Basic Computational Biology

High Performance Computing Technology(2)

Introduction to parallel programming

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Contents

- What is parallel programming?
- MPI between nodes
- OpenMP within nodes
- Advanced Topics
  - Programming for GPU (CUDA and OpenACC)
- Cloud Computing
  - Map-reduce

How to make computer fast?

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

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

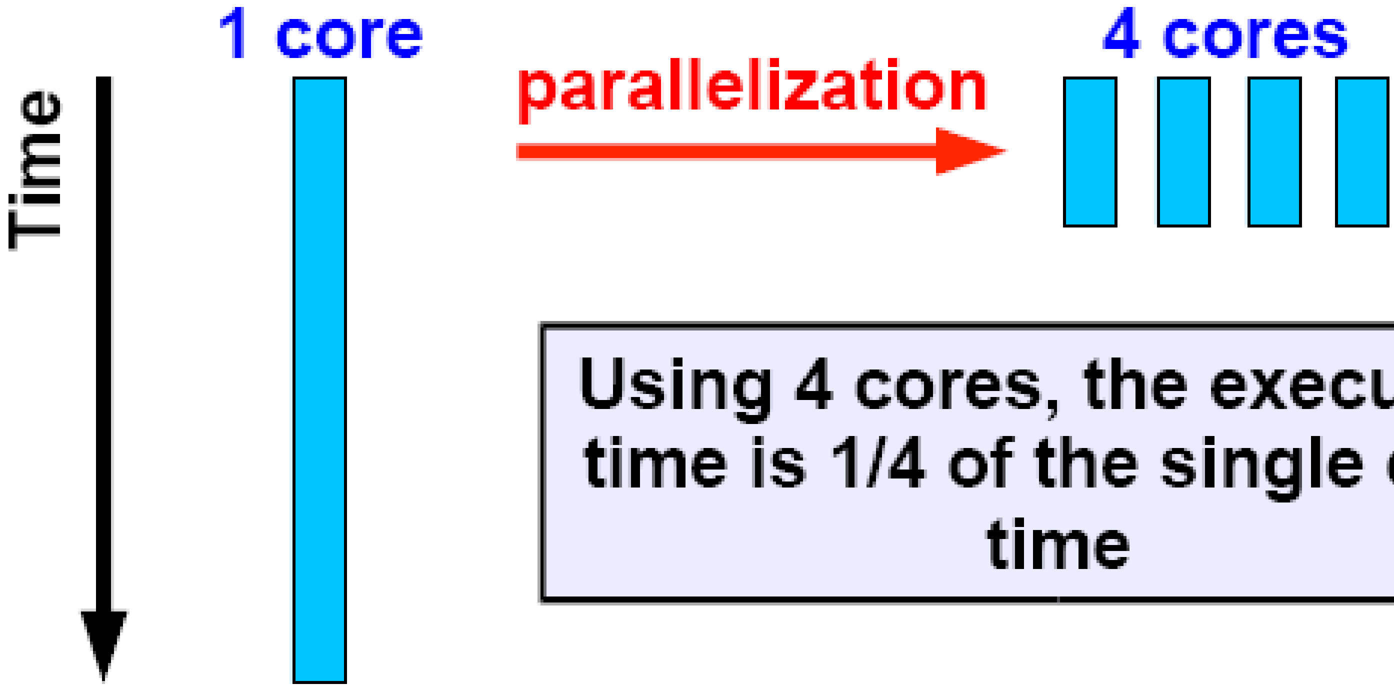
Pipeline
Superscalar

mulitcore

Shared memory multiprocessor

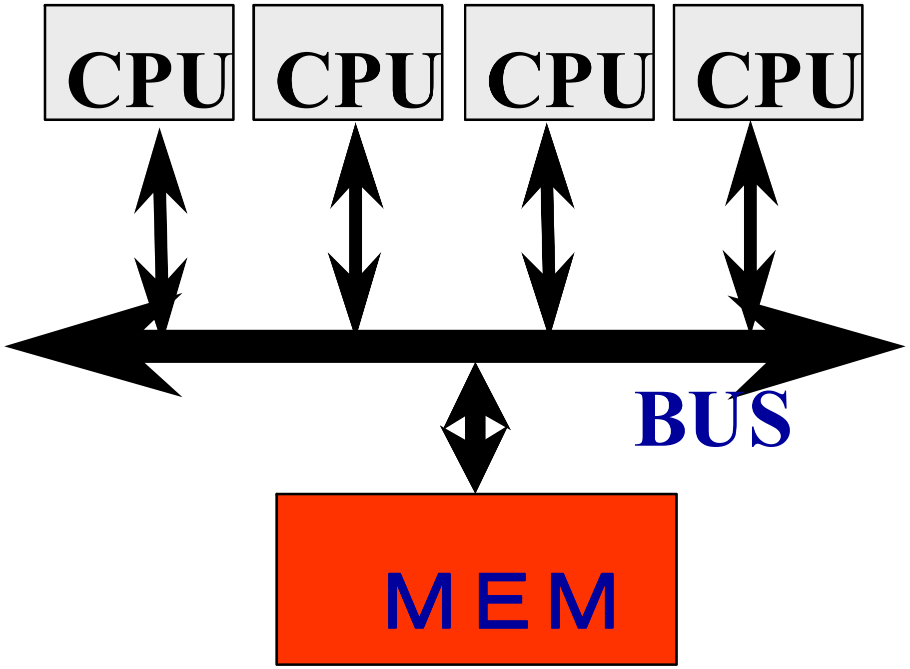
Distributed memory computer or Grid

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



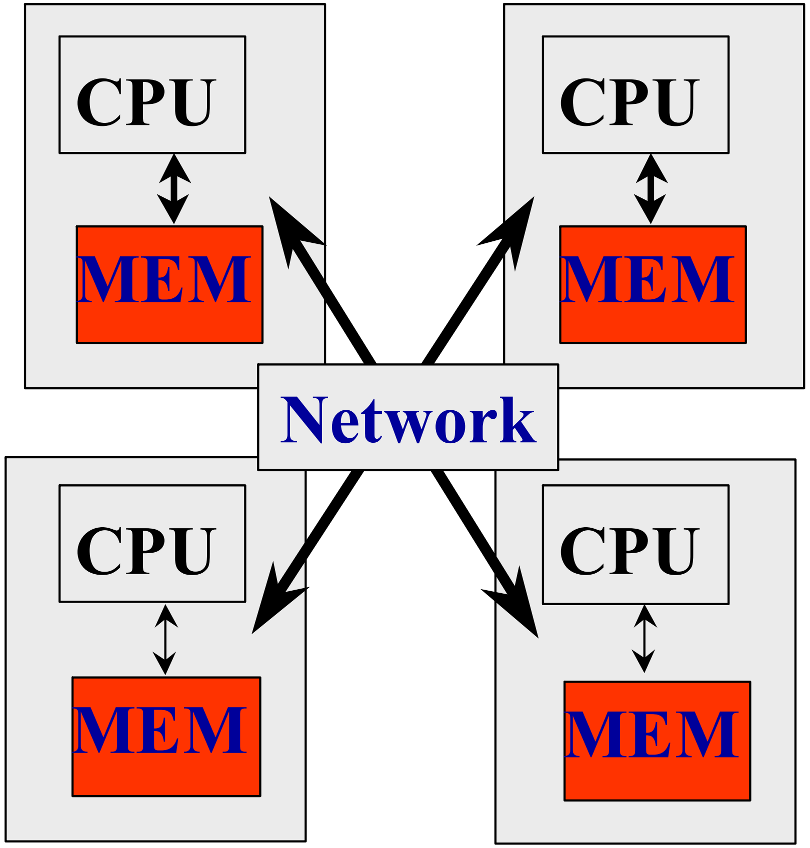
Using 4 cores, the execution time is 1/4 of the single core time

