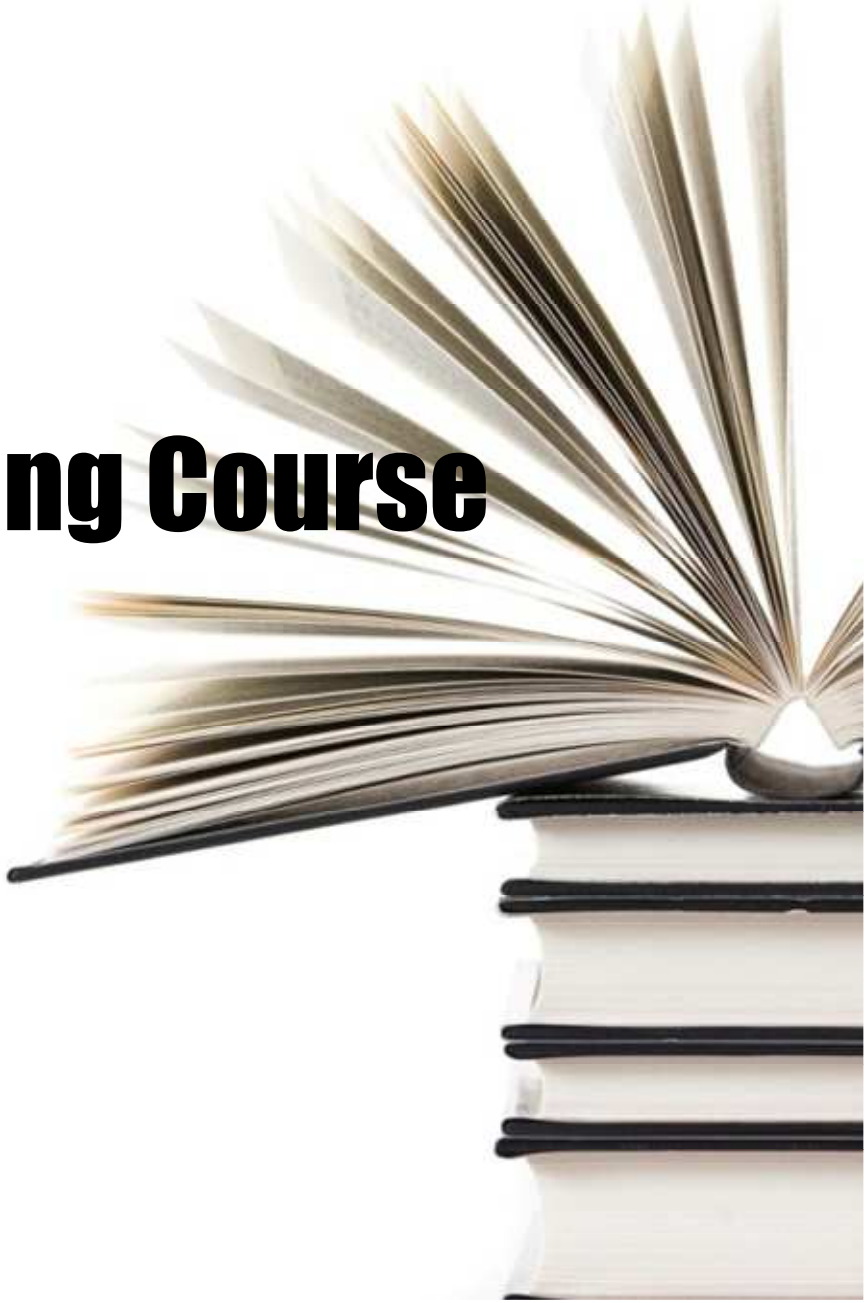
KiSTi SUPERCOMPUTING EDUCATION CENTER
www.kisti.re.kr

OpenMP Training Course



http://www.ksc.re.kr
http://edu.ksc.re.kr

Resources

- http://edu.ksc.re.kr
- http://www.openmp.org
- http://www.compunity.org
- https://computing.llnl.gov/tutorials/openMP/
- http://www.citutor.org
- http://docs.oracle.com/cd/E19422-01/819-3694/

Agenda (Basic Course)

OpenMP [1/2]

- 11:00 – 12:00 An Introduction to OpenMP Parallel Programming
- 12:00 – 13:30 Lunch
- 13:30 – 14:50 Creating Threads
- 15:10 – 16:30 Data Scope Attributes

OpenMP [2/2]

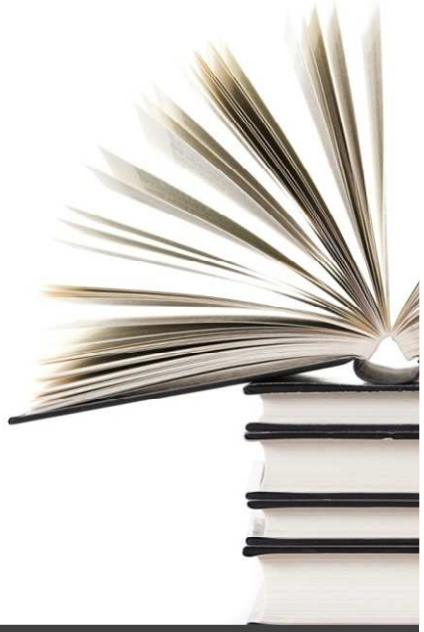
- 11:00 – 12:00 Parallel Loops
- 12:00 – 13:30 Lunch
- 13:30 – 14:50 Syncronization
- 15:10 – 16:30 Reduction

Agenda (Basic Course)

- Motivation
  - Why OpenMP?
  - Evolution of Processor
- Introduction to Education System
  - Check Environment
- OpenMP Basics I
  - Introduction to OpenMP
  - Creating Threads [2.4, 3.2]
  - Data Scope Attributes [2.4]
- OpenMP Basics II
  - Parallel Loops [2.5.1, 2.6.1]
  - Synchronization [2.8.2, 2.8.5, 2.8.3]
- OpenMP Basics III & Hands-on
  - Reduction [2.4, 2.5, 2.6.1]
  - Pi : formula (I), Numerical Integration (II), Monte Carlo (III)
- Summary (Review)

Motivation

1. Why Parallel Computing ?
2. Why OpenMP?
3. Evolution of Processor

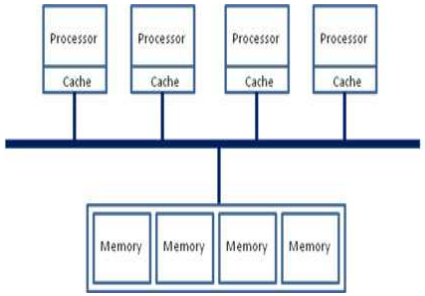


Why Parallel Computing ?

- Limits of serial computing
- Solve larger problems
- Provide concurrency
- Save time and Money
- Use of non-local resources

Why Parallel Computing ?

- Shared Memory
  - Single address space for all processors



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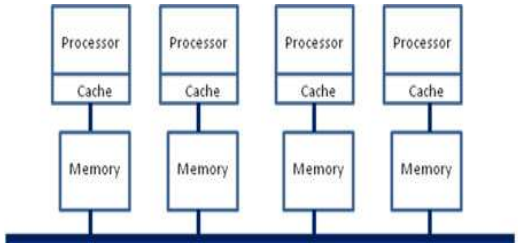
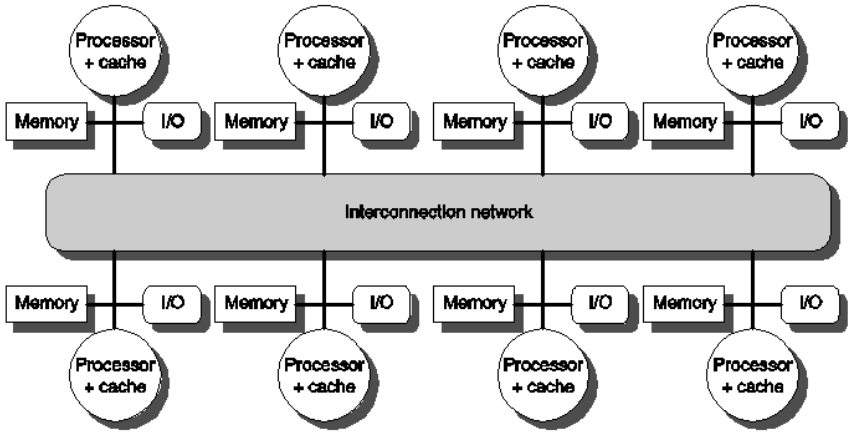


<NUMA>

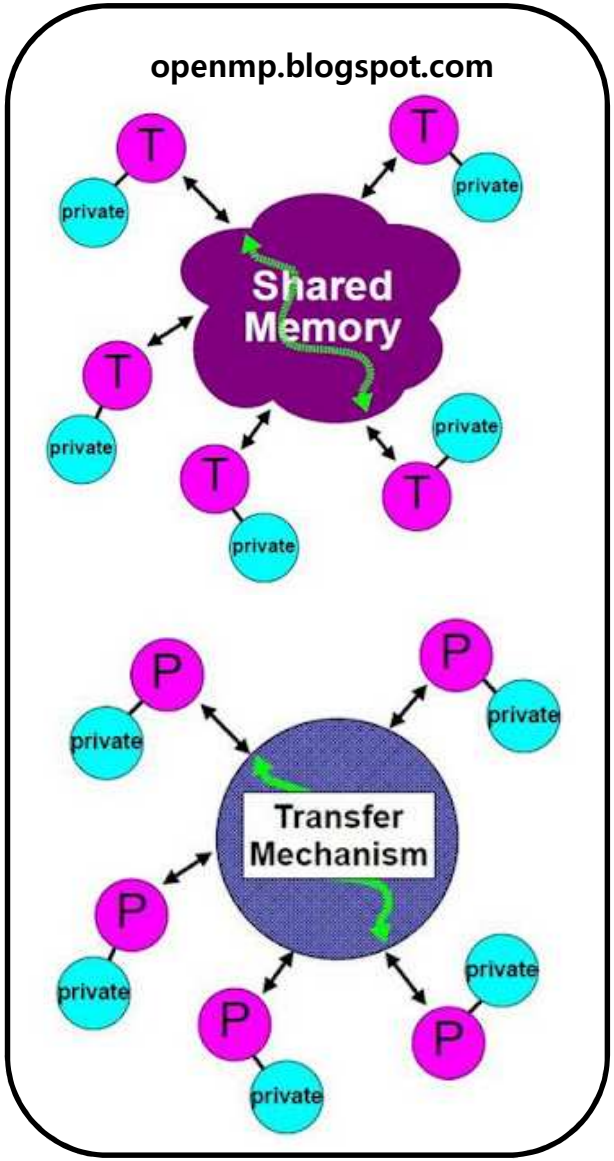
- Distributed Memory



Why Parallel Computing ?

- Shared Memory
  - share a global memory space
  - multiple cores
  - cores can efficiently exchange, share data

- Distributed Memory
  - each node uses its own local memory
  - collection of nodes which have multiple cores
  - communicate between nodes and cores via messages



Why Parallel Computing ?

- Directives-based parallel programming language(OpenMP)
  - Directives tell processor how to distribute data and work across the processors
  - Directives appear as comments in the serial code
  - implemented on shared memory architectures

- Distributed Memory(MPI)
  - Pass messages to send/receive data between processes
  - Each process has its own local variables
  - Can be used on either shared or distributed memory architectures

Why Parallel Computing ?

ABCPL
ACE
ACT++
Active messages
Adl
Adsmith
ADDAP
AFAPI
ALWAN
AM
AMDC
AppLeS
Amoeba
ARTS
Athapascan-0b
Aurora
Automap
bb_threads
Blaze
BSP
BlockComm
C*.
"C* in C
C**
CarlOS
Cashmere
C4
CC++
Chu
Charlotte
Charm
Charm++
Cid
Cilk
CM-Fortran
Converse
Code
COOL

CORRELATE
CPS
CRL
CSP
Cthreads
CUMULVS
DAGGER
DAPPLE
Data Parallel C
DC++
DCE++
DDD
DICE.
DIPC
DOLIB
DOME
DOSMOS.
DRL
DSM-Threads
Ease
ECO
Eiffel
Eilean
Emerald
EPL
ERLANG
Express
Falcon
Filaments
FM
FLASH
The FORCE
Fork
Fortran-M
FX
GA
GAMMA
Glenda

GLU
GUARD
HAsL
Haskell
HPC++
JAVAR.
HORUS
HPF
IMPACT
ISIS.
JAVAR
JADE
Java RMI
javaPG
JavaSpace
JIDL
Joyce
Khoros
Karma
KOAN/Fortran-S
LAM
Lilac
Linda
JADA
WWWinda
ISETL-Linda
ParLin
Eilean
P4-Linda
POSYBL
Objective-Linda
LiPS
Locust
Lparx
Lucid
Maisie
Manifold

Mentat
Legion
Meta Chaos
Midway
Millipede
CparPar
Mirage
MpC
MOSIX
Modula-P
Modula-2*
Multipol
MPI
MPC++
Munin
Nano-Threads
NESL
NetClasses++
Nexus
Nimrod
NOW
Objective Linda
Occam
Omega
OpenMP
Orca
OOF90
P++
P3L
Pablo
PADE
PADRE
Panda
Papers
AFAPI.
Para++
Paradigm

Parafrase2
Paralation
Parallel-C++
Parallaxis
ParC
ParLib++
ParLin
Parmacs
Parti
pC
PCN
PCP:
PH
PEACE
PCU
PET
PENNY
Phosphorus
POET.
Polaris
POOMA
POOL-T
PRESTO
P-RIO
Prospero
Proteus
pthreads
PVM
PSI
PSDM
Quake
Quark
Quick Threads
QPC++
Sage++
SCANDAL
SAM

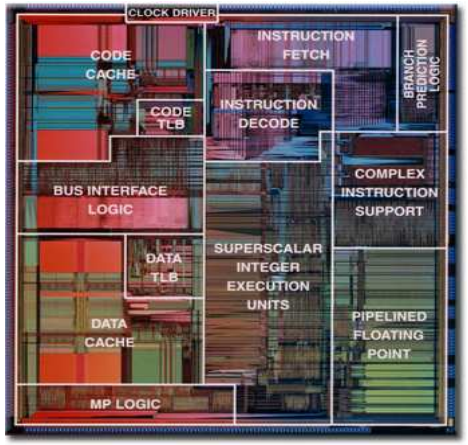
pC++
SCHEDULE
SciTL
SDDA.
SHMEM
SIMPLE
Sina
SISAL.
distributed smalltalk
SMI.
SONiC
Split-C.
SR
Sthreads
Strand.
SUIF.
Synergy
Telegrphos
SuperPascal
TCGMSG.
Threads.h++.
TreadMarks
TRAPPER
uC++
UNITY
UC
V
ViC*
Visifold V-NUS
VPE
Win32 threads
WinPar
XENOOPS
XPC
Zounds
ZPL

Why OpenMP?

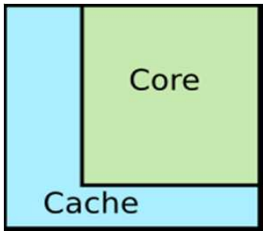
- De-facto and mature standard
- An OpenMP program is portable
- Good performance and scalability
- Requires little programming effort

Evolution of Intel Processor

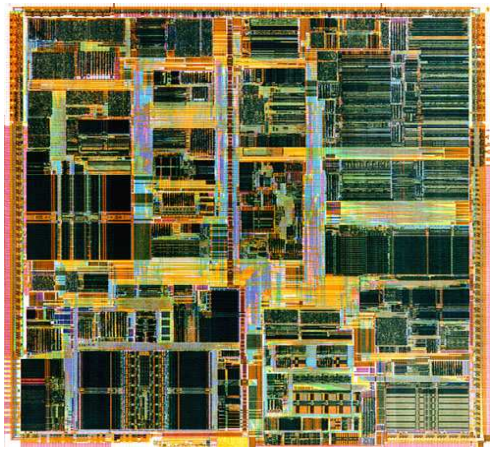
Pentium I

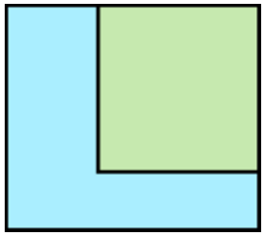


Chip area breakdown

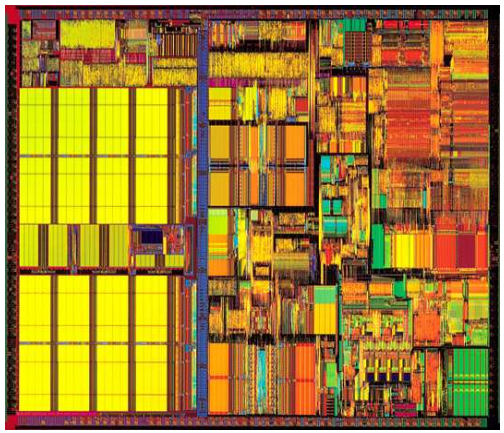


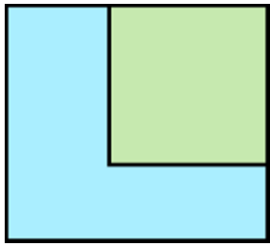
Pentium II



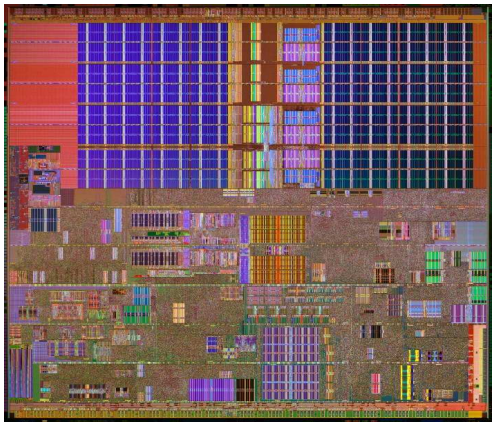


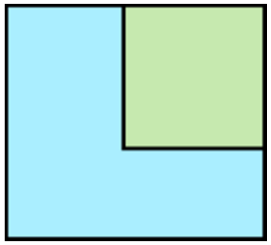
Pentium III





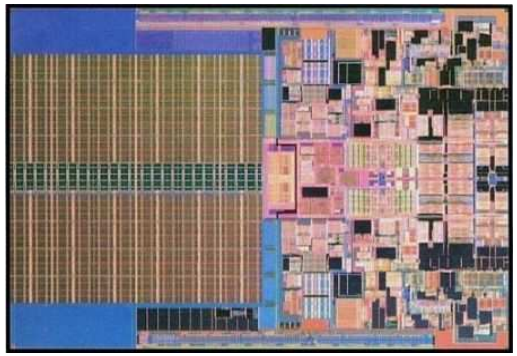
Pentium IV



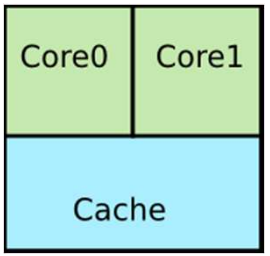


Evolution of Multi-core CPU

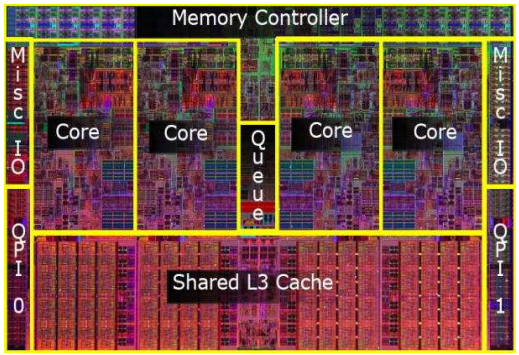
Penryn

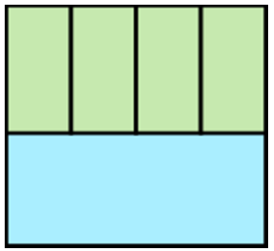


Multi-core

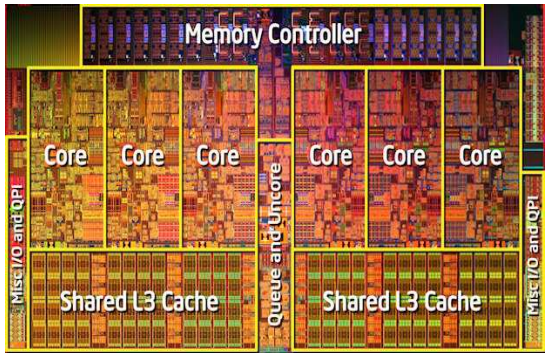


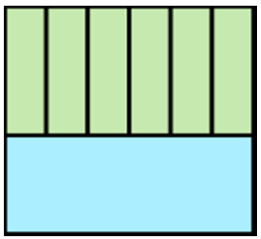
Bloomfield



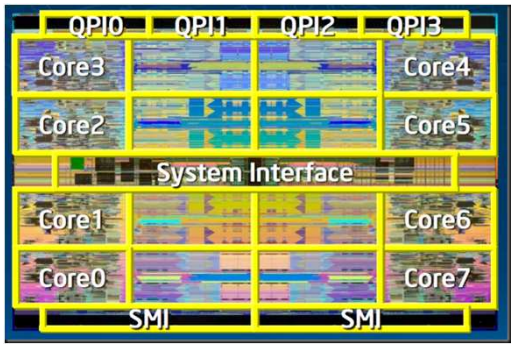


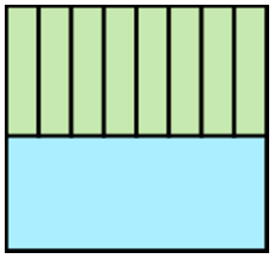
Gulftown



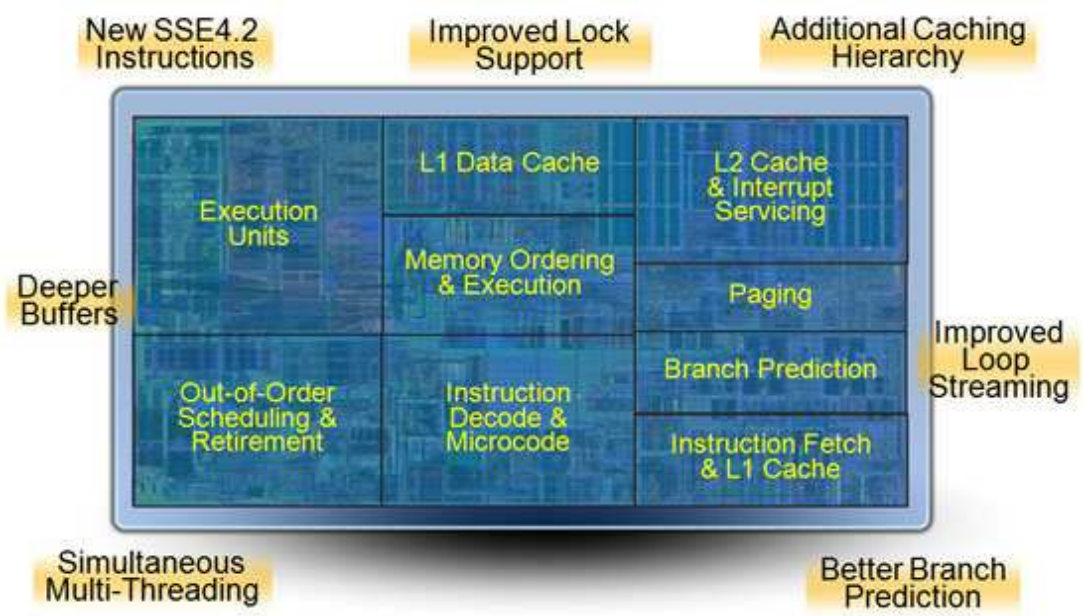


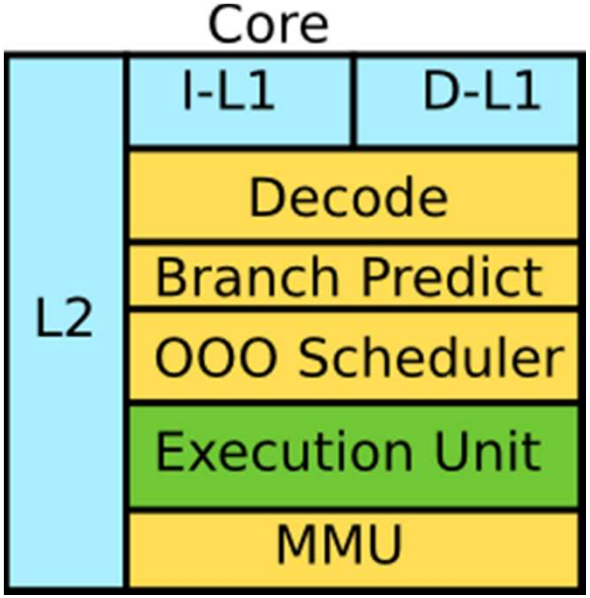
Beckton

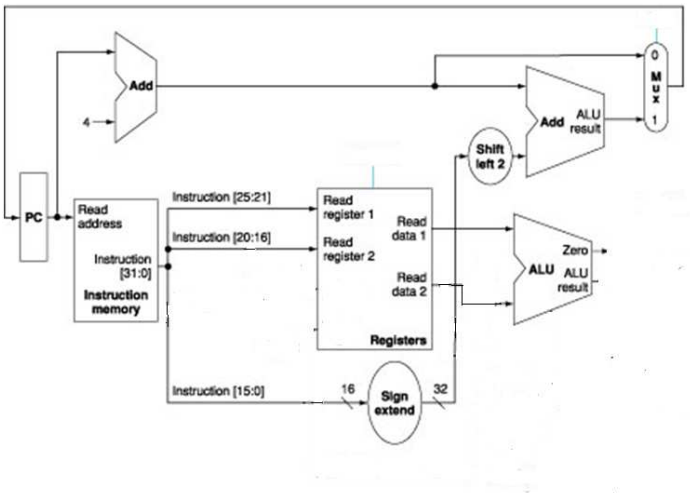


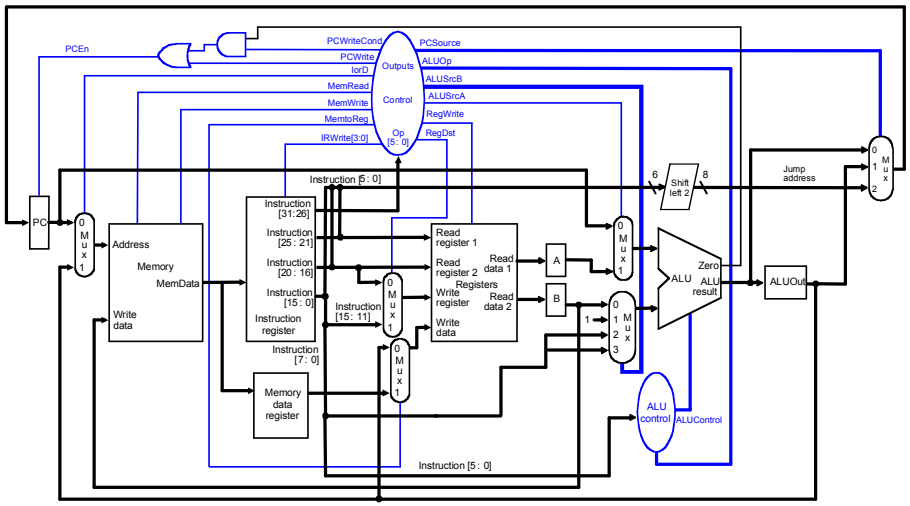


Design for Performance



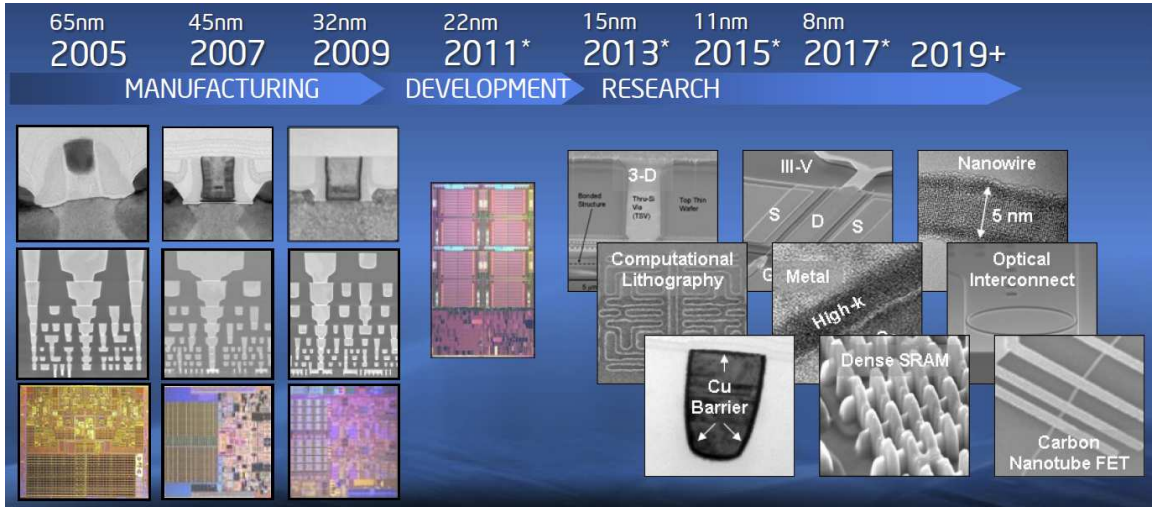






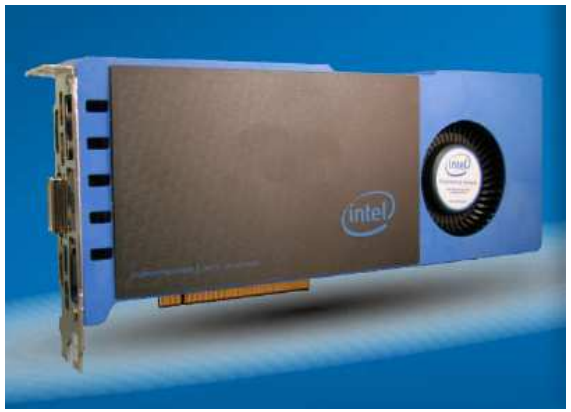
Tick-Tock Development Model

- Moore's Law
  - The number of transistors on a chip will double about every two years

