OpenMP

Parallel Programming for Multicore processors and GPU

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Agenda

- Trends of Multicore processor
- What's OpenMP
- Advanced topics
  - MPI/OpenMP Hybrid Programming
    - Programming for Multi-core cluster
  - OpenMP 3.0 (2007, approved)
    - Task parallelism
  - OpenACC (2012)
    - For GPU, by NVIDIA, PGI, Cray, ...
  - OpenMP 4.0 (2013, released)
    - Accelerator extension
    - SIMD extension
    - Task dependency description

How to make computer fast?

- Computer became faster and faster by
  - Device
  - Computer architecture

Pipeline
Superscalar

- Computer architecture to perform processing in parallel at several levels:
  - Inside of CPU (core)
  - Inside of Chip
  - Between chips (+GPU)
  - Between computer

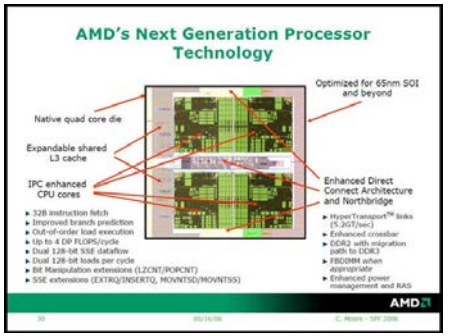
mulitcore

Shared memory multiprocessor

Distributed memory computer or Grid

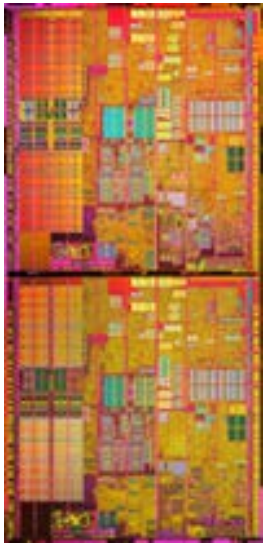
Trends of Mulitcore processors

- Faster clock speed, and Finer silicon technology
  - “now clock freq is 3GHz, in future it will reach to 10GHz!?”
    - Intel changed their strategy -> multicore!
    - Clock never become faster any more
  - Silicon technology 45 nm -> 7 nm in near future!



Good news & bad news!

- Progress in Computer Architecture
  - Superpipeline, super scalar, VLIW …
  - Multi-level cache, L3 cache even in microprocessor
  - Multi-thread architecture、Intel Hyperthreading
    - Shared by multiple threads
  - Multi-core：multiple CPU core on one chip dai



Programming support is required

Inetl ® Pentium® processor Dai of Extreme-edition

Multi-core processor：
Solution of Low power by parallel processing

CPU power dissipation

$$P = N \times \alpha \times C \times V^2 \times f$$

# CPU	Active rate of processors	Capacitance of circiuit	Voltage	Clock Freq

Apporach for Low power by parallel processing

increase N、↑ decrease V and f, ↓ improve perf. N × f ↑

- **Decreasing V and F, makes heat dissipation and power lower within a chip**
- Progress in silicon technology 130nm ⇒ 90nm⇒65nm,22nm （Decrease **C** and **V)**
- Use a silicon process for low power (embedded processor)（Small **α**）

- Performance improvement by Multi-core（N=2～16)
  - Number of transistors are increasing by “Moore’s Law”
- Parallel processing by low power processor

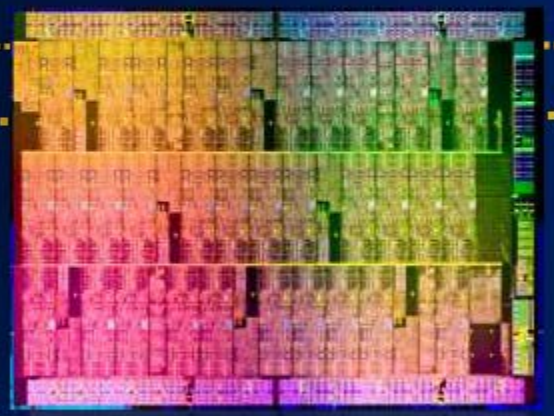
⇒ Solution by multi-core processors for High performance embedded system

Highly Parallel Performance

Intel® Many Integrated Core (Intel® MIC) Architecture

Delivered Performance

Launching on 22nm with >50 cores to provide outstanding performance for HPC users



Performance Density

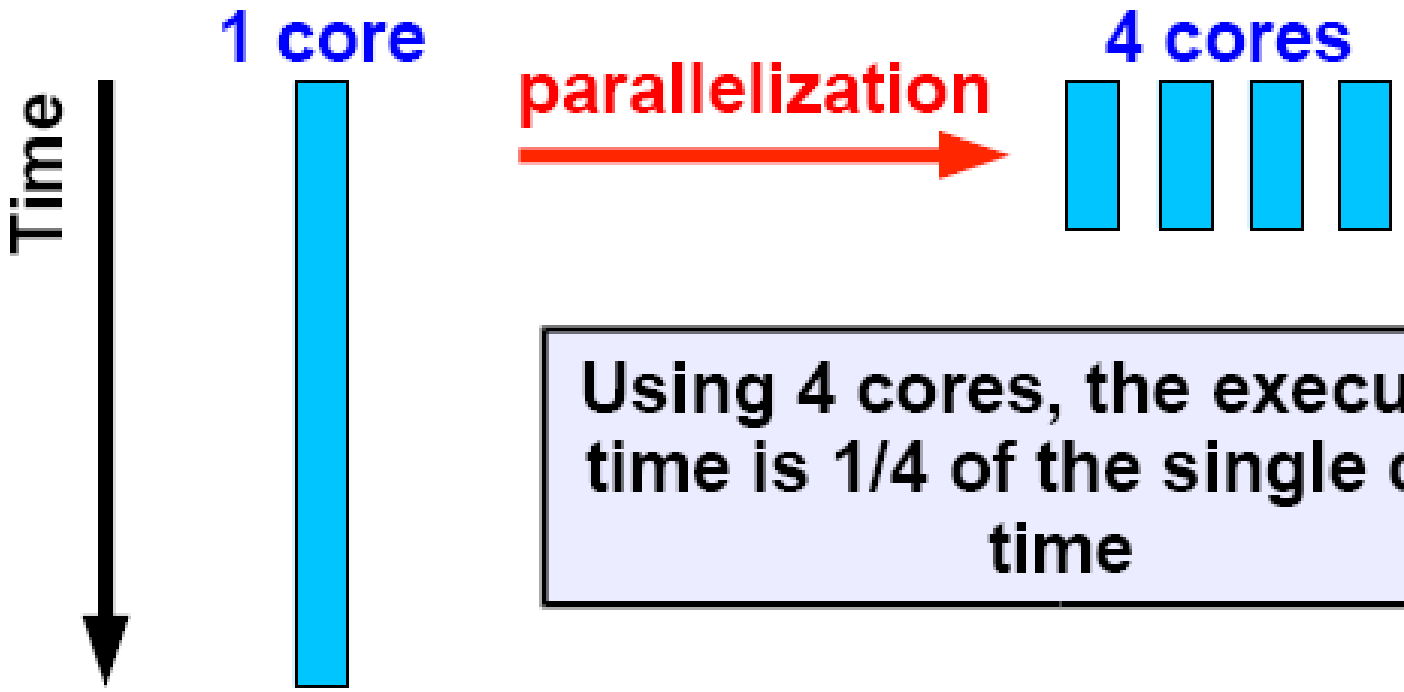
The compute density associated with specialty accelerators for parallel workloads

Programmability

The many benefits of broad Intel CPU programming models, techniques, and familiar x86 developer tools

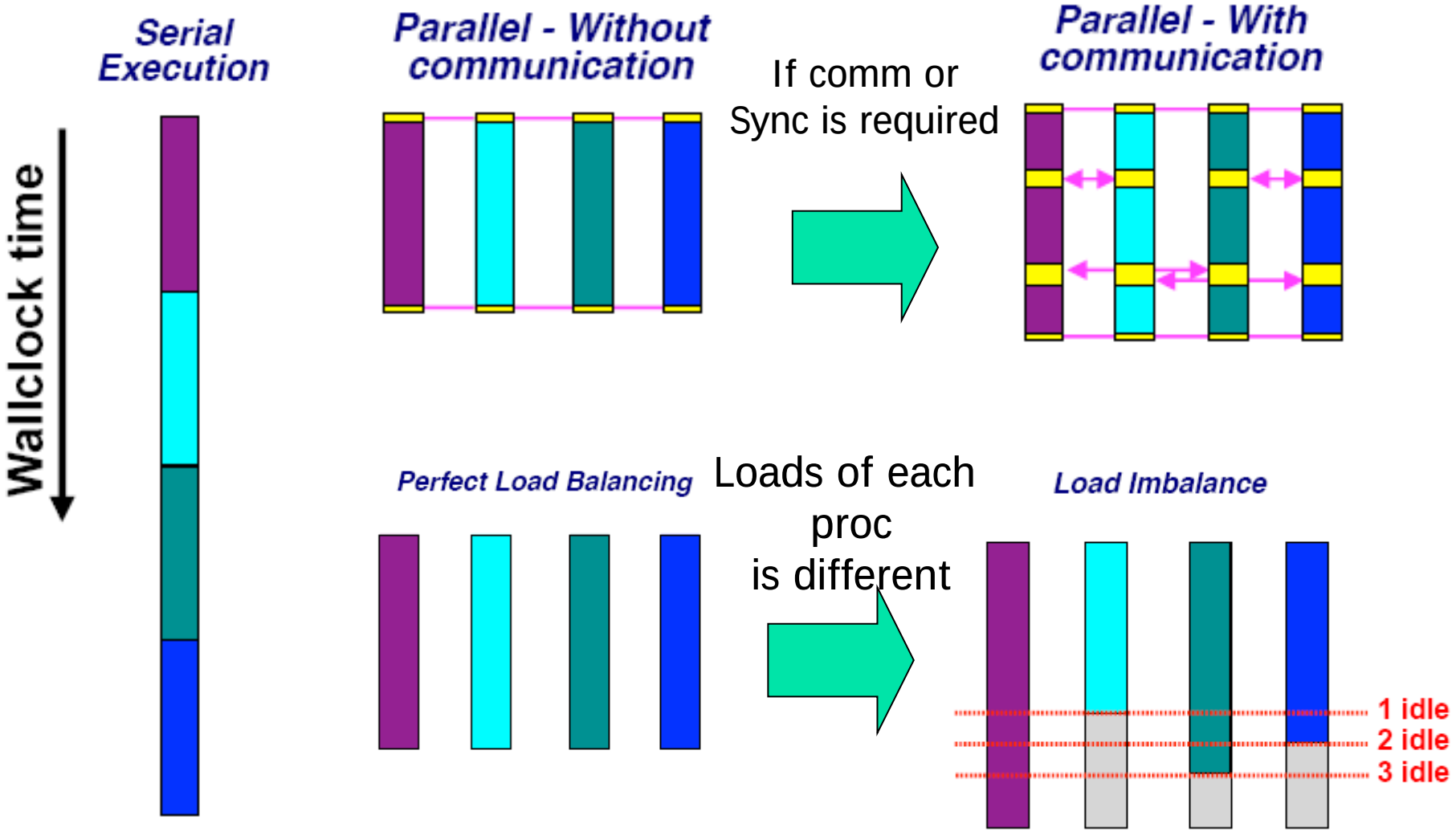
A Step Forward In Dealing With Efficient Performance & Programmability

Why parallelization needs?
4 times speedup by using 4 cores!

