2018 Practical Parallel Computing (実践的並列コンピューティング) No. 6

Shared Memory Parallel Programming with OpenMP (4)

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Considerations in Parallel Programming

Step1: How we can make "correct" parallel software

- Is dependency preserved?
- No race condition?

Step2: How we can make "fast" parallel software

- Is bottleneck small?
- Are tasks well balanced between threads?

Towards “Correct” Parallel Software

- We have learned several OpenMP syntaxes to make computations parallel
  - #pragma omp parallel
  - #pragma omp for
  - #pragma omp task

- But it is programmer’s responsibility to check whether the parallelization is correct or not

Dependency between Computations

- If partial computations C1 and C2 are independent, we can parallelize them
- If they are dependent, we cannot

C1: Read a, b and Write c
C2: Read d, e and Write f
C3: Read c and Write g
C4: Read e and Write h
C5: Read i and Write h

Which computations are independent?

C1&C2 → independent

C1&C3 → dependent

- c is written by C1, read by C3(!)

C2&C4 → independent

- e is read by C2&C4
- Read vs. Read is Ok

C4&C5 → dependent

- h is written by C4&C5
- Write vs. Write is NG

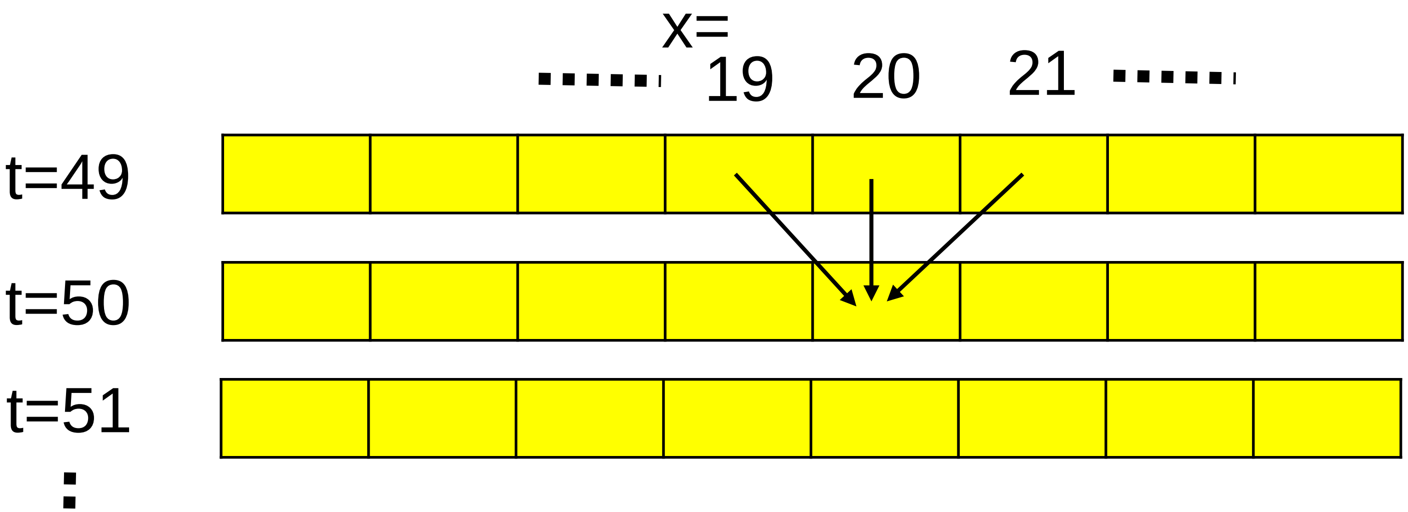
Dependency and Parallelism in Stencil Computations (1)

Consider a stencil computation:

$$f_{t+1,x} = (f_{t,x-1} + f_{t,x} + f_{t,x+1}) / 3.0$$

※ This is simpler than diffusion sample

- We focus on update of a single point
    - It includes 3 Read and 1 Write

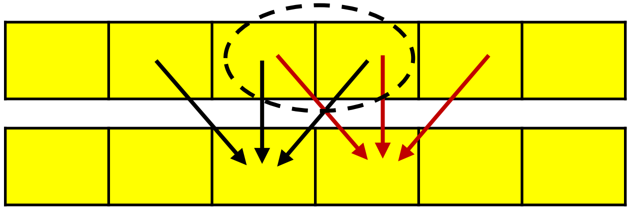


Dependency and Parallelism in Stencil Computations (2)