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

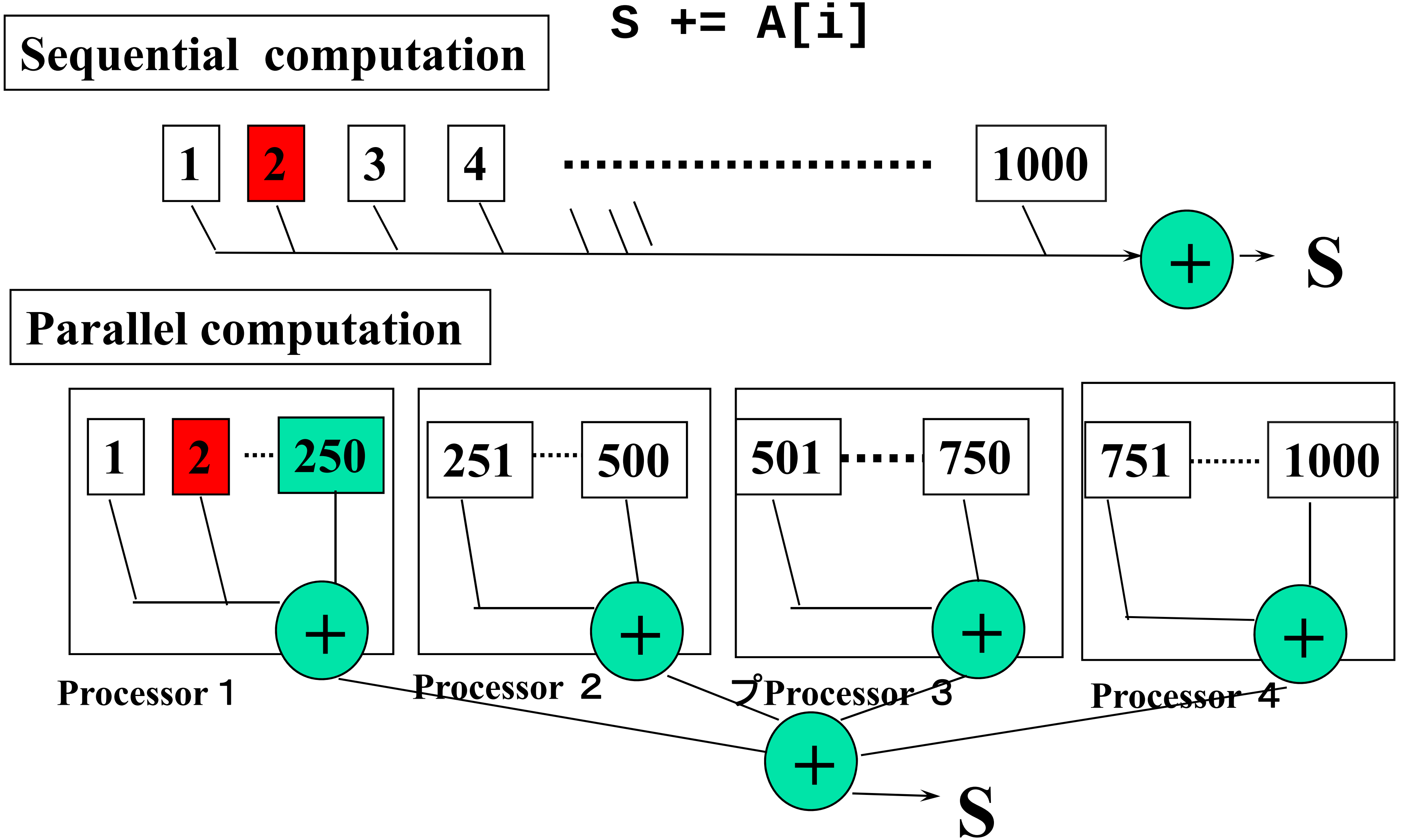
Distributed memory multi-processor



- ◆**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**

Very simple example of parallel computing

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



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)***

  Any Cluster and/or single SMP

  - ***Shared Memory***
    - ✔ ***Posix Threads (standardized, low level)***
    - ✔ ***OpenMP (de-facto standard)***
    - ✔ ***Automatic Parallelization (compiler does it for you)***

  SMP only

Simple example of Message Passing Programming

- Sum up 1000 element in array

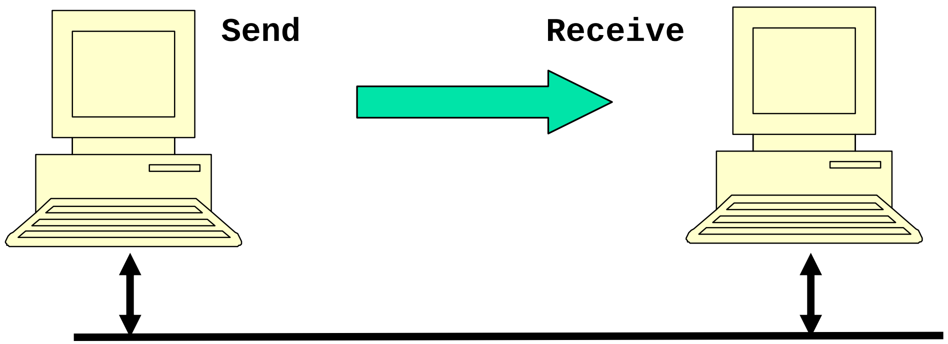
```
int a[250]; /* 250 elements are allocated in each node */

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

- Communication with message
  - point-to –point : Send/Receive
- Collective operations
  - Reduce/Bcast
  - Gather/Scatter



Communicator and rank of MPI

- A communicator specifies the process group that can send and receive messages to each other.
- Rank is a ID number within a group "communicator".
- The endpoint of communication specified by communicator and rank.
- A predefined communicator MPI_COMM_WORLD is provided by MPI.
  - It allows communication with all processes that are accessible after MPI initialization and processes are identified by their rank in it. Usually using only MPI_COMM_WORLD is enough.
- Users may define new communicators if necessary

point-to-point Comm. functions

- int MPI_Send(void *buf, int count, MPI_Datatype datatype, int dest, int tag, MPI_Comm comm)
- int MPI_Recv(void *buf, int count, MPI_Datatype datatype, int source, int tag, MPI_Comm comm, MPI_Status *status)
  - blocking send/receive operation
  - buf: initial address of send buffer
  - count: number of elements in send buffer
  - datatype: datatype of each send buffer element
  - dest: rank of destination
  - source: rank of source
  - tag: message tag
  - comm: communicator
  - status: status object (structure MPI_Status)

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);

    ....
```

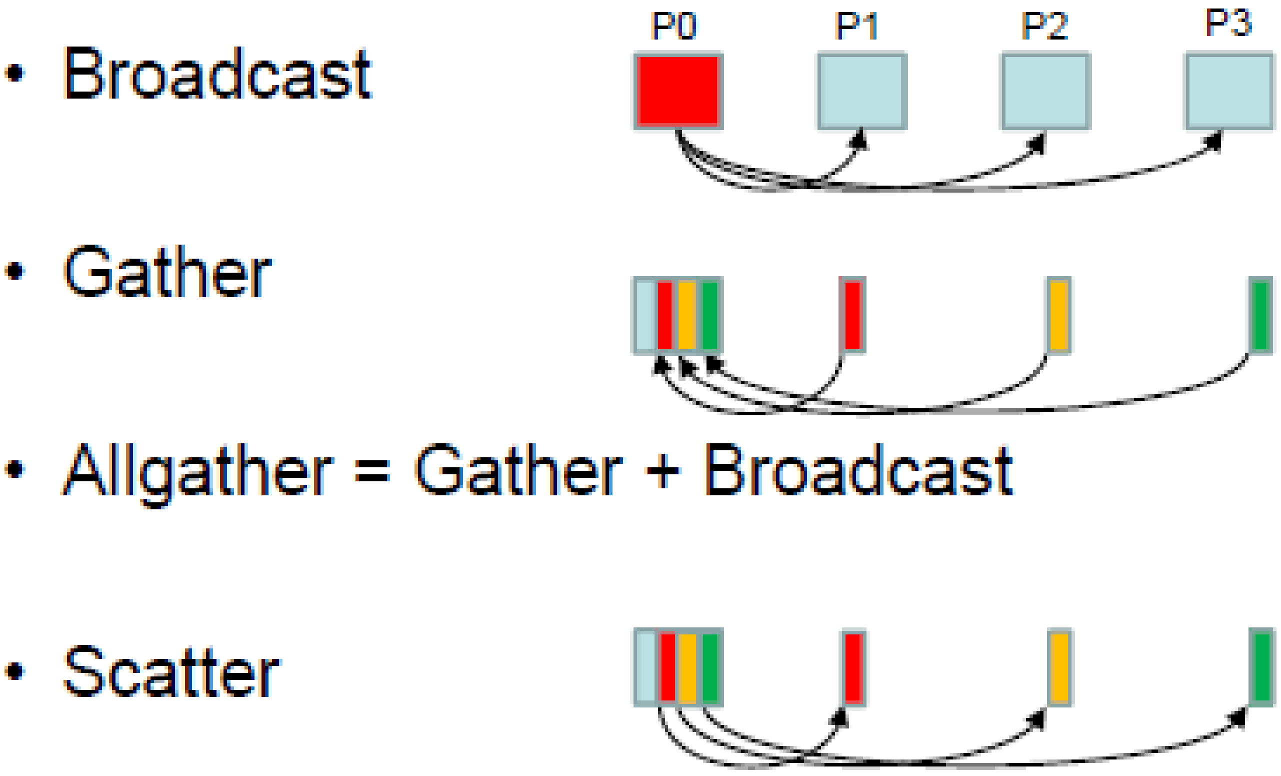
Programming in MPI

```
    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;
}
```

Collective communication

- Collective communication is defined as communication that involves a group of processes.