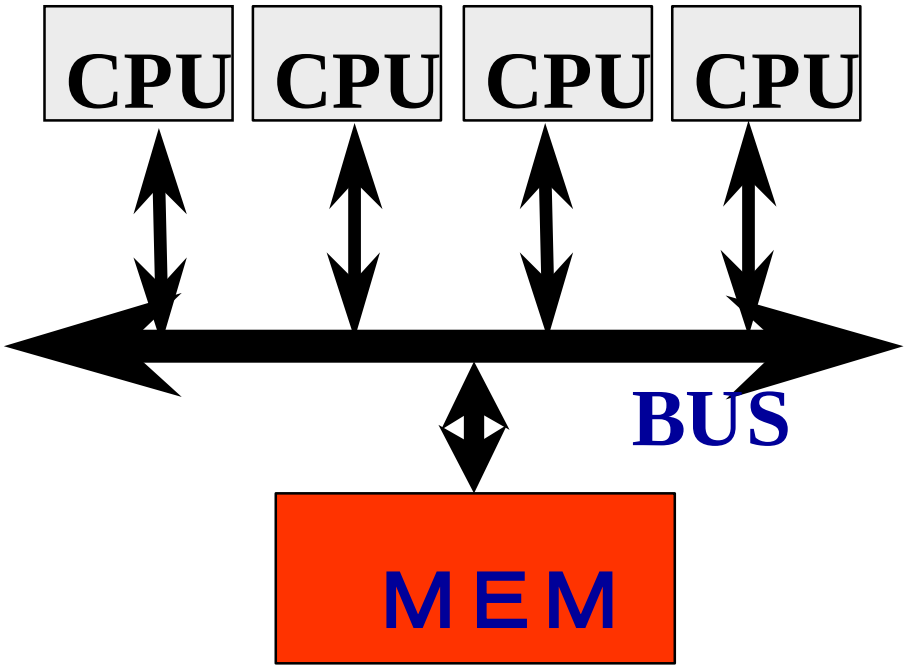


Using 4 cores, the execution time is 1/4 of the single core time

Overhead of parallel execution

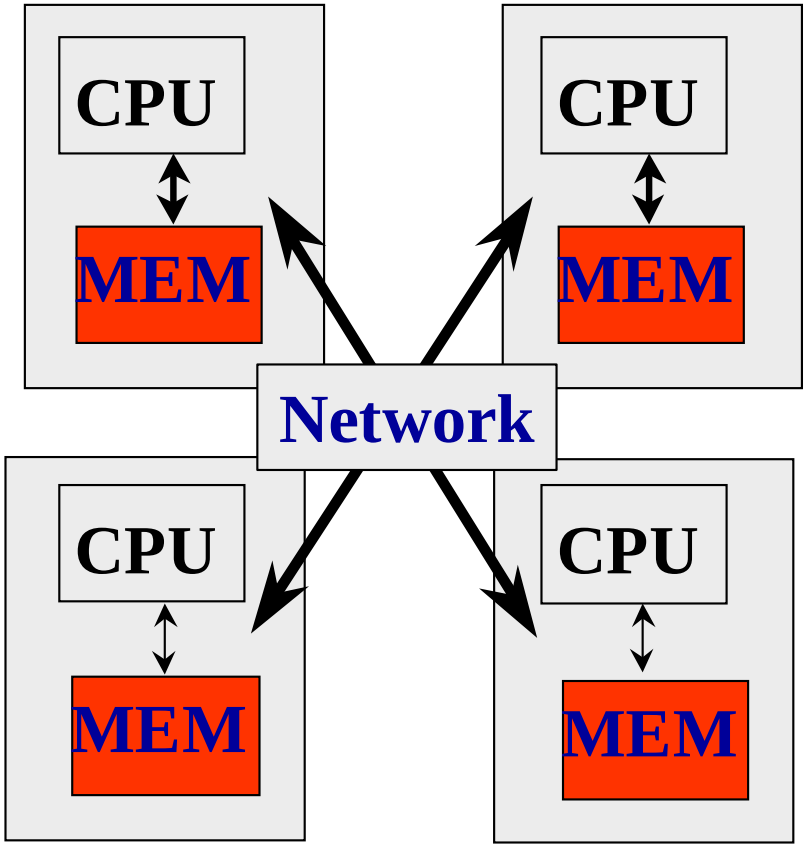


Shared memory multi-processor system



- **Multiple CPUs share main memory**
- **Threads executed in each core(CPU) communicate with each other by accessing shared data in main memory.**
- **Enterprise Server**
- **SMP Multi-core processors**

Distributed memory multi-processor

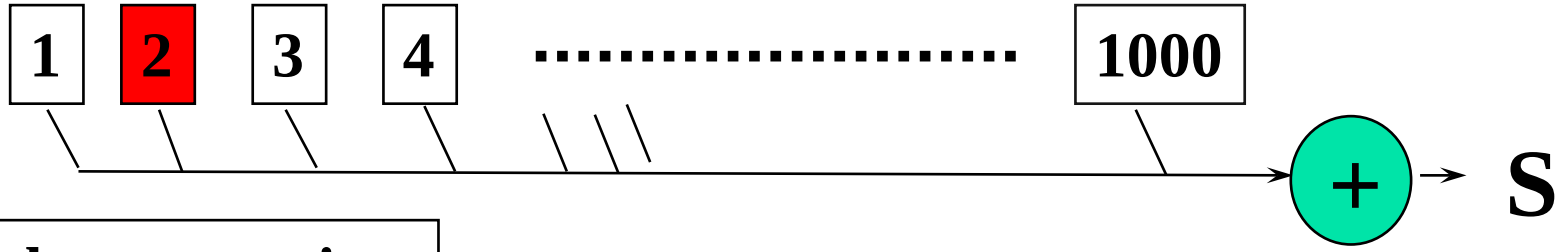


- **System with several computer of CPU and memory, connected by network.**
- **Thread executed in each computer communicate with each other by exchanging data (message) via network.タ**
- **PC Cluster**
- **AMP Multi-core processor**

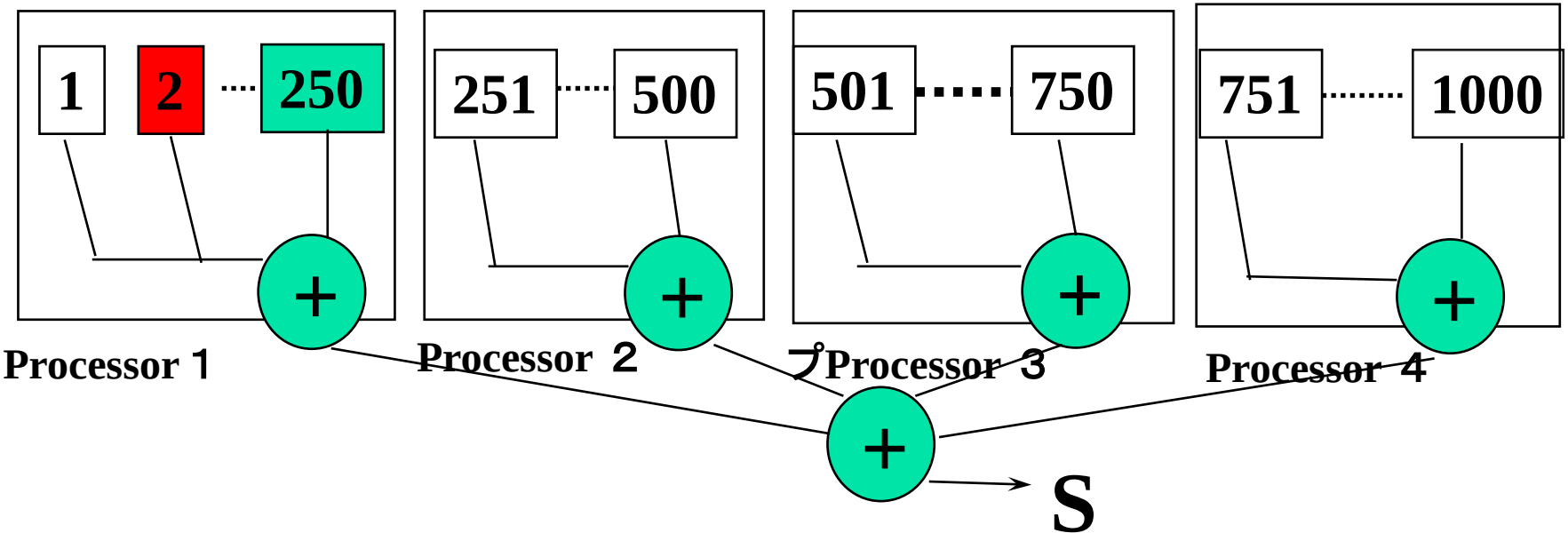
Very simple example of parallel computing for high performance

```
for(i=0;i<1000; i++)
    S += A[i]
```

Sequential computation



Parallel computation



Parallel programming model

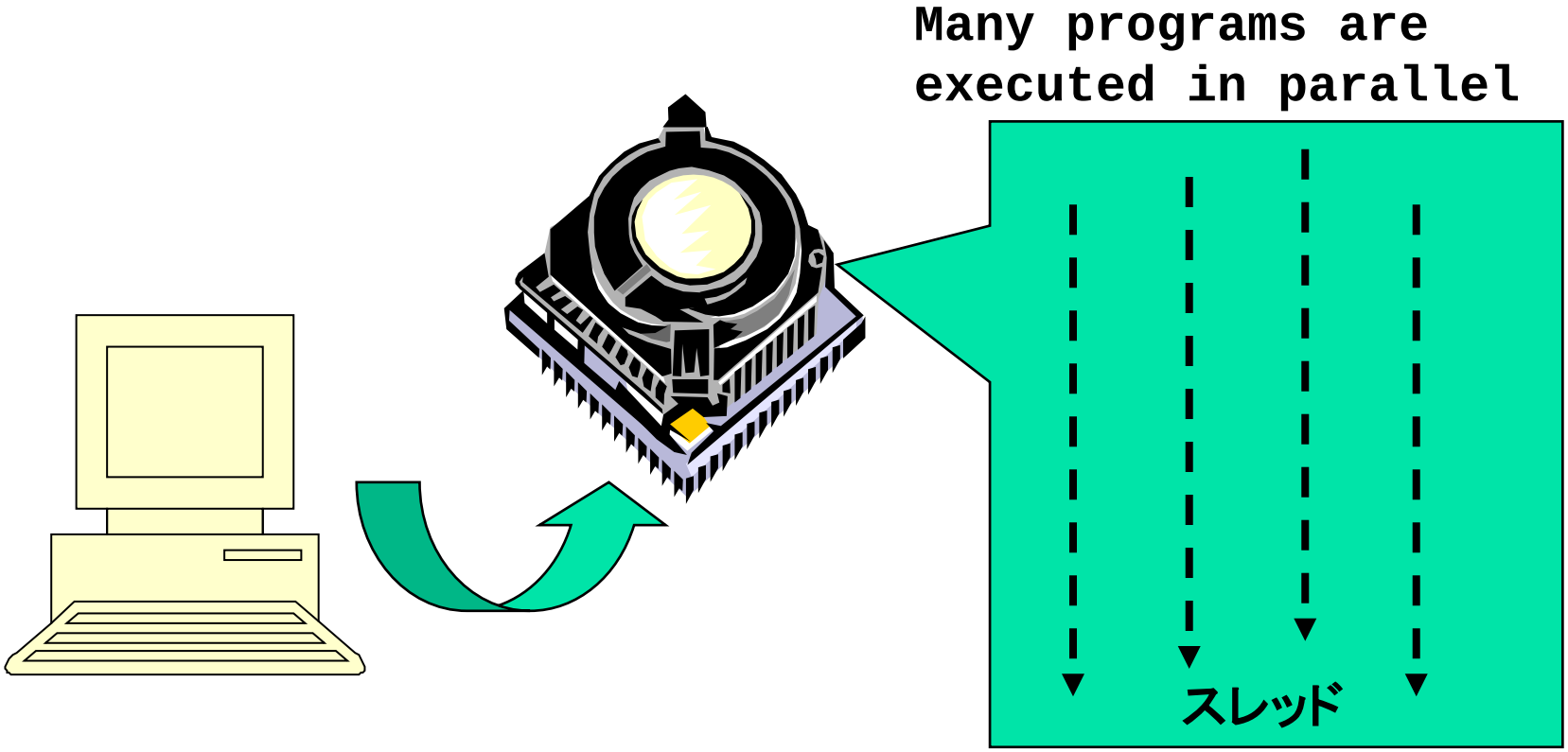
- Message passing programming model
  - Parallel programming by exchange data (message) between processors (nodes)
  - Mainly for distributed memory system (possible also for shared memory)
  - Program must control the data transfer explicitly.
  - Programming is sometimes difficult and time-consuming
  - Program may be scalable (when increasing number of Proc)
- Shared memory programming model
  - Parallel programming by accessing shared data in memory.
  - Mainly for shared memory system. (can be supported by software distributed shared memory)
  - System moves shared data between nodes (by sharing)
  - Easy to program, based on sequential version
  - Scalability is limited. Medium scale multiprocessors.