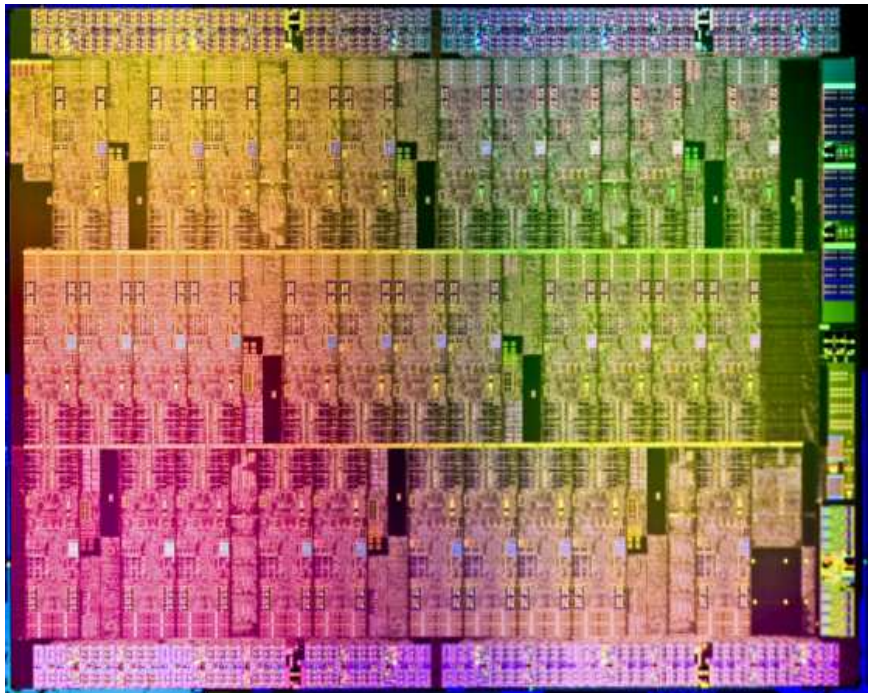


Intel MIC (Many Integrated Core)

- Knights Ferry
  - Software development platform
  - 32 cores, 1.2 GHz
  - 128 threads at 4 threads/core
  - 8MB shared coherent cache
  - 1-2GB GDDR5

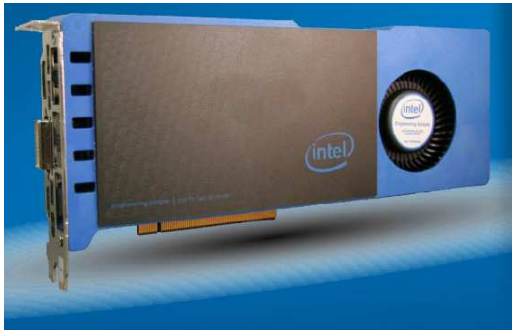


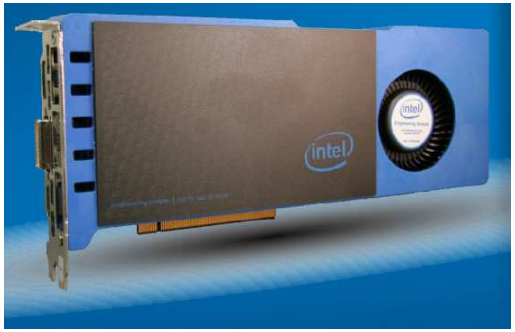
- Knights Corner
  - 1st Intel MIC product
  - 22 nm process
  - 57~61 intel architecture cores
  - 4 threads/core
  - 512bit vector unit/core
  - 6-8 GB GDDR5
  - Scalar unit(x86) & vector unit

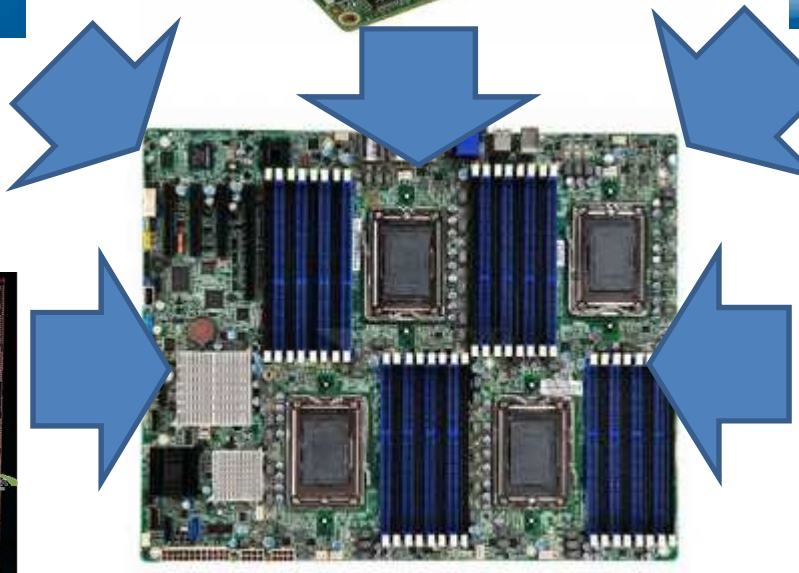


- Future Knights Products

Many-core System



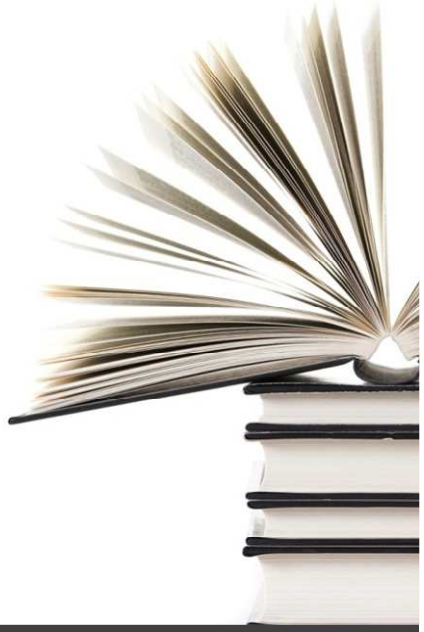




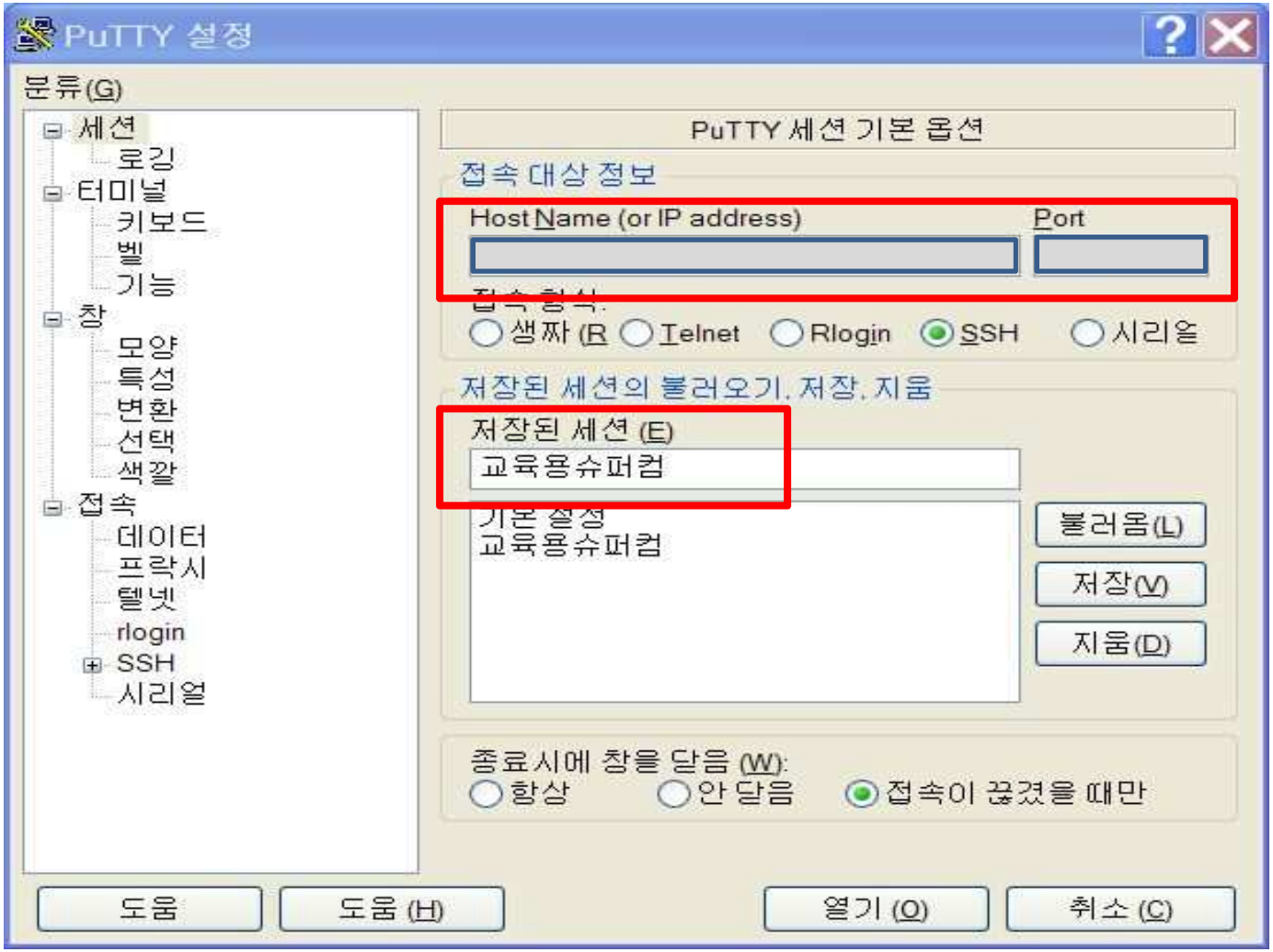
Break!!

Introduction to Education System

1. Education System
2. Check Environment

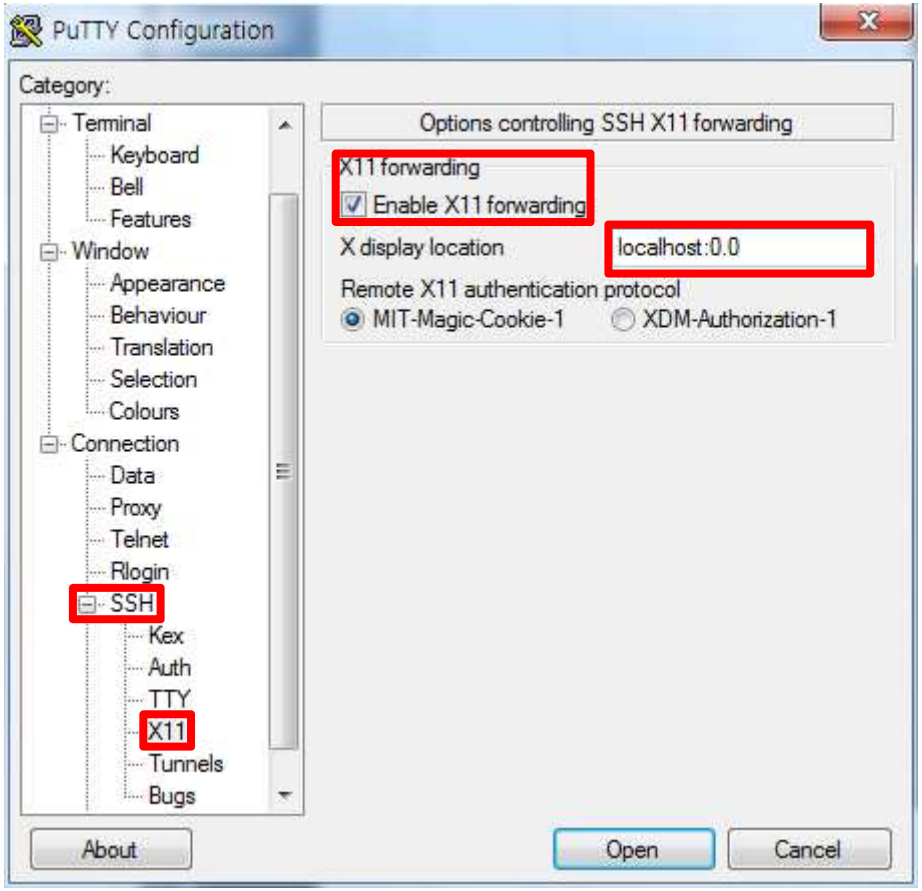


Putty 설정


PuTTY 설정
분류(G)
세션
로깅
터미널
키보드
벨
기능
창
모양
특성
변환
선택
색깔
접속
데이터
프락시
텔넷
rlogin
SSH
시리얼
PuTTY 세션 기본 옵션
접속 대상 정보
Host Name (or IP address)
Port
접속 형식:
생짜 (R
Telnet
Rlogin
SSH
시리얼
저장된 세션의 불러오기, 저장, 지움
저장된 세션 (E)
교육용슈퍼컴
기본 설정
교육용슈퍼컴
불러옴(L)
저장(V)
지움(D)
종료시에 창을 닫음 (W):
항상
안 닫음
접속이 끊겼을 때만
도움
도움 (H)
열기 (O)
취소 (C)

Putty 설정

- ssh => X11 [Enable X11 forwarding] 체크
- X display location : localhost : 0.0
- save



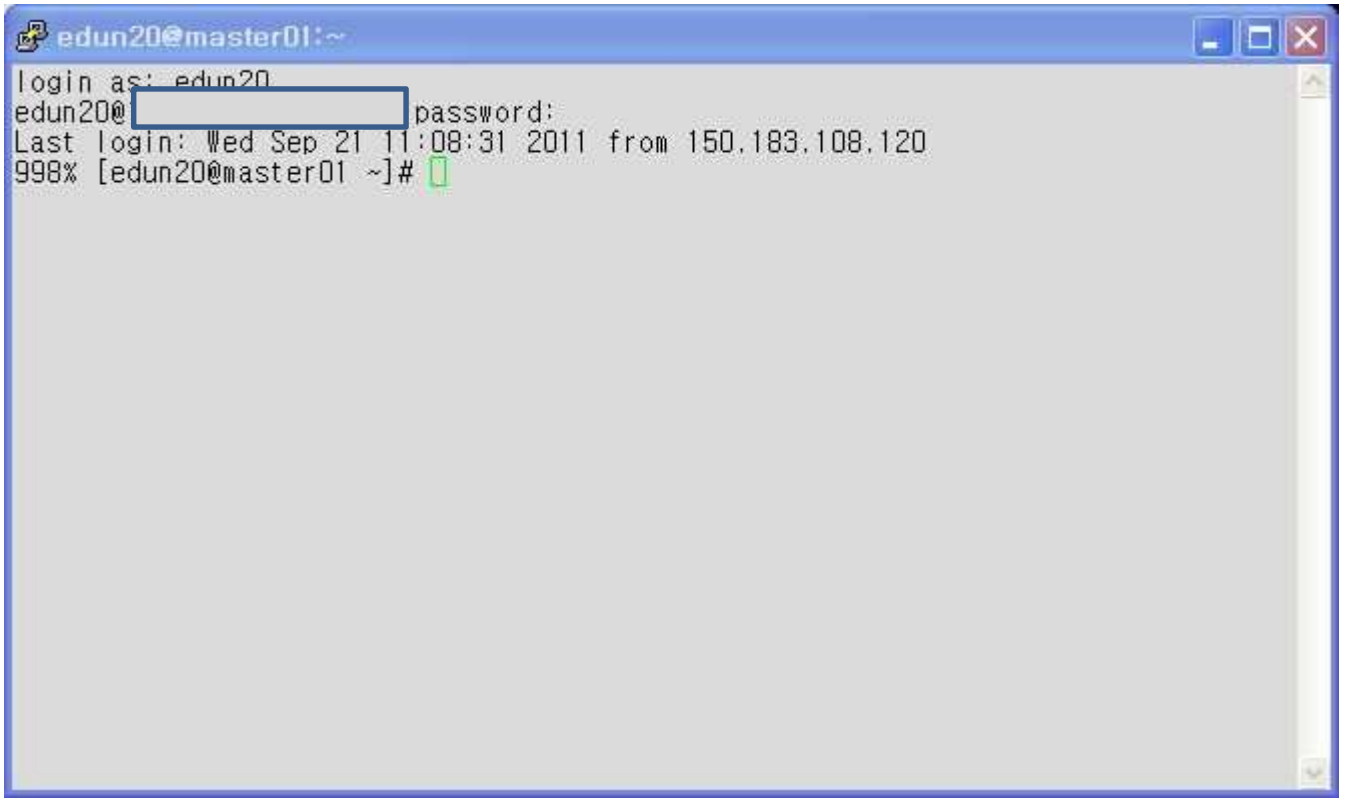
윈도우에서
Xming 실행

Putty 설정

- PuTTY Security Alert [예(y)] 선택

Putty 설정

- login as :
- edun##@xxx.xxx.xxx.xxx's password :



Xming

- Freeware
- 다운로드 웹싸이트
  - http://www.google.com 에서 Xming으로 검색
  - http://sourceforge.net/projects/xming/

- 설치 및 사용방법
  - 실행 파일 다운로드 후 설치
  - Xming 실행
  - Xwindows GUI 프로그램을 사용하기 위해서는 먼저 실행 필수

Checking Environment

- Move to debugging and computing node
  - Use **ssh**
  - Usage : ssh s000#
  - ex) ssh s0001

```
[edun20@master01 ~]$ ssh s0001
Last login: Thu Aug 30 13:33:46 2012 from master01
[edun20@s0001 ~]$ hostname
s0001
[edun20@s0001 ~]$
```

- Compiler Environment
  - Use **module** command
  - Usage : module add compiler/gcc-4.4.6

```
[edun20@s0001 ~]$ module avilable
----- /applic/Modules/modulefiles -----
(module list) …
[edun20@s0001 ~]$ module add compiler/gcc-4.4.6
[edun20@s0001 ~]$ module list
Currently Loaded Modulefiles:
  1) compiler/gcc-4.4.6
```

Checking Environment

Fortran	C

PROGRAM hello_world
 	
!$OMP PARALLEL
PRINT *, 'Hello World'
!$OMP END PARALLEL
 	
END
	#include <stdio.h>
	int main() {
	#pragma omp parallel
	{
	printf ("Hello World\n");
	}
	return 0;
	}

$ gfortran –o hello.x hello.f90
$ gfortran –fopenmp –o hello_omp.x hello.f90
$ ./hello.x
$ ./hello_omp.x
	$ gcc –o hello.x hello.c
	$ gcc –fopenmp –o hello_omp.x hello.c
	$ ./hello.x
	$ ./hello_omp.x

Intel : ifort **–o** hello.x hello.f90 GCC : gfortran **–o** hello.x hello.f90 PGI : pgf90 **–o** hello.x hello.f90	Intel : icc **–o** hello.x hello.c GCC : gcc **–o** hello.x hello.c PGI : pgcc **–o** hello.x hello.c
Intel : ifort **-openmp** –o hello_omp.x hello.f90 GCC : gfortran **-fopenmp** –o hello_omp.x hello.f90 PGI : pgf90 **-mp** –o hello_omp.x hello.f90	Intel : icc **–openmp** –o hello_omp.x hello.c GCC : gcc **–fopenmp** –o hello_omp.x hello.c PGI : pgcc **–mp** –o hello_omp.x hello.c

for output filename

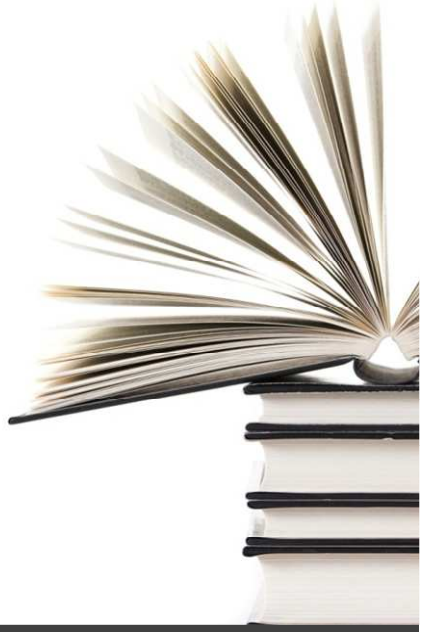
for output filename

for OpenMP

for OpenMP

OpenMP Basics I

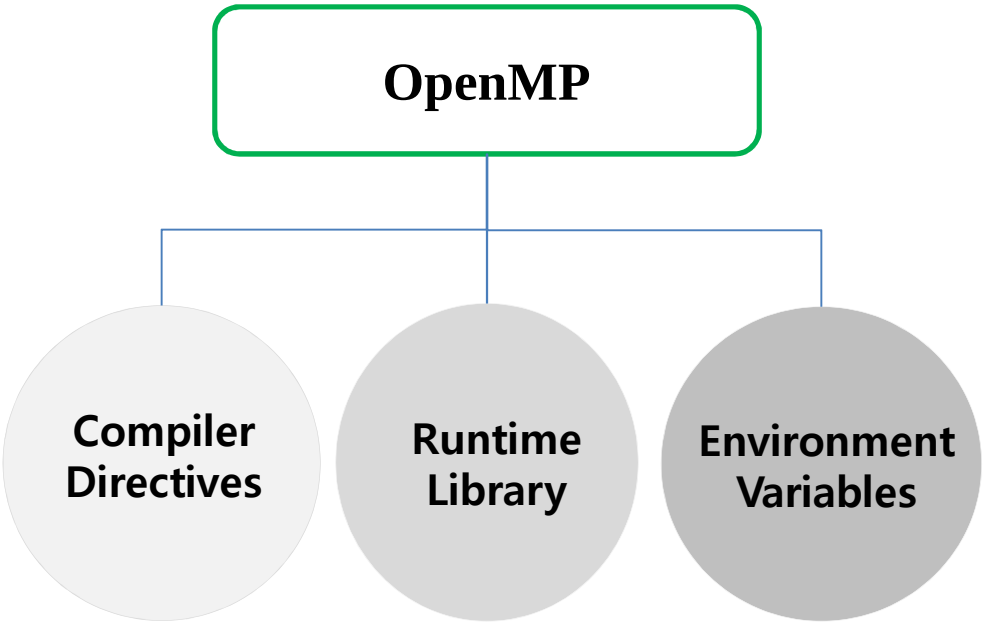
1. Introduction to OpenMP
2. Create Threads
3. Data Scope Attribute



What is OpenMP ?

- OpenMP is
  - De-facto standard API (Application Programming Interface) for multi-thread based shared memory parallel programming
  - Not a new programming language
  - Notation that can be added to a sequential program in C, C++ and Fortran

- Consists of
  - Compiler Directives
  - Runtime Library (Functions)
  - Environment Variables



Components of OpenMP (1/2)

- Compiler Directives
  - communicate with the compiler on parallelism

    ex) !$OMP PARALLEL DO

- Runtime Library (Functions)
  - enables the setting and querying of parallel parameters such as number of participating threads and the thread number

    ex) CALL omp_set_num_threads(128)

- Environmental Variables
  - define runtime system parallel parameters such as the number of threads

    ex) export OMP_NUM_THREADS=8

Components of OpenMP (2/2)

Fortran	C

PROGRAM omp_component
 	
INTEGER omp_get_thread_num
 	
!$OMP PARALLEL
PRINT *, 'Hello World', omp_get_thread_num()
!$OMP END PARALLEL
 	
END
	#include <stdio.h>
	#include <omp.h>
	
	int main()
	{
	#pragma omp parallel
	{
	printf ("Hello World %d\n", omp_get_thread_num());
	}
	
	return 0;
	}

$ gfortran -fopenmp –o omp_component.x omp_component.f90
$ export OMP_NUM_THREADS=4
$ ./omp_component.x
	$ gcc –fopenmp –o omp_component.x omp_component.c
	$ export OMP_NUM_THREADS=4
	$ ./omp_component.x

Compiler Directive

Compiler Directive

Runtime Library

Runtime Library

Environment Variable

Environment Variable

- OpenMP Syntax

	Fortran	C
Compiler Directive	!$OMP <directive>	#pragma omp <directive>
Runtime Library	omp_	omp_
Environmental Variable	OMP_	OMP_

Creating Threads (1/4)

Fortran

```
PROGRAM create_thread
      IMPLICIT NONE
      INTEGER omp_get_thread_num

!$OMP PARALLEL
      PRINT *, 'Hello World', omp_get_thread_num()
!$OMP END PARALLEL
      print *, ''

      CALL  omp_set_num_threads(4)
!$OMP PARALLEL
      PRINT *, 'Hello World', omp_get_thread_num()
!$OMP END PARALLEL
      print*, ''

!$OMP PARALLEL num_threads(2)
      PRINT *, 'Hello World', omp_get_thread_num()
!$OMP END PARALLEL

END
```

```
$ gfortran -fopenmp –o create_thread.x create_thread.f90
$ export OMP_NUM_THREADS=8
$ ./create_thread.x
```

C

```
#include <stdio.h>
#include <omp.h>

int main()
{
#pragma omp parallel
{
      printf ("Hello World %d\n", omp_get_thread_num());
}
      printf("\n");
      omp_set_num_threads(4);
#pragma omp parallel
{
      printf ("Hello World %d\n", omp_get_thread_num());
}
      printf("\n");
#pragma omp parallel num_threads(2)
{
      printf ("Hello World %d\n", omp_get_thread_num());
}

      return 0;
}
```

```
$ gcc –fopenmp –o create_thread.x create_thread.c
$ export OMP_NUM_THREADS=8
$ ./create_thread.x
```

Creating Threads (2/4)

- Parallel Region

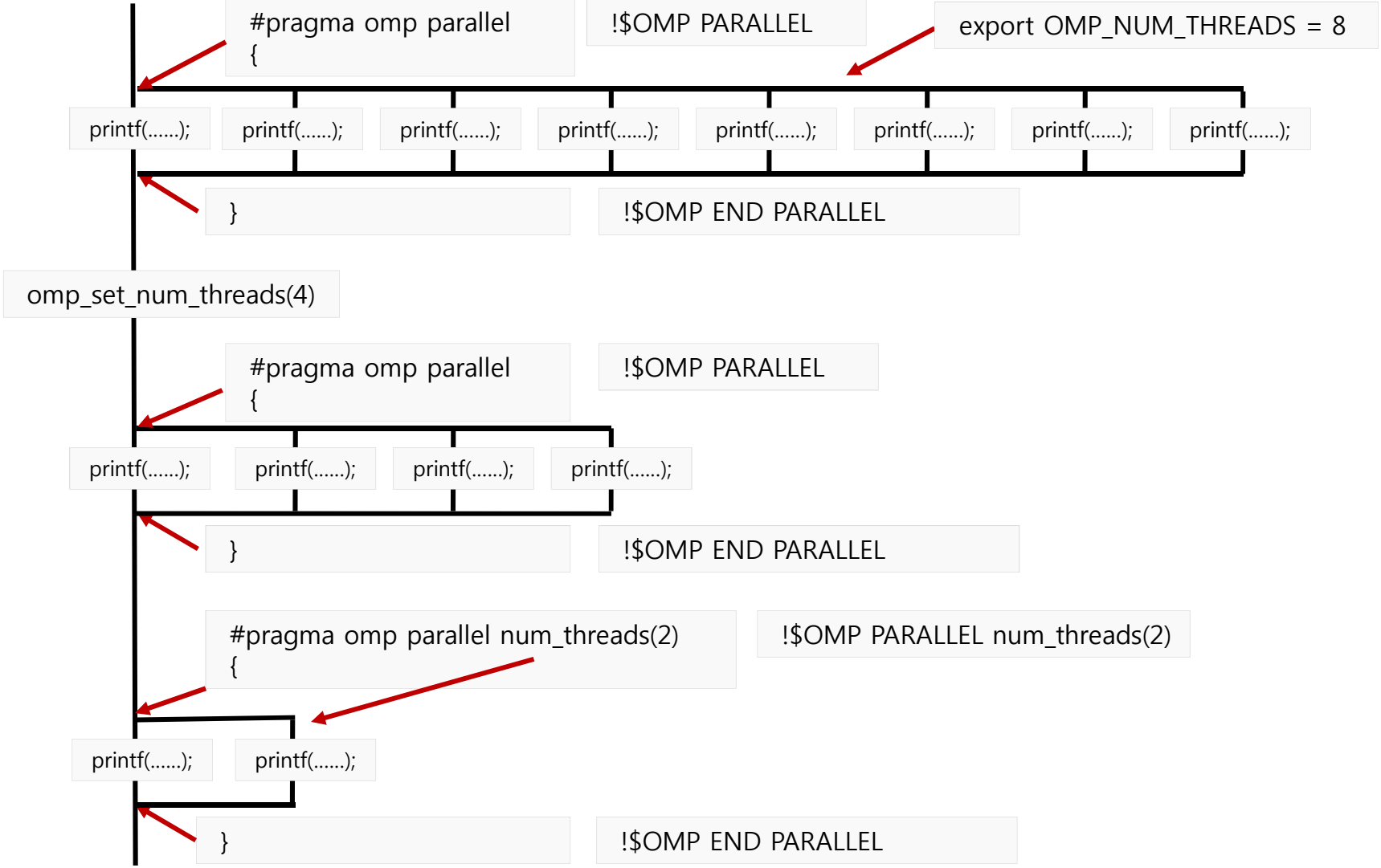
Fortran	C

!$OMP PARALLEL
!$OMP END PARALLEL
	#pragma omp parallel
	{
	}

- Set number of thread
  - Environment Variable : export OMP_NUM_THREADS = xxx
  - Runtime Library : omp_set_num_threads(xxx)
  - Directive : #pragma omp parallel num_threads(xxx)

- Runtime libraries related to thread
  - omp_set_num_threads(integer) : Affects the number of threads
  - omp_get_num_threads() : Returns the number of threads in the current team
  - omp_get_thread_num() : Returns the ID of the encountering thread
  - omp_get_max_threads()
  - omp_get_num_procs()

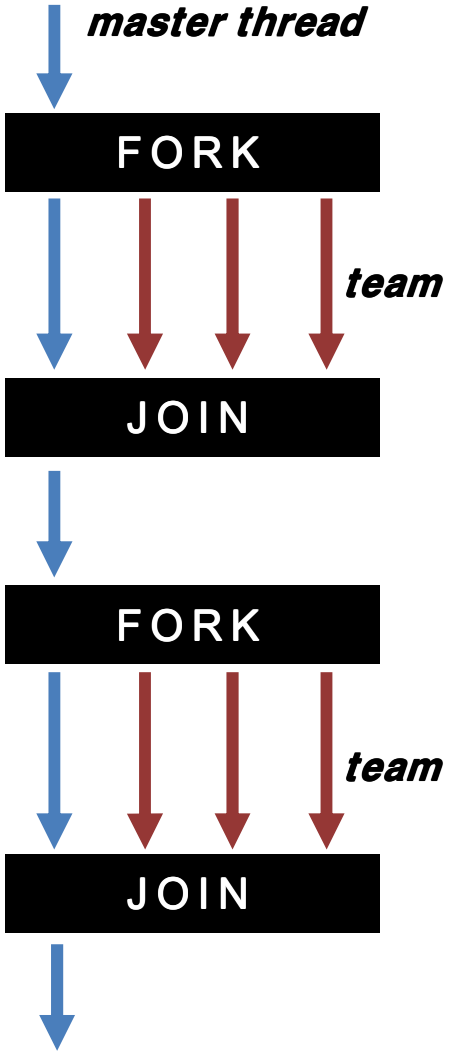
Creating Threads (3/4)



Creating Threads (4/4)

- OpenMP Programming Model
  - Thread-Based
  - Fork-Join Model

- Fork-Join Model
  - The master thread spawns a team of threads that joins at the end of the parallel region
  - Threads in the same team can collaborate to do work



Create Threads (Exercise)

Fortran	C

PROGRAM create_thread2
 	
INTEGER ??
 	