Parallel programming models

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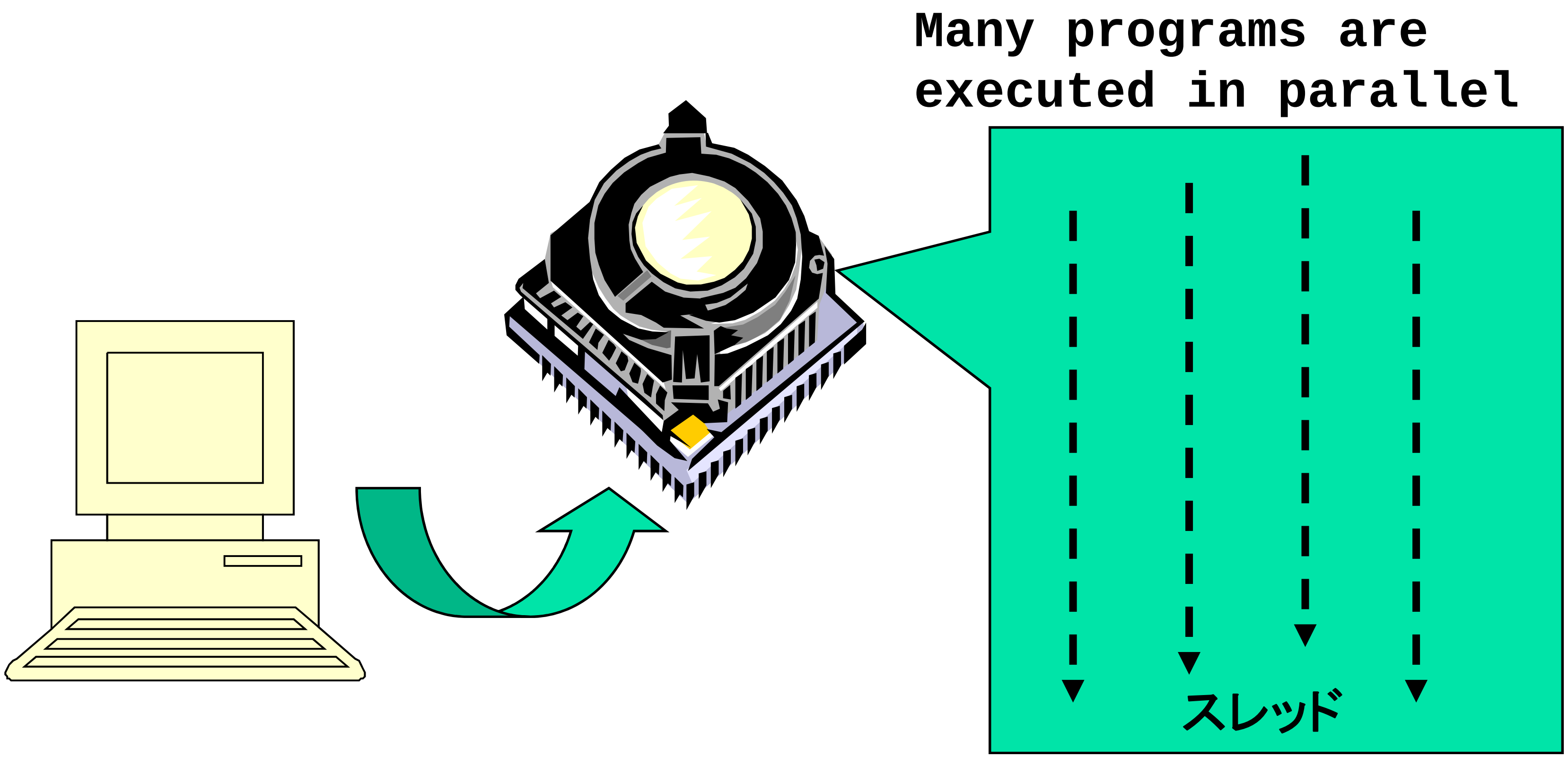
  SMP only

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



Very simple example of parallel computing

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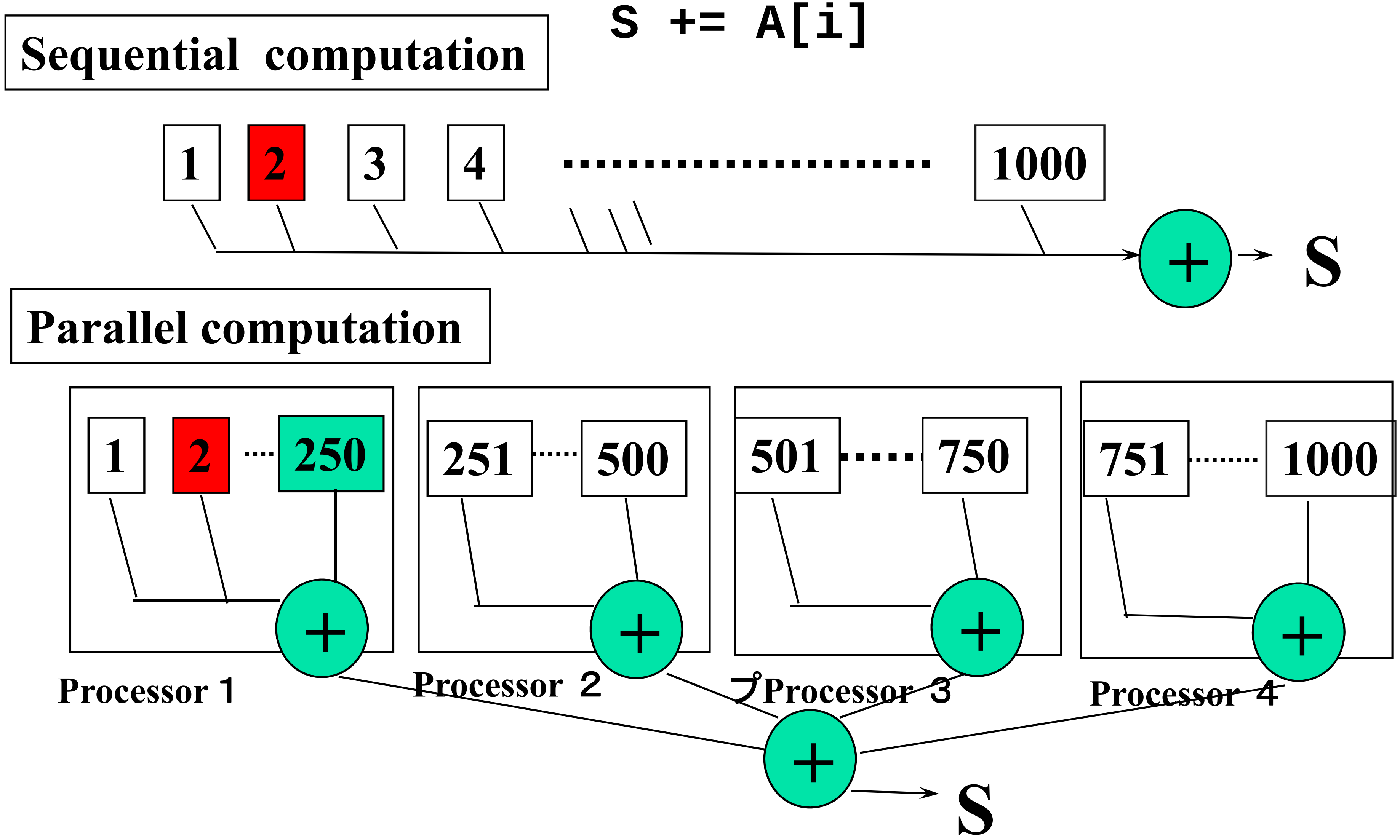
```



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();
```