- Can we compute $f_{50,20}$ and $f_{50,21}$ in parallel? *(t is same, x is different)*
  - $f_{50,20}$: Read $f_{49,19}$, $f_{49,20}$, $f_{49,21}$ and Write $f_{50,20}$
  - $f_{50,21}$: Read $f_{49,20}$, $f_{49,21}$, $f_{49,22}$ and Write $f_{50,21}$

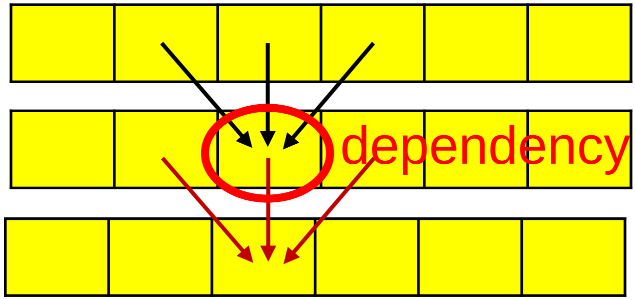
  → They are independent ☺ (for all pairs of x)

Read vs. Read is Ok



- Can we compute $f_{50,20}$ and $f_{51,20}$ in parallel? *(t is different)*
  - $f_{50,20}$: Read $f_{49,19}$, $f_{49,20}$, $f_{49,21}$ and Write $f_{50,20}$
  - $f_{51,20}$: Read $f_{50,19}$, $f_{50,20}$, $f_{50,21}$ and Write $f_{50,21}$

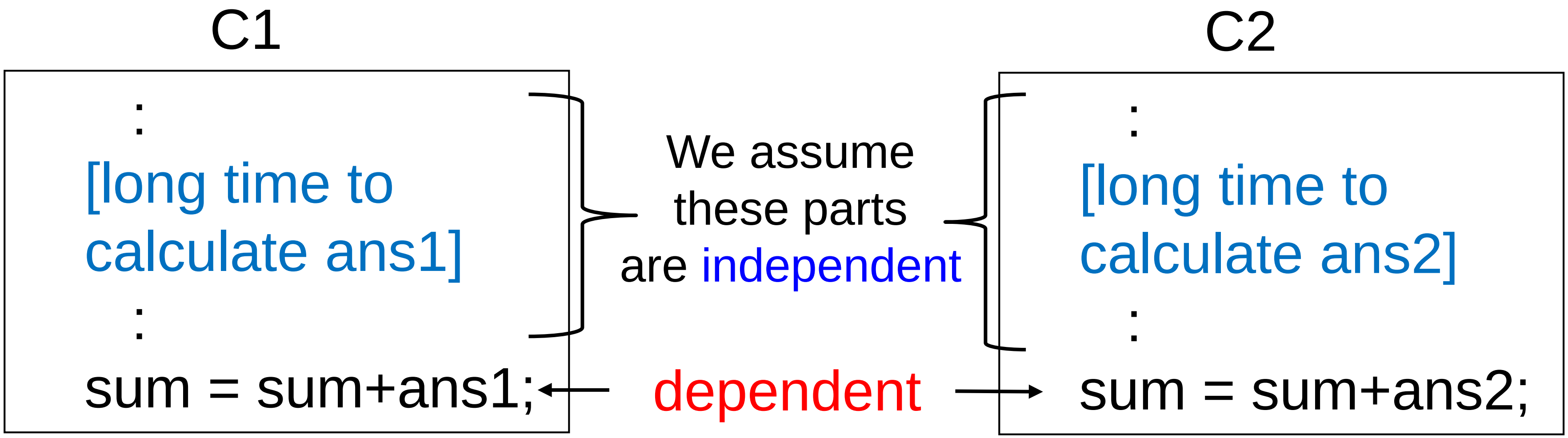
  → They are dependent ☹



In Assignment [O1]
- it is OK to parallelize x-loop or y-loop
- it is NG to parallelize t-loop

Partially Dependent Case

- Can we execute C1 and C2 in parallel?
  - Here, *sum* is a shared variable



C1

```
   :
[long time to
calculate ans1]
   :
sum = sum+ans1;
```

We assume these parts are independent

C2

```
   :
[long time to
calculate ans2]
   :
sum = sum+ans2;
```

dependent

- C1 and C2 are dependent, since both write *sum*

→ The answer is no. But do we have to abandon parallel execution?