!! print number of threads
PRINT *, “threads =“, ???
 	
!! create 3 threads
!! print thread id and number of threads
PRINT *, “tid =“, ???, “threads =“, ???
!! end multi threads
 	
!! print number of threads
PRINT *, “threads =“, ???
 	
!! create 5 threads using Environment Variable
!! print thread id and number of threads
PRINT *, “tid”, ???, “threads =“, ???
!! end multi threads
 	
!! print number of threads
PRINT *, “threads =”, ???
 	
END
	#include <stdio.h>
	#include <omp.h>
	
	int main()
	{
	// print number of threads
	printf(“threads = %d\n”, ???);
	// create 3 threads
	{
	// print thread id and number of threads
	printf(“tid = %d threads = %d\n”, ???, ???);
	}
	// print number of threads
	printf(“threads = %d\n”, ???);
	
	// create 5 threads using Environment Variable
	{
	// print thread id and number of threads
	printf(“tid = %d threads = %d\n”, ???, ???);
	}
	// print number of threads
	printf(“threads = %d\n”, ???);
	
	return 0;
	}

Create Threads (solution)

Fortran	C

PROGRAM create_thread2
IMPLICIT NONE
INTEGER omp_get_num_threads, omp_get_thread_num
 	
PRINT *, “threads =“, omp_get_num_threads()
 	
!$OMP PARALLEL num_threads(3)
PRINT *, “tid =“, omp_get_thread_num(), &
“threads =“, omp_get_num_threads()
!$OMP END PARALLEL
 	
PRINT *, “threads =“, omp_get_num_threads()
 	
!$OMP PARALLEL
PRINT *, “tid”, omp_get_thread_num(), &
“threads =“, omp_get_num_threads()
!$OMP END PARALLEL
 	
PRINT *, “threads =”, omp_get_num_threads()
 	
END
	#include <stdio.h>
	#include <omp.h>
	int main()
	{
	printf(“threads = %d\n”, omp_get_num_threads());
	
	#pragma omp parallel num_threads(3)
	{
	printf(“tid = %d threads = %d\n”,
	omp_get_thread_num(), omp_get_num_threads());
	}
	
	printf(“threads = %d\n”, omp_get_num_threads());
	
	#pragma omp parallel
	{
	printf(“tid = %d threads = %d\n”,
	omp_get_thread_num(), omp_get_num_threads());
	}
	printf(“threads = %d\n”, omp_get_num_threads());
	
	return 0;
	}

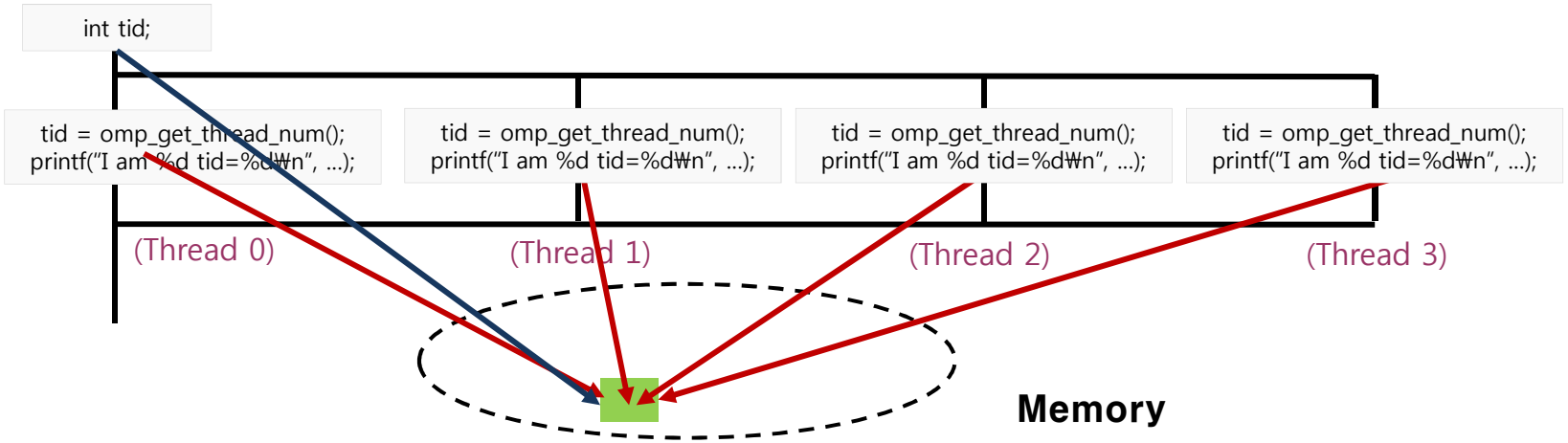
$ export OMP_NUM_THREADS=5
$ gfortran -fopenmp -o create_thread2.x create_thread2.f90
$ ./create_thread2.x
	$ export OMP_NUM_THREADS=5
	$ gcc -fopenmp -o create_thread2.x create_thread2.c
	$ ./create_thread2.x

Break!!

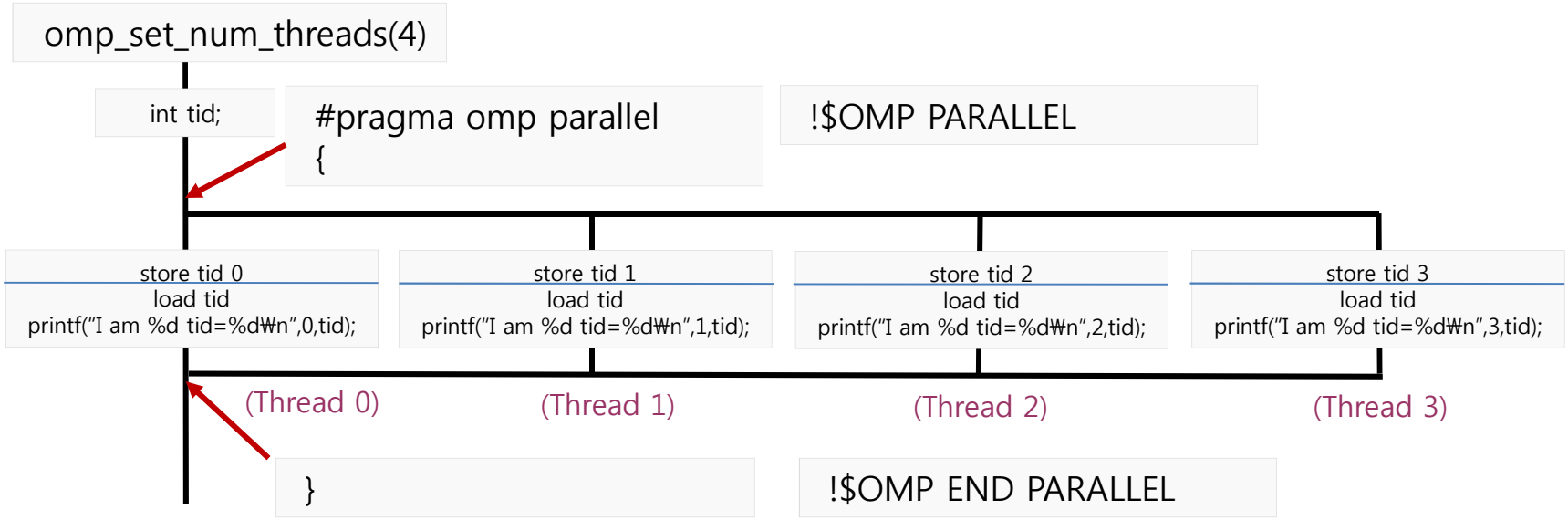
Data Scope Attribute (1/7)

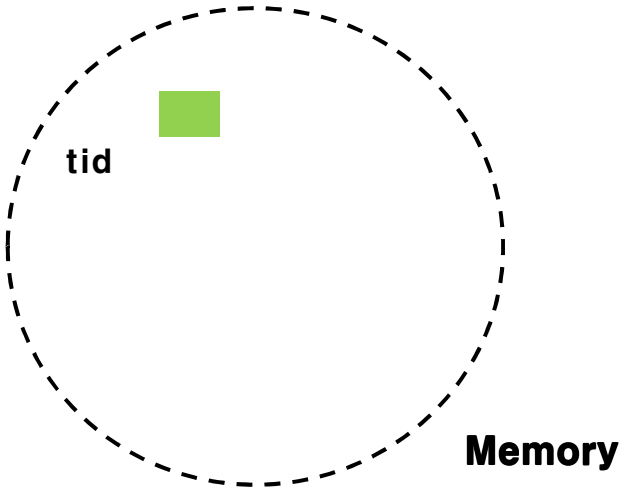
Fortran	C

PROGRAM hello_wrong
 	
INTEGER tid, omp_get_thread_num
 	
CALL omp_set_num_threads(4)
!$OMP PARALLEL
tid = omp_get_thread_num()
PRINT *, ‘ I am ’, omp_get_thread_num(), ‘ tid = ’, tid
!$OMP END PARALLEL
 	
END
	#include <stdio.h>
	#include <omp.h>
	int main()
	{
	int tid;
	
	omp_set_num_threads(4);
	#pragma omp parallel
	{
	tid = omp_get_thread_num(); //sleep(1);
	printf (“I am %d tid = %d\n”, omp_get_thread_num(), tid);
	}
	return 0;
	}



Data Scope Attribute (1/7)

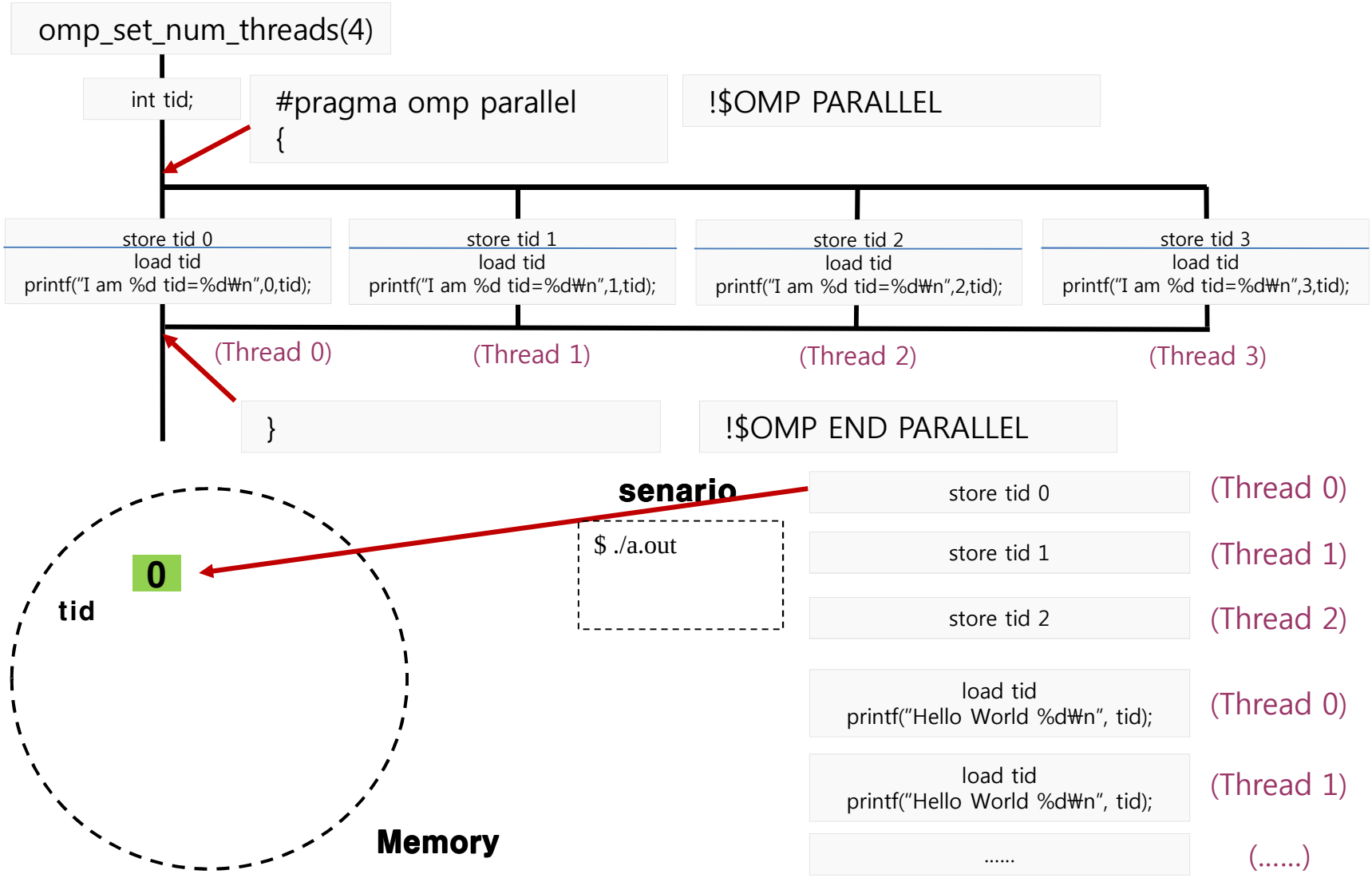




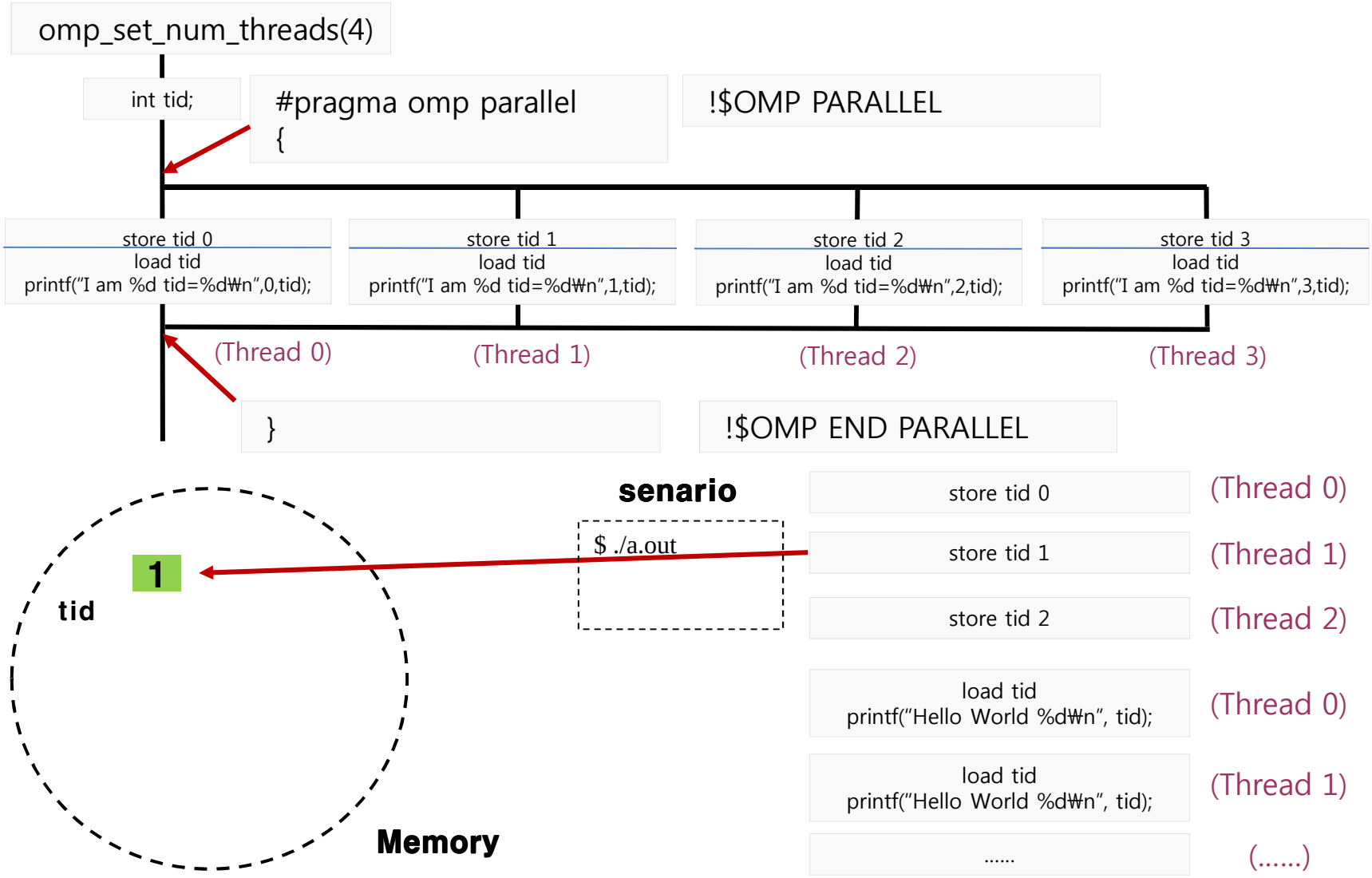
senario

store tid 0	(Thread 0)
store tid 1	(Thread 1)
store tid 2	(Thread 2)
load tid printf("Hello World %d₩n", tid);	(Thread 0)
load tid printf("Hello World %d₩n", tid);	(Thread 1)
.....	(.....)

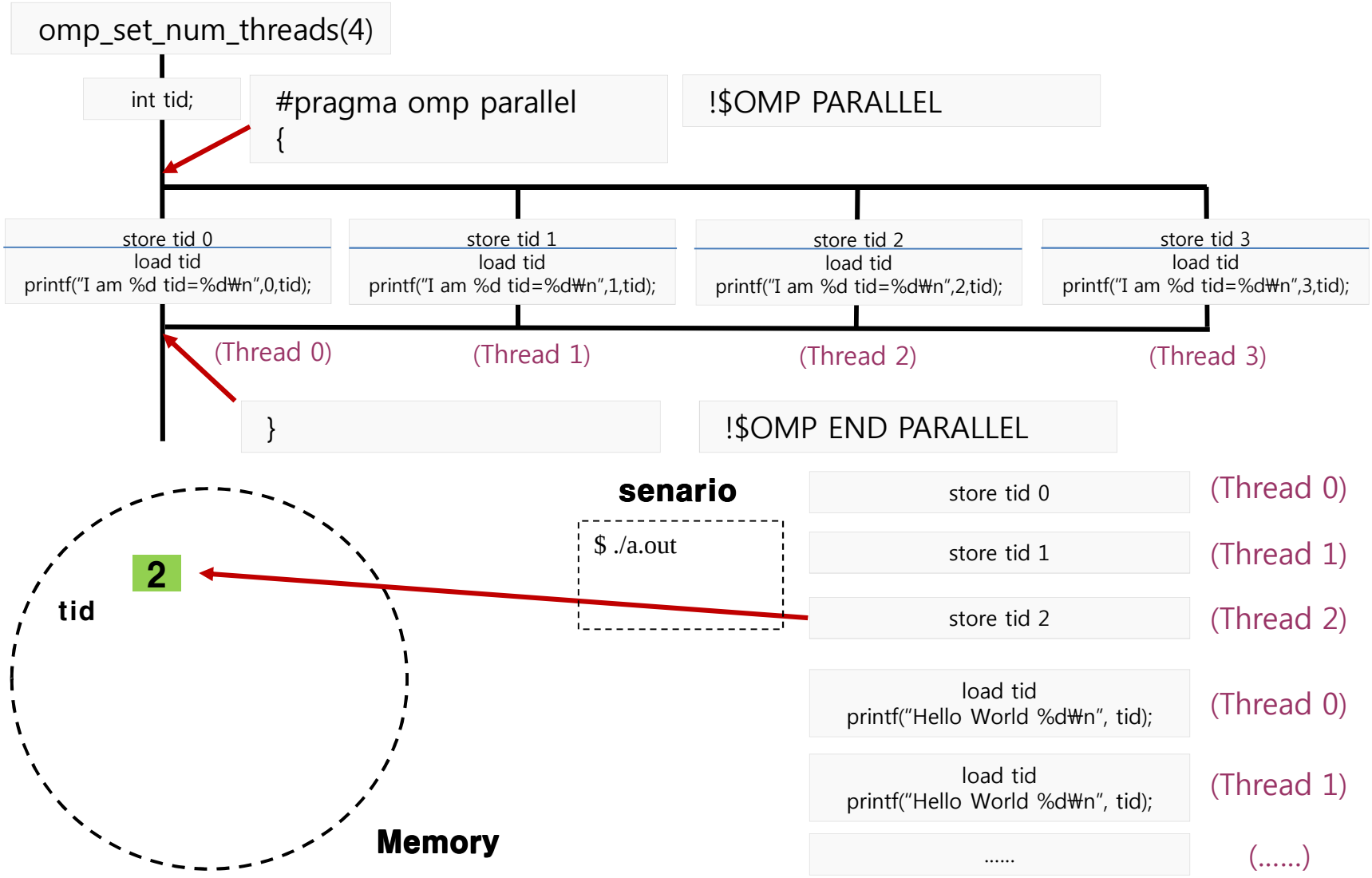
Data Scope Attribute (1/7)



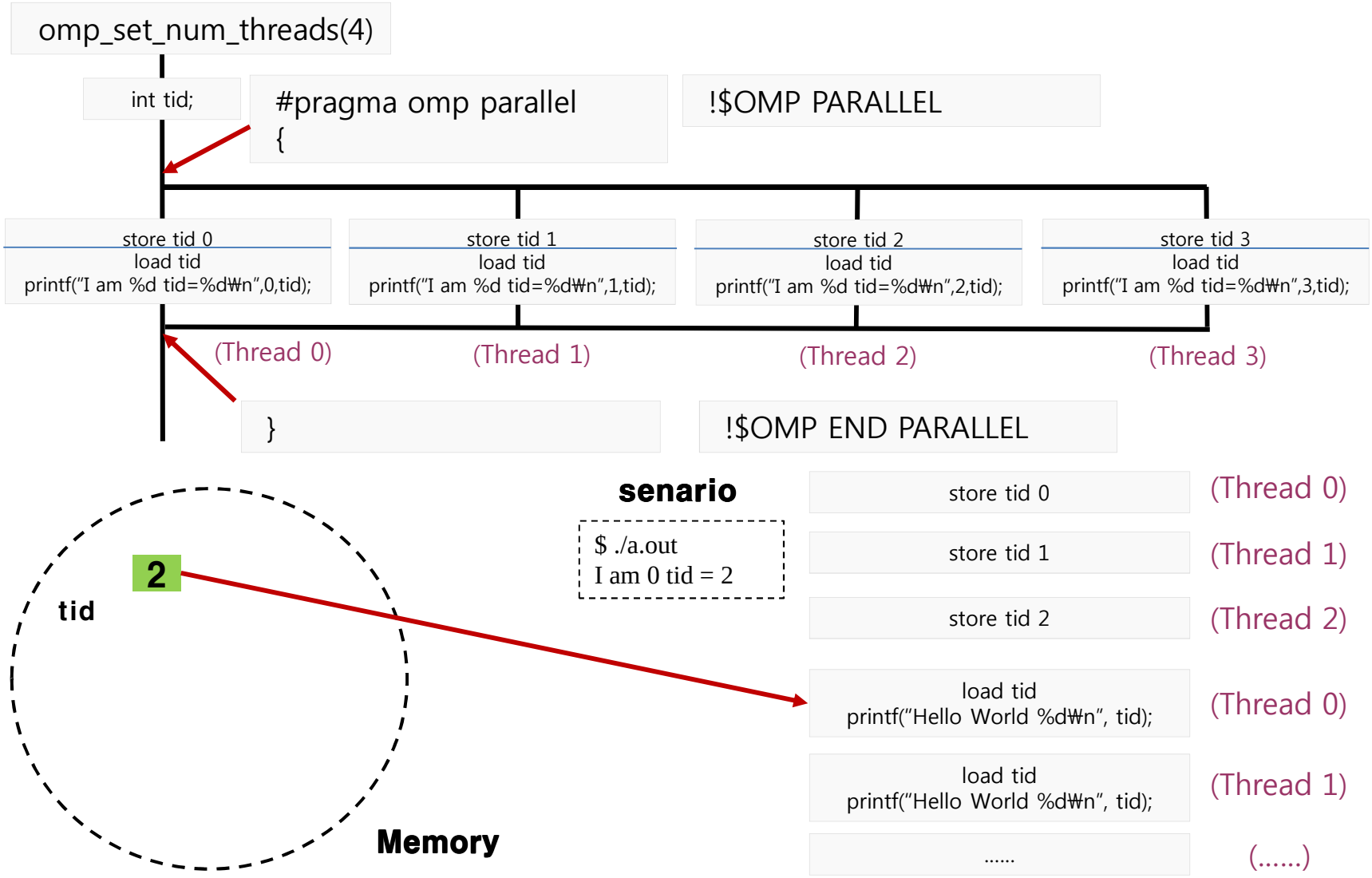
Data Scope Attribute (1/7)



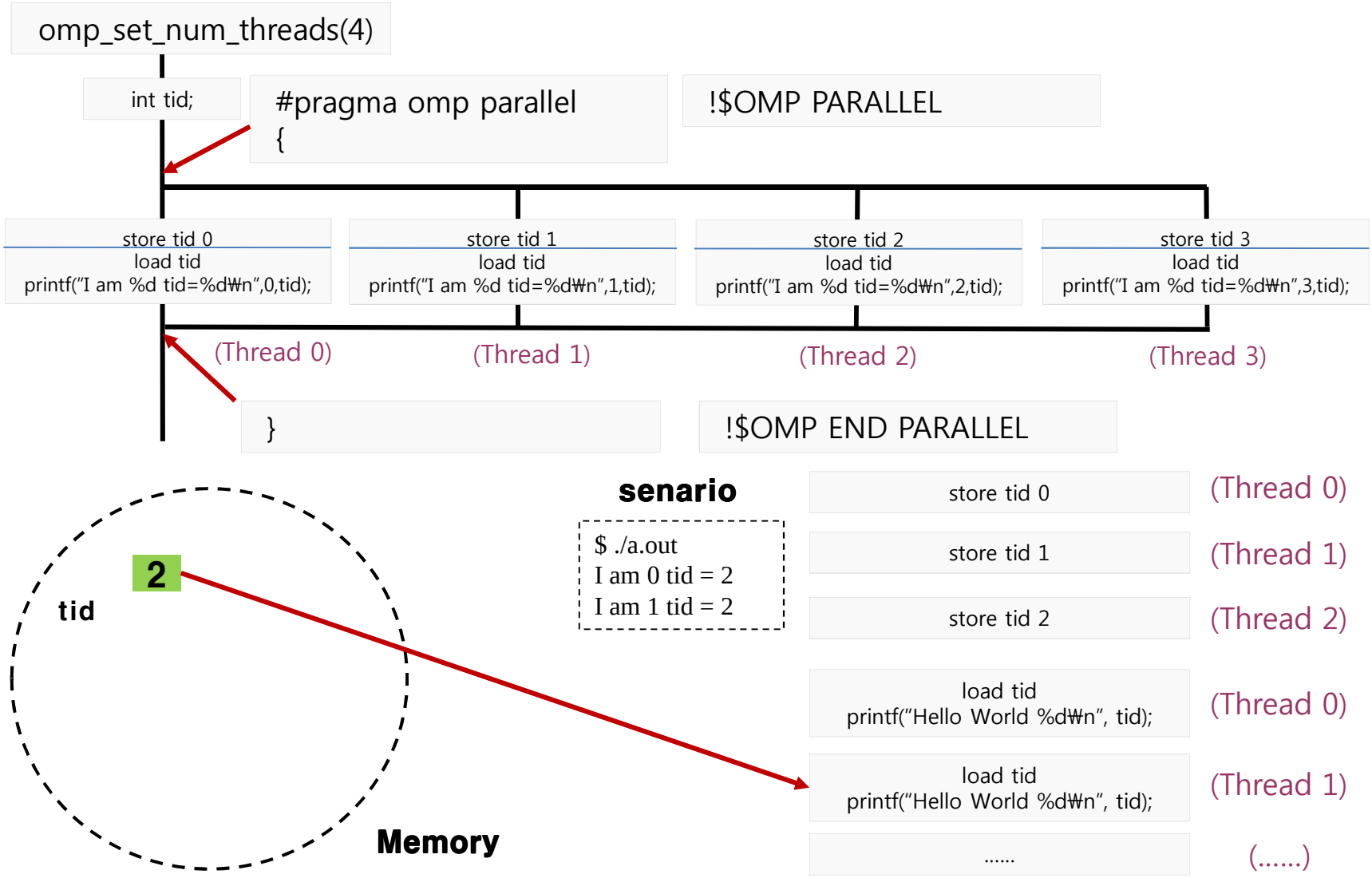
Data Scope Attribute (1/7)