Thread = Execution of program

- 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;
}
```

Programming in OpenMP

これだけで、OK!

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

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 3.0

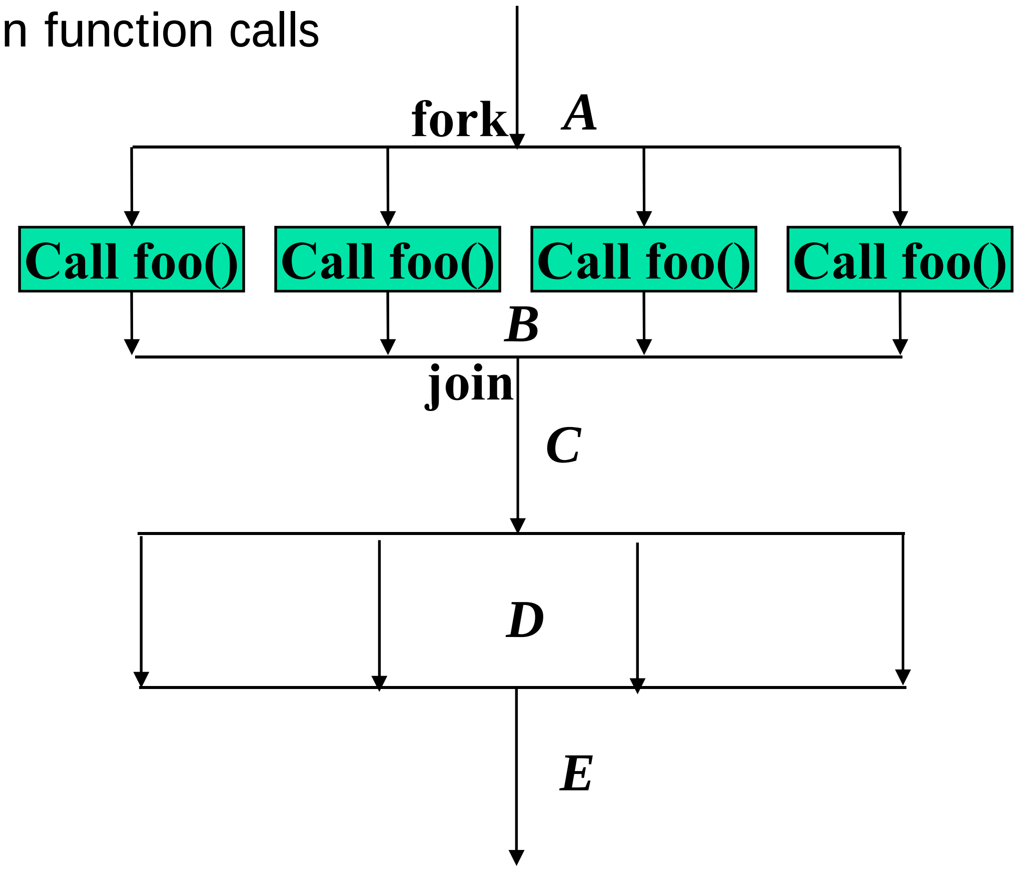
- http://www.openmp.org/

OpenMP™

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 …
```



Demo

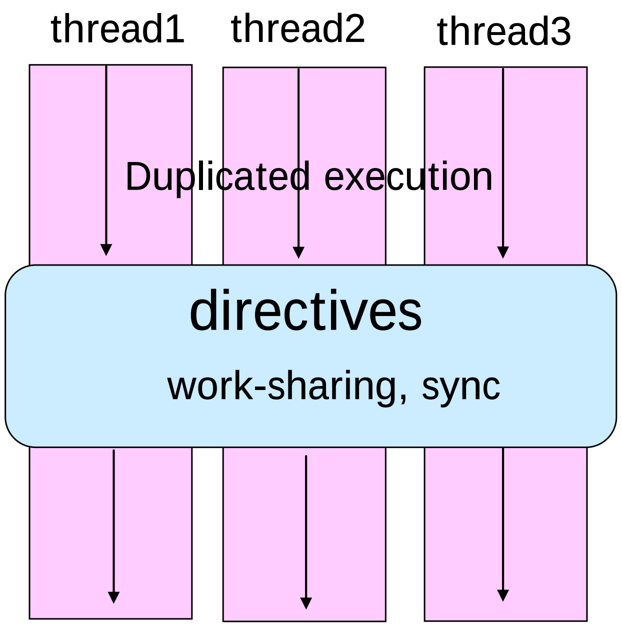
- Get CPU information by looking at /proc/cpuinfo
- gcc –fopenmp, gcc support OpenMP from 4.2, gfortran
- Control #proessors by OMP_NUM_THREADS

```
#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

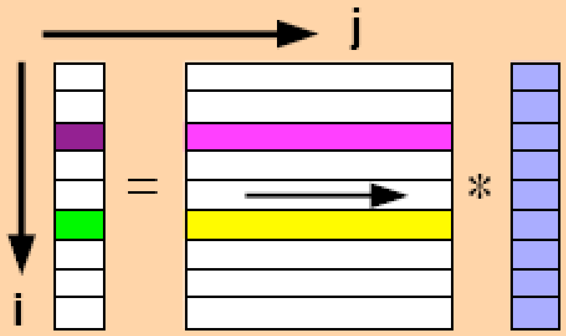
- Execute iterations specified For-loop in parallel
- For-loop specified by the directive must be in *canonical shape*

```
#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

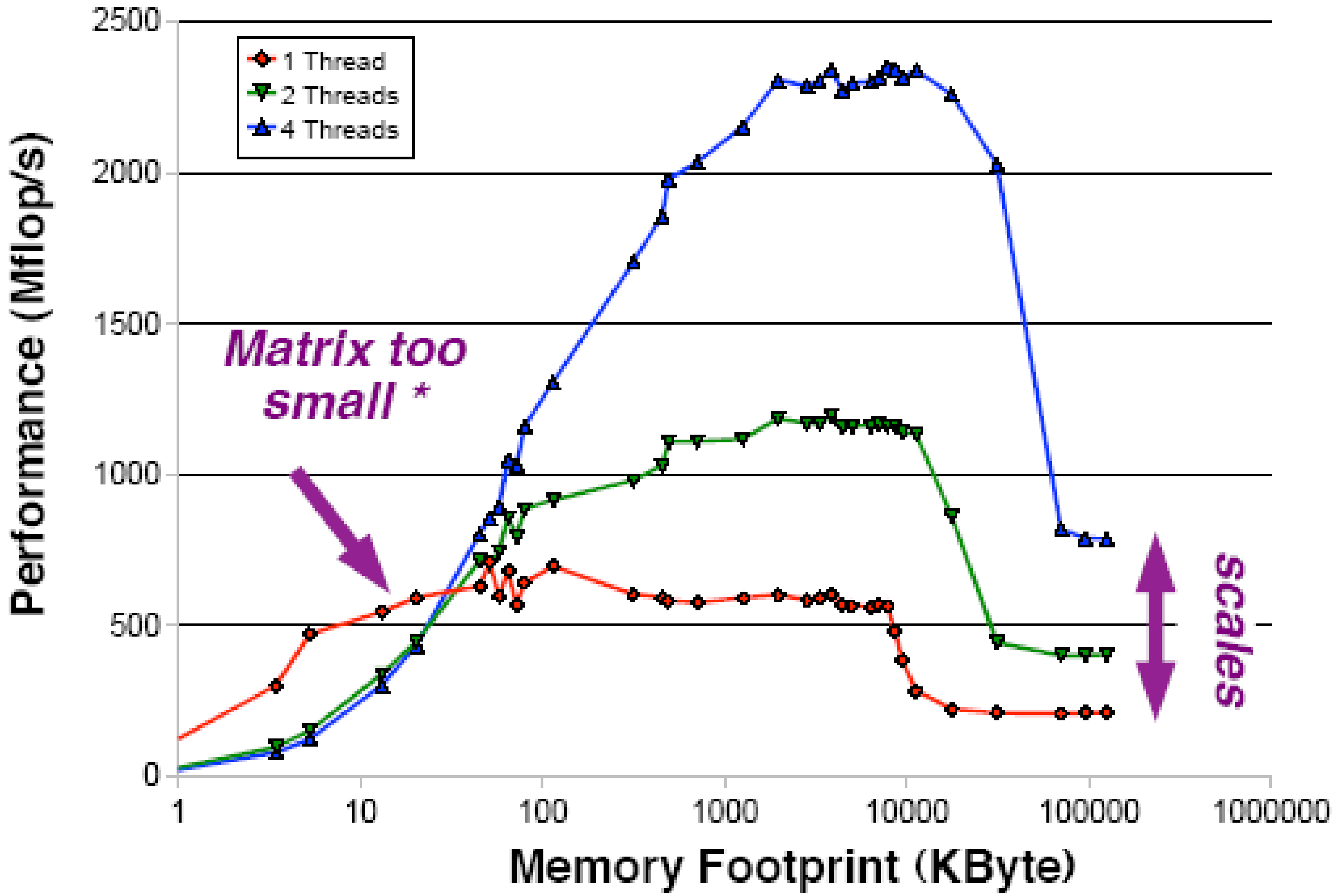
```
for (i=0,1,2,3,4)
 i = 0
   sum = Σ b[i=0][j]*c[j]
   a[0] = sum
 i = 1
   sum = Σ b[i=1][j]*c[j]
   a[1] = sum
```