What’s Wrong if Parallelized? (1)

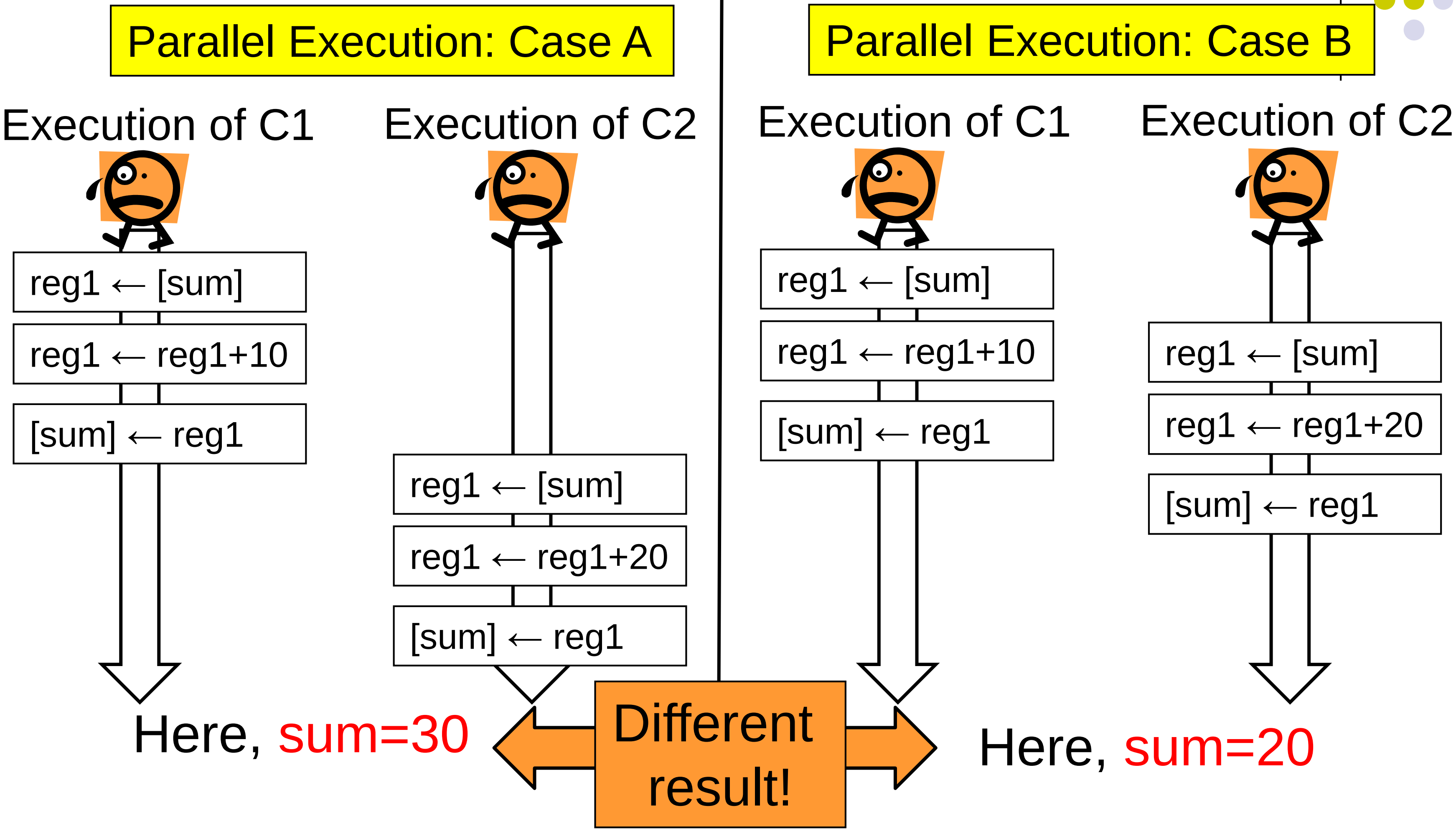
- What happens if C1, C2 are executed in sequential

```
sum = 0;
C1 (ans1=10)
C2 (ans2=20)
```

After execution, sum = 30

- To discuss parallel execution, let’s consider
  - In parallel, execution timing is non-deterministic
  - “sum = sum + 10” is compiled into machine codes like
    - reg1 ← [sum]
    - reg1 ← reg1+10
    - [sum] ← reg1

What’s Wrong if Parallelized? (2)



Parallel Execution: Case A

Execution of C1

reg1 ← [sum]

reg1 ← reg1+10

[sum] ← reg1

Execution of C2

reg1 ← [sum]

reg1 ← reg1+20

[sum] ← reg1

Here, sum=30

Different result!

