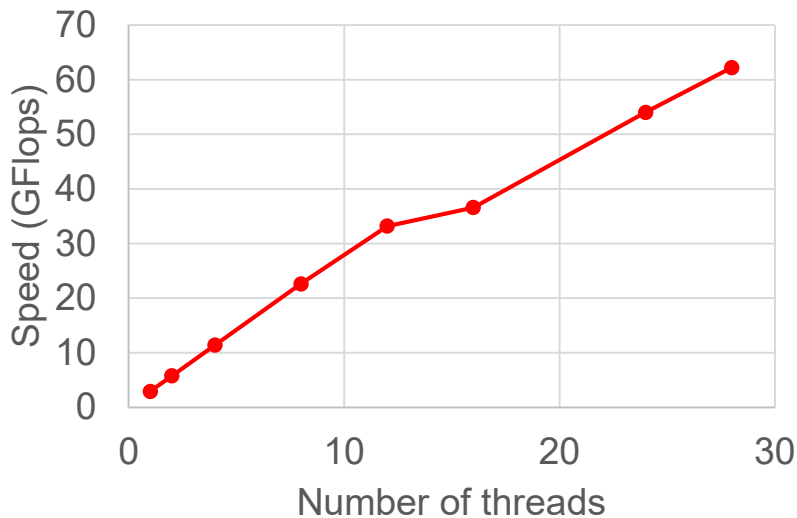
- What is “private” option? → explained later

Performance of mm sample

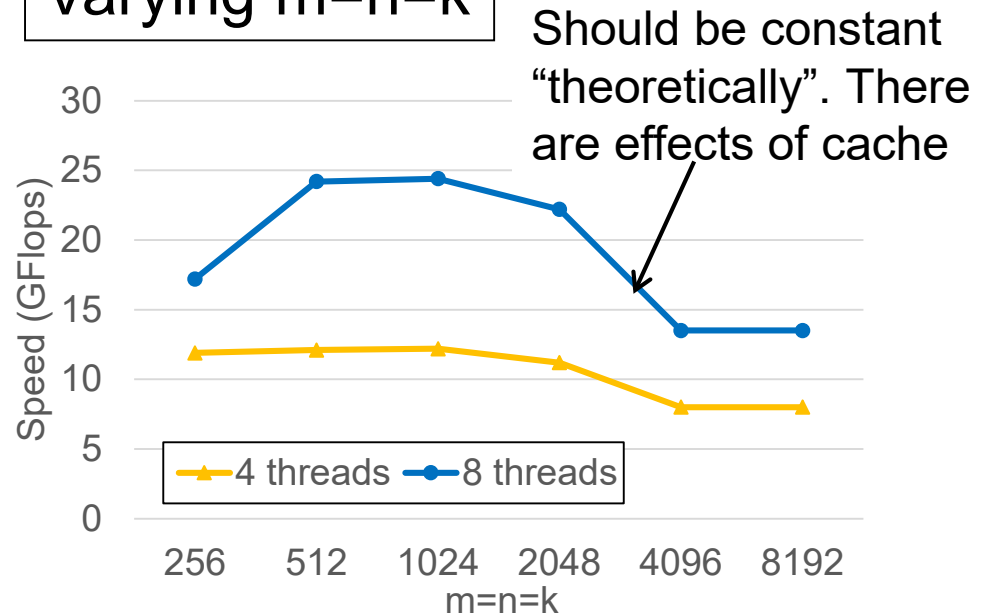


- A TSUBAME3 node (Xeon E5-2680 v4 x2 = 28core)
- Speed is (2mnk/t)

m=n=k=2048,
Varying # of threads



8 threads,
Varying m=n=k



Shared Variables & Private Variables (1)



While OpenMP uses “shared memory model”, **not all are shared**

In default, variables are classified as follows

- Variables declared **out of** parallel region \Rightarrow **Shared variables**
- Global variables \Rightarrow **Shared variables**
- Variables declared **inside** parallel region \Rightarrow **Private variables**