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
```

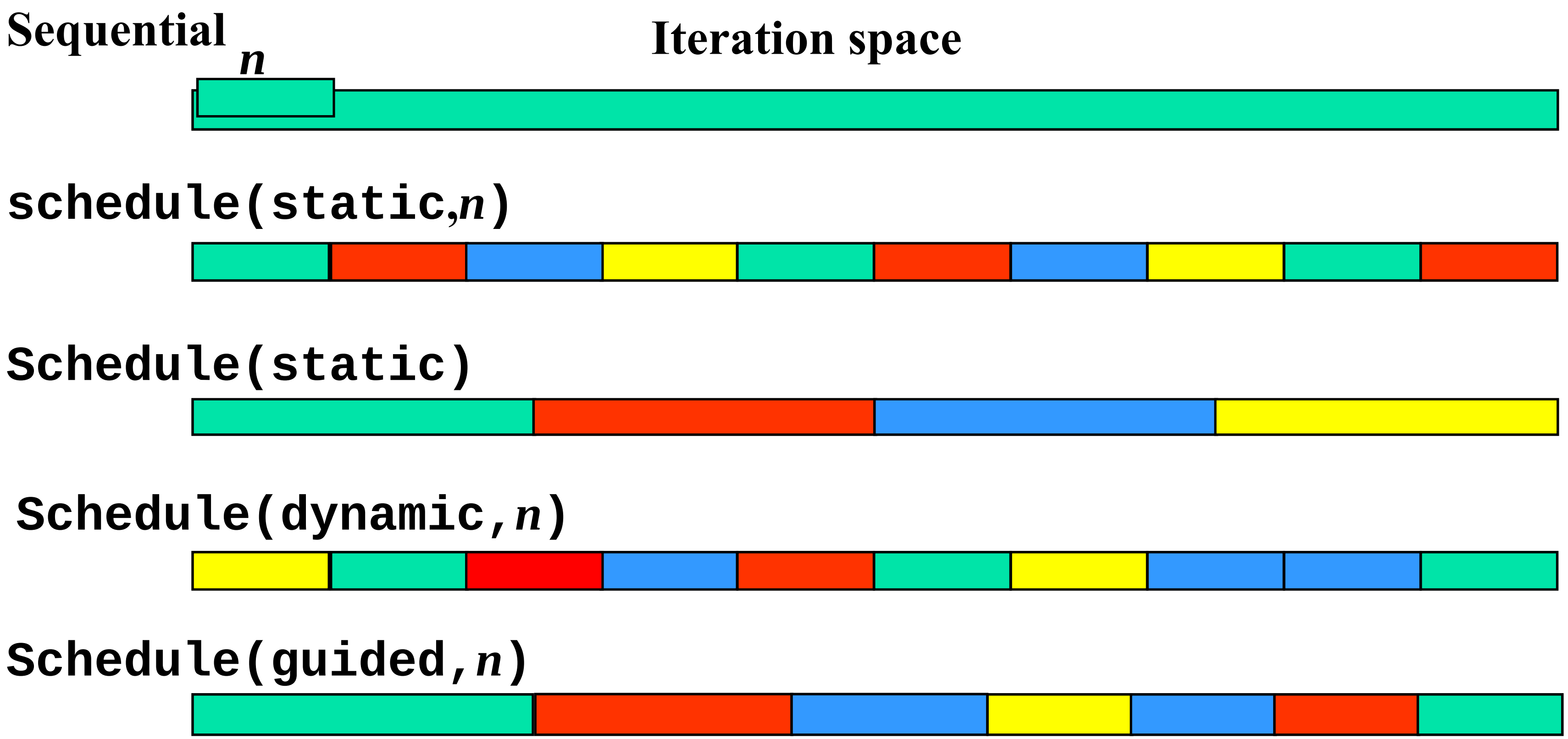
... etc ...

The performance looks like ...



Scheduling methods of parallel loop

- #processor = 4



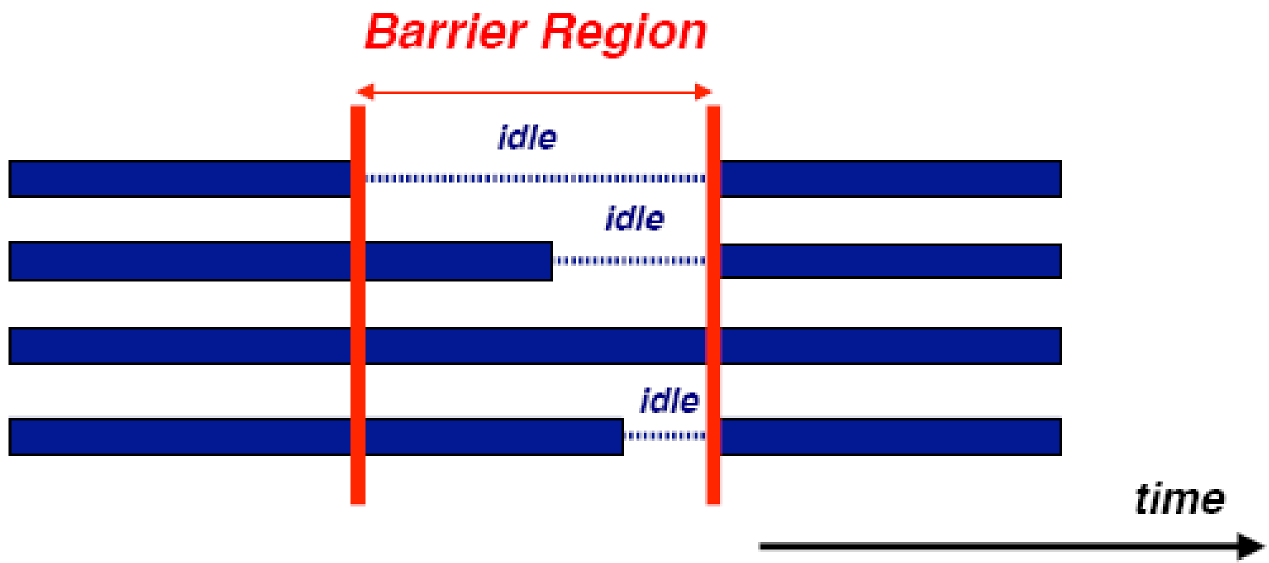
Data scope attribute clause

- 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

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
```



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

GPU Computing

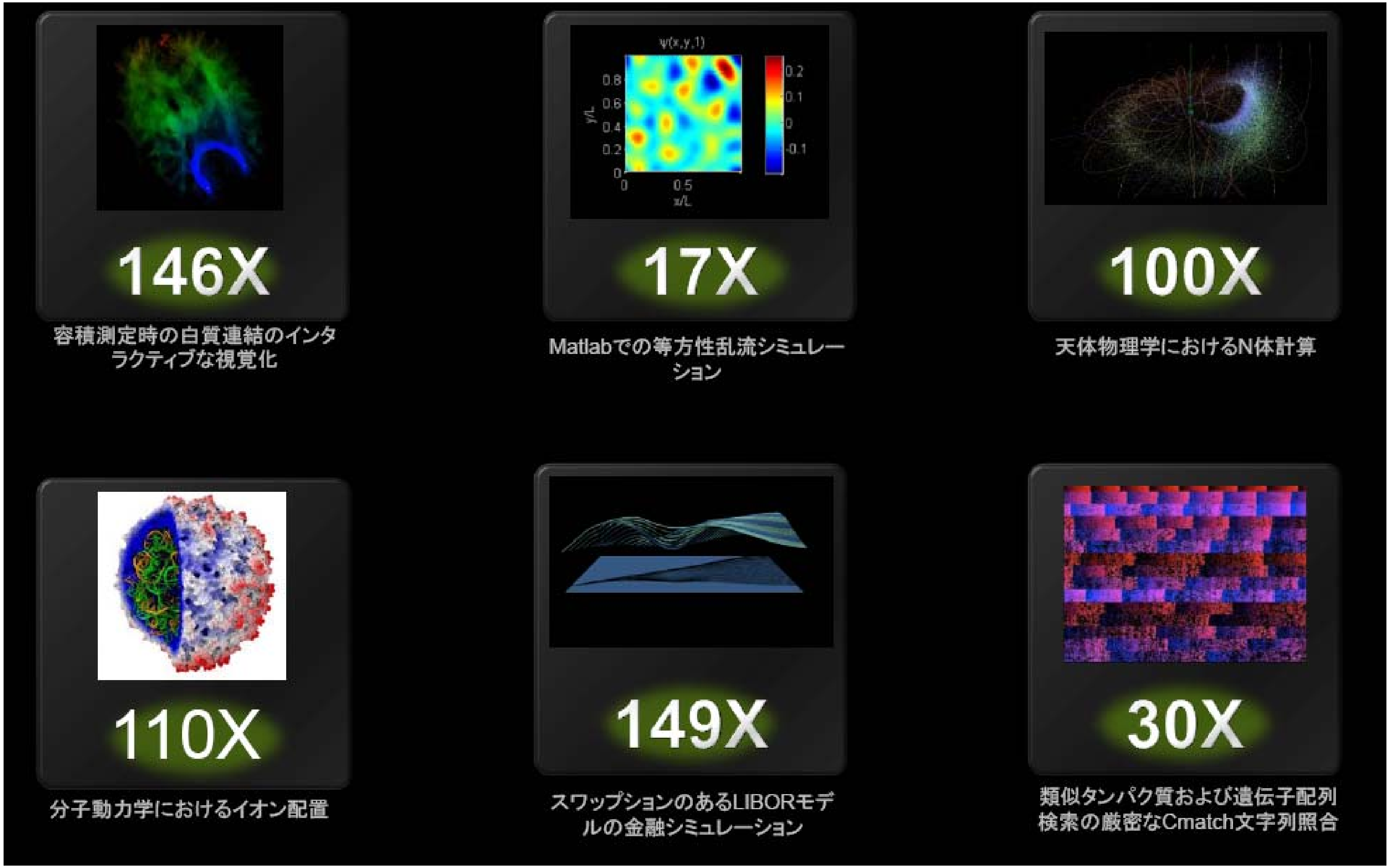
- GPGPU - General-Purpose Graphic Processing Unit
  - A technology to make use of GPU for general-purpose computing (scientific applications)

- CUDA（Compute Unified Device Architecture）
  - Co-designed Hardware and Software to exploit computing power of NVIDIA GPU for GP computing.
  - (In other words), at the moment, in order to obtain full performance of GPGPU, a program must be written in CUDA language.