Parallel programming models

- *There are numerous parallel programming models*
- *The ones most well-known are:*
  - *Distributed Memory*
    - ✔ *Sockets (standardized, low level)*
    - ✔ *PVM - Parallel Virtual Machine (obsolete)*
    - ✔ *MPI - Message Passing Interface (de-facto std)*
  - *Shared Memory*
    - ✔ *Posix Threads (standardized, low level)*
    - ✔ *OpenMP (de-facto standard)*
    - ✔ *Automatic Parallelization (compiler does it for you)*

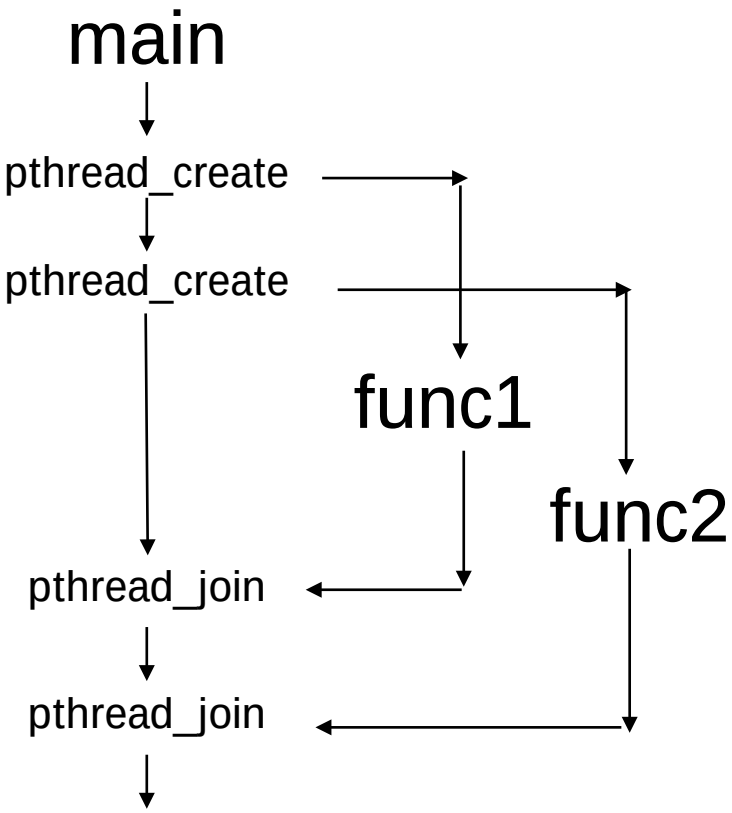
Multithread(ed) programming

- Basic model for shared memory
- Thread of execution = abstraction of execution in processors.
  - Different from process
    - Procss = thread + memory space
  - POSIX thread library = pthread



POSIX thread library

- Create thread: thread_create
- Join threads: pthread_join
- Synchronization, lock




```
#include <pthread.h>

void func1( int x );    void func2( int x );

main() {
        pthread_t t1 ;
        pthread_t t2 ;
           pthread_create( &t1, NULL,
                           (void *)func1, (void *)1 );
           pthread_create( &t2, NULL,
                           (void *)func2, (void *)2 );
           printf("main()¥n");
           pthread_join( t1, NULL );
           pthread_join( t2, NULL );
}
void func1( int x ) {
      int i ;
       for( i = 0 ; i<3 ; i++ ) {
             printf("func1( %d ): %d ¥n",x, i );
         }
}
void func2( int x ) {
             printf("func2( %d ): %d ¥n",x);
}
```

Programming using POSIX thread

- Create threads

Pthread, Solaris thread

```
for(t=1;t<n_thd;t++){
  r=pthread_create(thd_main,t)
}
thd_main(0);
for(t=1; t<n_thd;t++)
       pthread_join();
```

- Divide and assign iterations of loop
- Synchronization for sum

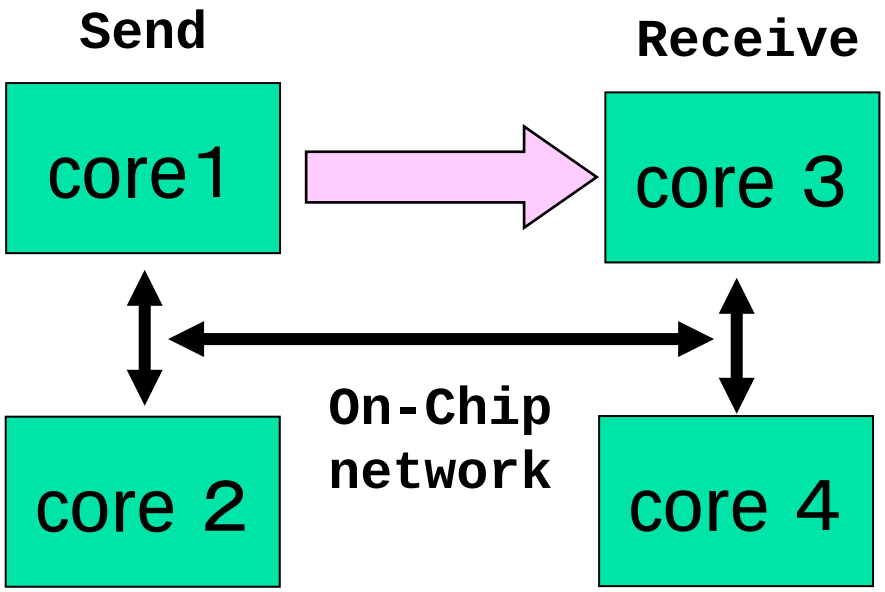
```
int s;  /* global */
int n_thd; /* number of threads */
int thd_main(int id)
{ int c,b,e,i,ss;
  c=1000/n_thd;
  b=c*id;
  e=s+c;
  ss=0;
  for(i=b; i<e; i++) ss += a[i];
  pthread_lock();
  s += ss;
  pthread_unlock();
  return s;
}
```

Thread =
Execution of program

Message passing programming

- General programming paradigm for distributed memory system.
  - Data exchange by “send” and “receive”

- Communication library, layer
  - POSIX IPC, socket
  - TIPC (Transparent Interprocess Communication)
  - LINX (on Enea’s OSE Operating System)
  - MCAPI (Multicore Communication API）
  - MPI (Message Passing Interface)



Simple example of Message Passing Programming

- Sum up 1000 element in array

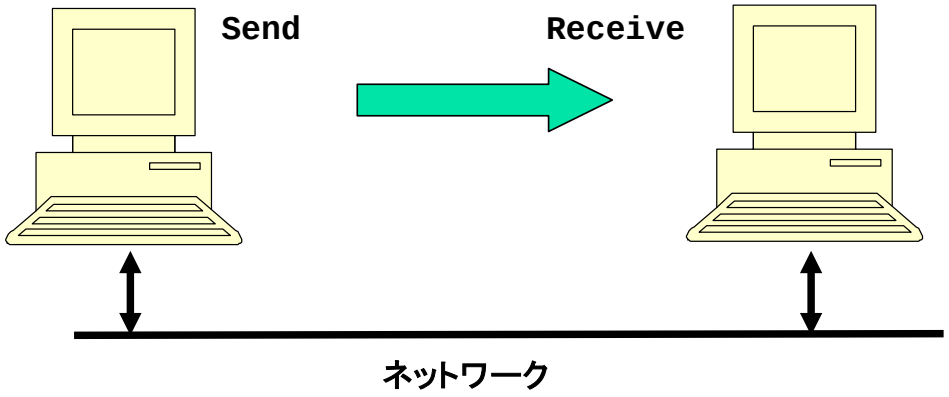
```
int a[250]; /* 250 elements are allocated in each node */

main(){    /* start main in each node */
   int i,s,ss;
   s=0;
   for(i=0; i<250;i++) s+= a[i]; /*compute local sum*/
   if(myid == 0){   /* if processor 0 */
      for(proc=1;proc<4; proc++){
         recv(&ss,proc);  /* receive data from others*/
         s+=ss;   /*add local sum to sum*/
      }
   } else {  /* if processor 1,2,3 */
      send(s,0);  /* send local sum to processor 0 */
   }
}
```

Parallel programming using MPI

- MPI (Message Passing Interface)
- Mainly, for High performance scientific computing
- Standard library for message passing parallel programming in high-end distributed memory systems.
  - Required in case of system with more than 100 nodes.
  - Not easy and time-consuming work
    - “assembly programming” in distributed programming

Over-specs for Embedded system Programming?!

- Communication with message
  - Send/Receive
- Collective operations
  - Reduce/Bcast
  - Gather/Scatter



Programming in MPI

```
#include "mpi.h"
#include <stdio.h>
#define MY_TAG 100
double A[1000/N_PE];
int main( int argc, char *argv[])
{
    int n, myid, numprocs, i;
    double sum, x;
    int  namelen;
    char processor_name[MPI_MAX_PROCESSOR_NAME];
    MPI_Status status;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);
    MPI_Get_processor_name(processor_name,&namelen);
    fprintf(stderr,"Process %d on %s¥n", myid, processor_name);

    ....
```

Programming in MPI

```
    sum = 0.0;
    for (i = 0; i < 1000/N_PE; i++){
       sum+ = A[i];
    }

    if(myid == 0){
       for(i = 1; i < numprocs; i++){
          MPI_Recv(&t,1,MPI_DOUBLE,i,MY_TAG,MPI_COMM_WORLD,&status
            sum += t;
        }
    } else
            MPI_Send(&t,1,MPI_DOUBLE,0,MY_TAG,MPI_COMM_WORLD);
    /* MPI_Reduce(&sum, &sum, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_
     MPI_Barrier(MPI_COMM_WORLD);
    ...
    MPI_Finalize();
    return 0;
}
```

What's OpenMP?

- Programming model and API for shared memory parallel programming
  - It is not a brand-new language.
  - Base-languages(Fortran/C/C++) are extended for parallel programming by directives.
  - Main target area is scientific application.
  - Getting popular as a programming model for shared memory processors as multi-processor and multi-core processor appears.

- OpenMP Architecture Review Board (ARB) decides spec.
  - Initial members were from ISV compiler venders in US.
  - Oct. 1997 Fortran ver.1.0 API
  - Oct. 1998 C/C++ ver.1.0 API
  - Latest version, OpenMP 4.5

- http://www.openmp.org/

Programming using POSIX thread

- Create threads

Pthread, Solaris thread

```
for(t=1;t<n_thd;t++){
  r=pthread_create(thd_main,t)
}
thd_main(0);
for(t=1; t<n_thd;t++)
       pthread_join();
```

- Divide and assign iterations of loop
- Synchronization for sum

```
int s;  /* global */
int n_thd; /* number of threads */
int thd_main(int id)
{ int c,b,e,i,ss;
  c=1000/n_thd;
  b=c*id;
  e=s+c;
  ss=0;
  for(i=b; i<e; i++) ss += a[i];
  pthread_lock();
  s += ss;
  pthread_unlock();
  return s;
}
```

Thread =
Execution of program

Programming in OpenMP

これだけで、OK!

```
#pragma omp parallel for reduction(+:s)
   for(i=0; i<1000;i++) s+= a[i];
```

OpenMP API

- It is not a new language!
  - Base languages are extended by compiler directives/pragma, runtime library, environment variable.
  - Base languages: Fortran 90, C, C++
    - Fortran: directive line starting with !$OMP
    - C: directive by #pragma omp

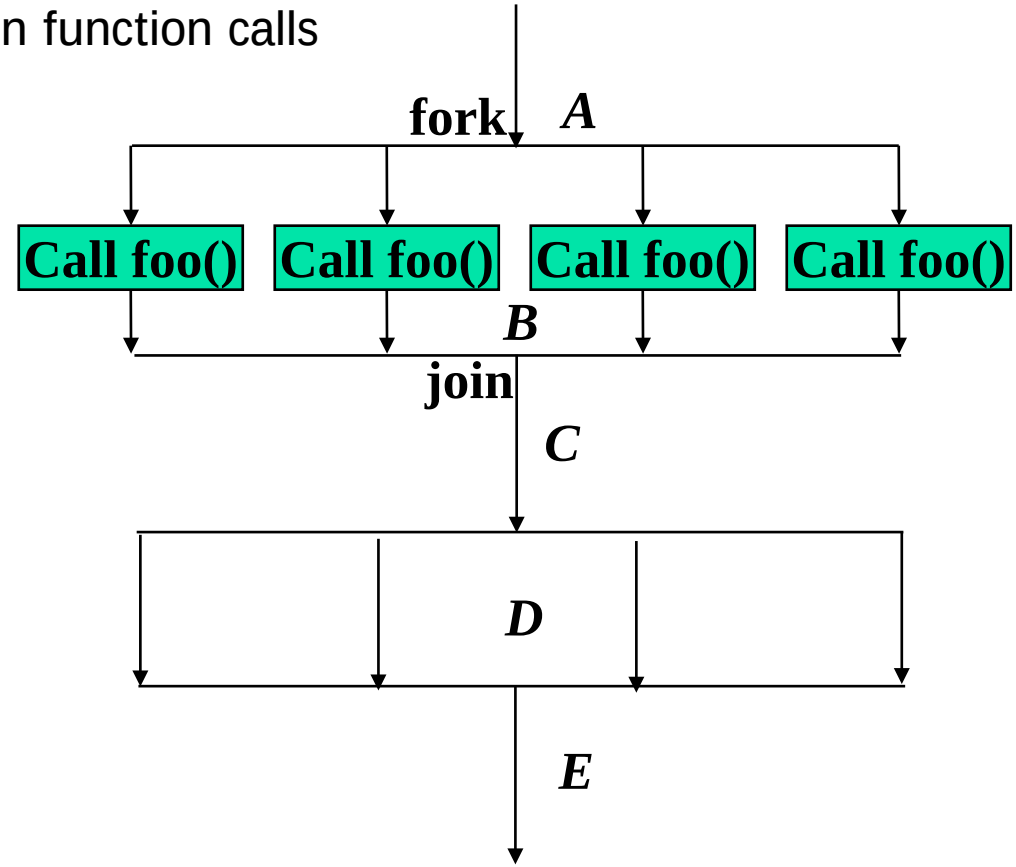
- Different from automatic parallelization
  - OpenMP parallel execution model is defined explicitly by a programmer.