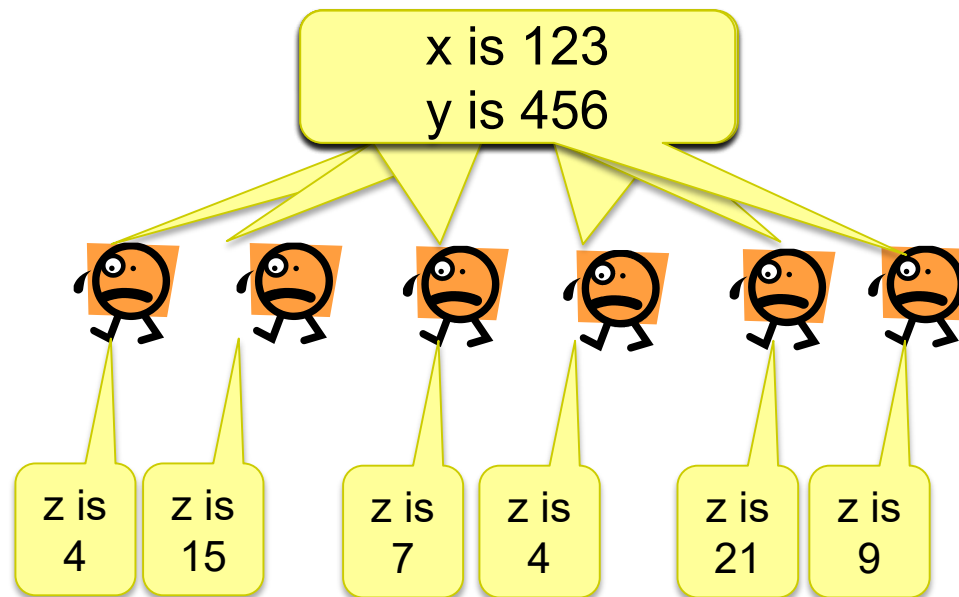
```
{  
    int s = 1000; shared  
    #pragma omp parallel  
    {  
        int i; private  
        i = func(s, omp_get_thread_num());  
        printf( "%d\n" , i);  
    }  
}
```

```
int func(int a, int b)  
{  
    int rc = a+b; private  
    return rc;  
}
```

Shared Variables & Private Variables (2)



We let x , y be shared, and z be private



*Single instance
for each x , y*

*Each thread has
its own instance for z*

- When a thread updates a shared variable, other threads are affected
 - We should be careful and careful!



Pitfall in Nested Loops (1)

- The following sample looks ok, but there is a bug
 - We do not see compile errors, but answers would be wrong ☹️

```
int i, j;  
#pragma omp parallel  
#pragma omp for  
for (i = 0; i < m; i++) {  
    for (j = 0; j < n; j++) {  
        ...  
    }  
}
```

Both i, j are declared
outside parallel region
→ Considered “shared”
It is a problem to share **j**

cf)

Thread A is executing i=5 loop
Thread B is executing i=8 loop

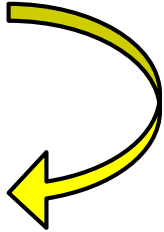
} The executions should be independent
Each execution must include
j=0, j=1...j=n-1 correctly
j must be private



Pitfall in Nested Loops (2)