Parallel Execution: Case B

Execution of C1

reg1 ← [sum]

reg1 ← reg1+10

[sum] ← reg1

Execution of C2

reg1 ← [sum]

reg1 ← reg1+20

[sum] ← reg1

Here, sum=20

Such a bad situation is called “Race Condition”

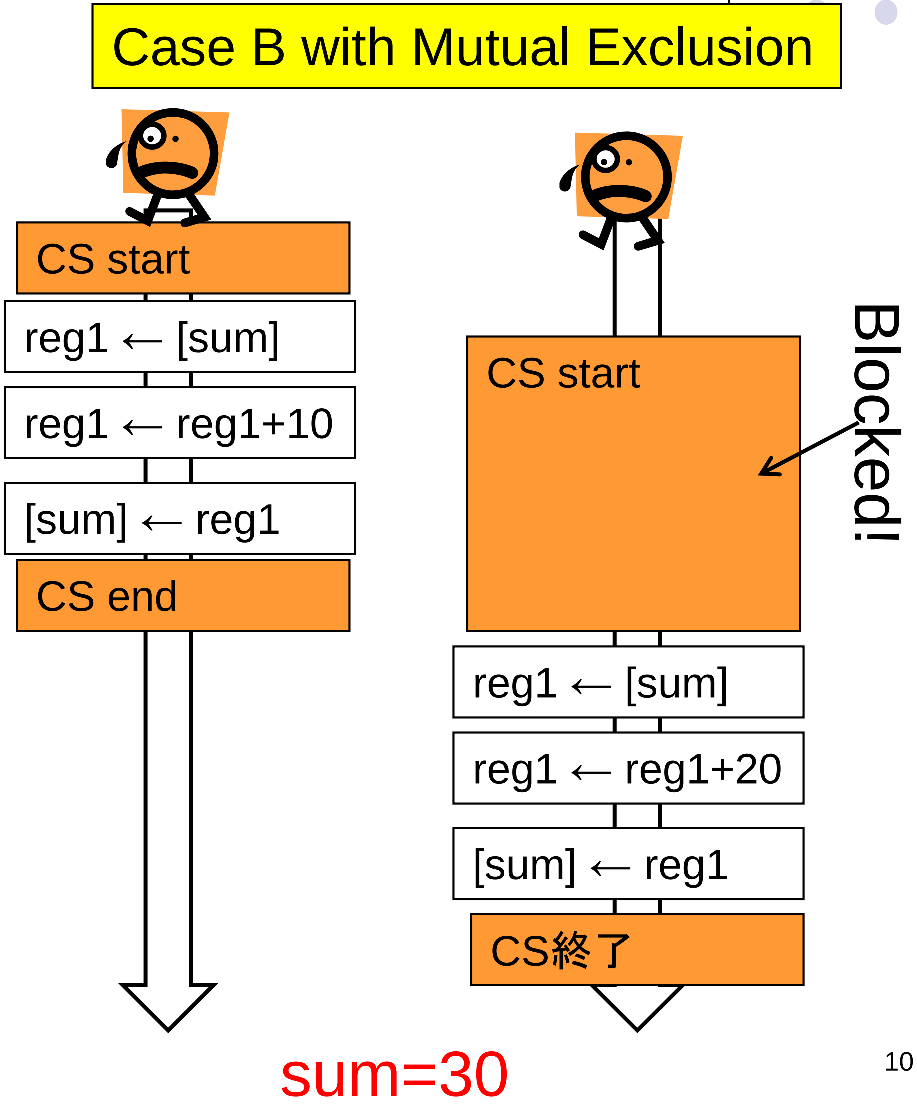
Mutual Exclusion to Avoid Race Condition

Mutual exclusion (mutex):