- If directives are ignored (removed), the OpenMP program can be executed as a sequential program
  - Can be parallelized in incrementally
  - Practical approach with respect to program development and debugging.
  - Can be maintained as a same source program for both sequential and parallel version.

OpenMP Execution model

- Start from sequential execution
- Fork-join Model
- parallel region
  - Duplicated execution even in function calls

```
… A …
#pragma omp parallel
{
   foo(); /* ..B… */
}
… C ….
#pragma omp parallel
{
… D …
}
… E …
```



Parallel Region

- A code region executed in parallel by multiple threads (team)
  - Specified by Parallel constructs
  - A set of threads executing the same parallel region is called “team”
  - Threads in team execute the same code in region (duplicated execution)

```
#pragma omp parallel
{
    …
    … Parallel region…
    …
}
```

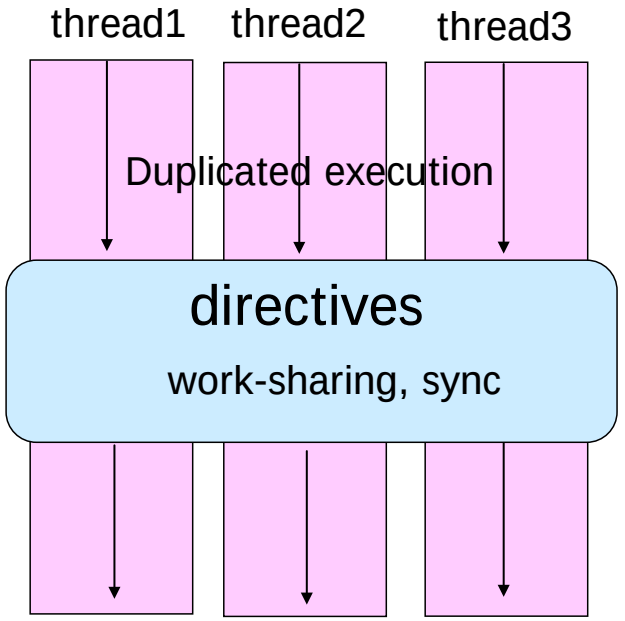
Demo

- How many threads? /proc/cpuinfo
- gcc –fopenmp, gcc suppots OpenMP from versio、4.2, gfortran
- You can specify the number of threads by environment variable OMP_NUM_THREADS

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

main()
{
   printf("omp-test ... n_thread=%d¥n",omp_get_max_threads());
#pragma omp parallel
   {
          printf("thread (%d/%d)...¥n",
                omp_get_thread_num(),omp_get_num_threads());
   }
   printf("end...¥n");
}
```

Work sharing Constructs

- Specify how to share the execution within a team
  - Used in parallel region
  - `for` Construct
    - Assign iterations for each threads
    - For data parallel program
  - `Sections` Construct
    - Execute each section by different threads
    - For task-parallelism
  - `Single` Construct
    - Execute statements by only one thread
  - Combined Construct with parallel directive
    - `parallel for` Construct
    - `parallel sections` Construct



For Construct

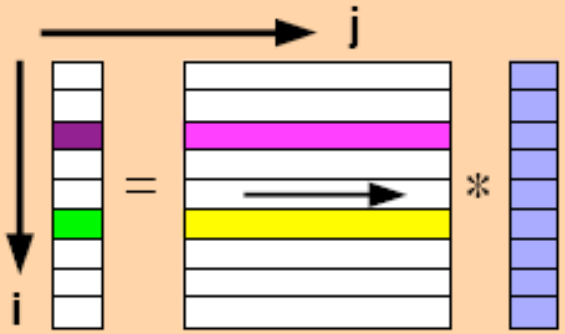
- Execute iterations specified For-loop in parallel
- For-loop specified by the directive must be in *canonical shape*

```
#pragma omp for [clause...]
 for(var=lb; var logical-op ub; incr-expr)
    body
```

  - *Var* must be loop variable of integer or pointer(automatically private)
  - *incr-expr*
    - ++*var*, *var*++, --*var*, *var*--, *var*+=*incr*, *var*-=*incr*
  - *logical-op*
    - <、<=、>、>=
  - Jump to ouside loop or break are not allows
  - Scheduling method and data attributes are specified in *clause*

Example: matrix-vector product

```
#pragma omp parallel for default(none) \
            private(i,j,sum) shared(m,n,a,b,c)
for (i=0; i<m; i++)
{
   sum = 0.0;
   for (j=0; j<n; j++)
     sum += b[i][j]*c[j];
   a[i] = sum;
 }
```



TID = 0

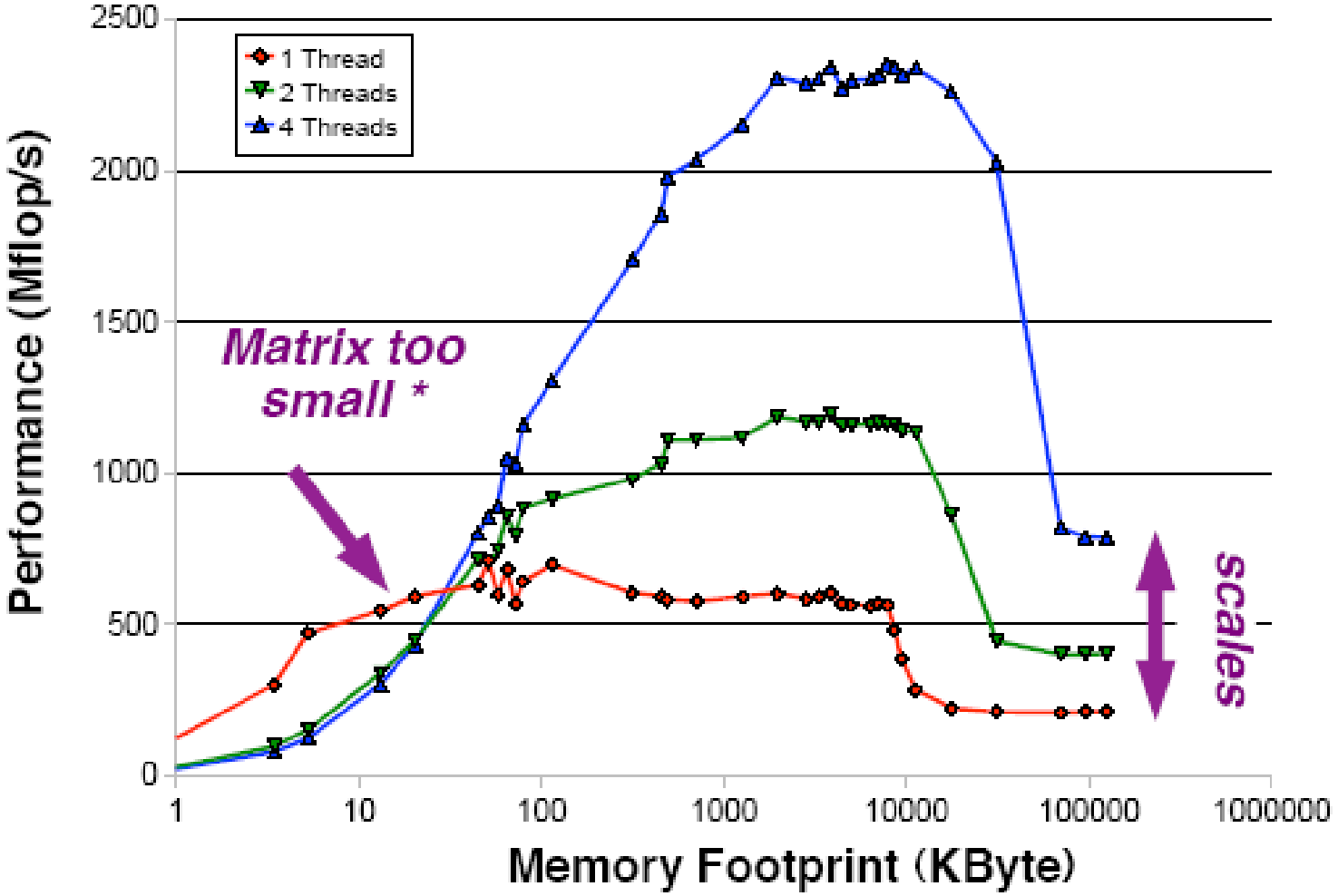
```
for (i=0,1,2,3,4)
 i = 0
   sum = Σ b[i=0][j]*c[j]
   a[0] = sum
 i = 1
   sum = Σ b[i=1][j]*c[j]
   a[1] = sum
```

TID = 1