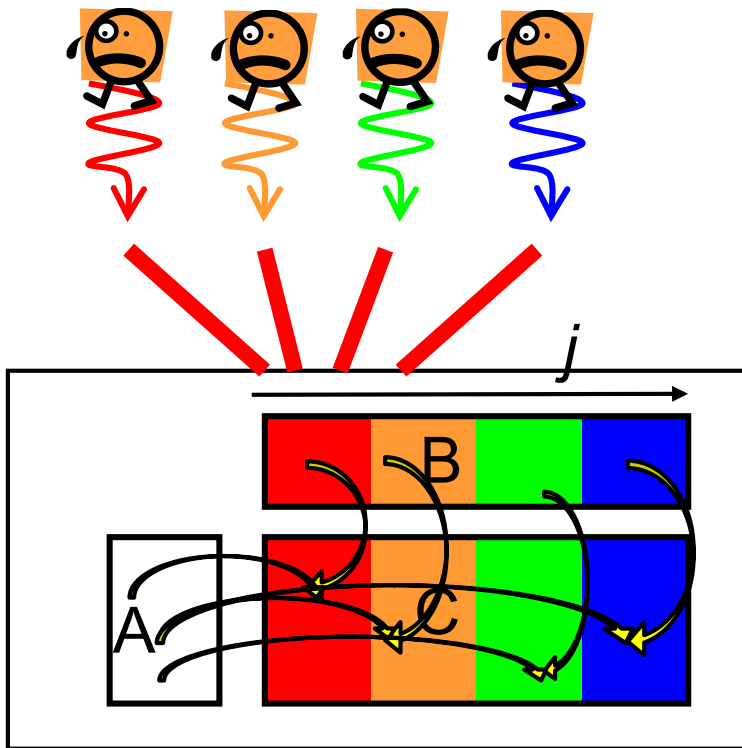
Two modifications (Either is ok)

```
int i;  
#pragma omp parallel for  
for (i = 0; i < m; i++) {  
    int j;    // j is private  
    for (j = 0; j < n; j++) {  
        ...  
    } }  
}
```



```
int i, j;  
#pragma omp parallel for private(j)  
// j is forcibly private  
for (i = 0; i < m; i++) {  
    for (j = 0; j < n; j++) {  
        ...  
    } }  
}
```

How about Arrays



- In mm sample, pointers A, B, C are global variables → shared variables
- Since all threads see same variables of A, B, C, contents of arrays are also shared
- It is programmers responsibility to make each thread does independent computation

OpenMP Version of mm (Again)



- One of loops is parallelized

```
#pragma omp parallel private(i,l)
```

```
#pragma omp for
```

```
for (j = 0; j < n; j++) {  
    for (l = 0; l < k; l++) {  
        for (i = 0; i < m; i++) {  
            C[i+j*ldc] += A[i+l*lda] * B[l+j*ldb];  
        } } }  
}
```

j loop is parallelized

→ Each thread executes computations
only for subset of [0, n)

[Q] What if we parallelize other loops?

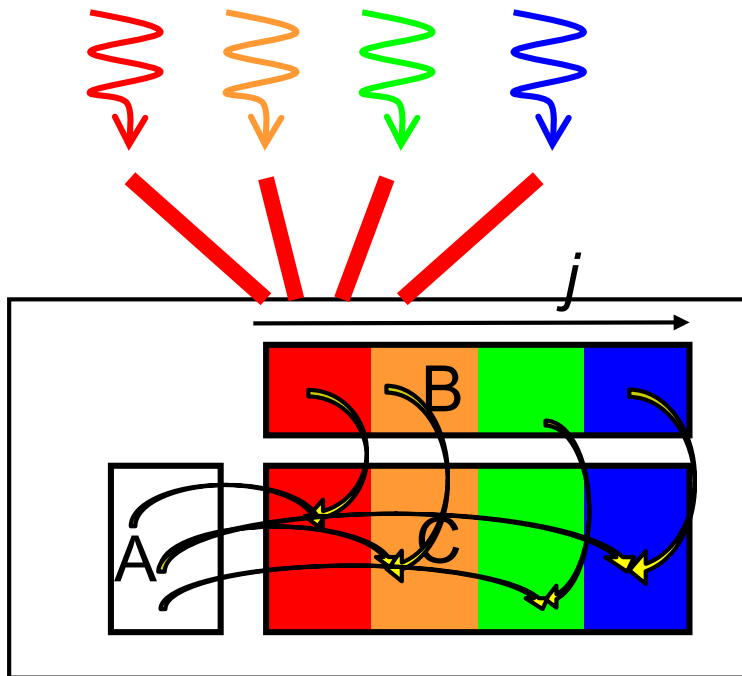
→ *i* loop is ok for correct answers, but may be slow

→ *l* loop causes wrong answers!