Control threads so that only a single thread can enter a “specific region”

- The region is called critical section

⇒ With mutual exclusion, race condition is avoided



Case B with Mutual Exclusion

CS start

reg1 ← [sum]

reg1 ← reg1+10

[sum] ← reg1

CS end

CS start

Blocked!

reg1 ← [sum]

reg1 ← reg1+20

[sum] ← reg1

CS終了

sum=30

Mutual Exclusion in OpenMP

#pragma omp critical makes the following block/sentence be critical section

```
   int sum = 0;
#pragma omp parallel
   {
      [ do something ]
#pragma omp critical
      {
         sum = sum + myans;
      }
   }
```

Examples available at ~endo-t-ac/ppcomp/18/count-omp/

cf) ./count-XXX [n]
→ Each thread adds 1 to a shared counter for *n* times
→ Correct answer would be *n* × OMP_NUM_THREADS

- count-bad: Wrong version
- count-good: Correct, but slow version with mutex
- count-fast: Correct and fast version

Towards “Fast” Parallel Software

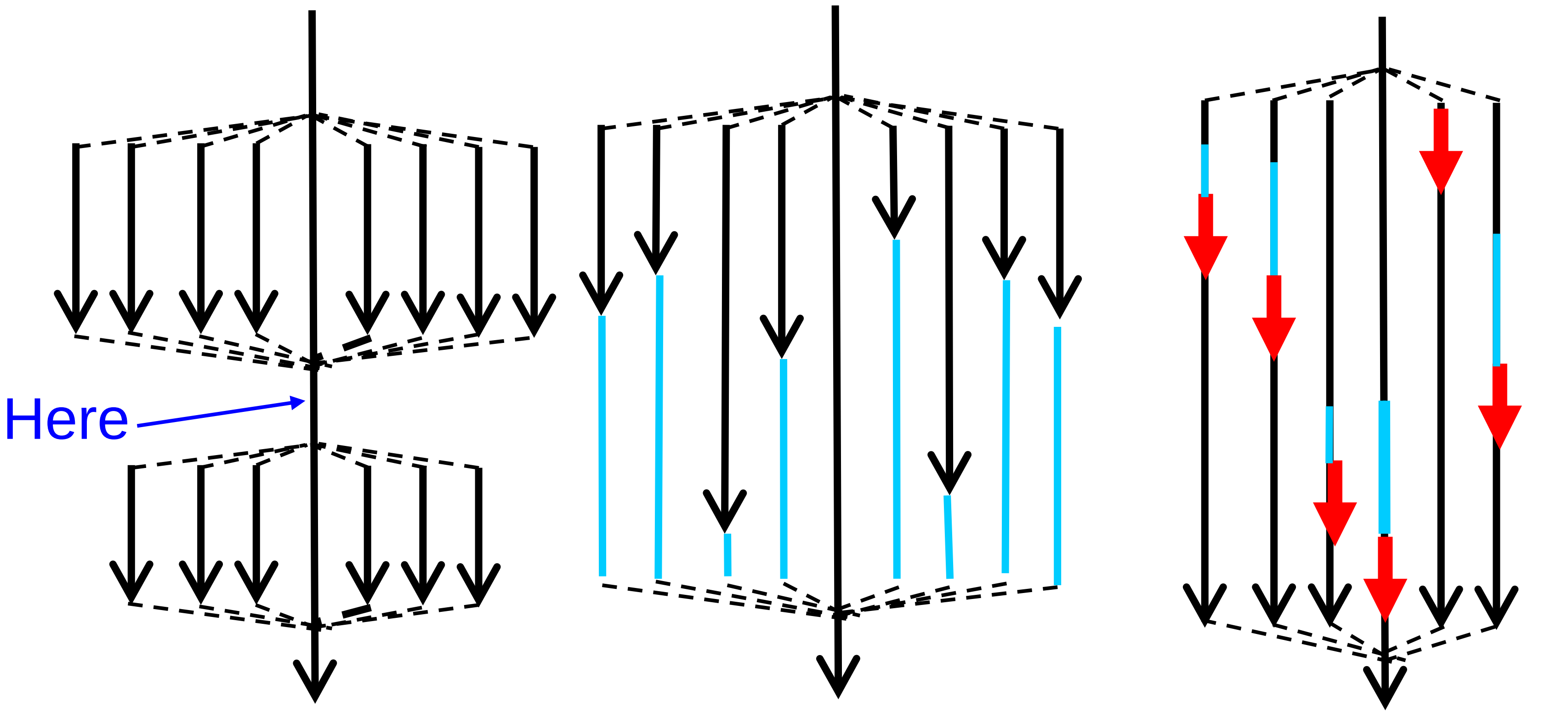
- Most algorithms include both
  - Computations that can be parallelized
  - Computations that cannot (or hardly) be parallelized