```
for (i=5,6,7,8,9)
 i = 5
   sum = Σ b[i=5][j]*c[j]
   a[5] = sum
 i = 6
   sum = Σ b[i=6][j]*c[j]
   a[6] = sum
```

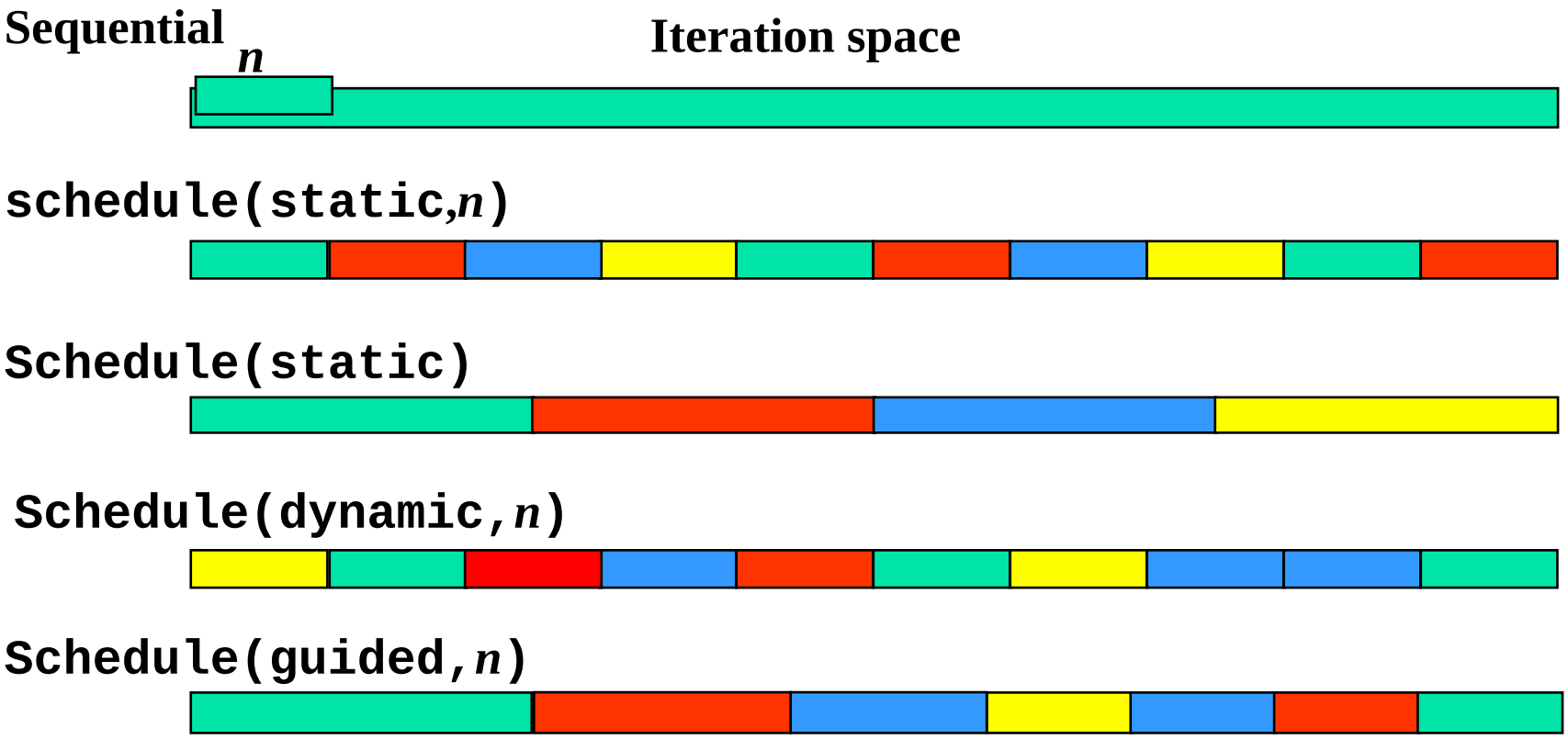
... etc ...

The performance looks like ...

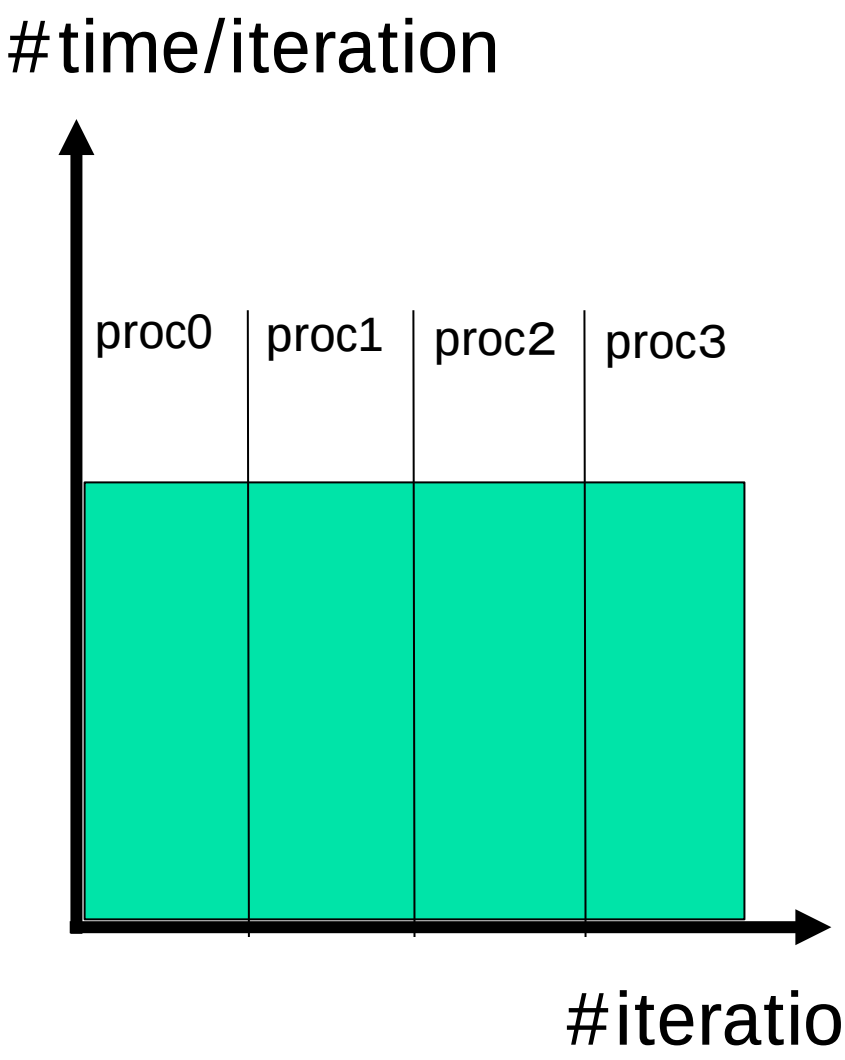


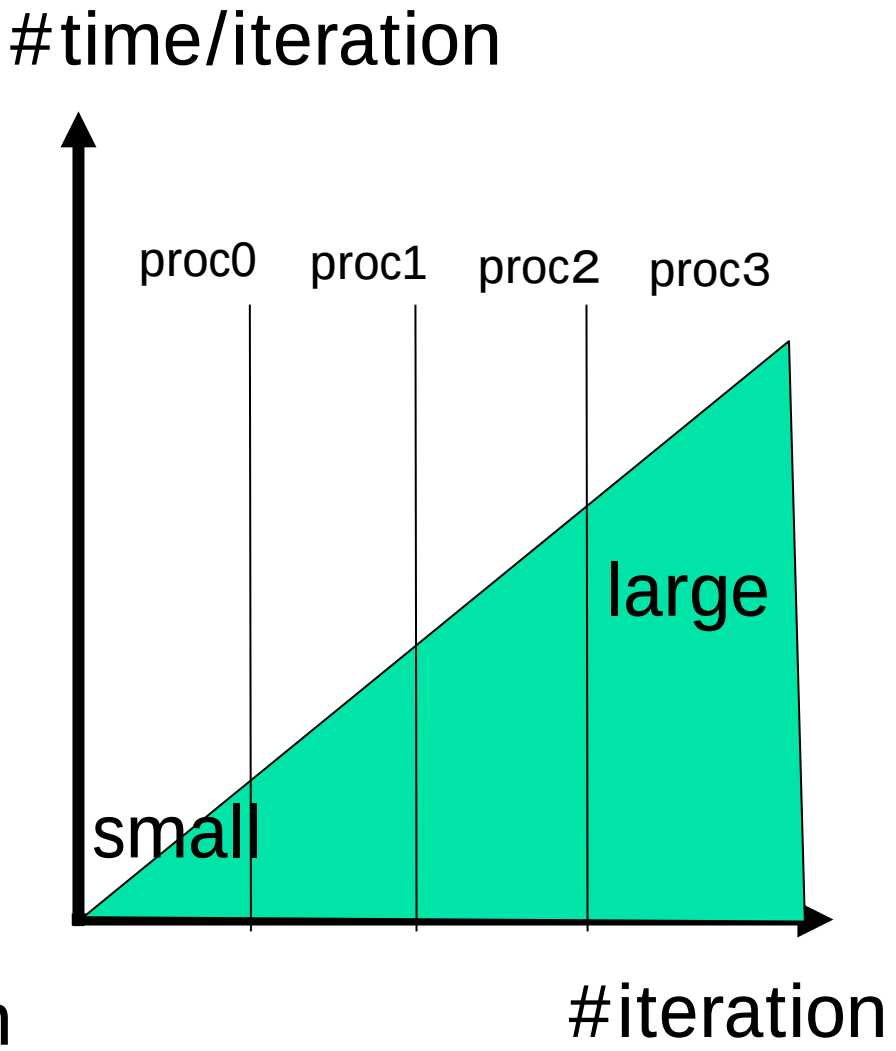
Scheduling methods of parallel loop

- #processor = 4

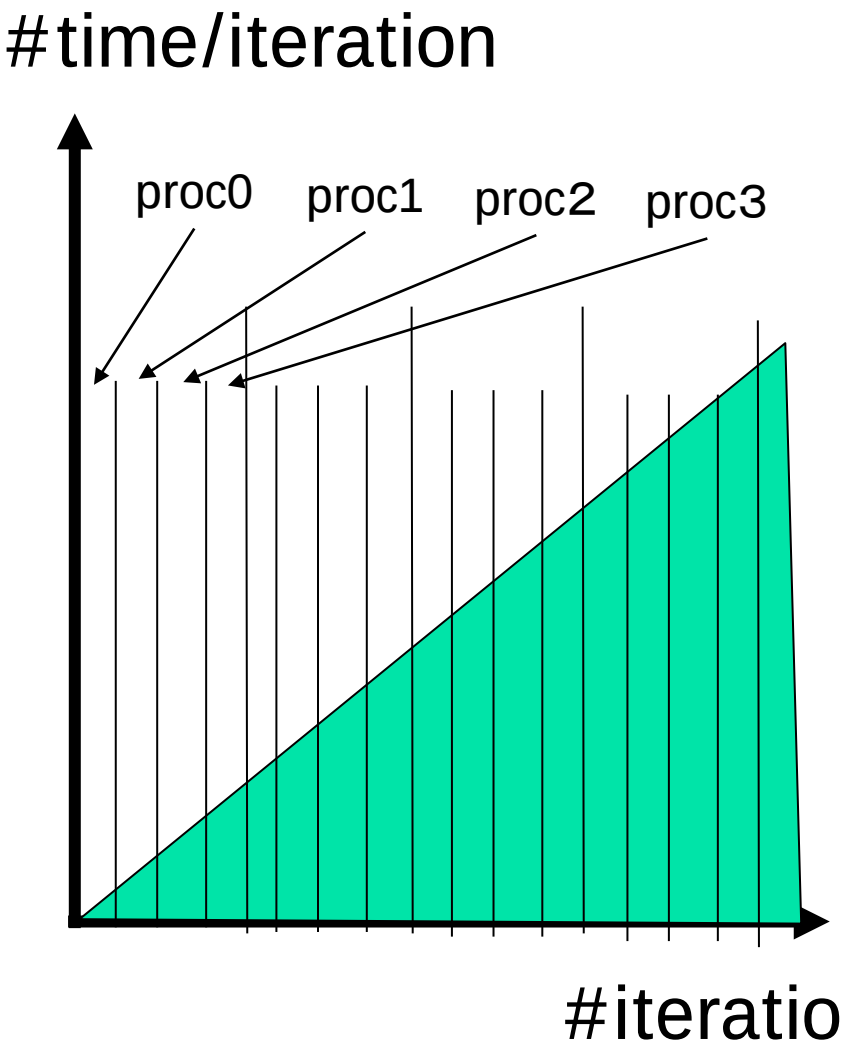


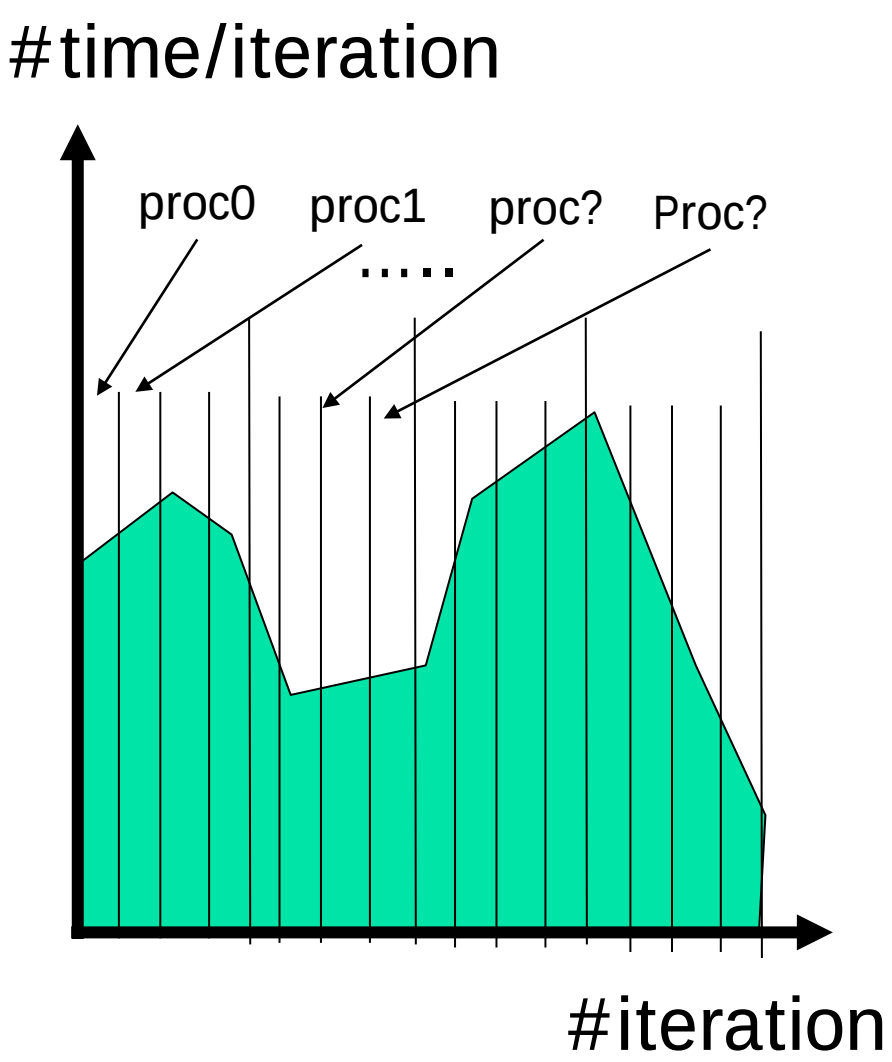
Static scheduling





Cyclic & dynamic scheduling

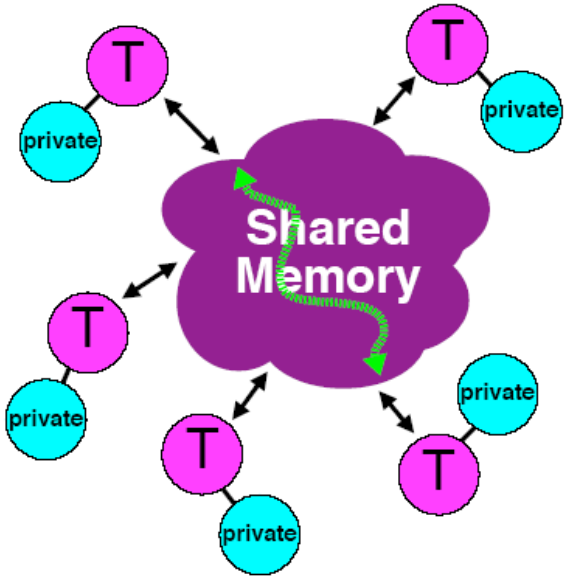




Data scope attribute clause

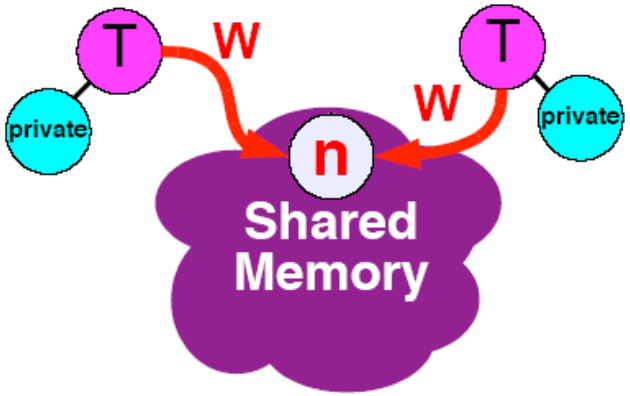
- Clause specified with `parallel`consruct、work sharing construct
- `shared(var_list)`
  - Specified variables are shared among threads.
- `private(var_list)`
  - Specified variables replicated as a private variable
- `firstprivate(var_list)`
  - Same as private, but initialized by value before loop.
- `lastprivate(var_list)`
  - Same as private, but the value after loop is updated by the value of the last iteration.
- `reduction(op:var_list)`
  - Specify the value of variables computed by reduction operation op.
  - Private during execution of loop, and updated at the end of loop

Data Race

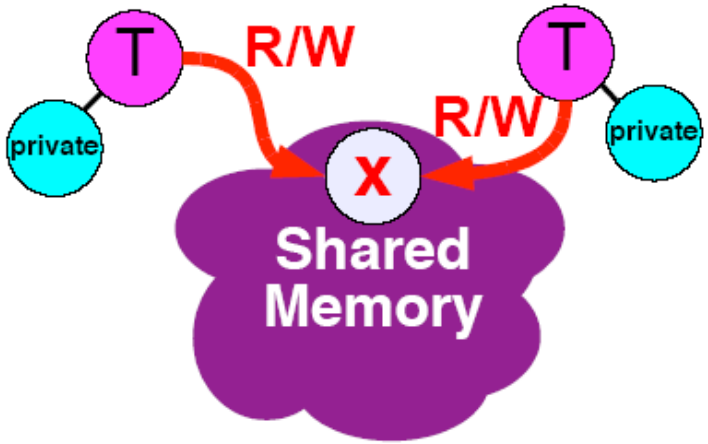


OpenMP
Is shared
Memory!