Correct Parallelization and Bad Parallelization



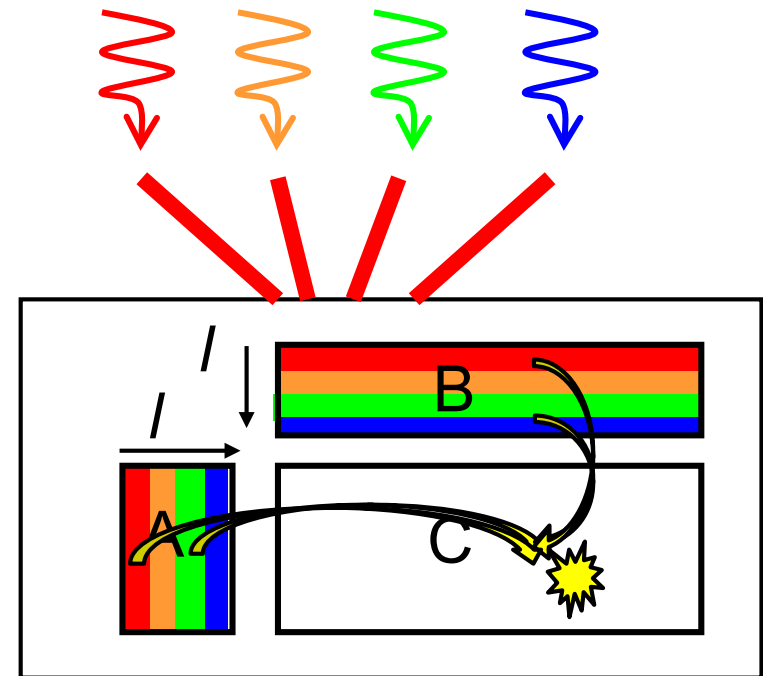
Parallelizing j loop



Simultaneous read from same data
(in this case, A) is OK

Similarly, parallelizing
 i loop is ok

Parallelizing i loop (??)



Possible simultaneous write to
same data

→ “Race condition” problem
may occur.

Answers may be wrong !!



Today's Summary

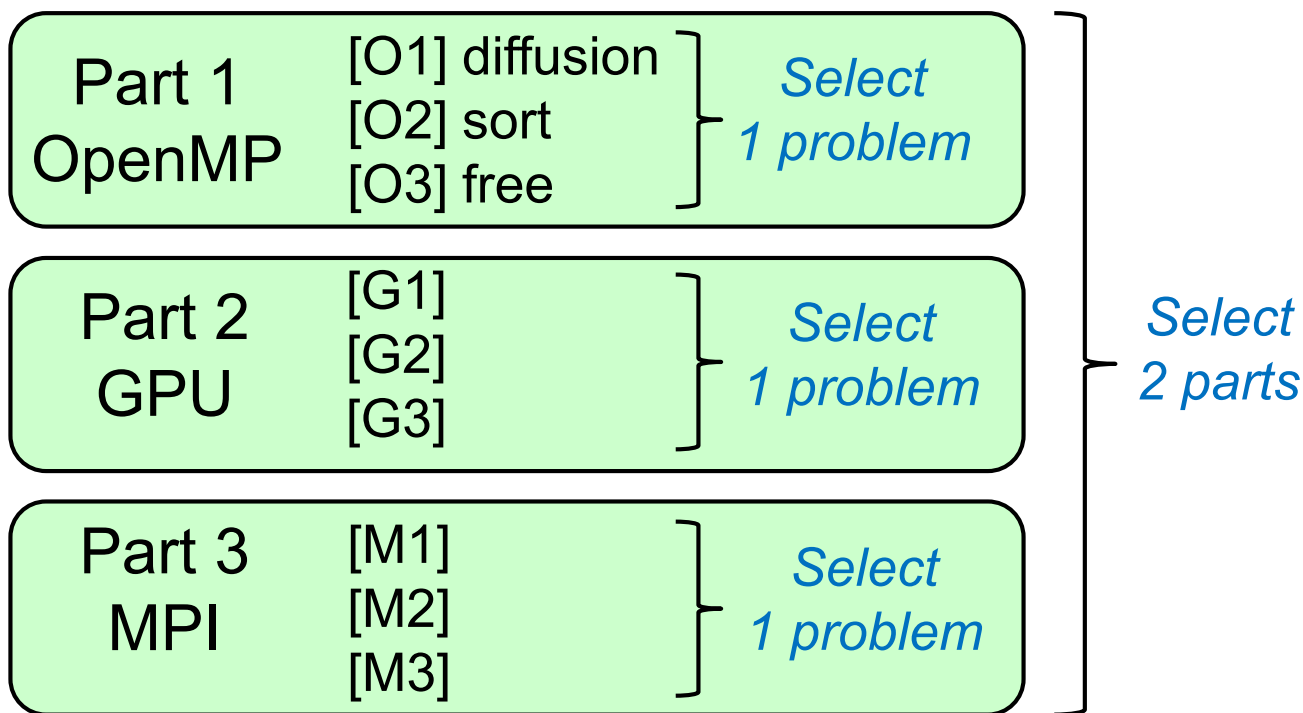
Introduction to OpenMP parallel programming