⇒ The later raises problems called “bottleneck”

Bottleneck

Bottle

Various Bottlenecks



Bottleneck by sequential part

Bottleneck by load imbalance

Bottleneck by critical sections

There are more, such as architectural bottlenecks

Amdahl's Law

- In an algorithm, we let
  - T_1 : execution time with 1 processor core
  - α be ratio of computation that can be parallelized
  - $1-\alpha$ be ratio that cannot be parallelized (bottleneck)

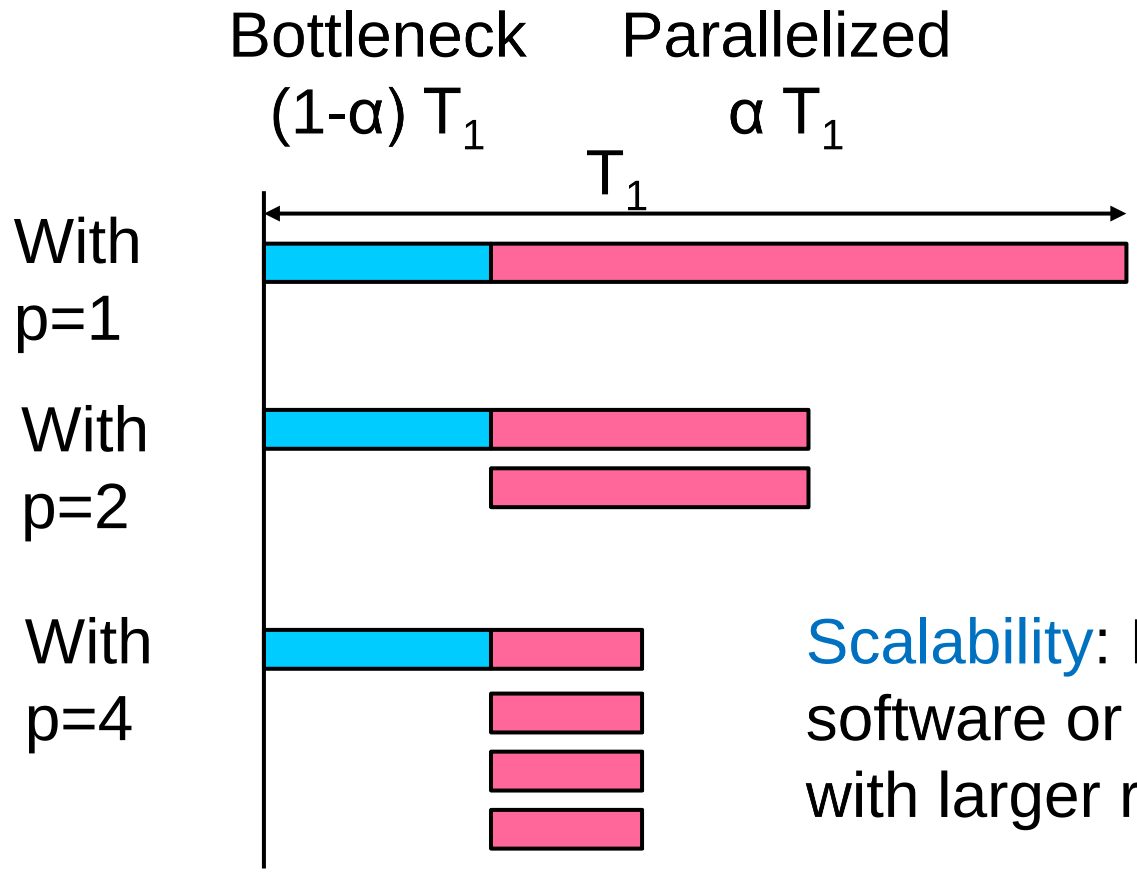
⇒ Estimated execution time with p processor cores is $T_p = ((1 – \alpha) + \alpha / p)\ T_1$