Data Scope Attribute (1/7)



Data Scope Attribute (1/7)



Data Scope Attribute (2/7)

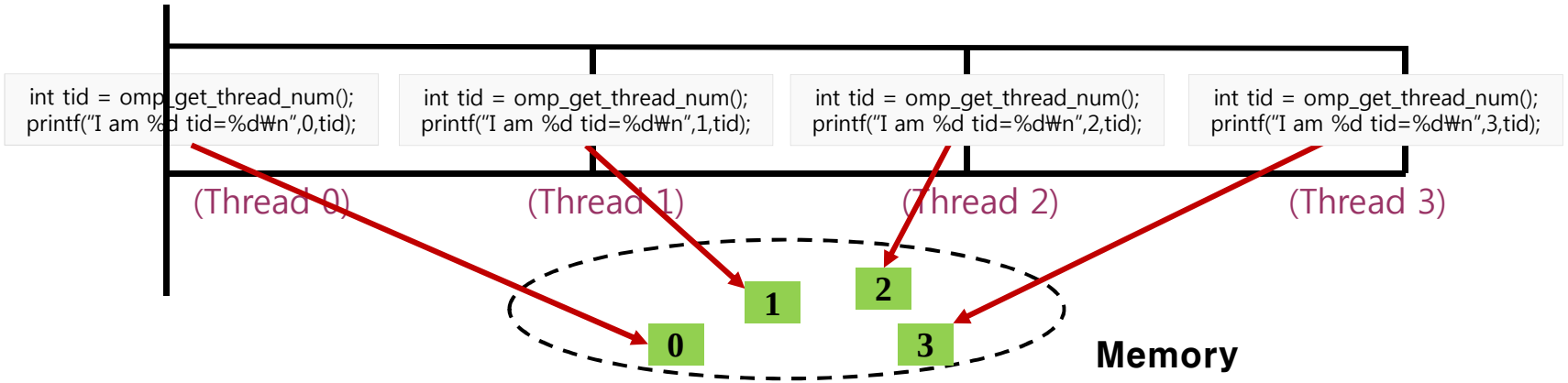
Fortran

```
PROGRAM hello_wrong
      INTEGER omp_get_thread_num
      call omp_set_num_threads(4)

!$OMP PARALLEL
      INTEGER tid
      tid = OMP_GET_THREAD_NUM()
      PRINT *, 'I am',    &
      OMP_GET_THREAD_NUM(), &
            'TID =' tid
!$OMP END PARALLEL

END
```

Not allowed

C

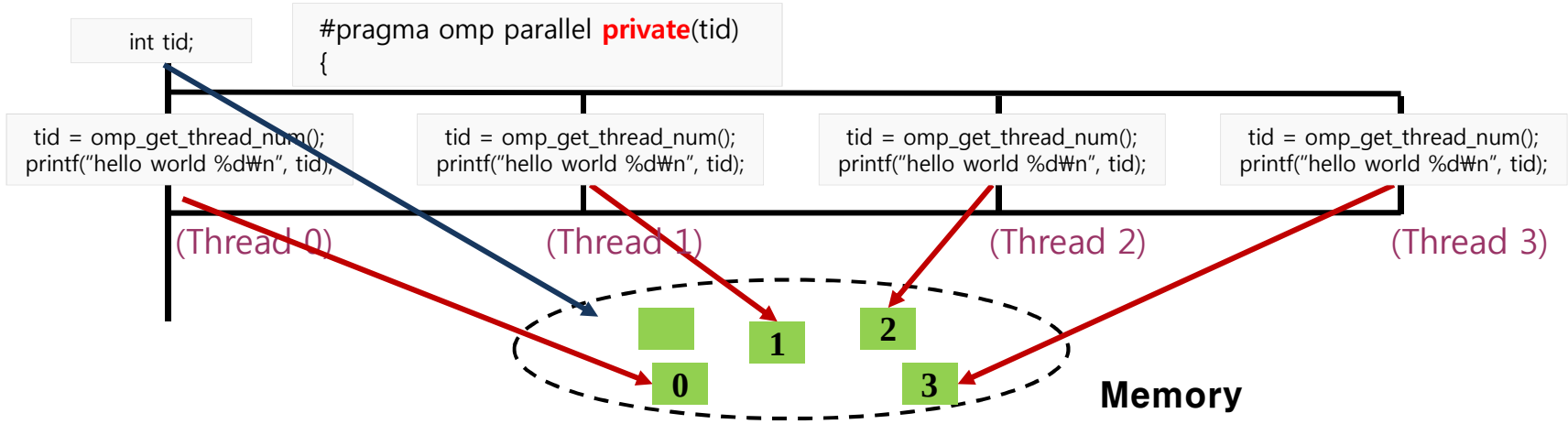
```
#include <stdio.h>
#include <omp.h>

int main()
{
      omp_set_num_threads(4);

#pragma omp parallel
{
      int tid = omp_get_thread_num();
      printf ("I am %d tid = %d\n", omp_get_thread_num(), tid);
}

      return 0;
}
```



Data Scope Attribute (3/7)

Fortran	C

PROGRAM hello_right
INTEGER tid, omp_get_thread_num
 	
CALL omp_set_num_threads(4)
!$OMP PARALLEL PRIVATE(tid)
tid = OMP_GET_THREAD_NUM()
PRINT *, 'I am ', OMP_GET_THREAD_NUM(), ' tid = ', tid
!$OMP END PARALLEL
 	
END
	#include <stdio.h>
	#include <omp.h>
	
	int main()
	{
	int tid;
	omp_set_num_threads(4);
	#pragma omp parallel private(tid)
	{
	tid = omp_get_thread_num();
	printf ("I am %d tid = %d\n", omp_get_thread_num(), tid);
	}
	return 0;
	}



Data Scope Attribute (4/7)

Fortran

```
PROGRAM firstprivate

      INTEGER :: i = 10, tid, omp_get_thread_num

      call omp_set_num_threads(4)
!$OMP PARALLEL PRIVATE(tid) FIRSTPRIVATE(i)
      tid = OMP_GET_THREAD_NUM()
      PRINT *, ‘tid =‘ , tid, ‘i =‘, i
      i = 20
!$OMP END PARALLEL
      print *, ‘tid = ‘, tid, ‘i =‘, i

END
```

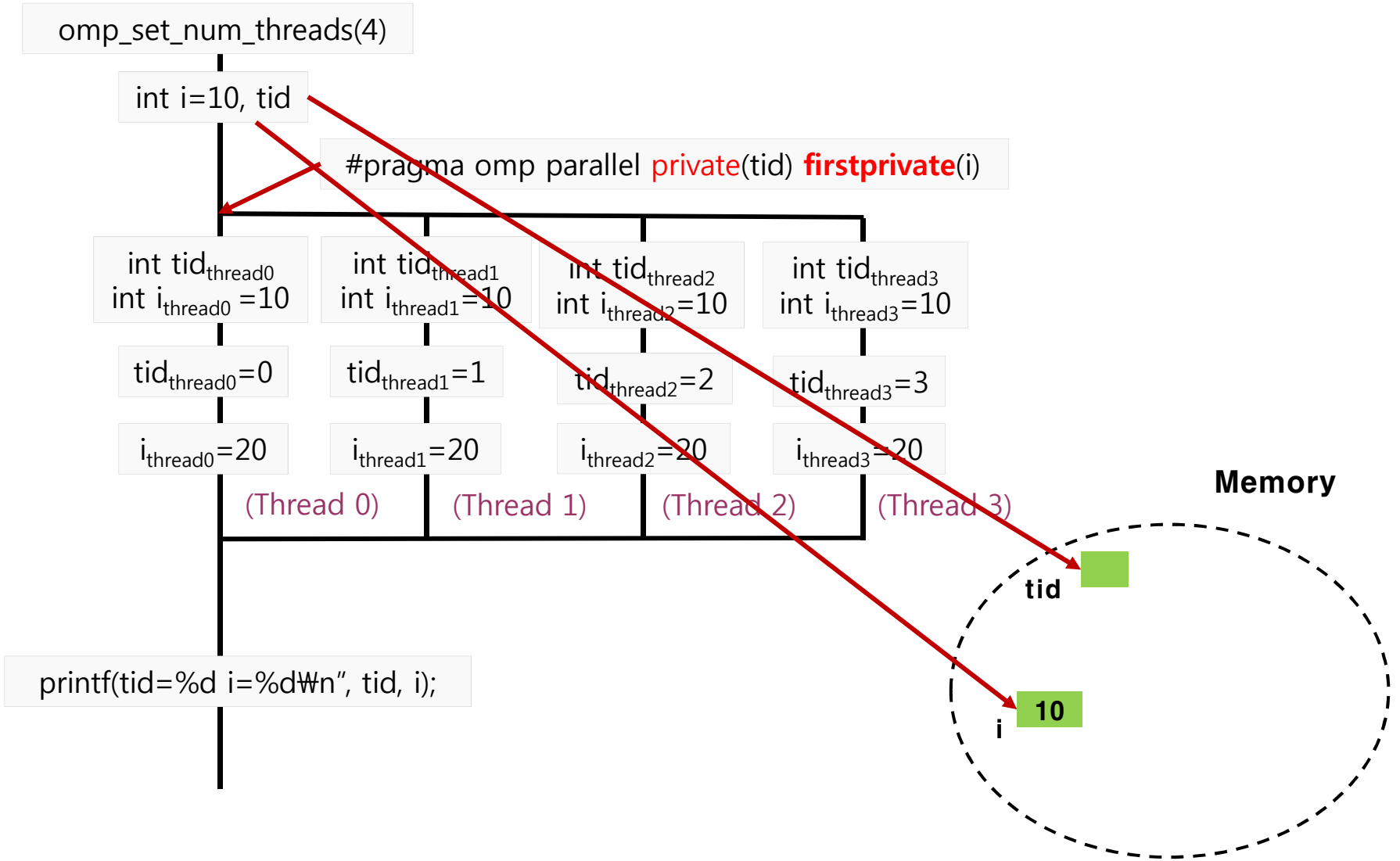
```
$ gfortran -fopenmp -o firstprivate.x firstprivate.f90
$ ./firstprivate.x
```

C

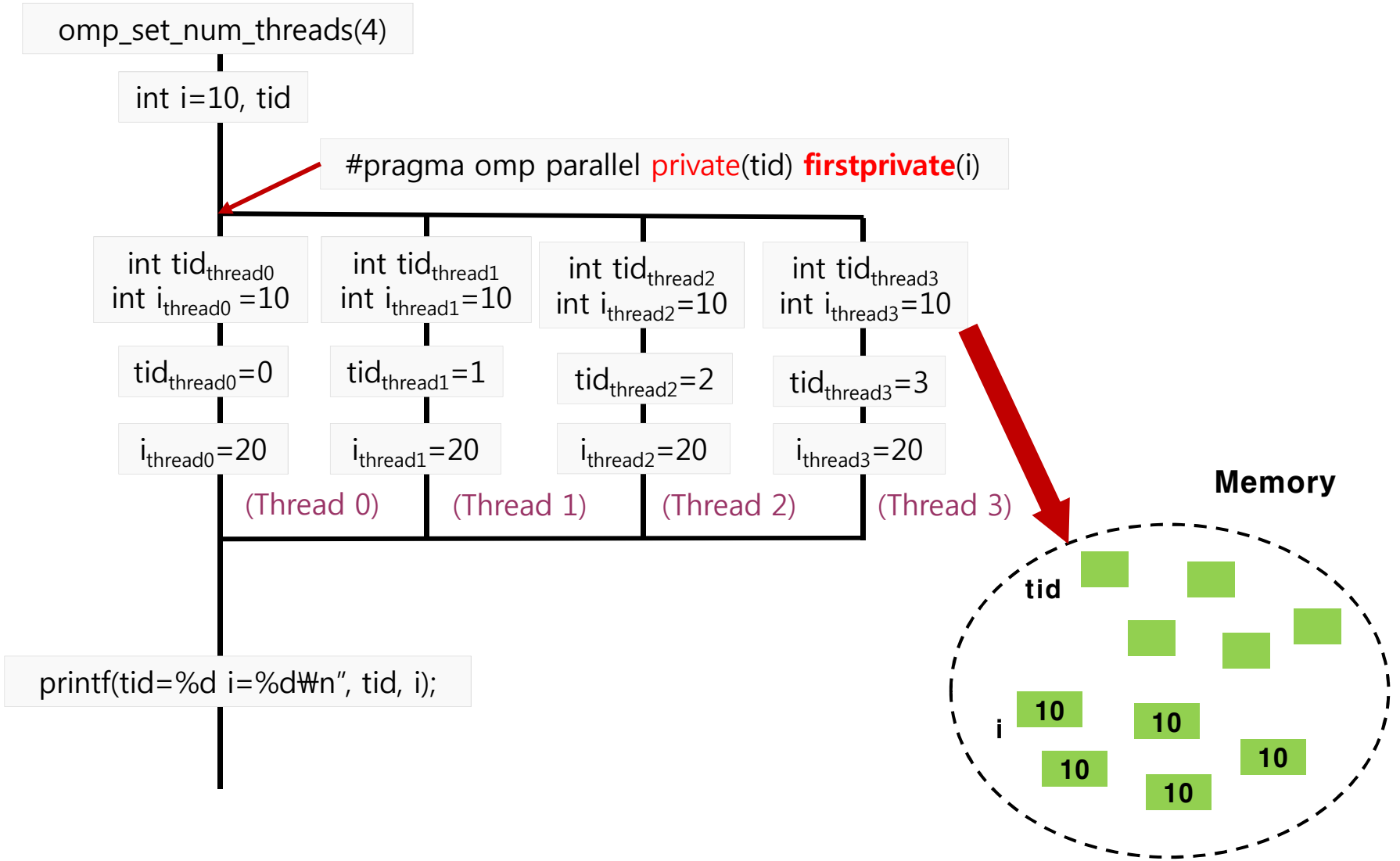
```
#include <stdio.h>
#include <omp.h>

int main()
{
      int i = 10, tid;

      omp_set_num_threads(4);
#pragma omp parallel private(tid) firstprivate(i)
{
      tid = omp_get_thread_num();
      printf (“tid = %d i = %d\n”, tid, i);
      i = 20;
}
      printf(“tid = %d i=%d\n”, tid, i);

      return 0;
}
```

```
$ gcc -fopenmp -o firstprivate.x firstprivate.c
$ ./firstprivate.x
```

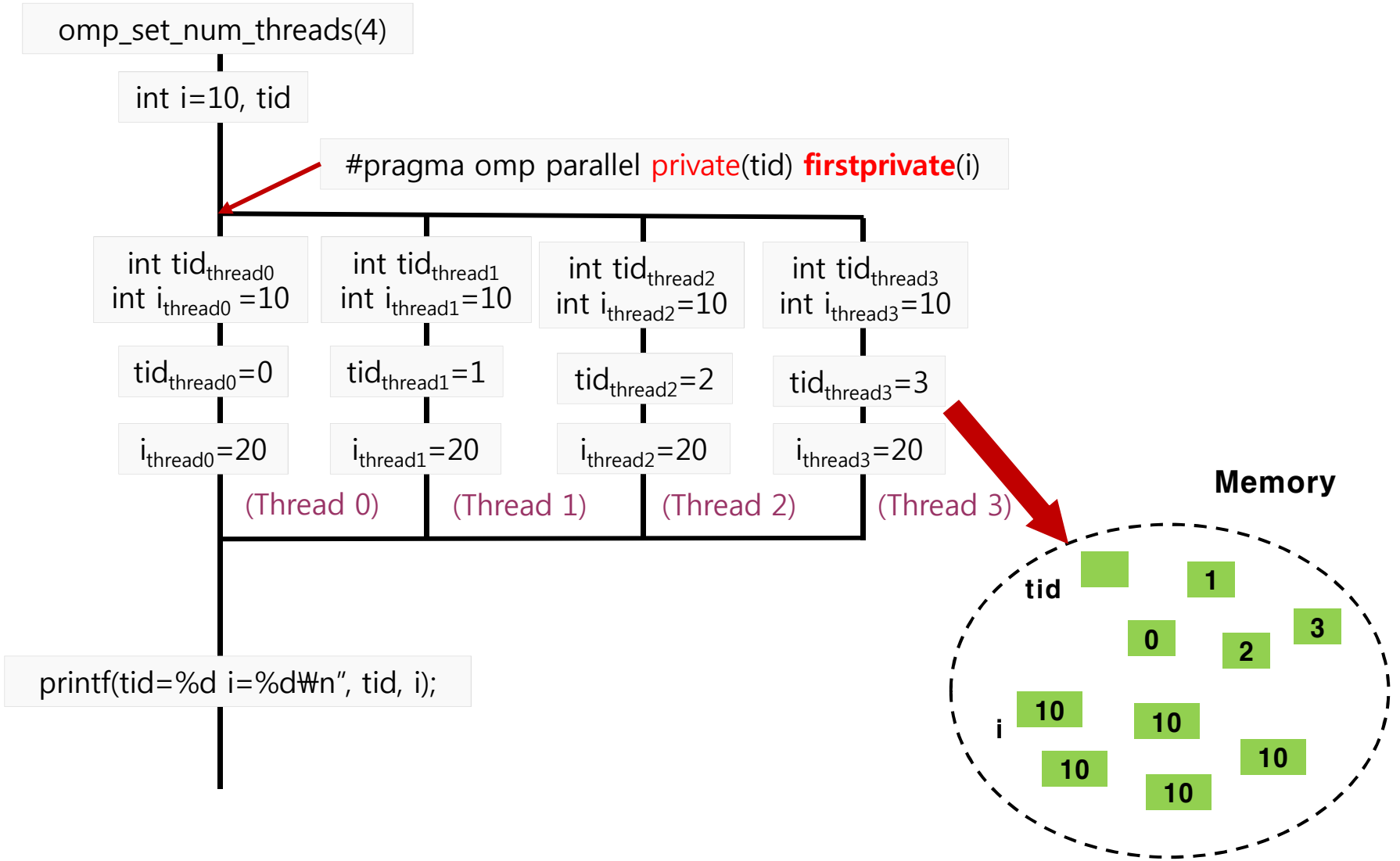
Data Scope Attribute (5/7)



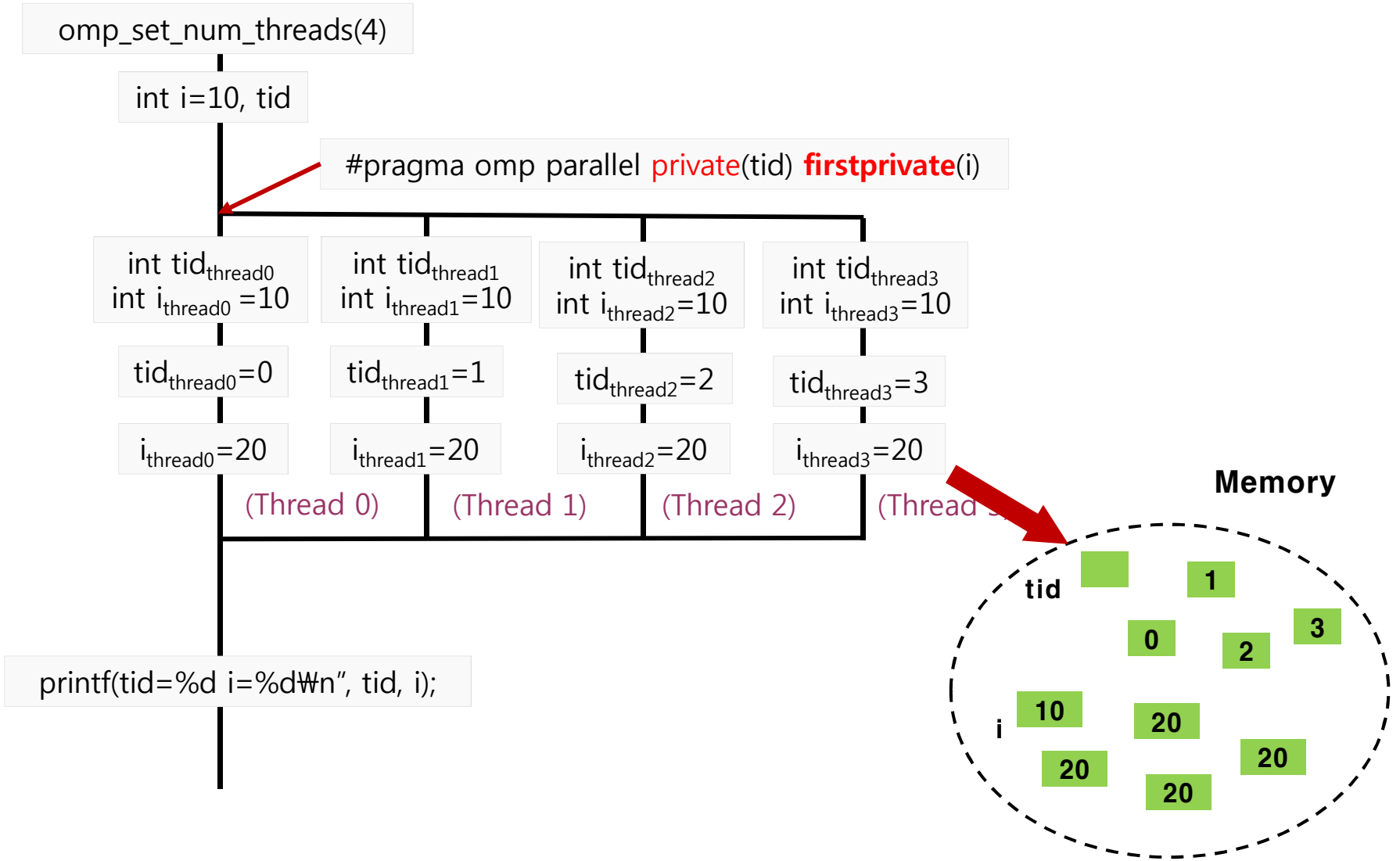
Data Scope Attribute (5/7)



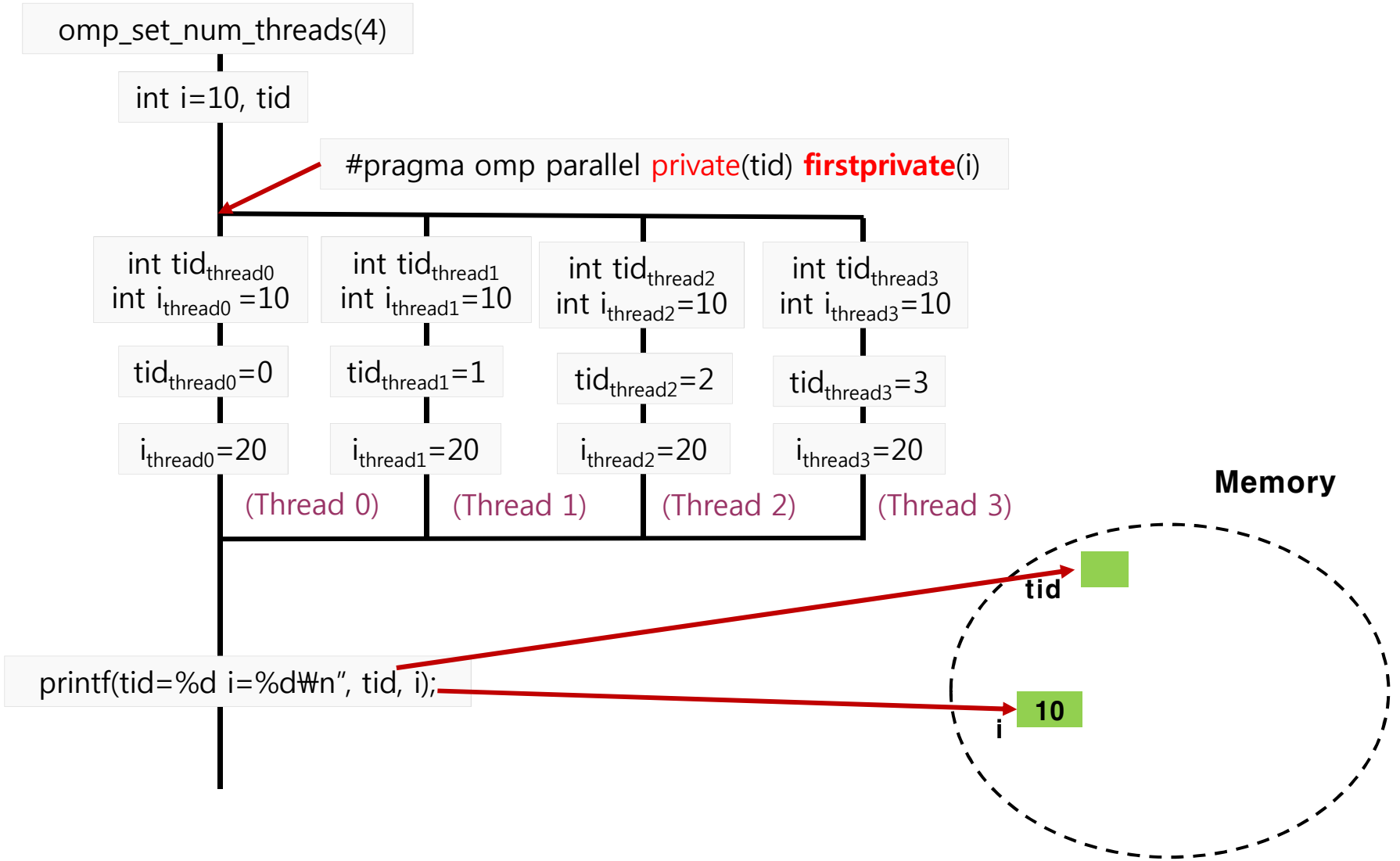
Data Scope Attribute (5/7)



Data Scope Attribute (5/7)



Data Scope Attribute (5/7)



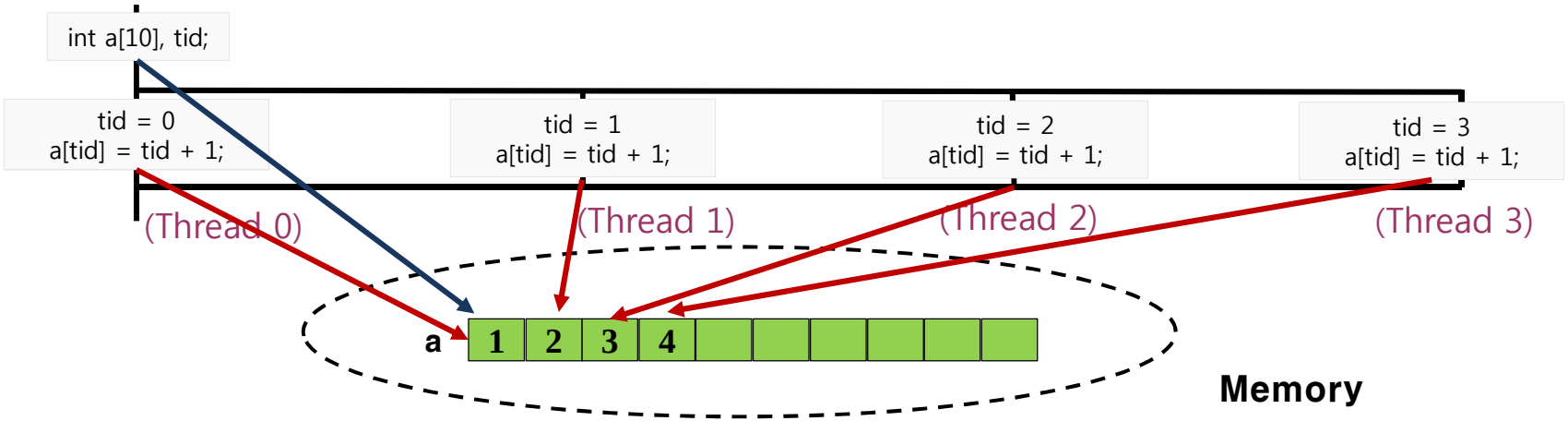
Data Scope Attribute (6/7)

Fortran

```
PROGRAM shared
      INTEGER a(0:9), tid, i, omp_get_thread_num

      CALL omp_set_num_threads(4)

!$OMP PARALLEL SHARED(a) PRIVATE(tid)
      tid = OMP_GET_THREAD_NUM()
      a(tid) = tid + 1
!$OMP END PARALLEL

      DO i=0, 3
         print *, 'a(', i, ') =', a(i)
      END DO

END
```

C

```
#include <stdio.h>
#include <omp.h>
int main()
{
      int a[10], tid, i;

      omp_set_num_threads(4);
#pragma omp parallel shared(a) private(tid)
{
      tid = omp_get_thread_num();
      a[tid] = tid + 1;
}
      for(i=0; i<4; i++)
      printf("a[%d] = %d\n", i, a[i]);

      return 0;
}
```