```
#pragma omp parallel shared(n)
{n = omp_get_thread_num();}
```




```
#pragma omp parallel shared(x)
{x = x + 1;}
```

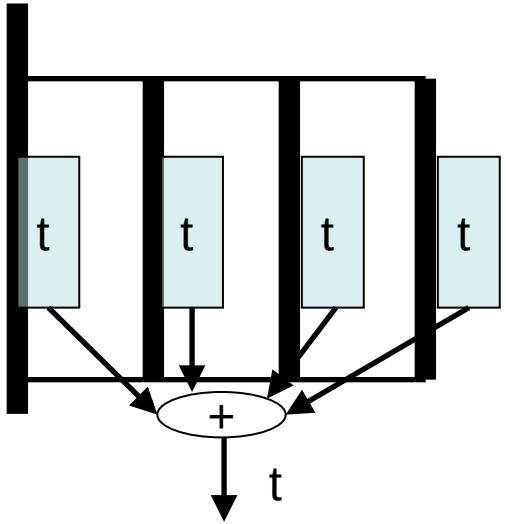


Data Race =
Write a same variable by
different threads

reduction clause

- The syntax of the reduction clause is as follows: **reduction** (*operator : list*)
- a private copy is created in each implicit task.
- After the end of the region, it is updated with the private copies using the specified operator.

```
#pragma omp parallel for reduction(+:t)
```



Operator	Initial value	Operator	Initial value
+	0	&	~0
*	1	|	0

Example of loop construct

```
#include <stdio.h>
#include <math.h>
double f( double a )
{
      return (4.0 / (1.0 + a*a));
}

int main( int argc, char *argv[])
{
      int n, I, thd;
      double PI25DT = 3.14159265358979323846264 3;
      double pi, h, sum, x;

      n = atoi(argv[1]); thd = atoi(argv[2]);
      h = 1.0 / (double) n;
      sum = 0.0;
#pragma omp parallel for private(x) reduction(+:sum) num_threads(thd)
      for (i = 1; i <=n; i++) {
          x = h * ((double) i - 0.5);
          sum += f(x);
      }
      pi = h * sum;
      printf("pi=%.16f, Error=%.16, n=%d, thd=%df¥n", pi, fabs(pi  - PI25DT), n, thd);
      return 0;
}
```

$$\pi = \int_0^1 \frac{4}{1+t^2}\,dt$$

Barrier directive

- Sync team by barrier synchronization
  - Wait until all threads in the team reached to the barrier point.
  - Memory write operation to shared memory is completed (flush) at the barrier point.
  - Implicit barrier operation is performed at the end of parallel region, work sharing construct without `nowait` clause

```
#pragma omp barrier
```

You cannot parallelize this loop

```
for (i=0; i<8; i++)
   a[i] = a[i] + b[i];
```

Every iteration in this loop is independent of the other iterations

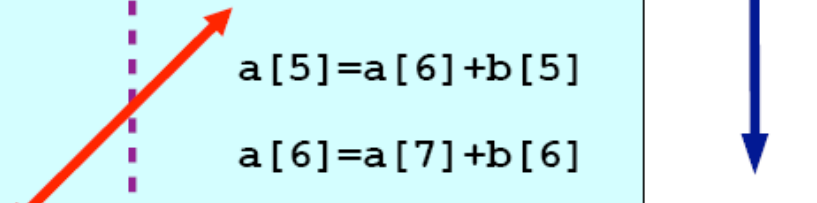
Thread 1	Thread 2
a[0]=a[0]+b[0]	a[4]=a[4]+b[4]
a[1]=a[1]+b[1]	a[5]=a[5]+b[5]
a[2]=a[2]+b[2]	a[6]=a[6]+b[6]
a[3]=a[3]+b[3]	a[7]=a[7]+b[7]

Time

```
for (i=0; i<8; i++)
   a[i] = a[i+1] + b[i];
```

The result is not deterministic when run in parallel !

Thread 1	Thread 2
a[0]=a[1]+b[0]	a[4]=a[5]+b[4]
a[1]=a[2]+b[1]	a[5]=a[6]+b[5]
a[2]=a[3]+b[2]	a[6]=a[7]+b[6]
a[3]=a[4]+b[3]	a[7]=a[8]+b[7]



Time

Barrier directive

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  - Wait until all threads in the team reached to the barrier point.
  - Memory write operation to shared memory is completed (flush) at the barrier point.
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#pragma omp barrier
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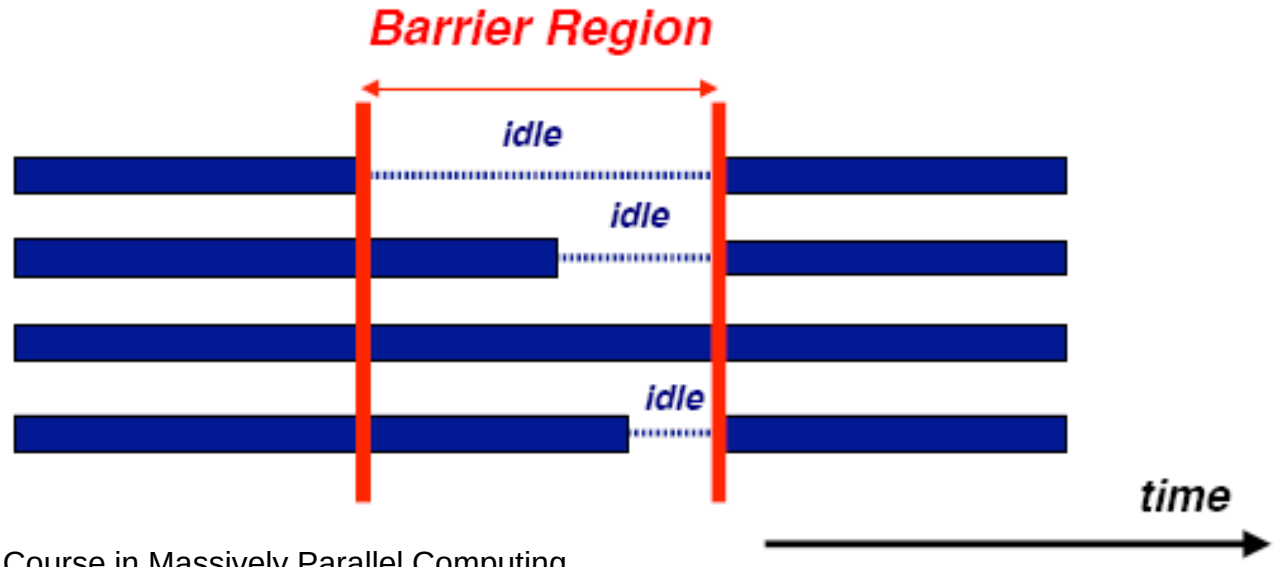
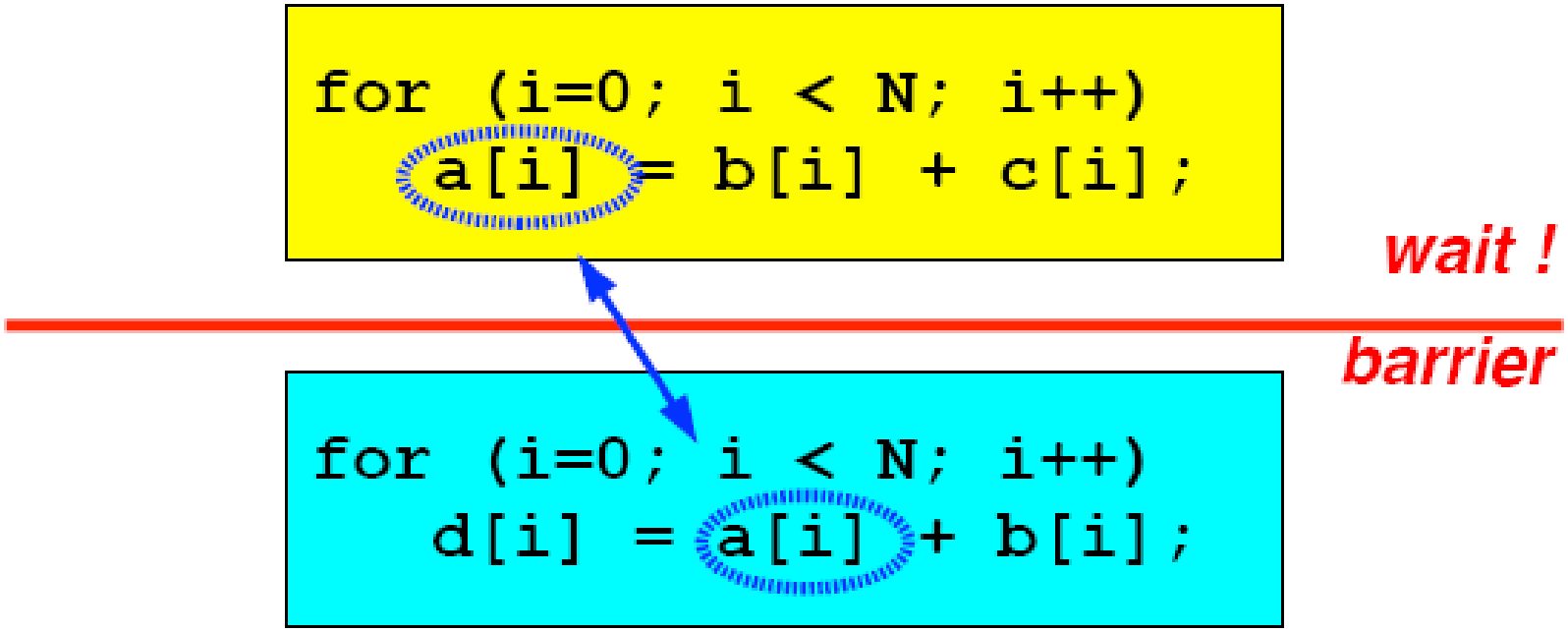


Barrier is important in this case



You don’t need to put barrier directive
Because for directive without nowait performs implicit barrier.

How to use nowait