  - *smaller is better*

Due to bottleneck, there is limitation in speed-up no matter how many cores are used

$T_\infty = (1-\alpha)\ T_1$

An Illustration of Amdahl’s Law



Bottleneck $(1-\alpha)\ T_1$

Parallelized $\alpha\ T_1$

T_1

With p=1

With p=2

With p=4

Scalability: Performance of software or algorithm is improved with larger resources (p)

Amdahl’s law tells us

- if we want scalability with p～10, α should be >0.9
- if we want scalability with p～100, α should be >0.99

The Fact is Stranger Than Theory

- According to Amdahl’s law, T_p is monotonically decreasing

→ Larger p is not harmful?

count-good sample in ~endo-t-ac/ppcomp/18/count-omp/ (TSUBAME3 node)

- p=1: 1 thread ×10M times → 0.18sec
- p=2: 2 threads × 5M times → 0.55～0.71sec
- p=5: 5 threads × 2M times → 1.0～1.4sec
- p=10: 10 threads × 1M times → 1.3～1.5sec

Slower

Reducing bottleneck is even more important (than Amdahl’s law tells)

Reducing Bottlenecks

- Approaches for reducing bottlenecks depend on algorithms!
  - We need to consider, consider
  - Some algorithms are essentially difficult to be parallelized

- Some directions
  - Reducing access to shared variables
  - Reducing length of dependency chains
    - called “critical path”
  - Reducing parallelization costs
    - entering/exiting “omp parallel”, “omp critical”… is not free

:

Case of “count-omp” Sample

- “count-good” version has too frequent access to a shared variables

→ count-fast version introduces private variables

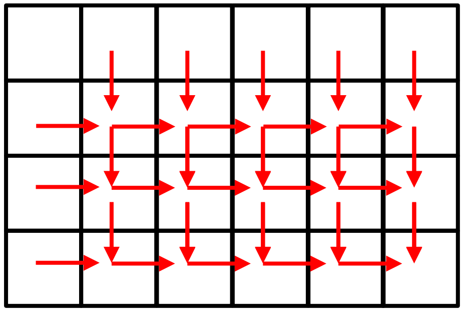
Step 1: Each thread accumulates values into private “local_s”

Step 2: Then each thread does “s += local_s” in a critical section once per thread

- With this version, 10threads × 1M times add → 4msec

※ “omp for reduction(…)” is internally compiled to use a similar method

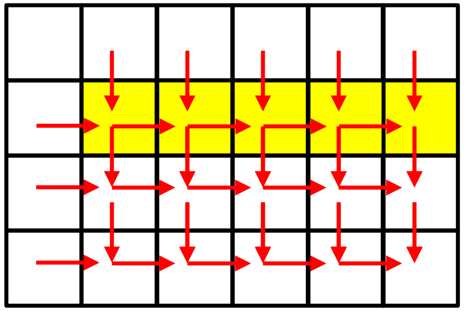
Case of a Simple Dynamic Programming



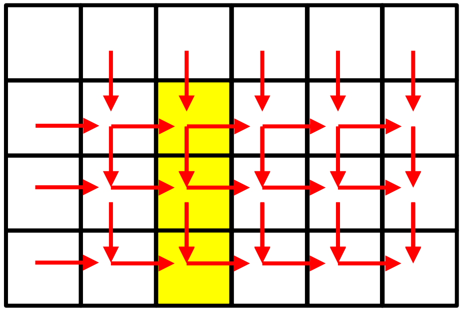
cf) “Edit distance” of two strings

```
for (y = 1; y < ny; y++) {
  for (x = 1; x < nx; x++) {
    $A_{x,y} = f(A_{x-1,y}, A_{x,y-1})$;
  }
}
```