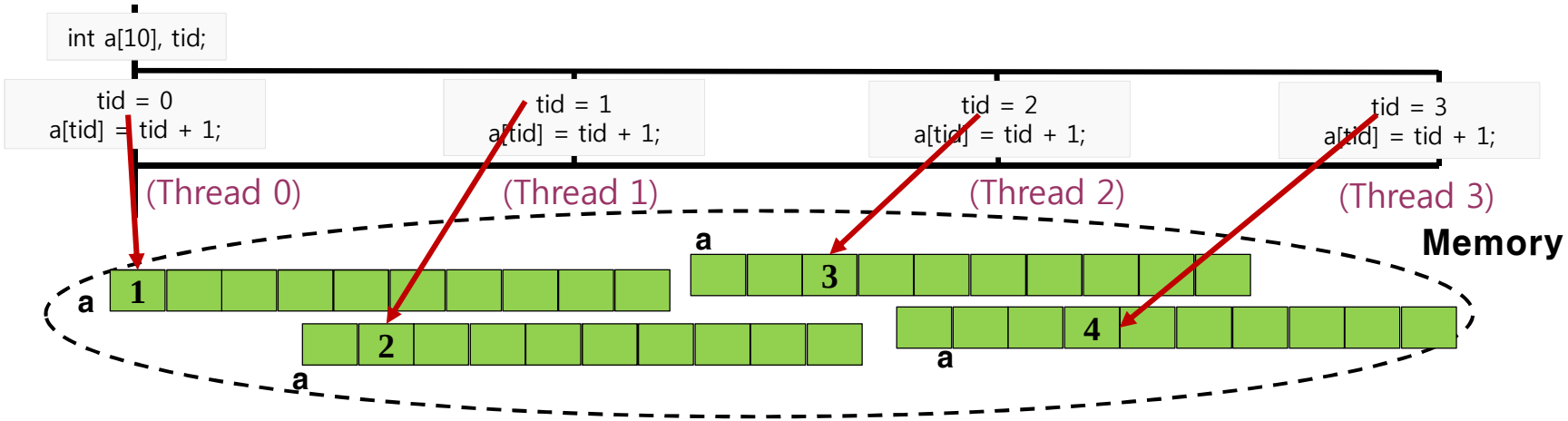
Data Scope Attribute (7/7)

Fortran

```
PROGRAM data_scope_private_array
      INTEGER a(0:9), tid, i, omp_get_thread_num

      CALL omp_set_num_threads(4)

!$OMP PARALLEL PRIVATE(a) PRIVATE(tid)
      tid = OMP_GET_THREAD_NUM()
      a(tid) = tid + 1
!$OMP END PARALLEL

      DO i=0, 3
            PRINT *, 'a(', i, ') =', a(i)
      END DO

END
```

C

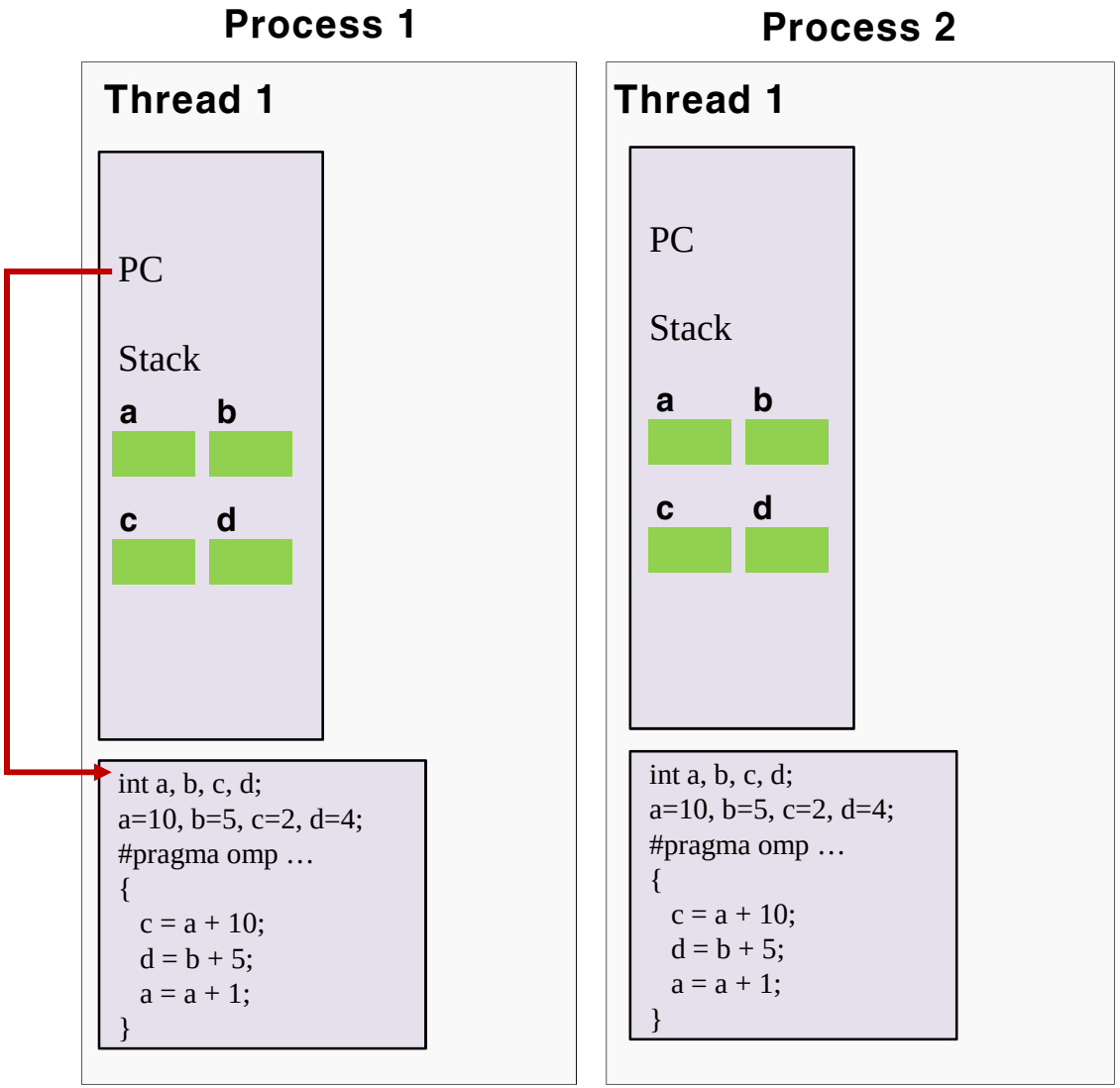
```
#include <stdio.h>
#include <omp.h>
int main()
{
      int a[10], tid, i;

      omp_set_num_threads(4);
#pragma omp parallel private(a) private(tid)
{
      tid = omp_get_thread_num();
      a[tid] = tid + 1;
}
      for(i=0; i<4; i++)
            printf("a[%d] = %d\n", i, a[i]);

      return 0;
}
```



Thread and Process

```
void foo()
{
  int a, b, c, d;
  a = 10;
  b = 5;
  c = 2;
  d = 4;

  #pragma omp parallel \
   private(c,d) \
   num_threads(2)
  {
    c = a + 10;
    d = b + 5;
    a = a + 1;
  }
}
```

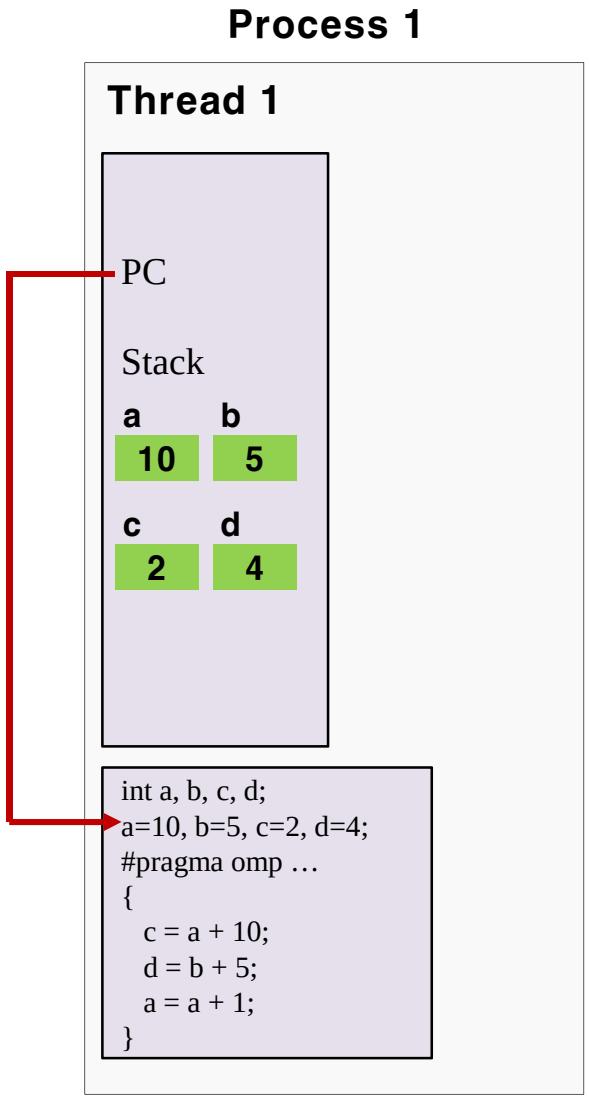
```
$ gcc  -fopenmp -o  foo.x  foo.c
$ ./foo.x
```



Thread and Process

```
void foo()
{
  int a, b, c, d;
  a = 10;
  b = 5;
  c = 2;
  d = 4;

  #pragma omp parallel \
   private(c,d) \
   num_threads(2)
  {
    c = a + 10;
    d = b + 5;
    a = a + 1;
  }
}
```

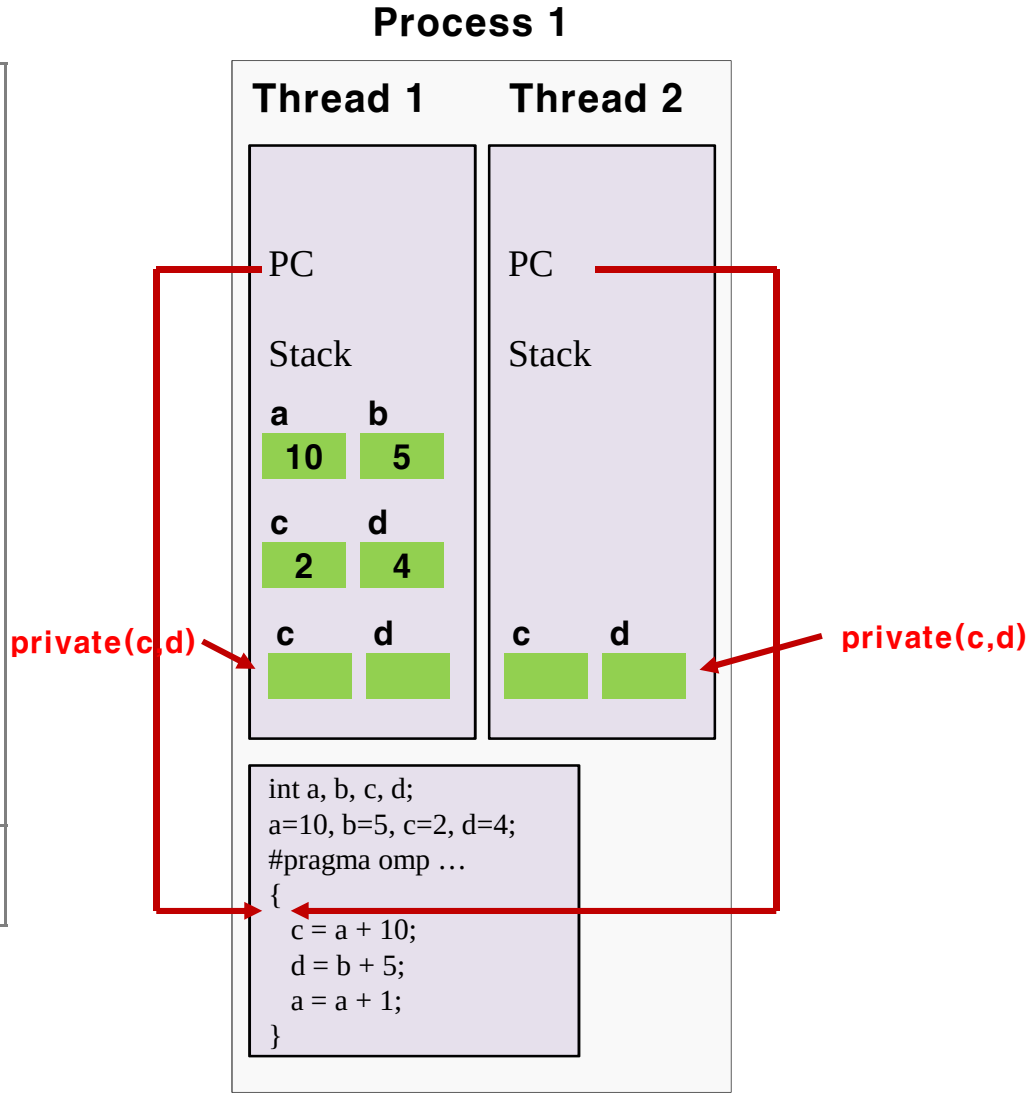
```
$ gcc  -fopenmp -o  foo.x  foo.c
$ ./foo.x
```



Thread and Process

```
void foo()
{
  int a, b, c, d;
  a = 10;
  b = 5;
  c = 2;
  d = 4;

  #pragma omp parallel \
    private(c,d) \
    num_threads(2)
  {
    c = a + 10;
    d = b + 5;
    a = a + 1;
  }
}
```

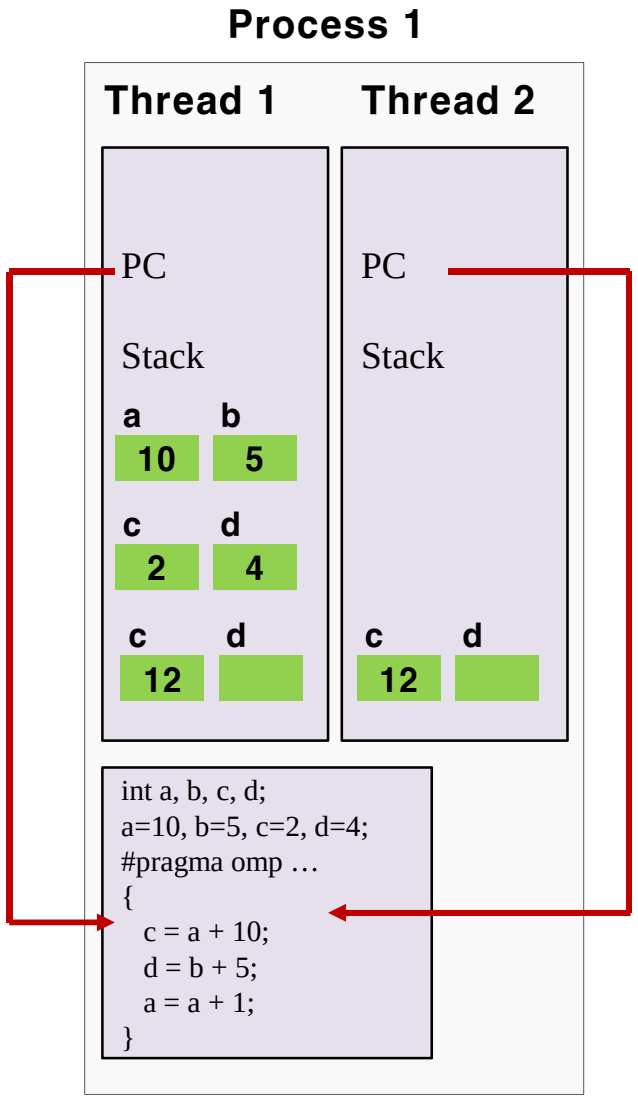
```
$ gcc  -fopenmp -o  foo.x  foo.c
$ ./foo.x
```



Thread and Process

```
void foo()
{
  int a, b, c, d;
  a = 10;
  b = 5;
  c = 2;
  d = 4;

  #pragma omp parallel \
   private(c,d) \
   num_threads(2)
  {
    c = a + 10;
    d = b + 5;
    a = a + 1;
  }
}
```

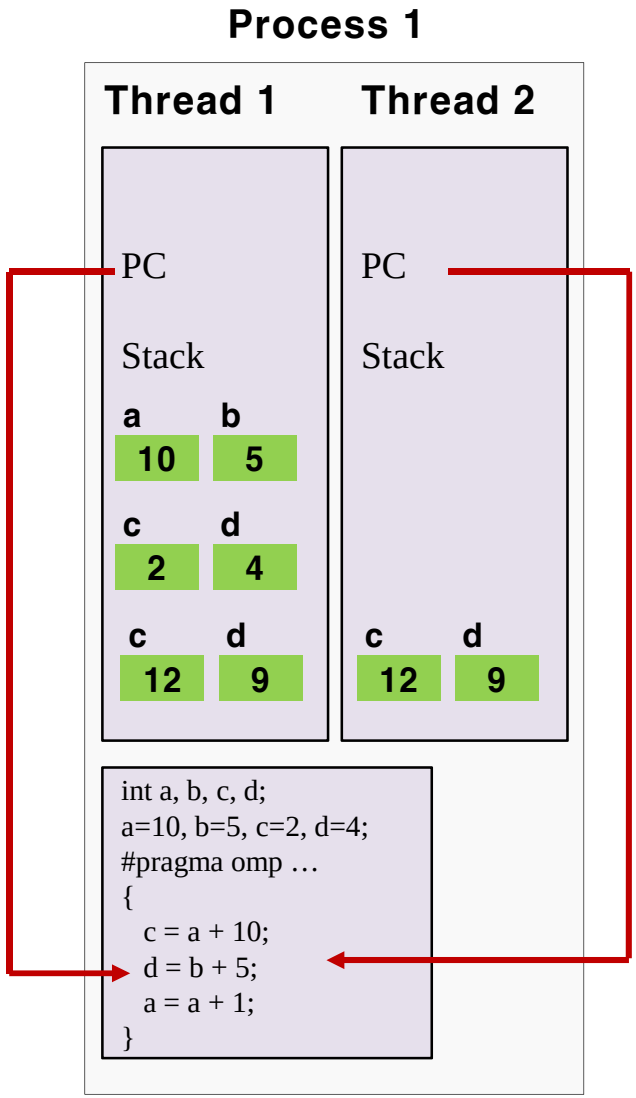
```
$ gcc  -fopenmp -o  foo.x  foo.c
$ ./foo.x
```



Thread and Process

```
void foo()
{
  int a, b, c, d;
  a = 10;
  b = 5;
  c = 2;
  d = 4;

  #pragma omp parallel \
   private(c,d) \
   num_threads(2)
  {
    c = a + 10;
    d = b + 5;
    a = a + 1;
  }
}
```

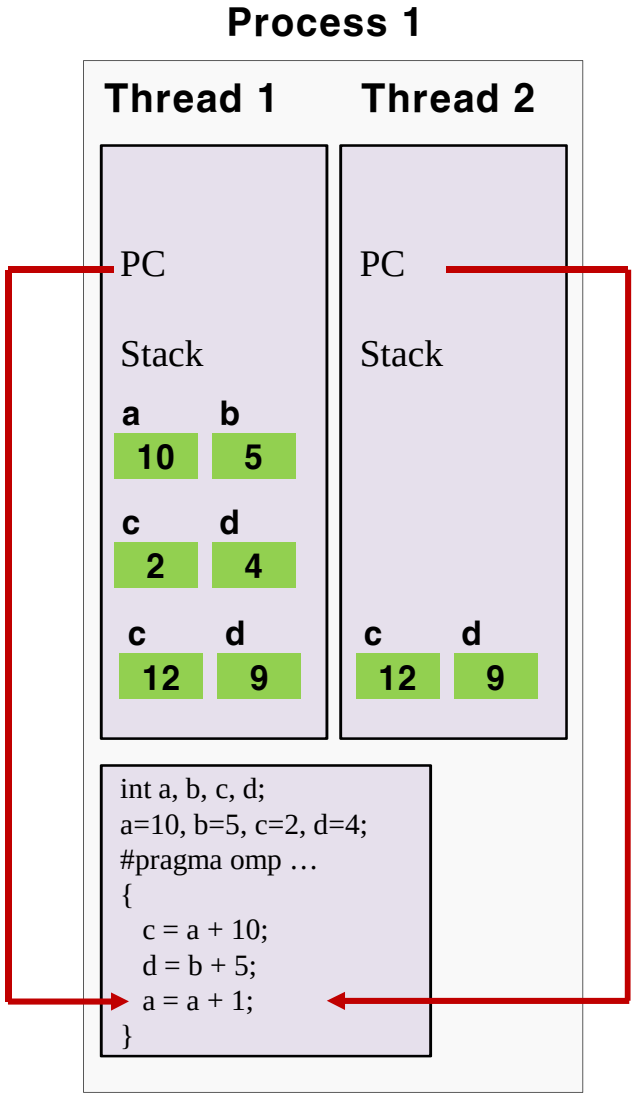
```
$ gcc  -fopenmp -o  foo.x  foo.c
$ ./foo.x
```



Thread and Process

```
void foo()
{
  int a, b, c, d;
  a = 10;
  b = 5;
  c = 2;
  d = 4;

  #pragma omp parallel \
   private(c,d) \
   num_threads(2)
  {
    c = a + 10;
    d = b + 5;
    a = a + 1;
  }
}
```

```
$ gcc  -fopenmp -o  foo.x  foo.c
$ ./foo.x
```



Thread 1

MEMORY :
a = 10
CPU :
a = 10 + 1
a = 11
MEMORY:
a = 11

Thread 2

MEMORY :
a = 10
CPU :
a = 10 + 1
a = 11
MEMORY :
a = 11

Thread 1

MEMORY:
a = 10
CPU :
a = 10 + 1
a = 11
MEMORY:
a = 11

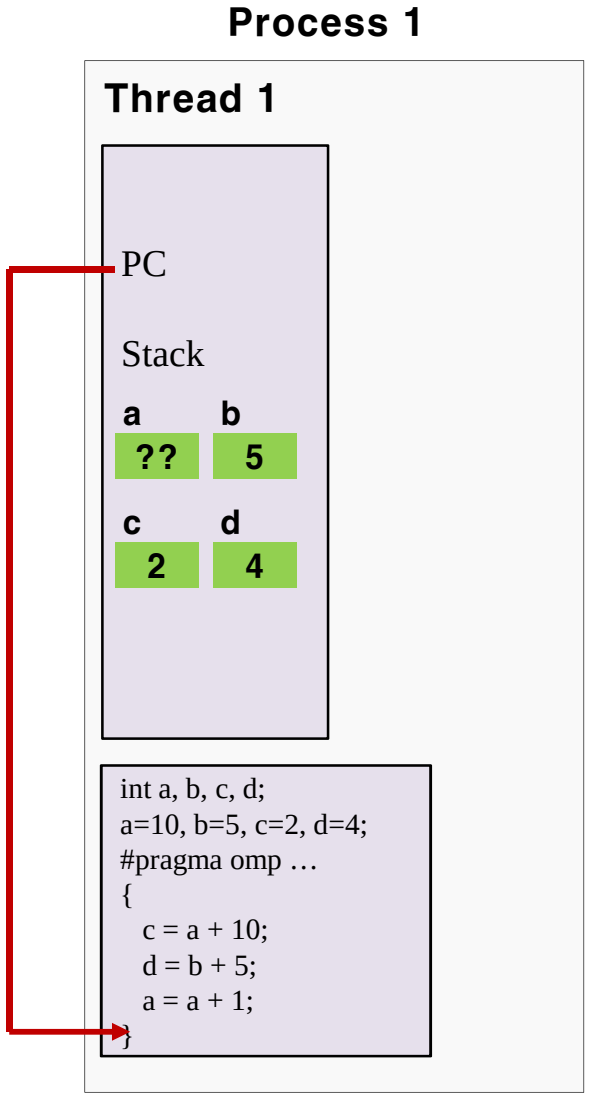
Thread 2

MEMORY:
a = 11
CPU :
a = 11 + 1
a = 12
MEMORY:
a = 12

Thread and Process

```
void foo()
{
  int a, b, c, d;
  a = 10;
  b = 5;
  c = 2;
  d = 4;

  #pragma omp parallel \
   private(c,d) \
   num_threads(2)
  {
    c = a + 10;
    d = b + 5;
    a = a + 1;
  }
}
```

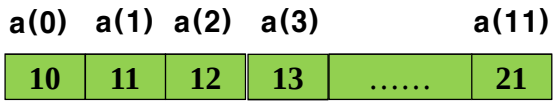
```
$ gcc  -fopenmp -o  foo.x  foo.c
$ ./foo.x
```



Data Scope Attribute (Exercise)

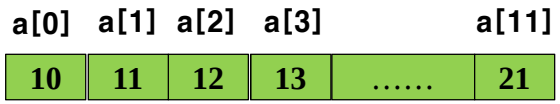
Fortran

```
PROGRAM data_scope_exercise

      INTEGER :: i=10,  a(0:11),  tid, …

      !! create 4 threads
      !! assign a rray index + I to each element of array
      !! ex) a(0) = 10, a(1) = 11, a(2) = 12, … , a(11) = 21

      DO i=0, 11
            PRINT *, ‘a(‘, i, ‘) =‘, a(i)
      END DO

END
```



C

```
#include <stdio.h>
#include <omp.h>

int main()
{
      int i=10, a[12], tid;

      // create 4 threads
      // assign array index + i to each element of array
      // ex) a[0] = 10, a[1] = 11, a[2] = 12, …, a[11] = 21

      for(i=0; i<12; i++)
      printf(“a[%d]=%d\n”, i, a[i]);

      return 0;
}
```



Data Scope Attribute (Solution)

Fortran

```
PROGRAM data_scope_sol
      INTEGER :: i=10, a(0:11), tid, omp_get_thread_num

      CALL omp_set_num_threads(4)

!$OMP PARALLEL shared(a) private(tid) firstprivate(i)
      tid = omp_get_thread_num()
      i = i + tid
      a(tid+0) = i+0;   a(tid+4) = i+4;   a(tid+8) = i+8
!$OMP END PARALLEL
!!! or
!$OMP PARALLEL shared(a) private(tid) firstprivate(i)
      tid = omp_get_thread_num() * 3
      i = i +tid
      a(tid+0) = i+0;  a(tid+1) = i+1;  a(tid+2) = i+2
!$OMP END PARALLEL

      DO i=0, 11
            PRiNT *, 'a(', i, ') =', a(i)
      END DO

END
```

```
$ gfortran -fopenmp -o data_scope_sol.x data_scope_sol.f90
$ ./data_scope_solution.x
```

C

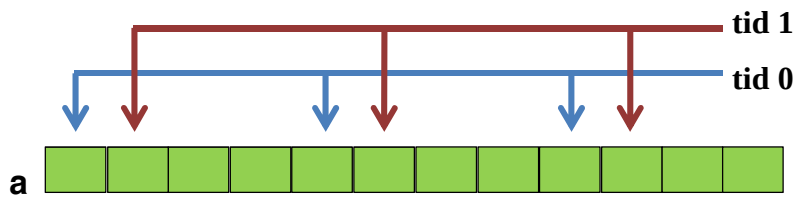
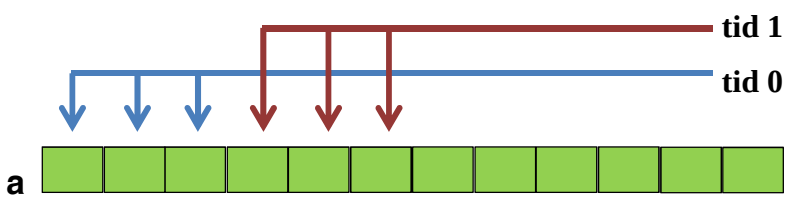
```
#include <stdio.h>
#include <omp.h>

int main()
{
      int i=10, a[12], tid;

      omp_set_num_threads(4);
#pragma omp parallel shared(a) private(tid) firstprivate(i)
{
      tid = omp_get_thread_num();
      i = i + tid;
      a[tid+0] = i+0;   a[tid+4] = i+4;  a[tid+8] = i+8;
}
  // or
#pragma omp parallel shared(a) private(tid) firstprivate(i)
{
      tid = omp_get_thread_num() * 3;
      i = i + tid;
      a[tid+0] = i+0;   a[tid+1] = i+1;  a[tid+2] = i+2;
}

      for(i=0; i<12; i++)
            printf("a[%d]=%d\n", i, a[i]);

      return 0;
}
```

```
$ gcc -fopenmp -o data_scope_sol.x data_scope_sol.c
$ ./data_scope_solution.x
```

Data Scope Attribute (Solution)

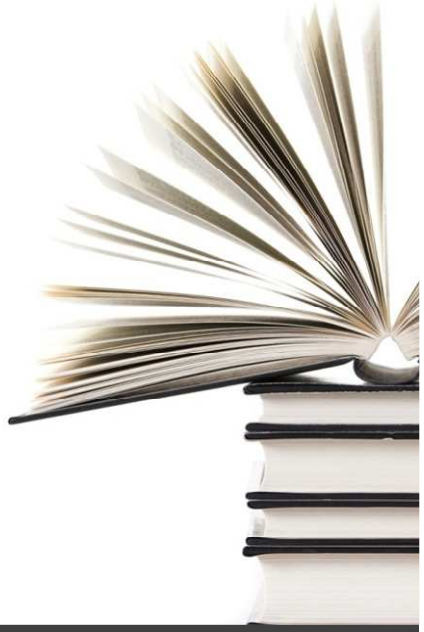
Fortran	C

[method 1]
tid = omp_get_thread_num()
i = i + tid
a(tid+0) = i+0; a(tid+4) = i+4; a(tid+8) = i+8
 	
[method 2]
tid = omp_get_thread_num() * 3
i = i +tid
a(tid+0) = i+0; a(tid+1) = i+1; a(tid+2) = i+2
	[method 1]
	tid = omp_get_thread_num();
	i = i + tid;
	a[tid+0] = i+0; a[tid+4] = i+4; a[tid+8] = i+8;
	