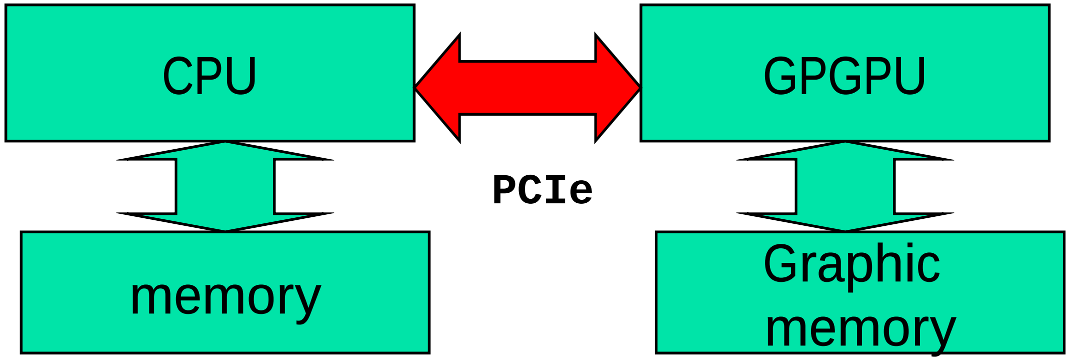
- It is attracting many people's interest since GPU enables great performance much more than that of CPU (even multi-core) in some scientific fields.

- Why GPGPU now?—— price (cost-performance)!!!

Applications（From NVIDIA’s slides）

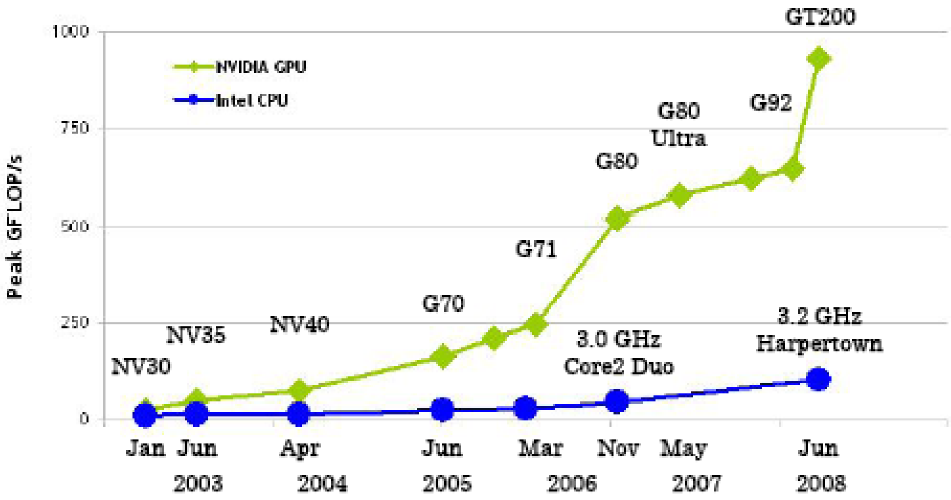


CPU vs. GPU



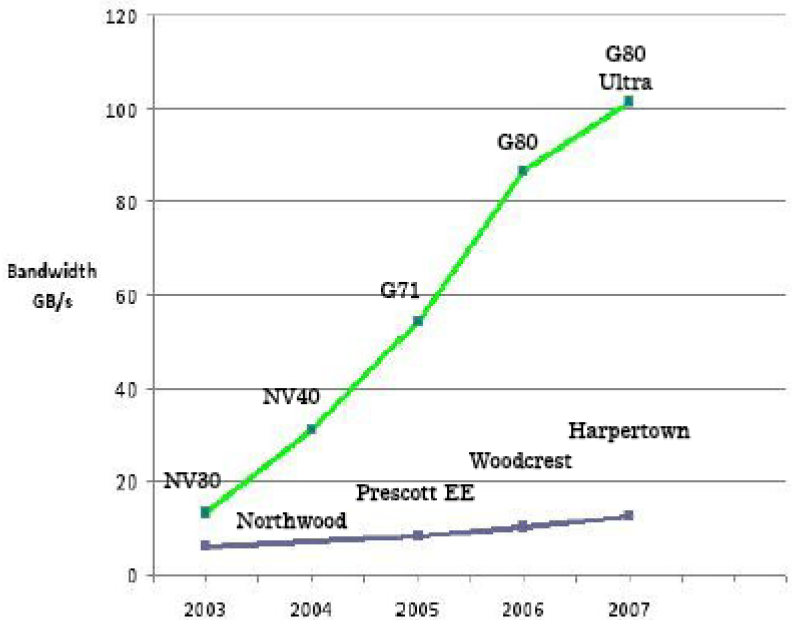
Connected via PCIexpress

Computing performance



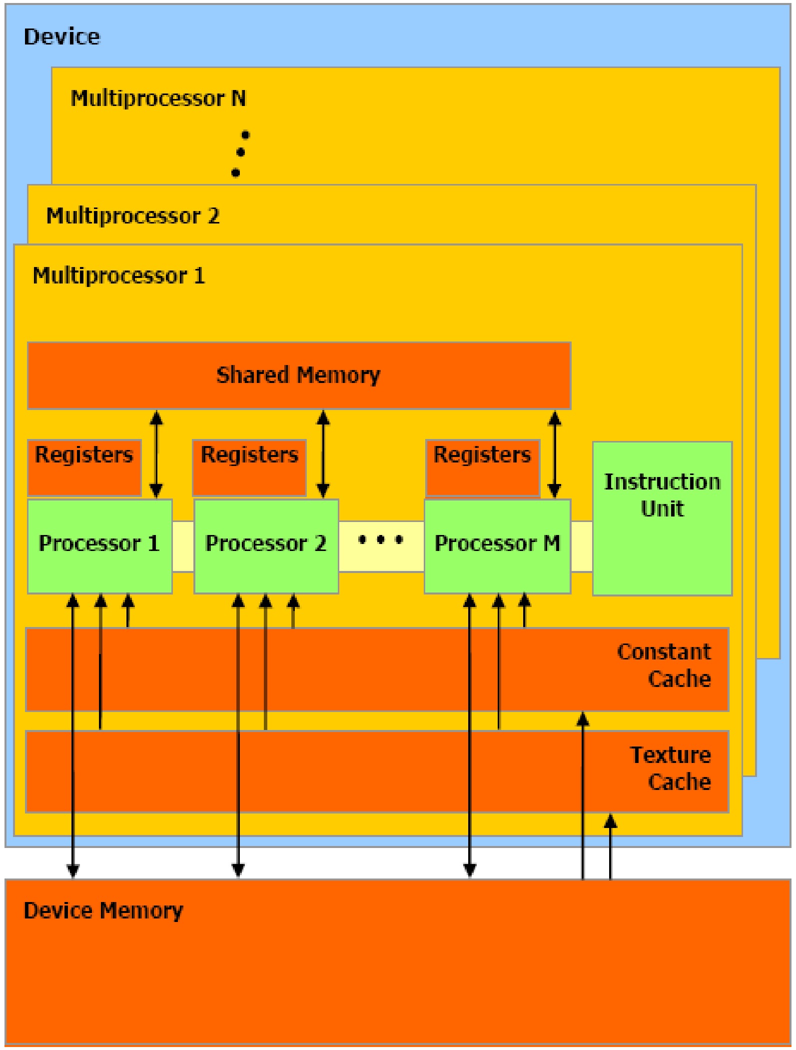
GT200 = GeForce GTX 280	G71 = GeForce 7900 GTX	NV35 = GeForce FX 5950 Ultra
G92 = GeForce 9800 GTX	G70 = GeForce 7800 GTX	NV30 = GeForce FX 5800
G80 = GeForce 8800 GTX	NV40 = GeForce 6800 Ultra	