Parallel X loop?
→ NG



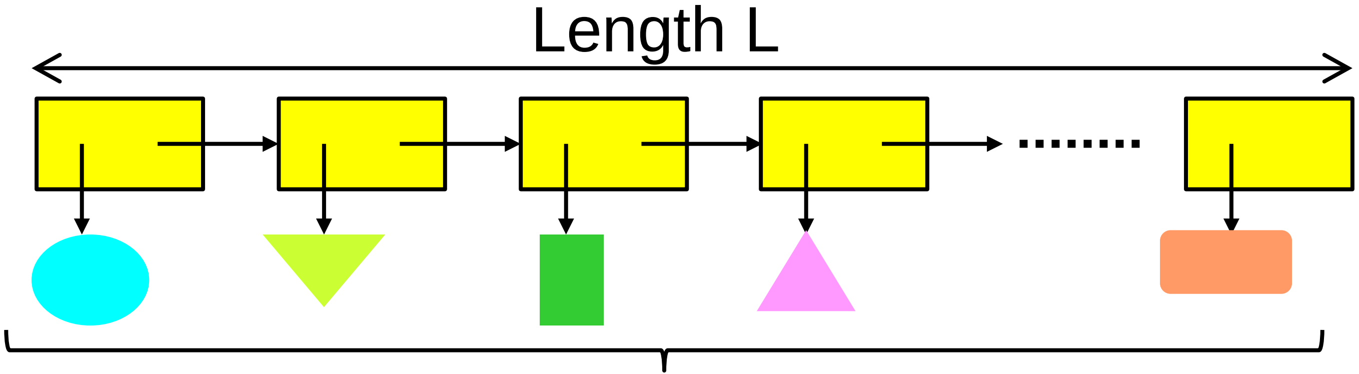
Parallel Y loop?
→ NG



Elements of the same color can be computed in parallel

	1	2	3	4	5
	2	3	4	5	6
	3	4	5	6	7

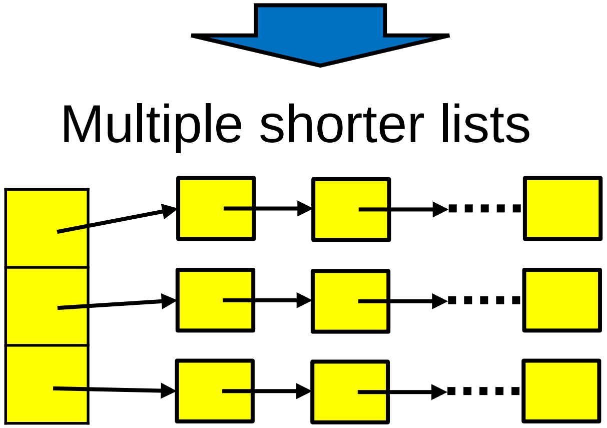
Case of List Tracing



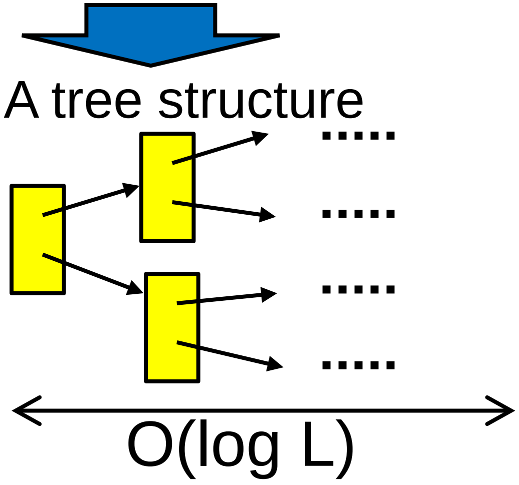
Length L

Something to do for each element

- “Critical path” has L length
  - If L is large and each task is small, tracing the list itself will become a bottleneck (ex. calling “omp task” for L times)



Multiple shorter lists



A tree structure

O(log L)

What We Have Learned in OpenMP Part

- OpenMP: A programming tool for parallel computation by using multiple processor cores
  - Shared memory parallel model
  - #pragma omp parallel → Parallel region
  - #pragma omp for → Parallelize for-loops
  - #pragma omp task → Task parallelism

- Processor cores we can use are limited a single node
- In MPI part, we will go over the wall of a node

Assignments in OpenMP Part (Abstract)

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

Due date: May 7 (Monday)

[O1] Parallelize “diffusion” sample program by OpenMP.

(~endo-t-ac/ppcomp/18/diffusion/ on TSUBAME)

[O2] Parallelize “sort” sample program by OpenMP.

(~endo-t-ac/ppcomp/18/sort/ on TSUBAME)

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

For more detail, please see No.3 slides or OCW-i.

Next Class:

- Part 2: Distributed Memory Parallel Programming with MPI (1)