	[method 2]
	tid = omp_get_thread_num() * 3;
	i = i + tid;
	a[tid+0] = i+0; a[tid+1] = i+1; a[tid+2] = i+2;

[method 1] 	[method 2] 

OpenMP Basics II

1. Parallel Loops
2. Synchronization



Parallel Loops

Fortran	C

PROGRAM serial_loop
 	
INTEGER, PARAMETER :: N=20
 	
INTEGER :: tid=0, i, istart=0, iend=N-1
 	
DO i=istart, iend
 	
PRINT *, 'Hello World', tid, i
 	
END DO
 	
END
	#include <stdio.h>
	
	#define N 20
	
	int main()
	{
	int tid = 0;
	int i;
	int istart=0, iend=N;
	
	for(i=istart; i<iend; i++)
	printf("Hello World %d %d\n", tid, i);
	
	return 0;
	}

$ gfortran -fopenmp -o serial_loop.x serial_loop.f90 $ ./serial_loop.x	$ gcc -fopenmp -o serial_loop.x serial_loop.c $ ./serial_loop.x

Parallel Loops

Fortran

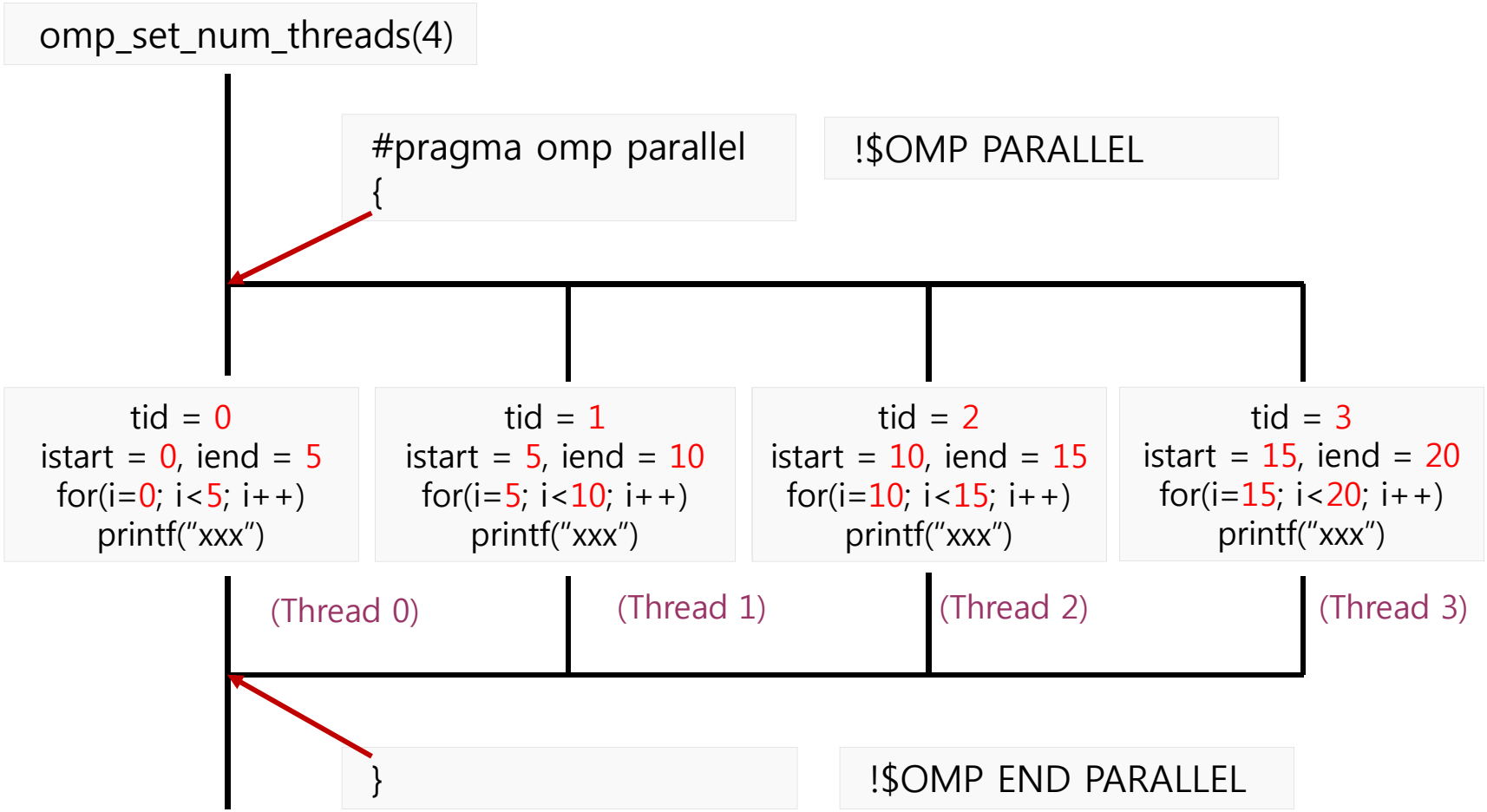
```
PROGRAM parallel_loop
      INTEGER, PARAMETER :: N=20
      INTEGER :: tid, i, istart, iend, omp_get_thread_num

      call omp_set_num_threads(4)
!$OMP PARALLEL private(tid, istart, iend)
      tid = omp_get_thread_num()
      istart=???; iend=???   !! hint : tid, N, 4
      DO i=istart, iend
            PRINT *, 'Hello World', tid, i
      END DO
!$OMP END PARALLEL

END
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int  tid,  i,  istart,  iend

      omp_set_num_threads(4);
#pragma omp parallel private(i, tid, istart, iend)
{
      tid = omp_get_thread_num();
      istart=???, iend=???;  // hint : tid, N, 4
      for(i=istart; i<iend; i++)
            printf("Hello World %d %d\n", tid, i);
}
      return 0;
}
```

```
Hello World 0 0     Hello World 1 5     Hello World 2 10    Hello World 3 15
Hello World 0 1     Hello World 1 6     Hello World 2 11    Hello World 3 16
Hello World 0 2     Hello World 1 7     Hello World 2 12    Hello World 3 17
Hello World 0 3     Hello World 1 8     Hello World 2 13    Hello World 3 18
Hello World 0 4     Hello World 1 9     Hello World 2 14    Hello World 3 19
```

Parallel Loops



Parallel Loops

Fortran	C

PROGRAM parallel_loop1
  INTEGER, PARAMETER :: N=20
 	
  INTEGER::tid, i, istart, iend, omp_get_thread_num
 	
  CALL omp_set_num_threads(4)
 	
!$OMP PARALLEL private(i, tid, istart, iend)
  tid = omp_get_thread_num()
 	
  istart = tid * N / 4
  iend = (tid+1) * N / 4 - 1
 	
  DO i=istart, iend
  PRINT *, 'Hello World', tid, i
  END DO
!$OMP END PARALLEL
 	
END
	#include <stdio.h>
	#include <omp.h>
	#define N 20
	
	int main()
	{
	  int i, tid, istart, iend;
	
	  omp_set_num_threads(4);
	
	#pragma omp parallel private(i, tid, istart, iend)
	{
	  tid = omp_get_thread_num();
	
	  istart= tid * N / 4;
	  iend= (tid+1) * N / 4;
	
	  for(i=istart; i<iend; i++)
	  printf("Hello World %d %d\n", tid, i);
	}
	  return 0;
	}

$ gfortran -fopenmp -o parallel_loop1.x parallel_loop1.f90 $ ./parallel_loop1.x	$ gcc -fopenmp -o parallel_loop1.x parallel_loop1.c $ ./parallel_loop1.x

Parallel Loops

Fortran	C

PROGRAM parallel_loop2
INTEGER, PARAMETER :: N=20
 	
INTEGER :: tid, i, istart, iend, nthreads, &
omp_get_thread_num, omp_get_num_threads
 	
CALL omp_set_num_threads(4)
!$OMP PARALLEL private(i, tid, istart, iend)
tid = omp_get_thread_num()
nthreads = omp_get_num_threads()
 	
istart = tid * N / nthreads
iend = (tid+1) * N / nthreads - 1
 	
DO i=istart, iend
PRINT *, 'Hello World', tid, i
END DO
!$OMP END PARALLEL
 	
END
	#include <stdio.h>
	#include <omp.h>
	#define N 20
	
	int main()
	{
	int i, tid, istart, iend, nthreads;
	omp_set_num_threads(4);
	#pragma omp parallel private(i,tid, istart, iend)
	{
	tid = omp_get_thread_num();
	nthreads = omp_get_num_threads();
	
	istart= tid * N / nthreads;
	iend= (tid+1) * N / nthreads;
	
	for(i=istart; i<iend; i++)
	printf("Hello World %d %d\n", tid, i);
	}
	return 0;
	}

$ gfortran -fopenmp -o parallel_loop2.x parallel_loop2.f90 $ ./parallel_loop2.x	$ gcc -fopenmp -o parallel_loop2.x parallel_loop2.f90 $ ./parallel_loop2.x

Parallel Loops

Fortran

```
PROGRAM parallel_loop
      INTEGER, PARAMETER  :: N=20

      INTEGER  :: tid, i, istart, iend, nthreads &
      omp_get_thread_num, omp_get_num_threads

      call omp_set_num_threads(4)
!$OMP PARALLEL private(i,tid, istart, iend)
      tid = omp_get_thread_num()
      nthreads = omp_get_num_threads()

      istart = tid*N / nthreads
      iend = (tid+1)*N / nthreads - 1

      DO i=0istart, N-1iend
            PRINT *, 'Hello World', tid, i
      END DO
!$OMP END PARALLEL

END
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int i, tid, istart, iend, nthreads;

      omp_set_num_threads(4);
#pragma omp parallel private(i,tid, istart, iend)
{
      tid = omp_get_thread_num();
      nthreads = omp_get_num_threads();
      istart= tid * N / nthreads;
      iend= (tid+1) * N / nthreads;
      for(i=0istart; i<Niend; i++)
            printf("Hello World %d %d\n", tid, i);
}
      return 0;
}
```

Break!!

Parallel Loops

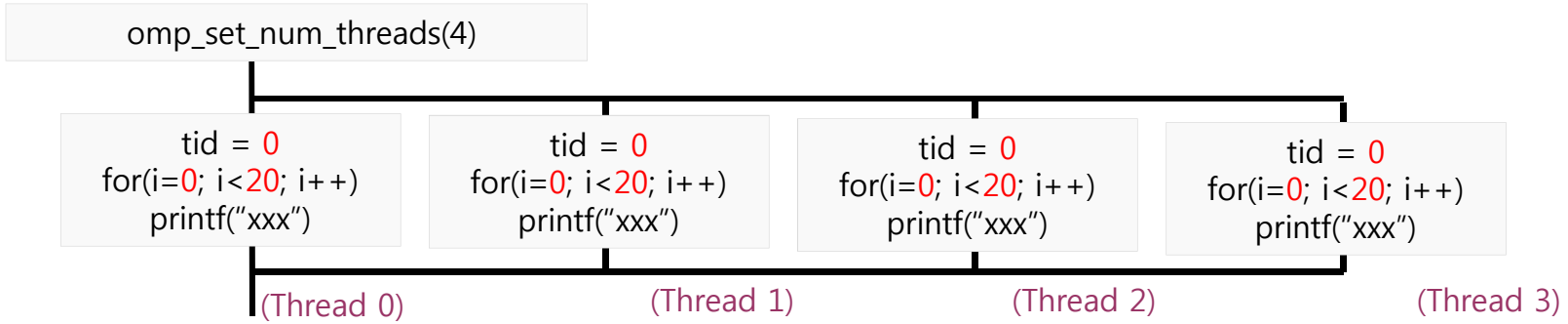
Fortran	C

PROGRAM parallel_for
INTEGER, PARAMETER :: N=20
INTEGER :: tid, i, omp_get_thread_num
 	
CALL omp_set_num_threads(4)
!$OMP PARALLEL private(tid) !!! i : shared??
tid = omp_get_thread_num()
 	
!$OMP DO
DO i=0, N-1
PRINT *, 'Hello World', tid, i
END DO
!$OMP END DO !!![optional]
!$OMP END PARALLEL
 	
END
	#include <stdio.h>
	#include <omp.h>
	#define N 20
	
	int main()
	{
	int tid, i;
	
	omp_set_num_threads(4);
	#pragma omp parallel private(tid) // i : shared?
	{
	tid = omp_get_thread_num();
	#pragma omp for
	for(i=0; i<N; i++)
	printf("Hello World %d %d\n", tid, i);
	}
	return 0;
	}

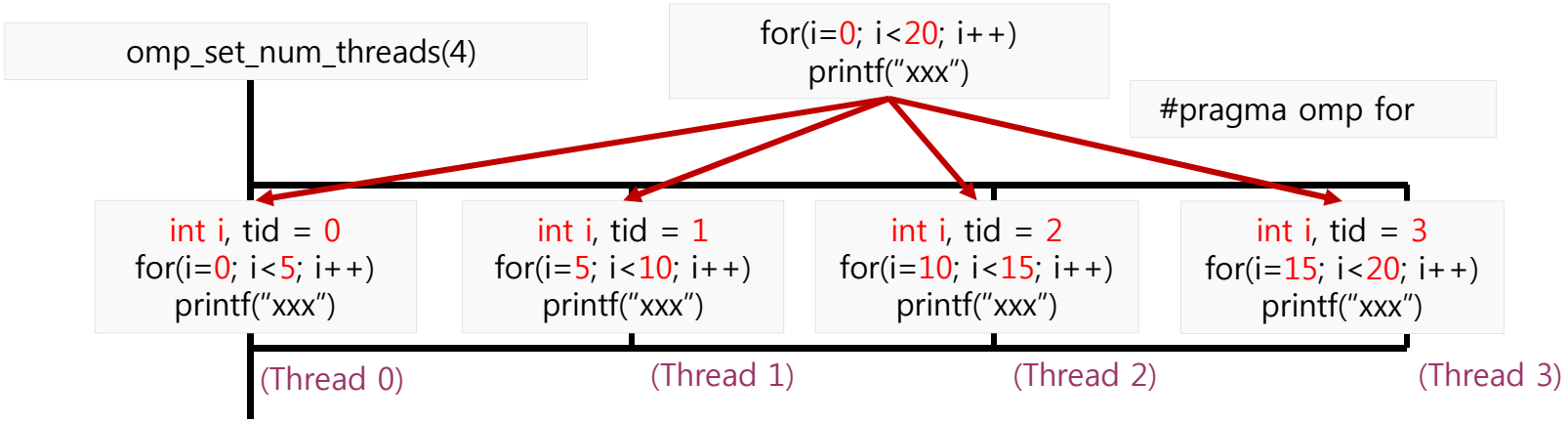
$ gfortran -fopenmp -o parallel_for.x parallel_for.f90 $ ./parallel_for.x	$ gcc -fopenmp -o parallel_for.x parallel_for.c $ ./parallel_for.x

Parallel Loops

- Without #pragma omp for



- With #pragma omp for



Parallel Loops

Fortran	C

!$OMP PARALLEL private(tid)
tid = omp_get_thread_num()
DO i=0, N-1
print *, “Hello World”, tid, i
END DO
!$OMP END PARALLEL
	#pragma omp parallel private(tid)
	{
	tid = omp_get_thread_num();
	
	for(i=0; i<N; i++)
	printf(“Hello World %d %d\n”, tid, i);
	}

!$OMP PARALLEL private(tid)
tid = omp_get_thread_num()
!$OMP DO
DO i=0, N-1
print *, “Hello World”, tid, i
END DO
!$OMP END DO [optional]
!$OMP END PARALLEL
	#pragma omp parallel private(tid)
	{
	tid = omp_get_thread_num();
	#pragma omp for
	for(i=0; i<N; i++)
	printf(“Hello World %d %d\n”, tid, i);
	}

- **Work Sharing**
  - Distribution of work across threads
  - **Do/for**, Sections/section, Single, Task construct, etc.
  - cf) SPMD (Single Program Multiple Data), WORKSHARE clause in Fortran

Parallel Loops

Fortran	C

!$OMP PARALLEL
!$OMP DO
DO i=0, N-1
print *, “Hello World”, i
END DO
!$OMP END DO
!$OMP END PARALLEL
	#pragma omp parallel
	{
	#pragma omp for
	for(i=0; i<N; i++)
	printf(“Hello World %d \n”, i);
	}

!$OMP PARALLEL DO
DO i=0, N-1
print *, “Hello World”, i
END DO
!$OMP END PARALLEL DO
	#pragma omp parallel for
	for(i=0; i<N; i++)
	printf(“Hello World %d %d\n”, i);

- **OpenMP shortcut**
  - Combined parallel/worksharing construct

Parallel Loops - Inner(dot) Product (Serial)

Fortran	C

PROGRAM inner_product
 	
INTEGER, PARAMETER :: N=20
INTEGER :: i, sum=0
INTEGER, DIMENSION(0:N-1) :: A, B
 	
DO i=0, N-1
A(i) = i+1
B(i) = i+2
ENDDO
 	
DO i=0, N-1
sum = sum + A(i) * B(i)
END DO
 	
print *, “sum =“, sum
 	
END
	#include <stdio.h>
	#include <omp.h>
	#define N 20
	
	int main()
	{
	int i, sum=0;
	int a[N], b[N];
	
	for (i=0; i<N; i++) {
	a[i] = i+1;
	b[i] = i+2;
	}
	
	for (i=0; i<N; i++)
	sum += a[i] * b[i];
	
	printf(“sum = %d\n”, sum);
	
	return 0;
	}

$ gfortran -fopenmp -o inner_product.x inner_product.f90 $ inner_product.x	$ gcc -fopenmp -o inner_product.x inner_product.f90 $ inner_product.x

Parallel Loops - Inner(dot) Product (Parallel)

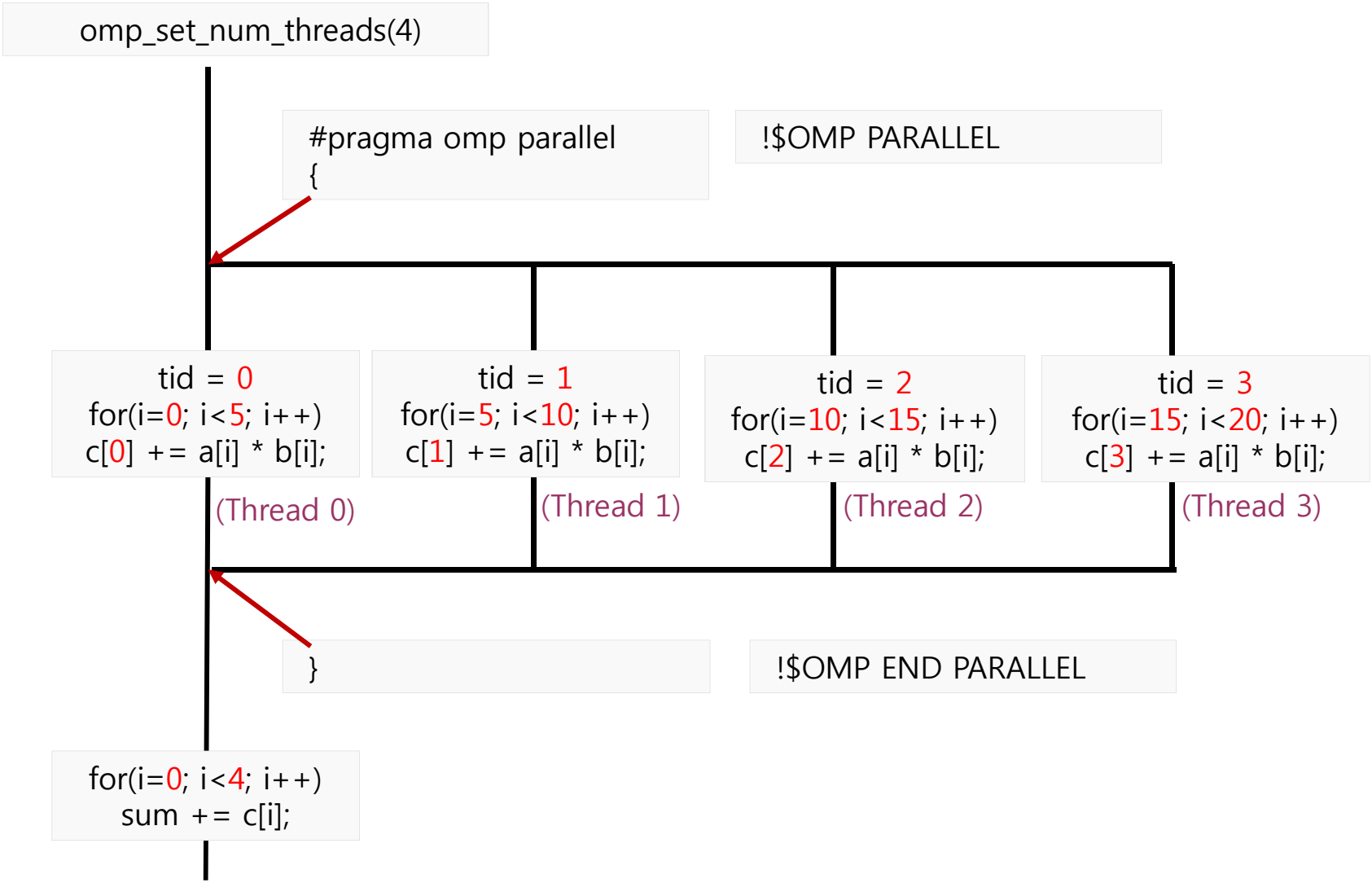
Fortran

```
PROGRAM inner_product

      INTEGER, PARAMETER :: N=20
      INTEGER :: i, tid, sum=0
      INTEGER, DIMENSION(0:N-1) :: A, B
      INTEGER, DIMENSION(0:3)  :: C

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      ENDDO
!! set # of threads = 4
!! create threads
      tid = !! get thread index
      C(tid) = 0
!! worksharing
      DO i=0, N-1
            C(tid) = C(tid) + A(i) * B(i)
      END DO
!! join threads
      DO i=0, 3
            sum = sum+C(i)
      END DO
      PRINT *, "sum =", sum

END
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int i, tid, sum=0;
      int a[N], b[N], c[4];

      for(i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
      }
// set # of threads = 4
// create threads
{
      tid = // get thread index
      c[tid] = 0;
// worksharing
      for(i=0; i<N; i++)
            c[tid] += a[i] * b[i];
}
      for(i=0; i<4; i++)
            sum += c[i];

      printf("sum = %d\n", sum);
}
      return 0;
}
```

Parallel Loops



Parallel Loops - BLAS1 Inner(dot) Product

Fortran

```
PROGRAM inner_product_omp
      INTEGER, PARAMETER :: N=20

      INTEGER :: i, tid, sum=0,  omp_get_thread_num
      INTEGER, DIMENSION(0:N-1) :: A, B
      INTEGER, DIMENSION(0:3)  :: C

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      END DO

      CALL omp_set_num_threads(4)
!$OMP PARALLEL private(tid)
      tid = omp_get_thread_num()
      C(tid) = 0
      !$OMP DO
      DO i=0, N-1
            C(tid) = C(tid) + A(i) * B(i)
      END DO
!$OMP END PARALLEL

      DO i=0, 3
            sum = sum+C(i)
      END DO
      PRINT *, “sum =“, sum

END
```

```
$ gcc  -fopenmp  -o  inner_product.x  inner_product.f90
$ ./inner_product_omp.x
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int i, tid, sum=0;
      int a[N], b[N],c[4];

      for(i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
   }
omp_set_num_threads(4);
#pragma omp parallel private(tid)
{
      tid = omp_get_thread_num();
      c[tid] = 0;
#pragma omp for
      for(i=0; i<N; i++)
            c[tid] += a[i] * b[i];
}
      for(i=0; i<4; i++)
            sum += c[i];

      printf(“sum = %d\n”, sum);

      return 0;
}
```

```
$ gcc -fopenmp -o inner_product_omp.x inner_product_omp.c
$ ./inner_product_omp.x
```

Synchronization - BLAS1 Inner(dot) Product

Fortran

```
PROGRAM inner_product_omp2
      INTEGER, PARAMETER :: N=20

      INTEGER :: i, tid, sum, omp_get_thread_num
      INTEGER, DIMENSION(0:N-1) :: A, B
      INTEGER, DIMENSION(0:3)  :: C

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      END DO

      CALL omp_set_num_threads(4)
!$OMP PARALLEL private(tid)
      tid = omp_get_thread_num()
      C(tid) = 0
!$OMP DO
      DO i=0, N-1
            sum = sum + A(i) * B(i)
      END DO
!$OMP END PARALLEL

      DO i=0, 3
            sum = sum+C(i)
      END DO
      PRINT *, “sum =“, sum

END
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int i, tid, sum=0;
      int a[N], b[N],c[4];

      for(i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
      }
omp_set_num_threads(4);
#pragma omp parallel private(tid)
{
      tid = omp_get_thread_num();
      c[tid] = 0;
#pragma omp for
      for(i=0; i<N; i++)
            c[tid] sum += a[i] * b[i];
}
      for(i=0; i<4; i++)
            sum += c[i];

      printf(“sum = %d\n”, sum);

      return 0;
}
```

Synchronization - BLAS1 Inner(dot) Product

Fortran

```
PROGRAM wrong_inner_prod
      INTEGER, PARAMETER :: N=20

      INTEGER :: i, sum=0
      INTEGER, DIMENSION(0:N-1) :: A, B

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      END DO

      CALL omp_set_num_threads(4)
!$OMP PARALLEL
!$OMP DO
      DO i=0, N-1
            sum = sum + A(i) * B(i)
      END DO
!$OMP END PARALLEL
      PRINT *, “sum =“, sum

END
```

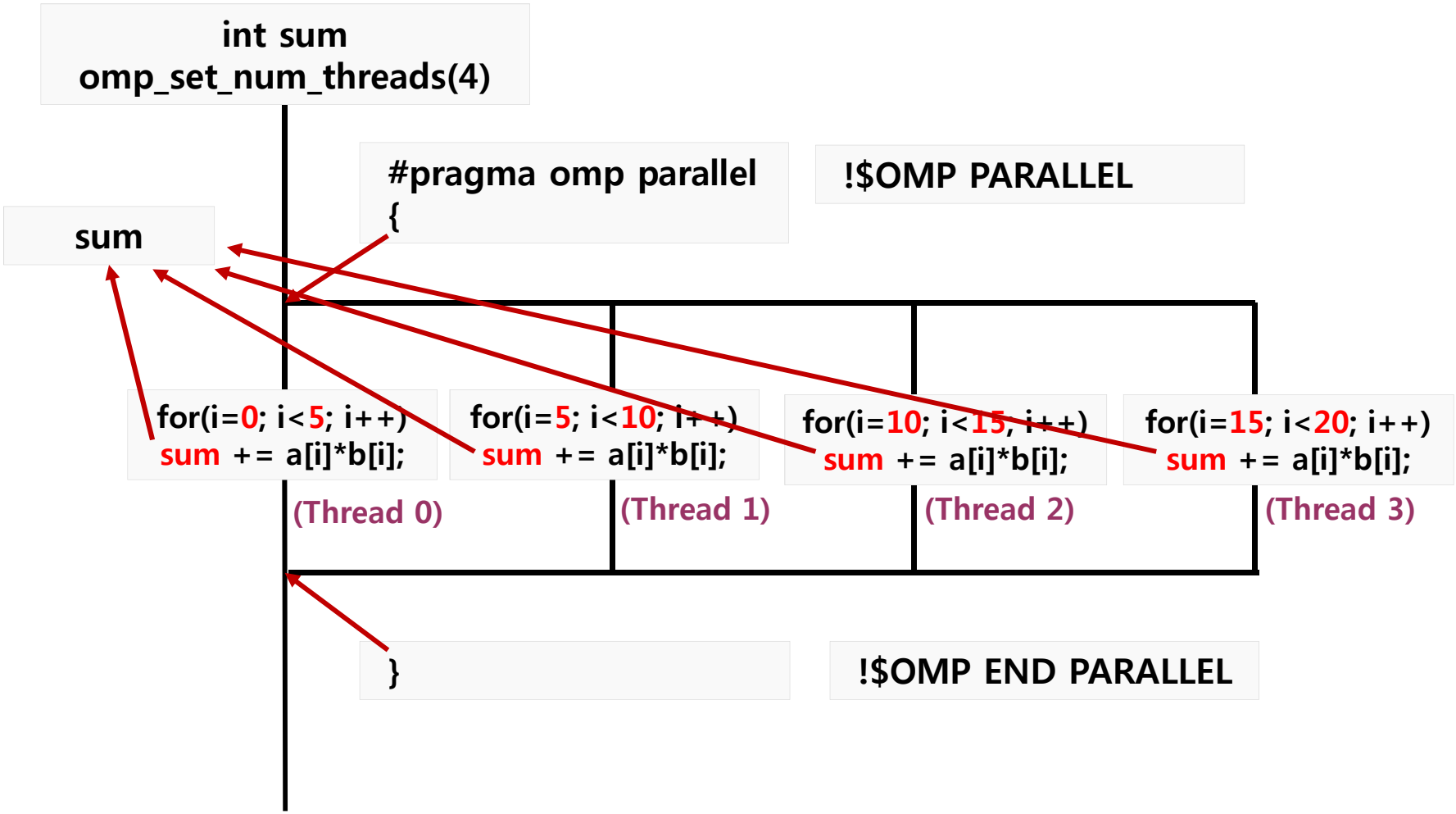
```
$ gfortran -fopenmp -o wrong_inner_prod.x wrong_inner_prod.f90
$ ./ wrong_inner_prod.x
( Different results value when repeated run.)
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int i, sum=0;
      int a[N], b[N];
      for(i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
      }
omp_set_num_threads(4);
#pragma omp parallel
{
#pragma omp for
      for(i=0; i<N; i++)
            sum += a[i] * b[i];
}
      printf(“sum = %d\n”, sum);

      return 0;
}
```

```
$ gcc -fopenmp -o wrong_inner_prod.x wrong_inner_prod.c
$ ./wrong_inner_prod.x
( Different results value when repeated run.)
```