- Multiple threads work simultaneously with `#pragma omp parallel`
- With `#pragma omp for`, loop-based programs can be parallelized easily
- But it is programmer's responsibility to avoid bugs caused by race conditions

Assignments in this Course



- There is homework for each part. Submissions of reports for **2 parts** are required
- Also attendances will be considered





Assignments in OpenMP Part (1)

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)

Optional:

- To make array sizes variable parameters, which are specified by execution options. “malloc” will be needed.
- To parallelize it without “omp for”
 - `omp_get_thread_num()`, `omp_get_num_threads()` are needed

Assignments in OpenMP Part (2)



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

Optional:

- Comparison with other algorithms than quick sort
 - Heap sort? Merge sort?

Assignments in OpenMP Part (3)



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

- cf) A problem related to your research
- More challenging one for parallelization is better
 - cf) Partial computations have dependency with each other
 - cf) Uniform task division is not good for load balancing

Notes in Report Submission (1)



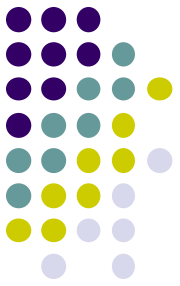
- Submit the followings via **OCW-i**
 - (1) **A report document**
 - PDF, MS-Word or text file
 - 2 pages or more
 - in English or Japanese (日本語もok)
 - (2) **Source code files** of your program
 - Try “zip” to submit multiple files

Notes in Report Submission (2)



The report document should include:

- Which problem you have chosen
- How you parallelized
 - It is even better if you mention efforts for high performance or new functions
- Performance evaluation on TSUBAME
 - With varying number of threads
 - On a interactive nodes, $1 \leq \text{OMP_NUM_THREADS} \leq 14$
 - To use more CPU cores, you need to do “job submission”
 - With varying problem sizes
 - Discussion with your findings
 - Other machines than TSUBAME are ok, if available



If You Have Not Done This Yet

Please do the followings as soon as possible

- Please make your account on TSUBAME
- Please send an e-mail to ppcomp@el.gsic.titech.ac.jp

Subject: [TSUBAME3 ppcomp account](#)

To: ppcomp@el.gsic.titech.ac.jp

Department name:

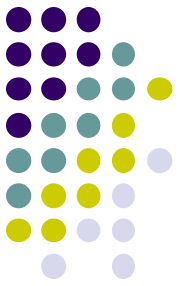
School year:

Name:

Your TSUBAME account name:

Then we will invite you to the TSUBAME group, [please click URL and accept the invitation](#)

その後、TSUBAMEグループへの招待を送ります。[メール中のURLをクリックして参加承諾してください](#)



Next Class:

- Part1: OpenMP (2)
 - diffusion: simple simulation of diffusion phenomena
 - Related to assignment [O1]