Memory bandwidth



NVIDIA GPGPU's architecture

- Many multiprocessor in a chip
  - eight Scalar Processor (SP) cores,
  - two special function units for transcendentals
  - a multithreaded instruction unit
  - on-chip shared Memory
- SIMT (single-instruction, multiple-thread).
  - The multiprocessor maps each thread to one scalar processor core, and each scalar thread executes independently with its own instruction address and register state.
  - creates, manages, schedules, and executes threads in groups of 32 parallel threads called warps.
- Complex memory hierarchy
  - Device Memory (Global Memory)
  - Shared Memory
  - Constant Cache
  - Texture Cache



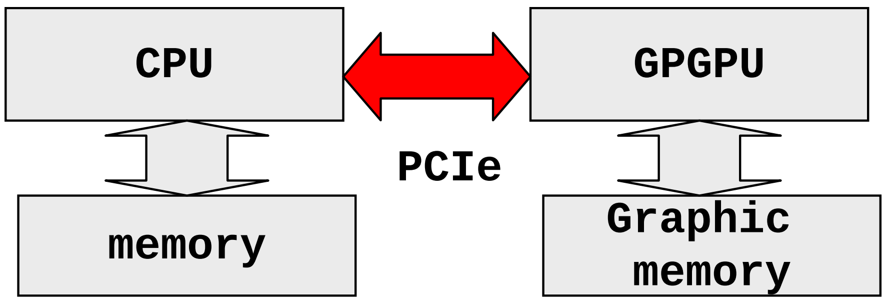
CUDA (Compute Unified Device Architecture)

- C programming language on GPUs
- Requires no knowledge of graphics APIs or GPU programming
- Access to native instructions and memory
- Easy to get started and to get real performance benefit
- Designed and developed by NVIDIA
- Requires an NVIDIA GPU (GeForce 8xxx/Tesla/Quadro)
- Stable, available (for free), documented and supported
- For both Windows and Linux

CUDA Programming model (1/2)

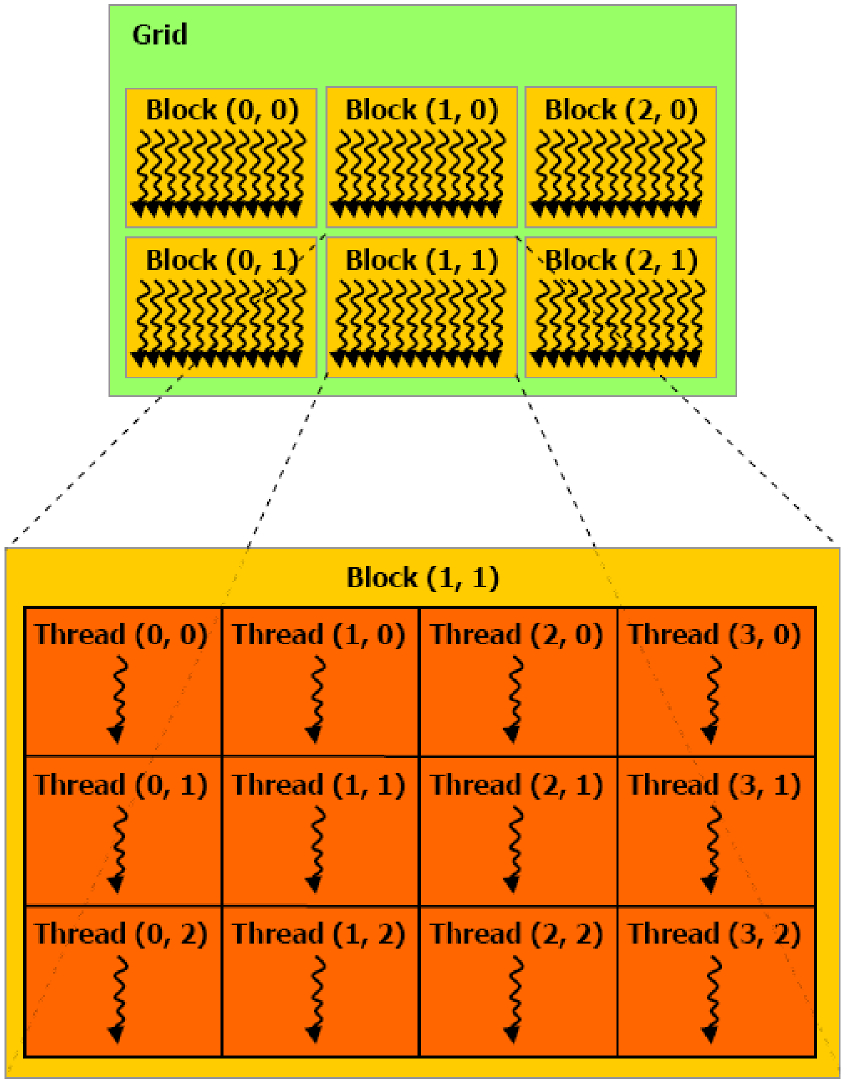
- GPU is programmed as a compute device working as co-processor from CPU(host).
  - Codes for data-parallel, compute intensive part are offloaded as functions to the device
  - Offload hot-spot in the program which is frequently executed on the same data
    - For example, data-parallel loop on the same data
  - Call "kernel" a code of the function compiled as a function for the device
  - Kernel is executed by multiple threads of device.
    - Only one kernel is executed on the device at a time.

  - Host (CPU) and device(GPU) has its owns memory, host memory and device memory
  - Data is copied between both memory.



CUDA Programming model (2/2)

- computational Grid is composed of multiple thread blocks
- thread block includes multiple threads
- Each thread executes kernel
  - A function executed by each thread called “kernel”
  - Kernel can be thought as one iteration in parallel loop
- computational Grid and block can have 1,2,3 dimension
- The reserved variable, blockID and threadID have ID of threads.



Example: Element-wise Matrix Add

```
void add_matrix
( float* a, float* b, float* c, int N ) {
  int index;
  for ( int i = 0; i < N; ++i )
  for ( int j = 0; j < N; ++j ) {
    index = i + j*N;
    c[index] = a[index] + b[index];
  }
}
int main() {
 add_matrix( a, b, c, N );
}
```

CPU program

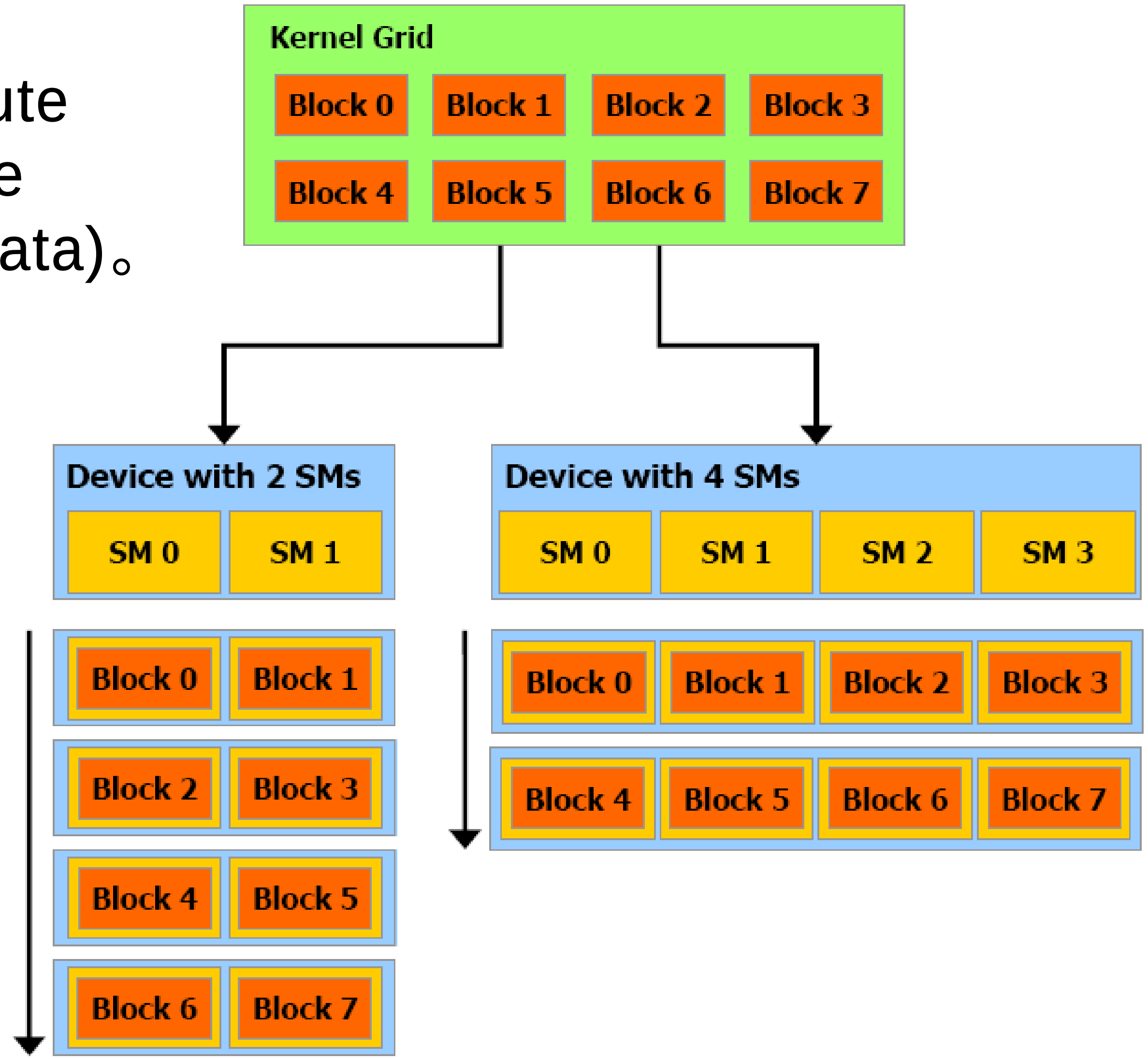
CUDA program

```
__global__ add_matrix
( float* a, float* b, float* c, int N ) {
 int i = blockIdx.x * blockDim.x + threadIdx.x;
 int j = blockIdx.y * blockDim.y + threadIdx.y;
 int index = i + j*N;
 if ( i < N && j < N )
  c[index] = a[index] + b[index];
}
int main() {
  dim3 dimBlock( blocksize, blocksize );
  dim3 dimGrid( N/dimBlock.x, N/dimBlock.y );
  add_matrix<<<dimGrid, dimBlock>>>( a, b, c, N );
}
```