Synchronization



Synchronization - BLAS1 Inner(dot) Product

Fortran

```
PROGRAM inner_prod_critical
      IMPLICIT NONE
      INTEGER, PARAMETER :: N=20
      INTEGER :: i, sum=0
      INTEGER, DIMENSION(0:N-1) :: A, B

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      END DO

      CALL omp_set_num_threads(4)
!$OMP PARALLEL
      !$OMP DO
      DO i=0, N-1
            !$OMP CRITICAL
            sum = sum + A(i) * B(i)
            !$OMP END CRITICAL
      END DO
!$OMP END PARALLEL

      PRINT *, “sum =“, sum

END
```

```
$ gfortran -fopenmp -o inner_prod_critical.x inner_prod_critical.f90
$ ./inner_prod_critical.x
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int i, sum=0;
      int a[N], b[N];

      for(i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
      }
omp_set_num_threads(4);
#pragma omp parallel
{
#pragma omp for
      for (i=0; i<N; i++)
#pragma omp critical (name1)
            sum += a[i] * b[i];
}
      printf(“sum = %d\n”, sum);

      return 0;
}
```

```
$ gcc -fopenmp -o inner_prod_critical.x inner_prod_critical.c
$ ./inner_prod_critical.x
```

Synchronization - BLAS1 Inner(dot) Product

Fortran

```
PROGRAM innor_prod_atomic
      IMPLICIT NONE
      INTEGER, PARAMETER :: N=20
      INTEGER :: i, sum=0
      INTEGER, DIMENSION(0:N-1) :: A, B

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      END DO

      CALL omp_set_num_threads(4)
!$OMP PARALLEL
      !$OMP DO
      DO i=0, N-1
            !$OMP ATOMIC
            sum = sum + A(i) * B(i)
      END DO
!$OMP END PARALLEL

      print *, “sum =“, sum

END
```

```
$ gfortran -fopenmp -o inner_prod_atomic.x inner_prod_atomic.f90
$ ./inner_prod_atomic.x
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int i, sum=0;
      int a[N], b[N];

      for (i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
      }
omp_set_num_threads(4);
#pragma omp parallel
{
#pragma omp for
      for (i=0; i<N; i++)
      #pragma omp atomic
            sum += a[i] * b[i];
}
      printf(“sum = %d\n”, sum);

      return 0;
}
```

```
$ gcc -fopenmp -o inner_prod_atomic.x inner_prod_atomic.c
$ ./inner_prod_atomic.x
```

Synchronization

Fortran		C	

!$OMP PARALLEL
DO i=0, 99
!$OMP CRITICAL(n1)
CALL sub(a,b)
!$OMP END CRITICAL
END DO
!$OMP END PARALLEL
	!$OMP PARALLEL
	DO i=0, 99
	!$OMP ATOMIC
	a = a + b
	END DO
	!$OMP END PARALLEL
		#pragma omp parallel
		{
		for (i=0; i<100; i++) {
		#pragma omp critical(n1)
		func1(a,b);
		}
		}
			#pragma omp parallel
			{
			for (i=0; i<100; i++) {
			#pragma omp atomic
			a += b;
			}
			}

- **Synchronization**
  - Imposing order constraints and protecting access to shared data
- **High level synchronization**
  - **critical, atomic, barrier**, ordered
- **Low level synchronization**
  - flush, locks
- **critical vs atomic**
  - critical : Only one thread at a time can enter a critical region, distinguished by name
  - atomic : Only applies to the update of a memory location
    Like mini-critical section

BARRIER

Fortran	C

PROGRAM barrier
INTEGER omp_get_thread_num
 	
CALL omp_set_num_threads(4)
 	
!$OMP PARALLEL
PRINT *,'A tid =', omp_get_thread_num()
 	
!$OMP BARRIER
PRINT *,'B tid =', omp_get_thread_num()
!$OMP END PARALLEL
 	
END
	#include <stdio.h>
	#include <omp.h>
	
	int main()
	{
	omp_set_num_threads(4);
	#pragma omp parallel
	{
	printf ("A tid = %d \n", omp_get_thread_num());
	
	#pragma omp barrier
	printf ("B tid = %d \n", omp_get_thread_num());
	}
	
	return 0;
	}

- **BARRIER**
  - The BARRIER directive synchronizes all threads in the team
  - When a BARRIER directive is reached, a thread will wait at that point until all other threads have reached that barrier. All threads then resume executing in parallel the code that follows the barrier
  - must be reached by all threads in team before any thread can proceed

Synchronization (Exercise)

Fortran

```
PROGRAM sync_exercise
      IMPLICIT NONE
      INTEGER, PARAMETER :: N=100
      INTEGER :: i, sum=0, local_sum

!! set number of threads
!! create threads
      local_sum = 0
      DO i=1, N
            local_sum = local_sum + i

            sum = sum + local_sum
      END DO
!! join threads
      print *, 'sum =', sum

END
```

C

```
#include <stdio.h>
#define N 100

int main()
{
      int i, sum = 0, local_sum;

      // set number of threads
      // create threads
{
      local_sum = 0;
      for(i=1; i<=N; i++)
            local_sum = local_sum + i;

      sum = sum + local_sum;
}
      printf("sum = %d\n", sum);

      return 0;
}
```

Synchronization (Solution)

Fortran

```
PROGRAM sync_solution
      IMPLICIT NONE
      INTEGER, parameter :: N=100
      INTEGER:: i, sum=0, local_sum

      CALL omp_set_num_threads(4)
!$OMP PARALLEL private(local_sum)
      local_sum = 0

      !$OMP DO
      DO i=1, N
            local_sum = local_sum + i
      END DO

      !$OMP ATOMIC
      sum = sum + local_sum
!$OMP END PARALLEL

      print *, 'sum =', sum

END
```

```
$ gfortran -fopenmp -o sync_solution.x sync_solution.f90
$ ./sync_solution.x
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 100

int main()
{
      int i, sum = 0, local_sum;

      omp_set_num_threads(4);
#pragma omp parallel private(local_sum)
{
      local_sum = 0;
      #pragma omp for
      for(i=1; i<=N; i++)
            local_sum = local_sum + i;

      #pragma omp atomic
//    sum = sum + local_sum; // compile error
      sum += local_sum;
}
      printf("sum = %d\n", sum);

      return 0;
}
```

```
$ gcc -fopenmp -o sync_solution.x sync_solution.c
$ ./sync_solution.x
```

Synchronization (Solution) - Using Environmental Variable

Fortran

```
PROGRAM sync_solution
      IMPLICIT NONE
      INTEGER, parameter :: N=100
      INTEGER:: i, sum=0, local_sum

!$OMP PARALLEL private(local_sum)
      local_sum = 0

      !$OMP DO
      DO i=1, N
            local_sum = local_sum + i
      END DO

      !$OMP ATOMIC
      sum = sum + local_sum
      !$OMP END PARALLEL

      PRINT *, 'sum =', sum

END
```

```
$ gfortran -fopenmp -o sync_solution2.x sync_solution2.f90
$ export OMP_NUM_THREADS=7
$ ./ sync_solution2.x
```

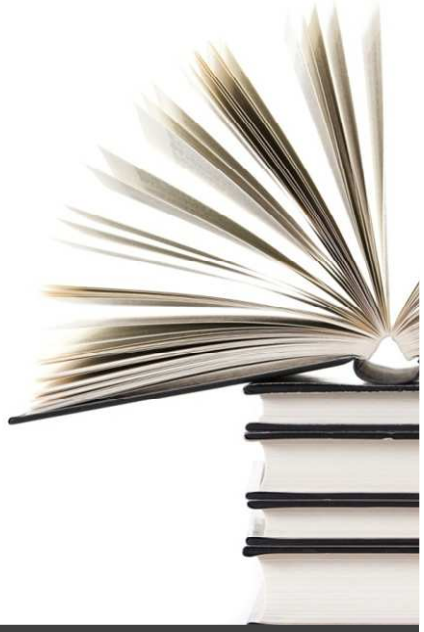
C

```
#include <stdio.h>
#define N 100

int main()
{
      int i, sum = 0, local_sum;

#pragma omp parallel private(local_sum)
{
      local_sum = 0;
      #pragma omp for
      for(i=1; i<=N; i++)
            local_sum = local_sum + i;

      #pragma omp atomic
      sum +=  local_sum;
}
      printf("sum = %d\n", sum);

      return 0;
}
```

```
$ gcc -fopenmp -o sync_solution2.x sync_solution2.c
$ export OMP_NUM_THREADS=7
$ ./ sync_solution2.x
```

OpenMP Basics III

1. Reduction



Reduction - BLAS1 Inner(dot) Product

Fortran

```
PROGRAM sync_atomic
      IMPLICIT NONE
      INTEGER, PARAMETER :: N=200000
      INTEGER :: i, sum=0
      INTEGER, DIMENSION(0:N-1) :: A, B

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      ENDDO

      CALL omp_set_num_threads(4)
!$OMP PARALLEL
     !$OMP DO
      DO i=0, N-1
            !$OMP ATOMIC
            sum = sum + A(i) * B(i)
      ENDDO
!$OMP END PARALLEL

      PRINT *, “sum =“, sum

END
```

```
$ gfortran -fopenmp -o sync_atomic.x sync_atomic.f90
$ ./sync_atomic.x
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 200000

int main()
{
      int i, sum=0;
      int a[N], b[N];
      for(i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
      }
      omp_set_num_threads(4);
#pragma omp parallel
{
#pragma omp for
      for(i=0; i<N; i++)
        #pragma omp atomic
            sum += a[i] * b[i];
}
      printf(“sum = %d\n”, sum);

      return 0;
}
```

```
$ gcc -fopenmp -o sync_atomic.x sync_atomic.c
$ ./sync_atomic.x
```

Reduction - BLAS1 Inner(dot) Product

Fortran

```
PROGRAM reduction
      IMPLICIT NONE
      INTEGER, PARAMETER :: N=200000
      INTEGER :: i, sum=0
      INTEGER, DIMENSION(0:N-1) :: A, B

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      END DO

      CALL omp_set_num_threads(4)
!$OMP PARALLEL
      !$OMP DO reduction(+: sum)
      DO i=0, N-1
            sum = sum + A(i) * B(i)
      END DO
!$OMP END PARALLEL

      PRINT *, “sum =“, sum

END
```

```
$ gfortran -fopenmp -o reduction.x reduction.f90
$ ./reduction.x
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 200000

int main()
{
      int i, sum=0;
      int a[N], b[N];

      for(i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
      }
      omp_set_num_threads(4);
#pragma omp parallel
{
      #pragma omp for reduction (+:sum)
      for (i=0; i<N; i++)
            sum += a[i] * b[i];
}
      printf(“sum = %d\n”, sum);

      return 0;
}
```

```
$ gcc -fopenmp -o reduction.x reduction.c
$ ./reduction.x
```

Reduction - BLAS1 Inner(dot) Product

Fortran

```
PROGRAM reduction_shortcut
      IMPLICIT NONE
      INTEGER, PARAMETER :: N=200000
      INTEGER :: i, sum=0
      INTEGER, DIMENSION(0:N-1) :: A, B

      DO i=0, N-1
            A(i) = i+1; b(i)= i+2
      END DO

      CALL omp_set_num_threads(4)
!$OMP PARALLEL DO reduction (+ : sum)
      DO i=0, N-1
            sum = sum + A(i) * B(i)
      END DO
!$OMP END PARALLEL DO

      PRINT *, “sum =“, sum

END
```

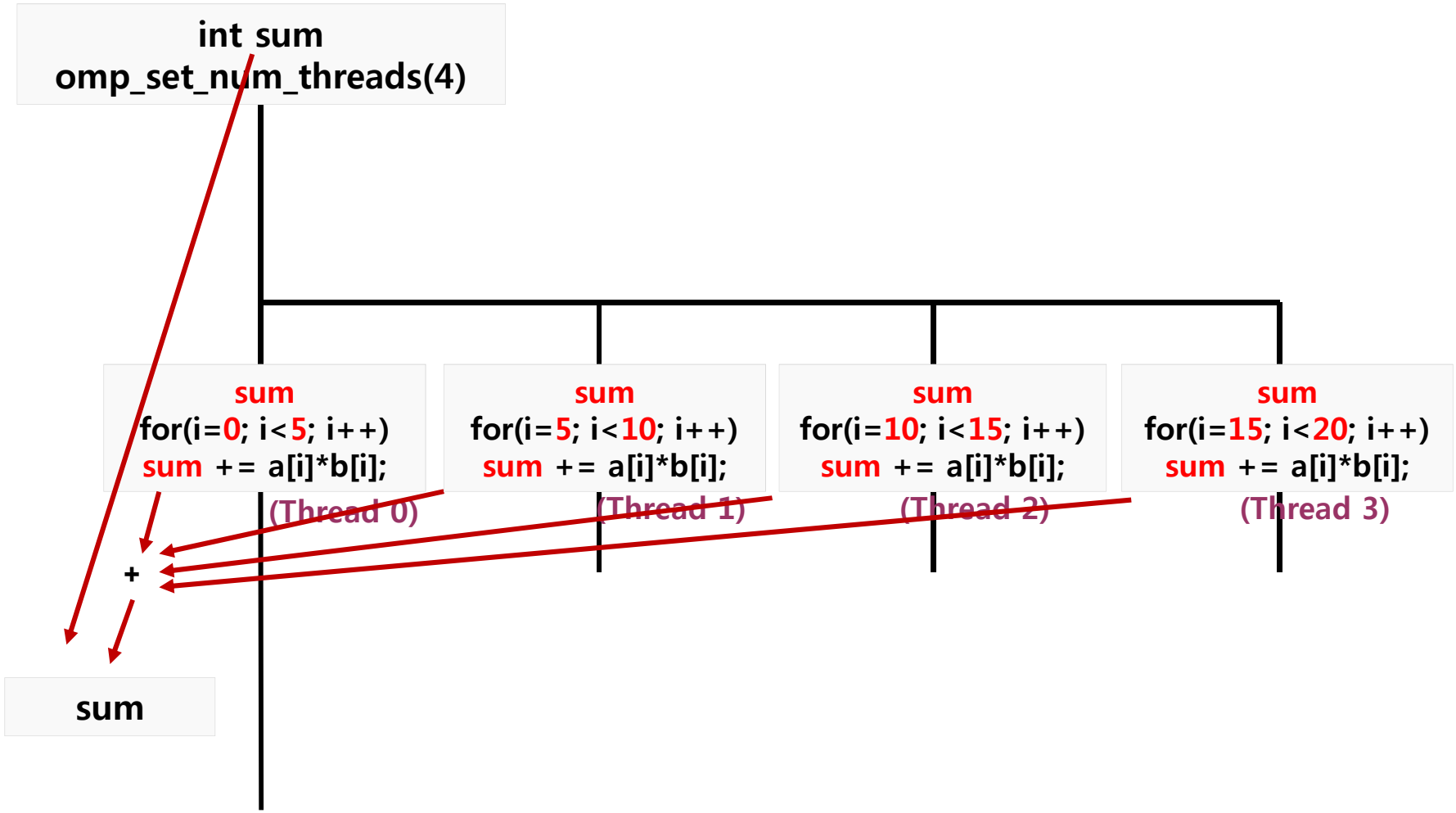
```
$ gfortran -fopenmp -o reduction_short.x reduction_short.f90
$ ./reduction_short.x
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 200000

int main()
{
      int i, sum=0;
      int a[N], b[N];

      for(i=0; i<N; i++) {
            a[i] = i+1; b[i] = i+2;
      }
omp_set_num_threads(4);
#pragma omp parallel for reduction (+:sum)
      for(i=0; i<N; i++)
            sum += a[i] * b[i];

      printf(“sum = %d\n”, sum);

      return 0;
}
```

```
$ gcc -fopenmp -o reduction_short.x reduction_short.c
$ ./reduction_short.x
```

Reduction


int sum
omp_set_num_threads(4)
sum
for(i=0; i<5; i++)
sum += a[i]*b[i];
(Thread 0)
sum
for(i=5; i<10; i++)
sum += a[i]*b[i];
(Thread 1)
sum
for(i=10; i<15; i++)
sum += a[i]*b[i];
(Thread 2)
sum
for(i=15; i<20; i++)
sum += a[i]*b[i];
(Thread 3)
+
sum

Reduction

➢ Reduction Operators : Fortran

Operator	Data Types	Initial Value
+	integer, floating point (complex or real)	0
*	integer, floating point (complex or real)	1
-	integer, floating point (complex or real)	0
.AND.	logical	.TRUE.
.OR.	logical	.FALSE.
.EQV.	logical	.TRUE.
.NEQV.	logical	.FALSE.
MAX	integer, floating point (real only)	가능한 최소값
MIN	integer, floating point (real only)	가능한 최대값
IAND	integer	all bits on
IOR	integer	0
IEOR	integer	0

Reduction

- Reduction Operators : C

Operator	Data Types	Initial Value
+	integer, floating point	0
*	integer, floating point	1
-	integer, floating point	0
&	integer	all bits on
|	integer	0
^	integer	0
&&	integer	1
||	integer	0

Reduction (Exercise1) - Factorial

Fortran	C

PROGRAM reduction_exercise
  INTEGER, PARAMETER :: N=10
 	
  INTEGER :: i, fac=1
 	
  DO i=1, N
  fac = fac * i
  END DO
 	
  PRINT *, “factorial =“, fac
 	
END
	#include <stdio.h>
	
	#define N 10
	
	int main()
	{
	  int i, fac = 1;
	
	  for(i=1; i<=N; i++)
	  fac *= i;
	
	  printf(“factorial = %d\n”, fac);
	
	  return 0;
	}

$ gfortran -o factorial.x factorial.f90 $ ./factorial.x	$ gcc -o factorial.x factorial.c $ ./factorial.x

Reduction (Solution)

Fortran	C

PROGRAM reduction_solution
  IMPLICIT NONE
  INTEGER, PARAMETER :: N=10
  INTEGER :: i, fac=1
 	
  CALL omp_set_num_threads(4)
!$OMP PARALLEL DO reduction(*:fac)
  DO i=1, N
  fac = fac * i
  END DO
!$OMP END PARALLEL DO
 	
  PRINT *, “factorial =“, fac
 	
END
	#include <stdio.h>
	#include <omp.h>
	
	#define N 10
	
	int main()
	{
	  int i, fac = 1;
	
	  omp_set_num_threads(4);
	#pragma omp parallel for reduction (*:fac)
	  for(i=1; i<=N; i++)
	  fac *= i;
	
	  printf(“factorial = %d\n”, fac);
	
	  return 0;
	}

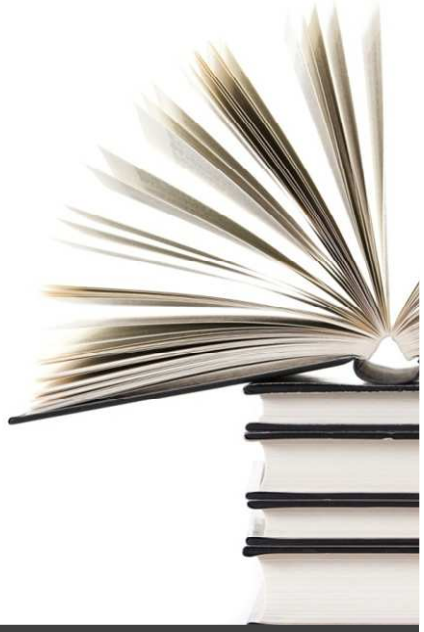
$ gfortran -fopenmp -o factorial_sol.x factorial_sol.f90 $ ./factorial_sol.x	$ gcc -fopenmp -o factorial_sol.x factorial_sol.c $ ./factorial_sol.x

Reduction (Exercise2)

- 1. Modify inner(dot) product using reduction
- 2. Compare time among atomic, local_sum and reduction

Summary

1. Review
2. common problems



Review

- OpenMP Compile Option
  - GCC : -fopenmp, Intel : -openmp, PGI : -mp
- OpenMP Components and Syntax
  - Compiler Directives, Runtime Library (functions), Environment Variables
- Create Threads
  - Parallel region
  - Set/Get # of thread, Get thread ID
  - Fork/Join model
- Data Scope
  - shared, private, firstprivate
- Parallel Loop
  - do/for
  - Work Sharing
- Synchronization
  - critical, atomic, barrier
- Reduction

Parallel Block (1/2)

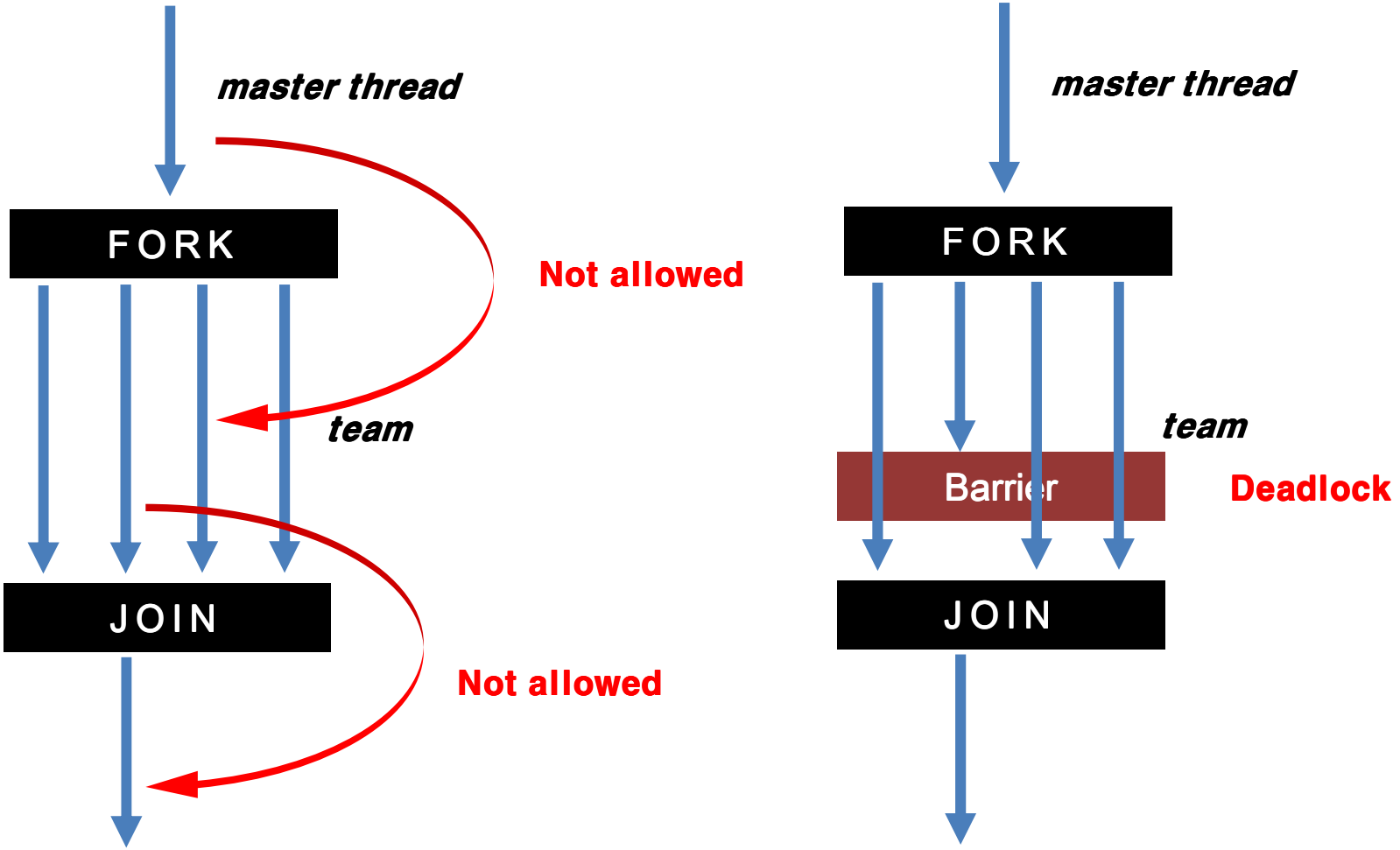
Fortran

```
PROGRAM wrong_parallel_block
      IMPLICIT NONE
      INTEGER omp_get_thread_num

  call omp_set_num_threads(4)

      goto 100
!$OMP PARALLEL
100  IF ( omp_get_thread_num() == 1 ) &
      goto 200
!$OMP END PARALLEL

200 continue

!$OMP PARALLEL
      IF ( omp_get_thread_num() == 1 ) THEN
            !$OMP BARRIER
      END IF
!$OMP END PARALLEL

END
```

C

```
#include <stdio.h>
#include <omp.h>

int main()
{
      omp_set_num_threads(4);
      goto L1;
#pragma omp parallel
{
L1:
      if( omp_get_thread_num() == 1 )
            goto L2;
}
L2:
#pragma omp parallel
{
      if( omp_get_thread_num() == 1 ) {
      #pragma omp barrier
      }
}
      return 0;
}
```

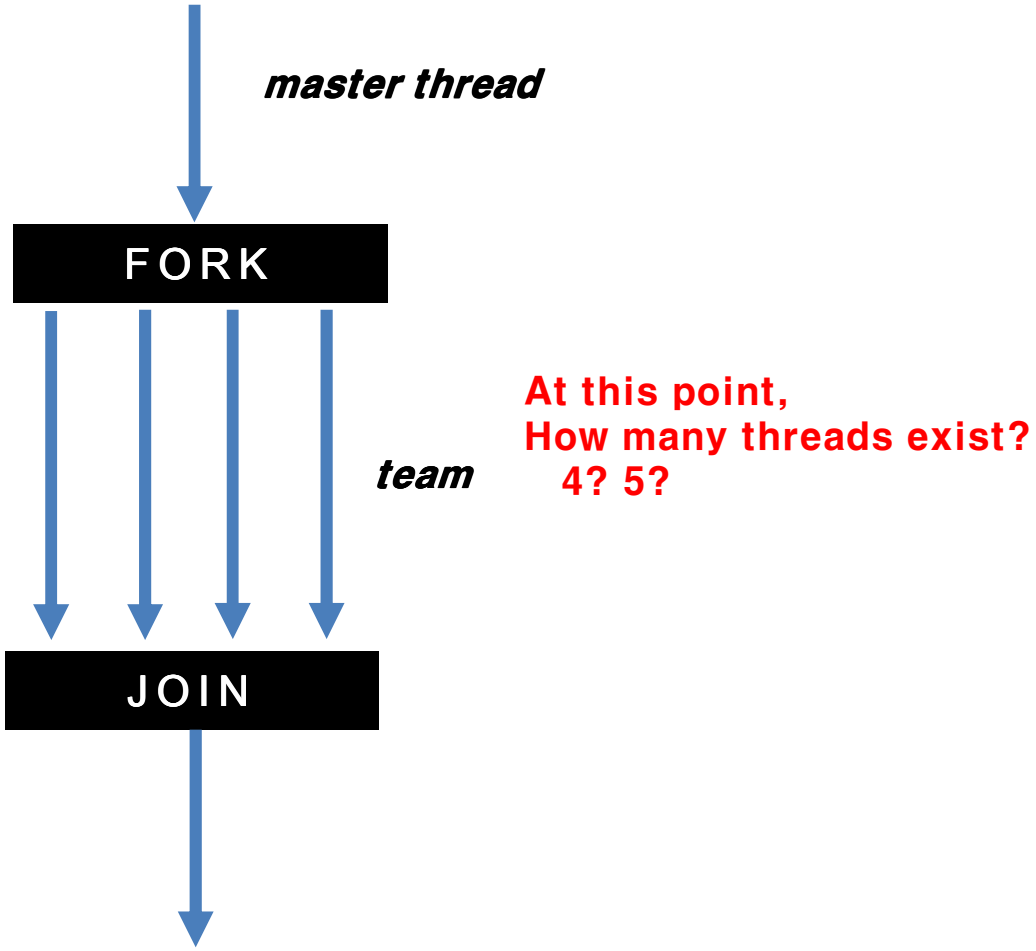
Parallel Block (2/2)



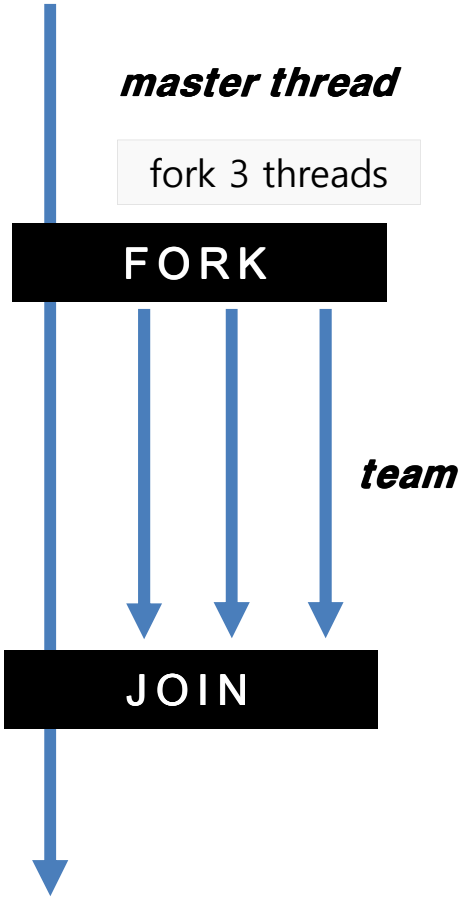
Only exit() is possible inside parallel region

Fork-Join Model

- Fork-Join Model
  - Master thread forks new threads at the beginning parallel regions