```
#pragma omp parallel default(none)\
        shared(n,a,b,c,d) private(i)
  {
    #pragma omp for nowait
      for (i=0; i<n-1; i++)
          b[i] = (a[i] + a[i+1])/2;
    #pragma omp for nowait
      for (i=0; i<n; i++)
          d[i] = 1.0/c[i];

  } /*-- End of parallel region --*/
```

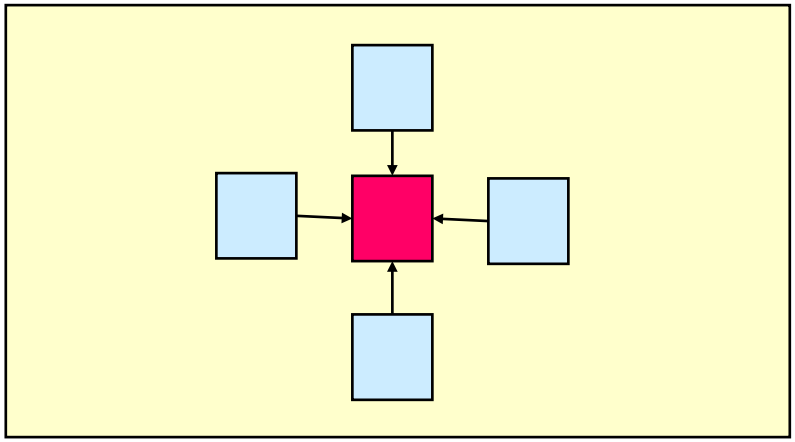
(implied barrier)

Other directives

- Single construct： to specify a region executed by one thread.
- Master construct: to specify a region executed by master thread.
- Section construct: to specify regions executed by different threads (task parallelism)
- Critical construct： to specify critical region executed exclusively between threads
- Flush construct
- Threadprivate construct

Example of OpenMP program：laplace

- Explicit solver of Laplace equation
  - Stencil operation: update value with 4-points of up/down/left/right.
  - Use array of “old” and “new”. Compute new by old and replace old with new.
  - Typical parallelization by domain decomposition
  - At each iteration, compute residual



- OpenMP version: lap.c
  - Parallelize 3 loops
    - OpenMP support only loop parallelization of outer loop.
  - For loop directive is orphan, in dynamic extent of parallel directive.

```
void lap_solve()
{
    int x,y,k;
    double sum;

#pragma omp parallel private(k,x,y)
{
    for(k = 0; k < NITER; k++){
        /* old <- new */
#pragma omp for
        for(x = 1; x <= XSIZE; x++)
          for(y = 1; y <= YSIZE; y++)
            uu[x][y] = u[x][y];
        /* update */
#pragma omp for
        for(x = 1; x <= XSIZE; x++)
          for(y = 1; y <= YSIZE; y++)
            u[x][y] = (uu[x-1][y] + uu[x+1][y] + uu[x][y-1] + uu[x][y+1])/4.0;
    }
 }

/* check sum */
    sum = 0.0;
#pragma omp parallel for private(y) reduction(+:sum)
    for(x = 1; x <= XSIZE; x++)
        for(y = 1; y <= YSIZE; y++)
          sum += (uu[x][y]-u[x][y]);
    printf("sum = %g¥n",sum);
}
```

What about performance?

- OpenMP really speedup my problem?!
- It depends on hardware and problem size/characteristics
- Esp. problem sizes is an very important factor
  - Trade off between overhead of parallelization and grain size of parallel execution.
- To understand performance, …
  - How to lock
  - How to exploit cache
  - Memory bandwidth

Advanced topics

- MPI/OpenMP Hybrid Programming
  - Programming for Multi-core cluster
- OpenMP 3.0 (2007, approved)
  - Task parallelism
- OpenACC (2012)
  - For GPU, by NVIDIA, PGI, Cray, ...
- OpenMP 4.0 (2013, released)
  - Accelerator extension
  - SIMD extension
  - Task dependency description

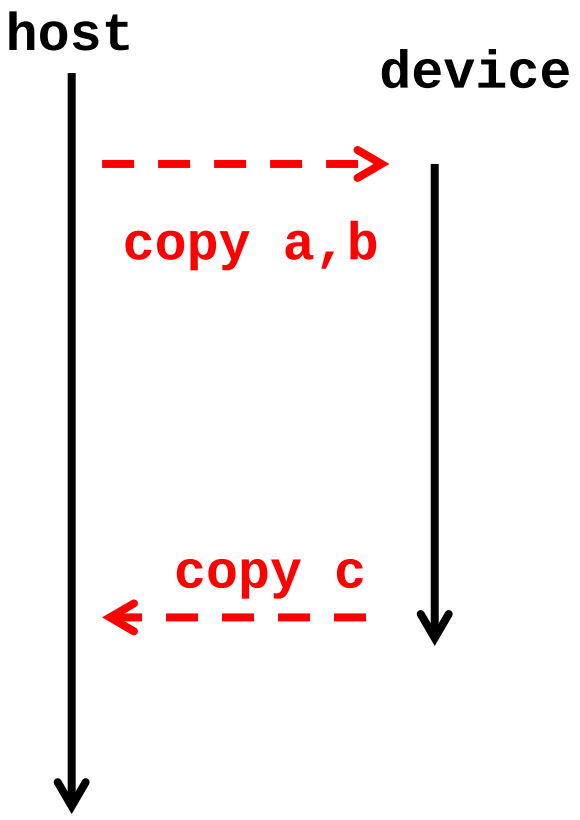
OpenACC

- A spin-off activity from OpenMP ARB for supporting accelerators such as GPGPU and MIC
- NVIDIA, Cray Inc., the Portland Group (PGI), and CAPS enterprise
- Directive to specify the code offloaded to GPU.

A simple example

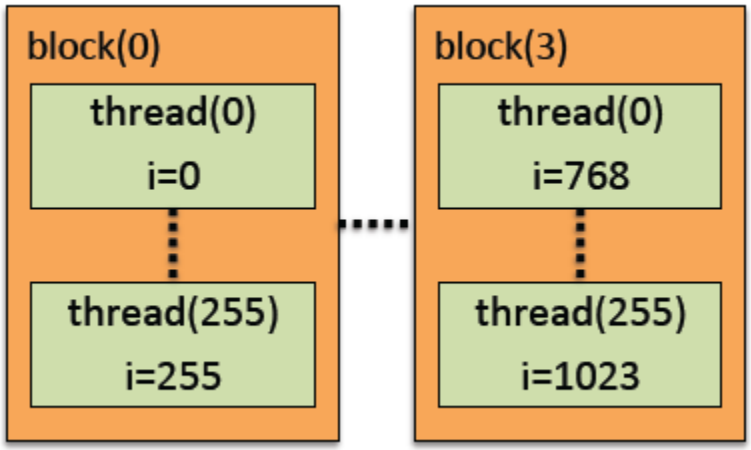
direction	copy	copyin	copyout
Host->device	○	○	
Device->Host	○		○

```
#define N 1024
int main(){
int i;
int a[N], b[N],c[N];
#pragma acc data copyin(a,b) copyout(c)
{
 #pragma acc parallel
 {
 #pragma acc loop
   for(i = 0; i < N; i++){
      c[i] = a[i] + b[i];
   }
 }
}
}
```



A simple example

```
#define N 1024
int main(){
int i;
int a[N], b[N],c[N];
#pragma acc data copyin(a,b) copyout(c)
{
 #pragma acc parallel
 {
 #pragma acc loop
   for(i = 0; i < N; i++){
      c[i] = a[i] + b[i];
   }
 }
}
}
```



execute iterations like CUDA kernel

Matrix Multiply in OpenACC

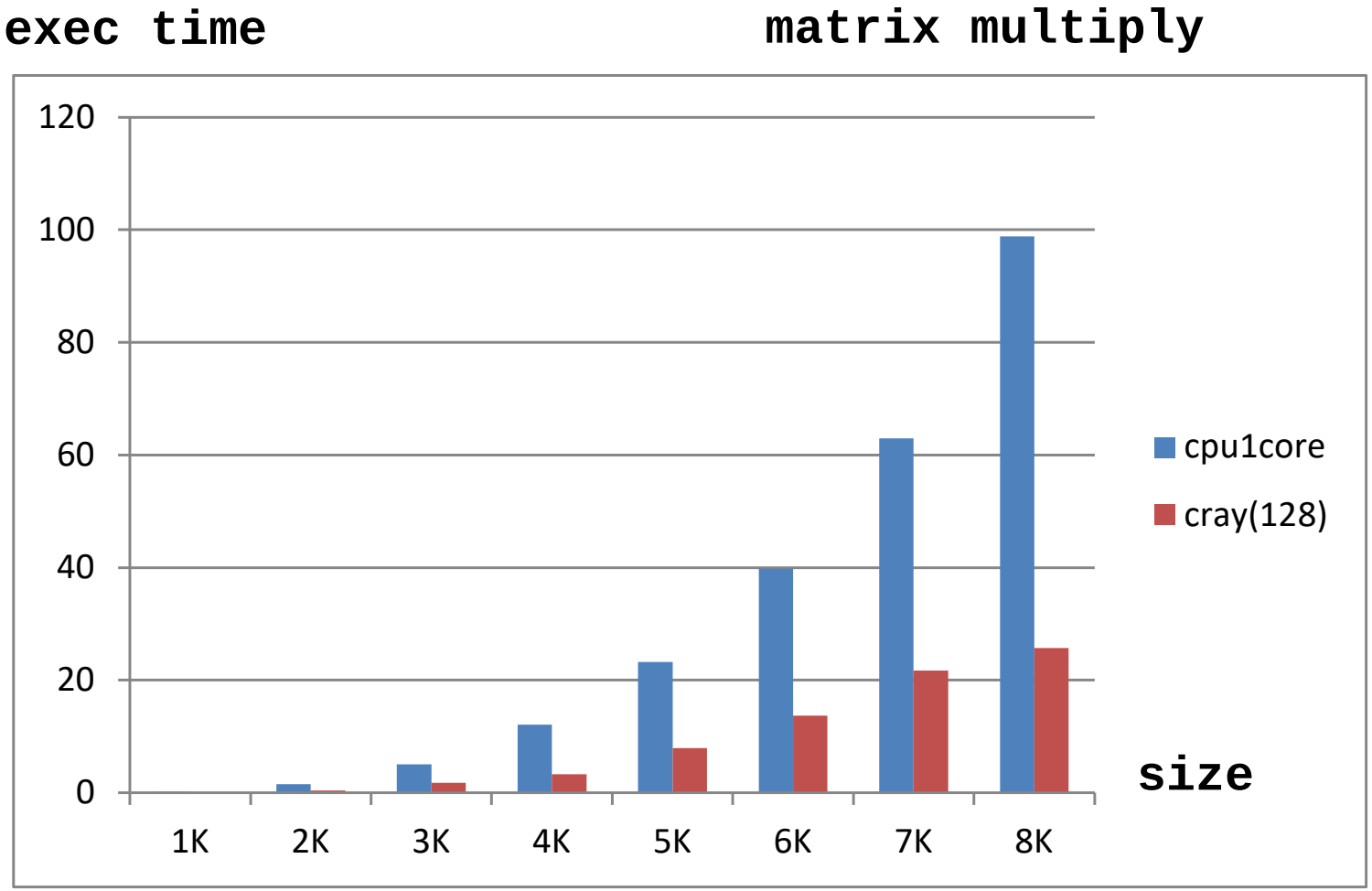
```
#define N 1024

void main(void)
{
  double a[N][N], b[N][N], c[N][N];
  int i,j;
  // ... setup data ...
#pragma acc parallel loop copyin(a, b) copyout(c)
  for(i = 0; i < N; i++){
#pragma acc loop
    for(j = 0; j < N; j++){
      int k;
      double sum = 0.0;
      for(k = 0; k < N; k++){
       sum += a[i][k] * b[k][j];
      }
      c[i][j] = sum;
    }
  }
}
```

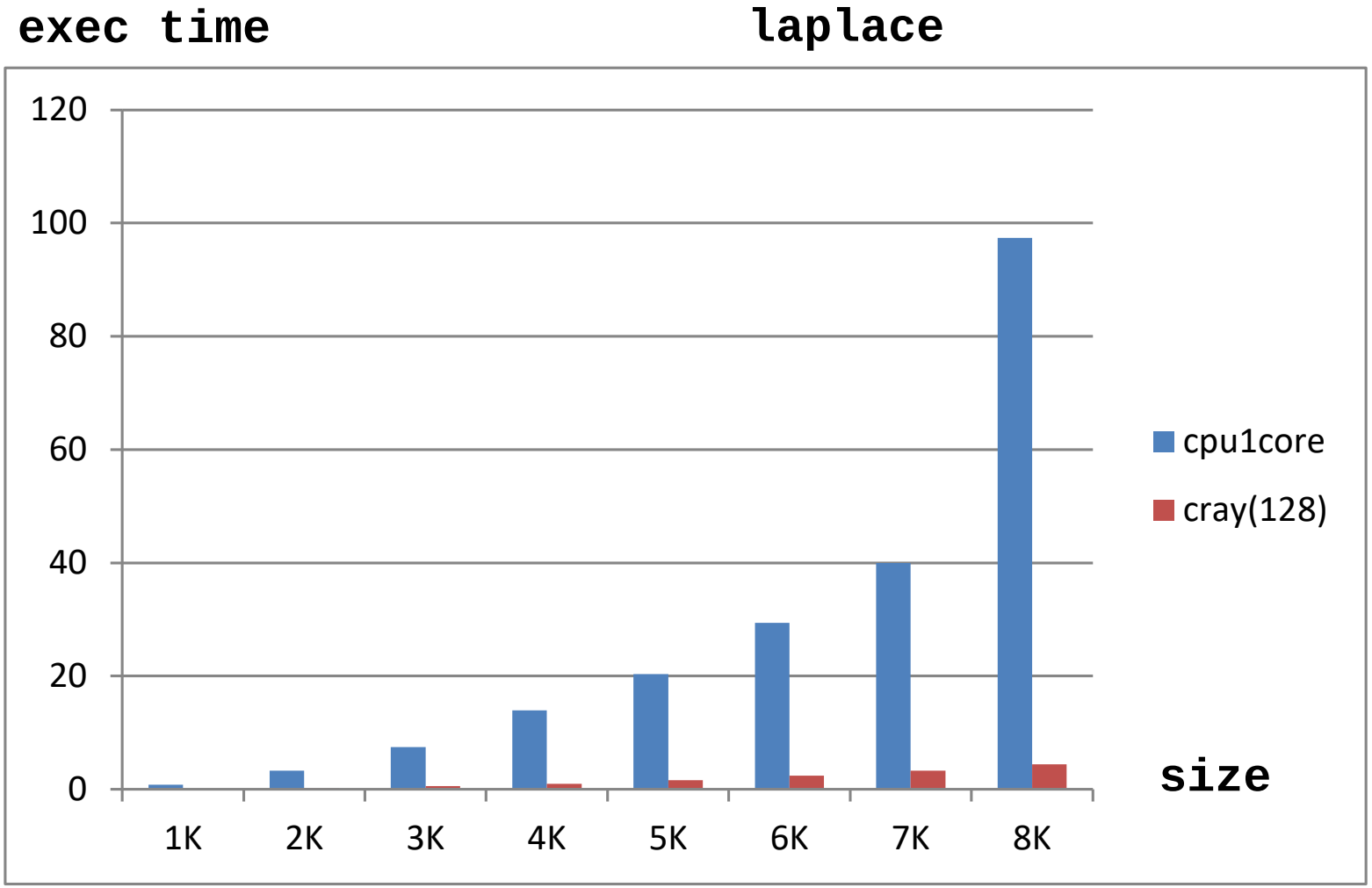
Stencil Code (Laplace Solver) in OpenACC

```
#define XSIZE 1024
#define YSIZE 1024
#define ITER 100
int main(void){
  int x, y, iter;
  double u[XSIZE][YSIZE], uu[XSIZE][YSIZE];
  // setup ...
#pragma acc data copy(u, uu)
  {
    for(iter = 0; iter < ITER; iter++){
      //old <- new
#pragma acc parallel loop
      for(x = 1; x < XSIZE-1; x++){
#pragma acc loop
        for(y = 1; y < YSIZE-1; y++)
          uu[x][y] = u[x][y];
      }
      //update
#pragma acc parallel loop
      for(x = 1; x < XSIZE-1; x++){
#pragma acc loop
        for(y = 1; y < YSIZE-1; y++)
            u[x][y] = (uu[x-1][y] + uu[x+1][y]
                       + uu[x][y-1] + uu[x][y+1]) / 4.0;
      }}
  } //acc data end
}
```

Performance of OpenACC code



Performance of OpenACC code

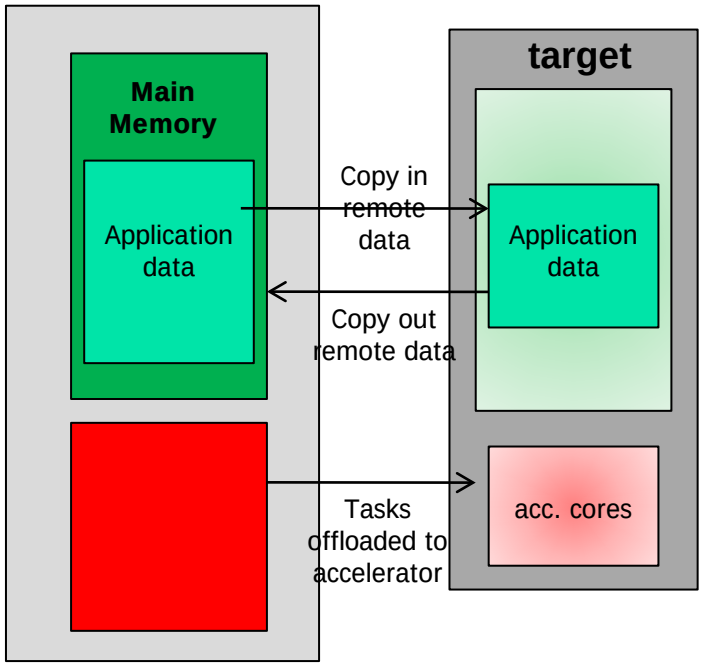


OpenMP 4.0

- Released July 2013
  - http://www.openmp.org/mp-documents/OpenMP4.0.0.pdf
  - A document of examples is expected to release soon
- Changes from 3.1 to 4.0 (Appendix E.1):
  - *Accelerator: 2.9*
  - *SIMD extensions: 2.8*
  - *Places and thread affinity: 2.5.2, 4.5*
  - *Taskgroup and dependent tasks: 2.12.5, 2.11*
  - *Error handling: 2.13*
  - *User-defined reductions: 2.15*
  - *Sequentially consistent atomics: 2.12.6*
  - *Fortran 2003 support*

Accelerator (2.9): offloading

- Execution Model: Offload data and code to accelerator
- *target* construct creates tasks to be executed by devices
- Aims to work with wide variety of accs
  - GPGPUs, MIC, DSP, FPGA, etc
  - A target could be even a remote node, intentionally




```
#pragma omp target
{
      /* it is like a new task
        * executed on a remote device */
{
```

Accelerator: explicit data mapping

- Relatively small number of truly shared memory accelerators so far
- Require the user to explicitly *map* data to and from the device memory
- Use array region

```
long a = 0x858;
long b = 0;
int anArray[100]

#pragma omp target data map(to:a)
¥¥
   map(tofrom:b,anArray[0:64])
{
    /* a, b and anArray are mapped
      * to the device */

   /* work here */
}
/* b and anArray are mapped
  * back to the host */
```

Accelerator: hierarchical parallelism

- Organize massive number of threads
  - teams of threads, e.g. map to CUDA grid/block
- Distribute loops over teams

```
#pragma omp target

#pragma omp teams num_teams(2)
            num_threads(8)
{
     //-- creates a “league” of teams
    //-- only local barriers permitted
#pragma omp distribute
for (int i=0; i<N; i++) {

}

}
```

Only target directive makes it as accelerator region

target and map examples

```
void vec_mult(int N)
{
   int i;
   float p[N], v1[N], v2[N];
   init(v1, v2, N);
   #pragma omp target map(to: v1, v2) map(from: p)
   #pragma omp parallel for
   for (i=0; i<N; i++)
     p[i] = v1[i] * v2[i];
   output(p, N);
}
```

```
void vec_mult(float *p, float *v1, float *v2, int N)
{
   int i;
   init(v1, v2, N);
   #pragma omp target map(to: v1[0:N], v2[:N]) map(from: p[0:N])
   #pragma omp parallel for
   for (i=0; i<N; i++)
     p[i] = v1[i] * v2[i];
   output(p, N);
}
```

target date example

```
void vec_mult(float *p, float *v1, float *v2, int N)
{
   int i;
   init(v1, v2, N);
   #pragma omp target data map(from: p[0:N])
   {
      #pragma omp target map(to: v1[:N], v2[:N])
      #pragma omp parallel for
      for (i=0; i<N; i++)
        p[i] = v1[i] * v2[i];
      init_again(v1, v2, N);
      #pragma omp target map(to: v1[:N], v2[:N])
      #pragma omp parallel for
      for (i=0; i<N; i++)
        p[i] = p[i] + (v1[i] * v2[i]);
   }
   output(p, N);
}
```

Note mapping inheritance

teams and distribute loop example

```
float dotprod_teams(float B[], float C[], int N, int num_blocks,
  int block_threads)
{
    float sum = 0;
    int i, i0;
    #pragma omp target map(to: B[0:N], C[0:N])
    #pragma omp teams num_teams(num_blocks) thread_limit(block_threads)
      reduction(+:sum)
    #pragma omp distribute
    for (i0=0; i0<N; i0 += num_blocks)
       #pragma omp parallel for reduction(+:sum)
       for (i=i0; i< min(i0+num_blocks,N); i++)
           sum += B[i] * C[i];
    return sum;
}
```

Double-nested loops are mapped to the two levels of thread hierarchy (league and team)