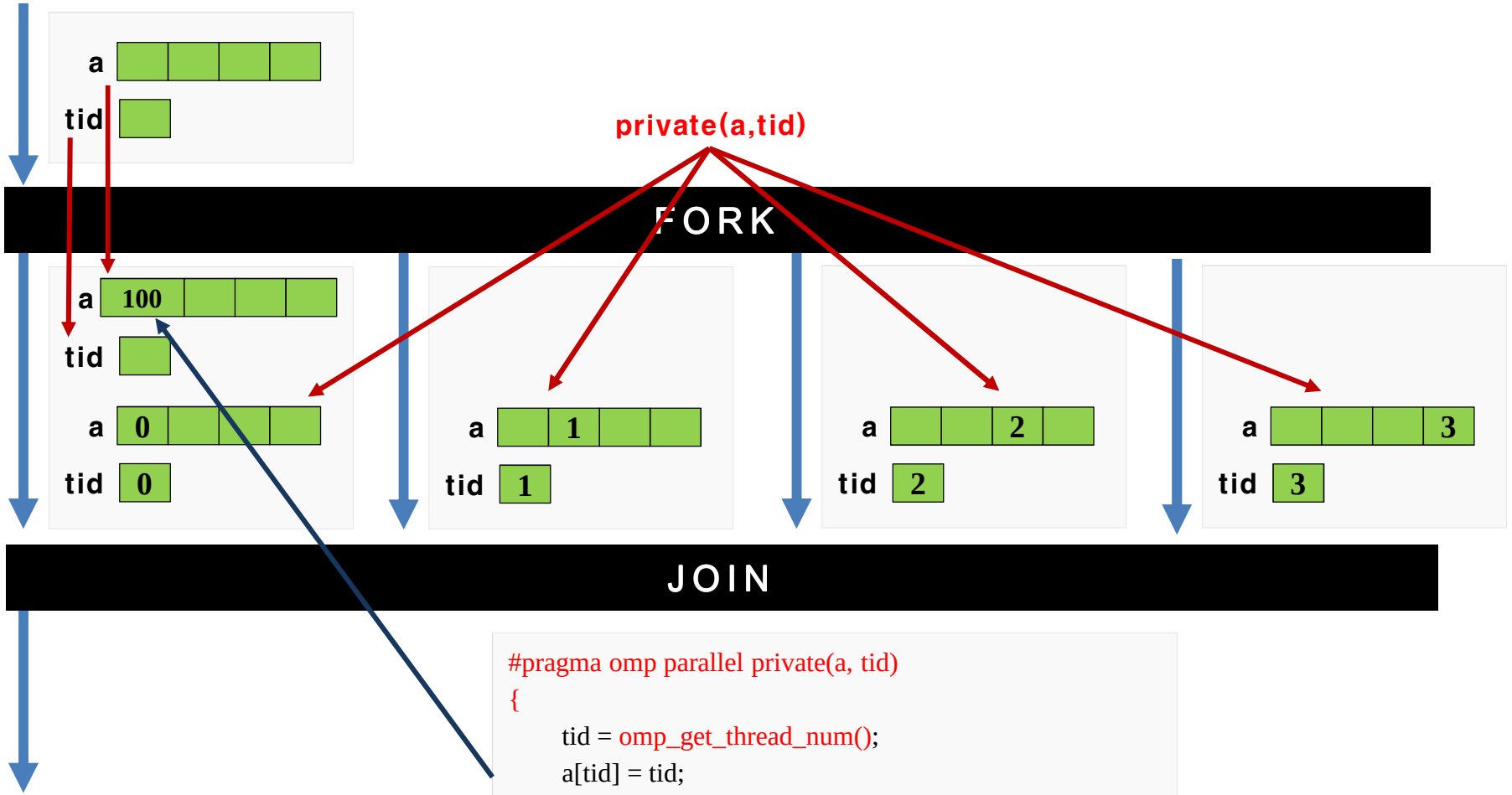
Fork-Join Model



Fortran	C

PROGRAM fork_join_test
INTEGER :: a(0:3),tid
INTEGER omp_get_thread_num
a=0
 	
CALL omp_set_num_threads(4)
!$OMP PARALLEL private(a, tid)
tid = omp_get_thread_num()
a(tid) = tid
PRINT *, 'a(', tid, ') =", a(tid), '&
in', tid, '-th thread'
a(0) = 100
!$OMP END PARALLEL
 	
PRINT *, "a(0) = ", a(0)
 	
END
	#include <stdio.h>
	#include <omp.h>
	
	int main()
	{
	int a[4] = { 0 }, tid;
	
	omp_set_num_threads(4);
	#pragma omp parallel private(a,tid)
	{
	tid = omp_get_thread_num();
	a[tid] = tid;
	printf("a[%d] = %d in %d-th thread\n",
	tid, a[tid], tid);
	a[0] = 100;
	}
	printf("a[0] = %d\n", a[0]);
	
	return 0;
	}

Fork-Join Model




```
#pragma omp parallel private(a, tid)
{
        tid = omp_get_thread_num();
        a[tid] = tid;
        printf("a[%d] = %d in %d-th thread\n", tid, a[tid], tid);
        a[16] = 100;
}
```

Parallel Loops (1/3)

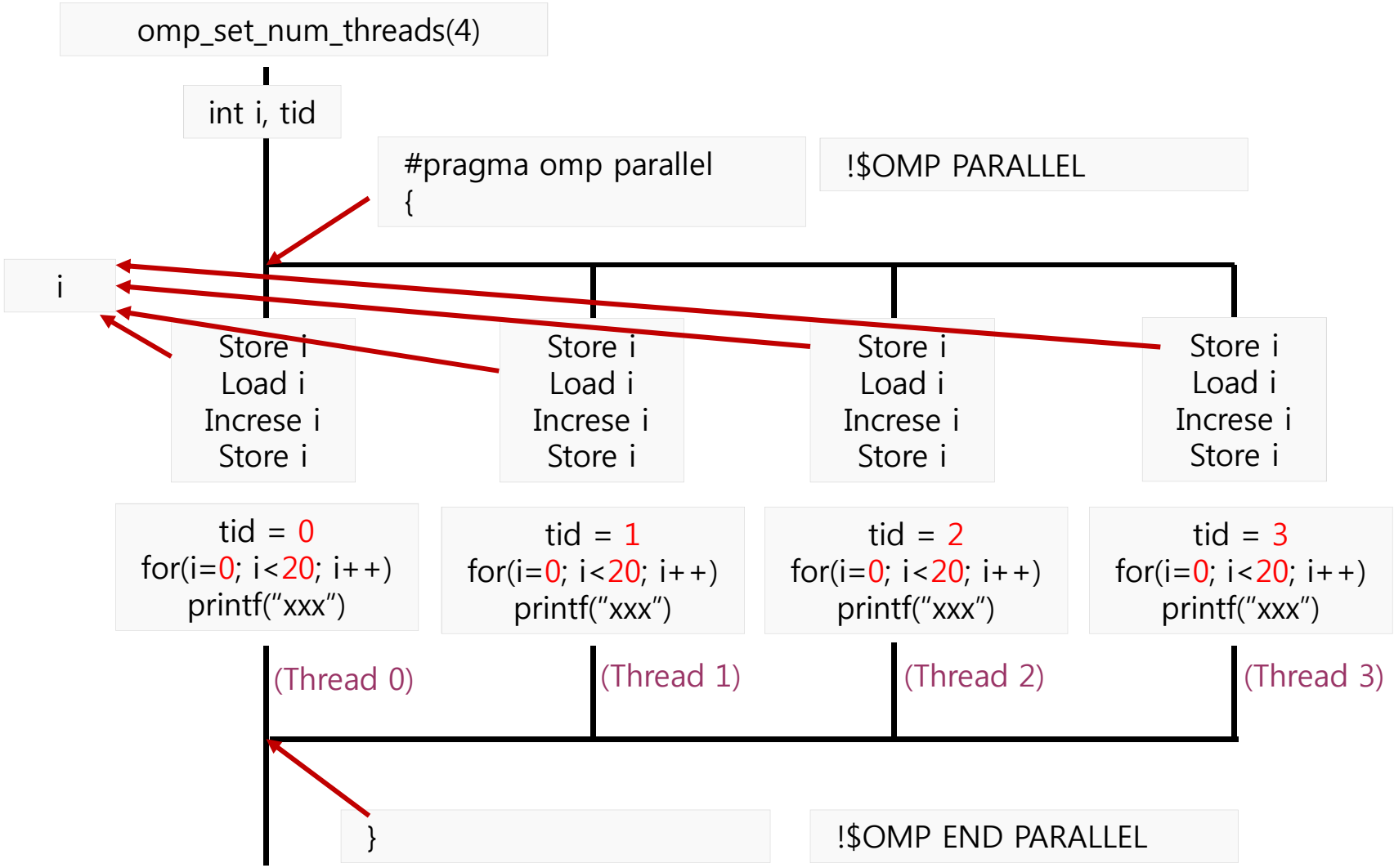
Fortran

```
PROGRAM wrong_parallel_loop
      IMPLICIT NONE
      INTEGER, PARAMETER  :: N=20

      INTEGER  :: tid, i, omp_get_thread_num

      CALL omp_set_num_threads(4)
!$OMP PARALLEL private(tid)
      tid = omp_get_thread_num()
      !$OMP DO
      DO i=0, N-1
            PRINT *, 'Hello World', tid, i
      END DO
!$OMP END PARALLEL

END
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int tid, i;
      omp_set_num_threads(4);
#pragma omp parallel private(tid)
{
      tid = omp_get_thread_num();
#pragma omp for
      for(i=0; i<N; i++)
            printf("Hello World %d %d\n", tid, i);
}
      return 0;
}
```

Parallel Loops (2/3)



Parallel Loops (3/3)

Fortran

```
PROGRAM nested_parallel_do
      IMPLICIT NONE
      INTEGER, PARAMETER  :: N=20

      INTEGER  :: tid, i, omp_get_thread_num

      CALL omp_set_num_threads(4)
!$OMP PARALLEL private(tid)
      tid = omp_get_thread_num()
      !$OMP PARALLEL DO !! ???
      !! netsted parallel (tomorrow)
      DO i=0, N-1
            PRINT *, 'Hello World', tid, i
      END DO
!$OMP END PARALLEL

END
```

C

```
#include <stdio.h>
#include <omp.h>
#define N 20

int main()
{
      int tid, i;

      omp_set_num_threads(4);
#pragma omp parallel private(tid)
{
      tid = omp_get_thread_num();
      #pragma omp parallel for // ???
      // nested parallel (tomorrow)
      for (i=0; i<N; i++)
            printf("Hello World %d %d\n", tid, i);
}
      return 0;
}
```

Synchronization : critical option(name) (1/2)

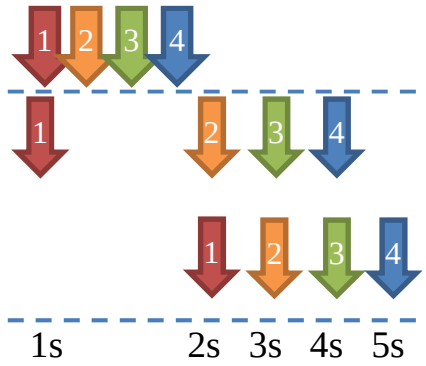
Fortran

```
PROGRAM sync_test

      IMPLICIT NONE

      CALL omp_set_num_threads(4)

!$OMP PARALLEL
      !$OMP CRITICAL (n1)
      CALL   sleep(1)
      !$OMP END CRITICAL (n1)

      !$OMP CRITICAL (n2)
      CALL   sleep(1)
      !$OMP END CRITICAL (n2)

!$OMP END PARALLEL

END
```

```
$ gfortran -fopenmp -o sync_test.x sync_test.f90
$ time ./ sync_test.x
real      0m5.014s
```

C

```
#include <stdio.h>
#include <omp.h>

int main()
{
      omp_set_num_threads(4);

#pragma omp parallel
{
      #pragma omp critical (n1)
      {   sleep(1);   }

      #pragma omp critical (n2)
      {   sleep(1);   }
}
      return 0;
}
```




```
$ gcc -fopenmp -o sync_test.x sync_test.c
$ time ./ sync_test.x
real    0m5.024s
```

Synchronization : critical option(name) (2/2)

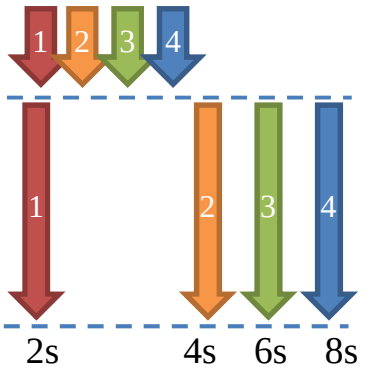
Fortran

```
PROGRAM sync_test

      IMPLICIT NONE

      CALL omp_set_num_threads(4)

!$OMP PARALLEL
      !$OMP CRITICAL (n1)
      CALL   sleep(1)
      !$OMP END CRITICAL (n1)

      !$OMP CRITICAL (n1)
      CALL   sleep(1)
      !$OMP END CRITICAL (n1)

!$OMP END PARALLEL

END
```

```
$ gfortran -fopenmp -o sync_test.x sync_test.f90
$ time ./ sync_test.x
real    0m8.015s
```

C

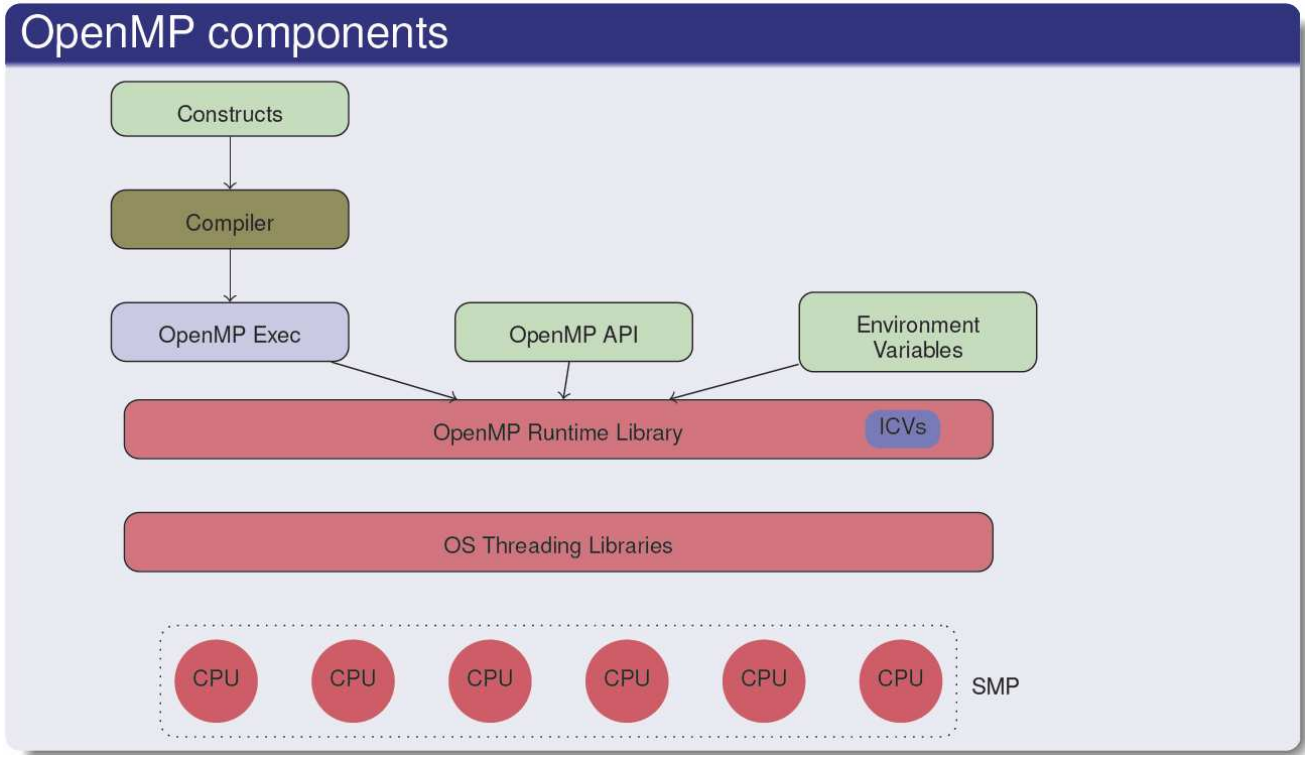
```
#include <stdio.h>
#include <omp.h>

int main()
{
      omp_set_num_threads(4);

#pragma omp parallel
{
      #pragma omp critical (n1)
      {   sleep(1);   }

      #pragma omp critical (n1)
      {   sleep(1);   }
}
      return 0;
}
```




```
$ gcc -fopenmp -o sync_test.x sync_test.c
$ time ./ sync_test.x
real    0m8.013s
```

ICV (Internal Control Variable)

- The number of threads : nthreads-var
- The dynamic adjustment of threads : dyn-var
- Runtime schedule type and chunk size : run-sched-var
- To enable or to disable nested parallelism : nested-var

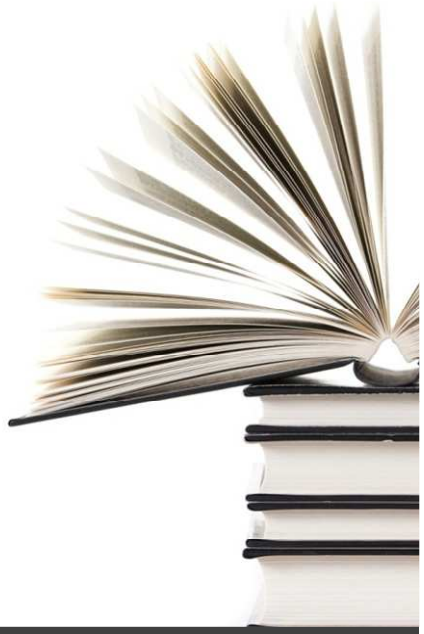


Ref. : Parallel Programming with OpenMP, BSC (Barcelona Supercomputing Center), Spain

Break!!

Hands-on

1. Pi : fomula
2. Pi : Numerical Integration
3. Pi : Monte-carlo
4. N-body Problem

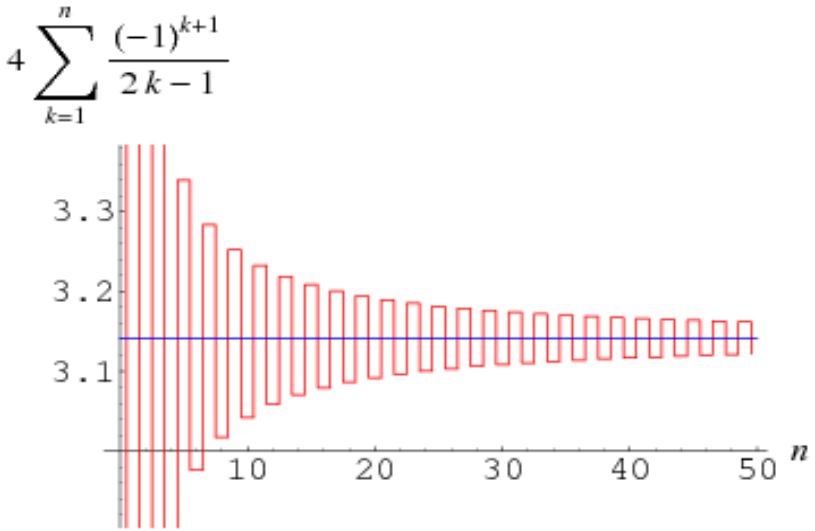


ex1. Formula Pi

- Pi calculation for Formulas

1. There are many formulas of π of many series.
2. Gregory and Leibniz found

$$\frac{\pi}{4} = \sum_{k=1}^{\infty} \frac{(-1)^{k+1}}{2k-1} = 1 - \frac{1}{3} + \frac{1}{5} - \cdots$$



ex1. Formula Pi

Fortran

```
!! KISTI educational PI calculation
!! Copyright (c) 2012 KISTI Supercomputing Center

PROGRAM Pi_cal3
IMPLICIT NONE
      !! Number of count
      INTEGER(KIND=8), PARAMETER :: num_cnt=100000000
      INTEGER(KIND=8) :: i
      DOUBLE PRECISION :: pi

      WRITE(*,200)
      pi = 0.0d0

      DO i=0, num_cnt-1
            pi = pi + 4.0d0 * (dble(-1)**i/ dble(2*i+1))
      ENDDO

      WRITE(*, 100) pi, dabs(dacos(-1.0d0)-pi)
      WRITE(*, 200)

100 FORMAT("PI =', F17.15, "(Error =", E11.5,")")
200 FORMAT("-------------------------------------------------------")
      STOP

END PROGRAM
```

```
$ gfortran –o formular_pi.x formula_pi.f90
$ ./formular_pi.x
```

C

```
// KISTI educational PI calculation
// Copyright(c) 2012 KISTI Supercomputing Center

#include <stdio.h>
#include <math.h>

int main() {
      const long num_cnt=100000000;
      long i;
      double pi;

      printf("-------------------------------------------------------\n");

      pi = 0.0;

      for (i=0; i<num_cnt; i++)
            pi += 4.0 * (double)pow(-1,i) / (double)(2*i+1);

      printf("PI = %17.15lf (Error = %e)\n", pi, fabs(acos(-1.0)-pi));
      printf("-------------------------------------------------------\n");

      return 0;
}
```

```
$ gcc –o formular_pi.x formula_pi.c -lm
$ ./formular_pi.x
```

ex2. Numerical Integration Pi

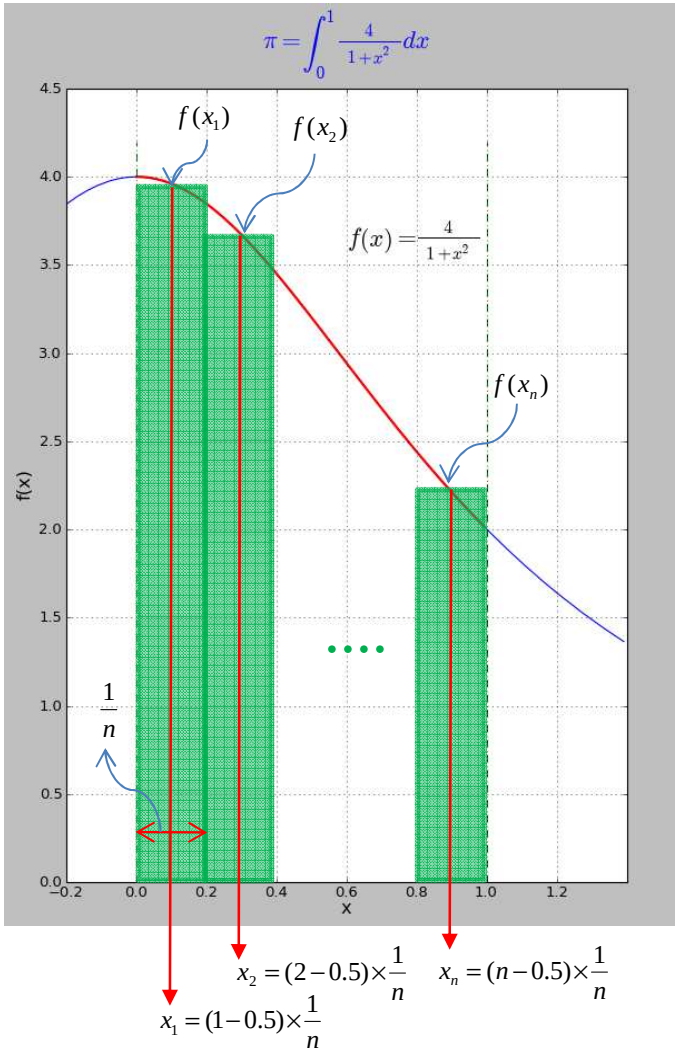
- Pi calculation for Numerical integration

$$\int_0^1 \frac{4}{1+x^2}\,dx \qquad x = \tan\theta \qquad dx = \sec^2\theta\ d\theta$$

$$\Rightarrow \int_0^{\frac{\pi}{4}} \frac{4}{1+\tan^2\theta}\sec^2\theta\ d\theta$$

$$\Rightarrow \int_0^{\frac{\pi}{4}} 4\times\cos^2\theta\frac{1}{\cos^2\theta}\,d\theta$$

$$\Rightarrow \int_0^{\frac{\pi}{4}} 4\ d\theta = \pi$$



ex2. Numerical Integration Pi

Fortran

```
!! KISTI educational PI calculation
!! Copyright (c) 2012 KISTI Supercomputing Center

PROGRAM Pi_cal
      IMPLICIT NONE
      !! Number of steps
      INTEGER(KIND=8), PARAMETER :: num_step=100000000
      INTEGER :: i
      DOUBLE PRECISION :: sum, step, pi, x
      step = (1.0d0/dble(num_step))
      sum = 0.0d0
      WRITE(*,200)

      DO i=0, num_step-1
            x = (dble(i)-0.5d0)*step
            sum = sum + 4.0d0/(1.0d0+x*x)
      ENDDO
      pi = step * sum

      WRITE(*, 100) pi, dabs(dacos(-1.0d0)-pi)
      WRITE(*, 200)

100 FORMAT("PI =", F17.15, "(Error =", E11.5,")")
200 FORMAT("-----------------------------------------")
      STOP

END PROGRAM
```

```
$ gfortran -fopenmp -o pi_cal.x pi_cal.f90
$ ./pi_cal.x
```

C

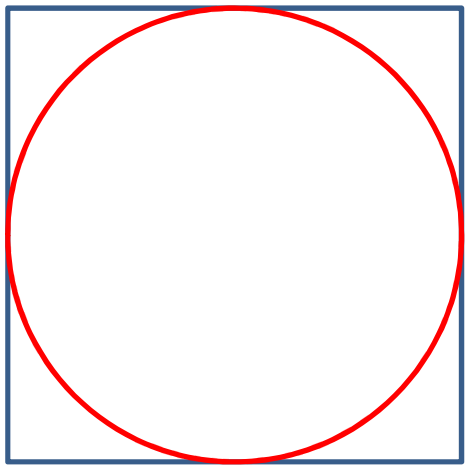
```
// KISTI educational PI calculation
// Copyright(c) 2012 KISTI Supercomputing Center

#include <stdio.h>
#include <math.h>

int main() {
      const long num_step=100000000;
      long i;
      double sum, step, pi, x;

      step = (1.0/(double)num_step);
      sum=0.0;
      printf("-----------------------------------------------------------\n");
      for (i=0; i<num_step; i++) {
            x = ((double)i - 0.5) * step;
            sum += 4.0/(1.0+x*x);
      }

      pi = step * sum;

      printf("PI = %5lf (Error = %e)\n", pi, fabs(acos(-1.0)-pi));
      printf("-----------------------------------------------------------\n");

      return 0;
}
```

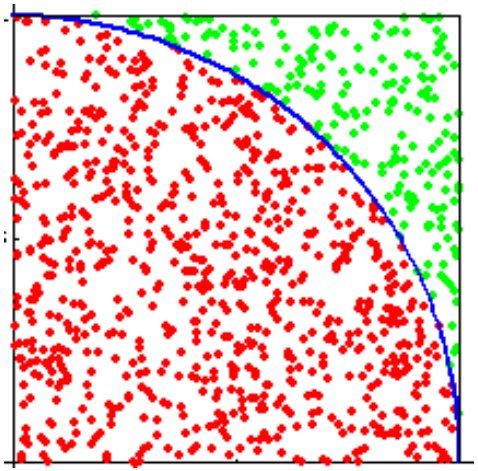
```
$ gcc -fopenmp -o pi_cal.x pi_cal.c  -lm
$ ./pi_cal.x
```

ex3. Monte carlo Pi

Monte carlo Method for Pi

1. A circle with radius r=1 inscribed within a square.
2. The area of the circle is $\pi r^2 = \pi 1^2 = \pi$
3. And the area of the square is $(2r)^2 = 2^2 = 4$
4. $\pi \approx 4 \times \frac{\text{number of points of in the Circle}}{\text{total number of points}}$





ex3. Monte carlo Pi

Fortran

```
!! KISTI educational PI calculation
!! Copyright (c) 2012 KISTI Supercomputing Center

PROGRAM Pi_cal3
      IMPLICIT NONE
      INTEGER(KIND=8), PARAMETER :: num_cnt=100000000
      INTEGER(KIND=8) :: i, cnt
      DOUBLE PRECISION :: pi, x, y, r

      WRITE(*,200)
      pi = 0.0d0:     cnt = 0;    r = 0.0d0;

      DO i=0, num_cnt-1
            CALL random_number(x)
            CALL random_number(y)
            r = sqrt(x*x + y*y)
            IF (r <= 1) THEN
                  cnt = cnt + 1
            ENDIF
      ENDDO
      pi = 4.0d0 * dble(cnt) / dble(num_cnt)
      WRITE(*, 100) pi, dabs(dacos(-1.0d0)-pi)
      WRITE(*, 200)
100 FORMAT("PI =", F17.15, "(Error =", E11.5,")")
200 FORMAT("------------------------------------------------------")
      STOP

END PROGRAM
```

```
$ gfortran -fopenmp -o pi_monte.x pi_monte.f90
$ ./pi_monte.x
```

C

```
// KISTI educational PI calculation
// Copyright(c) 2012 KISTI Supercomputing Center

#include <stdio.h>
#include <stdlib.h>
#include <math.h>

int main() {
        const long num_step=100000000;
        long i, cnt;
        double pi, x, y, r;

       printf("------------------------------------------------------\n");
       pi = 0.0;
       cnt = 0;
       r = 0.0;
       for (i=0; i<num_step; i++) {
             x = rand() / (RAND_MAX+1.0);
             y = rand() / (RAND_MAX+1.0);
             r = sqrt(x*x + y*y);
       if (r<=1) cnt += 1;
       }
       pi = 4.0 * (double)(cnt) / (double)(num_step);
       printf("PI = %17.15lf (Error = %e)\n", pi, fabs(acos(-1.0)-pi));
       printf("------------------------------------------------------\n");

    return 0;
}
```

```
$ gcc -fopenmp -o pi_monte.x pi_monte.c -lm
$ ./pi_monte.x
```


Q&A


Thank
you