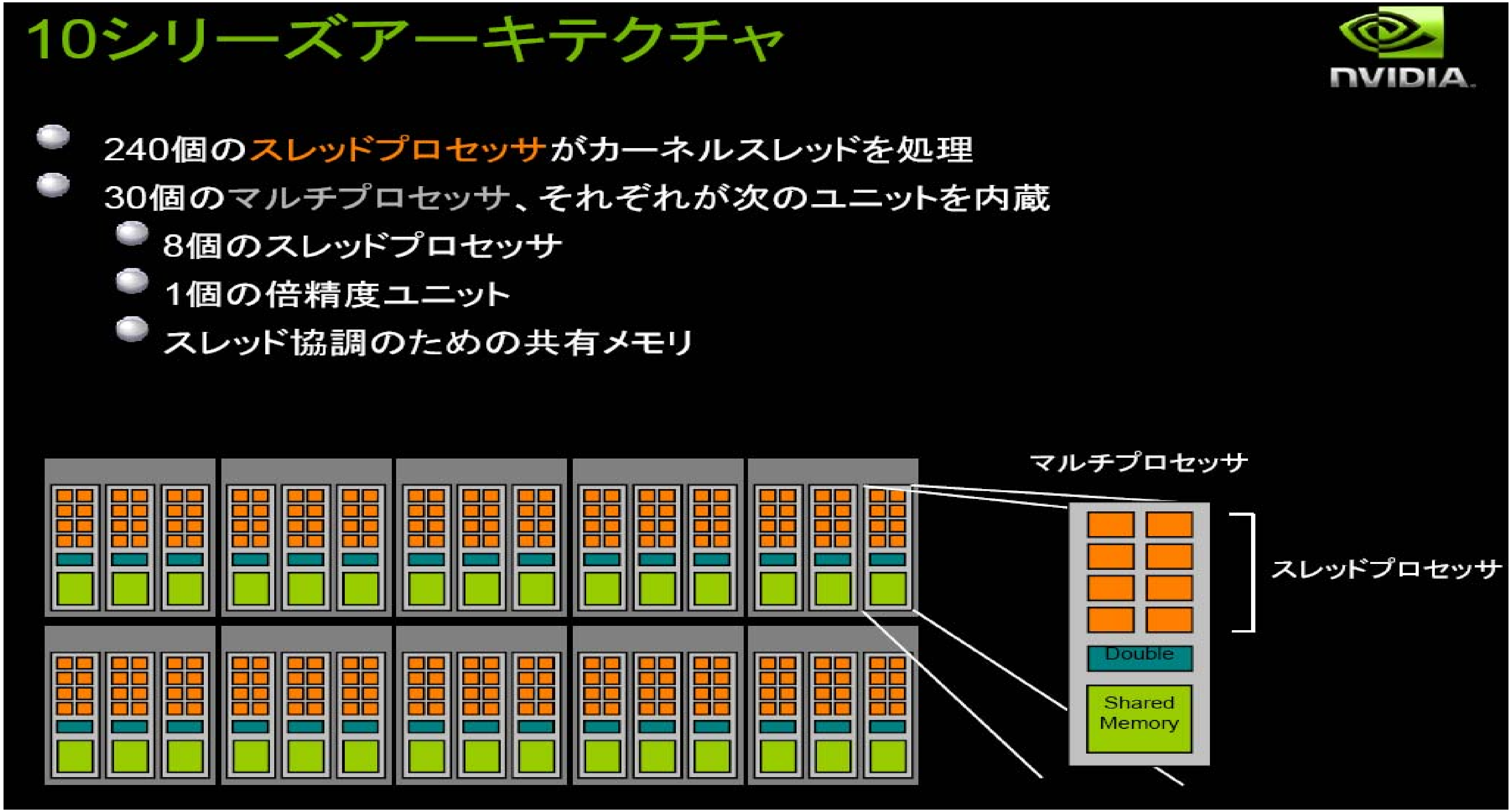
The nested for-loops are replaced with an implicit grid →

How to be executed

- SM (Streaming Multiprocessor) execute blocks in SIMD (single instruction/multiple data)。
- SM consists of 8 processors



An example of GPGPU configuration



	Number of Multiprocessors (1 Multiprocessor = 8 Processors)	Compute Capability
GeForce GTX 295	2x30	1.3
GeForce GTX 285, GTX 280	30	1.3
GeForce GTX 260	24	1
GeForce 9800 GX2	2x16	1
GeForce GTS 250, GTS 150, 9800 GTX, 9800 GTX+, 8800 GTS 512	16	1
GeForce 8800 Ultra, 8800 GTX	16	1
GeForce 9800 GT, 8800 GT, GTX 280M, 9800M GTX	14	1
GeForce GT 130, 9600 GSO, 8800 GS, 8800M GTX, GTX 260M, 9800M GT	12	1
[illegible]		

Tesla S1070		
Tesla C1060	30	1.3
Tesla S870	4x16	1.0
Tesla D870	2x16	1.0
Tesla C870	16	1.0
Quadro Plex 2200 D2	2x30	1.3
Quadro Plex 2100 D4	4x14	1.1
Quadro Plex 2100 Model S4	4x16	1.0

Tesla C1060

コア数: 240コア
プロセッサ周波数: 1.3GHz
搭載メモリ: 4GB
単精度浮動小数点演算性能: 933GFlops (ピーク)
倍精度浮動小数点演算性能: 78GFlops (ピーク)
メモリ帯域: 102GB/sec
標準電力消費量: 187.8W
浮動小数点演算: IEEE 754 単精度/倍精度
ホスト接続: PCI Express x16 (PCI-E2.0対応)

Invoke (Launching) Kernel

- Host processor invoke the execution of kernel in this form similar to function call:

```
kernel<<<dim3 grid, dim3 block, shmem_size>>>(…)
```

- Execution Configuation (“<<< >>>”)
  - Dimension of computational grid : x and y
  - Dimension of thread block: x、y、z

```
dim3 grid(16 16);
dim3 block(16,16);
kernel<<<grid, block>>>(...);
kernel<<<32, 512>>>(...);
```

Memory management (1/2)

- CPU and GPU have different memory space.
- Hosts（CPU）manages device (GPU）memory

- Allocation and Deallocation of GPU memory
  - `cudaMalloc(void ** pointer, size_t nbytes)`
  - `cudaMemset(void * pointer, int value, size_t count)`
  - `cudaFree(void* pointer)`

```
int n = 1024;
int nbytes = 1024*sizeof(int);
int *d_a = 0;
cudaMalloc( (void**)&d_a nbytes );
cudaMemset( d_a, 0, nbytes);
cudaFree(d_a);
```

Memory management (2/2)

- Data copy operation between CPU and device
  - `cudaMemcpy(void *dst, void *src, size_t nbytes, enum cudaMemcpyKind direction);`
    - Direction specifies how to copy from src to dst , see below
    - Block a caller of CPU thread (execution) until the memory transfer completes.
    - Copy operation starts after previous CUDA calls.
  - `enum cudaMemcpyKind`
    - `cudaMemcpyHostToDevice`
    - `cudaMemcpyDeviceToHost`
    - `cudaMemcpyDeviceToDevice`

Example (host-side program)

```
// allocate host memory
int numBytes = N * sizeof(float)
float* h_A = (float*) malloc(numBytes);

// allocate device memory
// float* d_A = 0;
cudaMalloc((void**)&d_A, numbytes);

// Copy data from host to device
cudaMemcpy(d_A, h_A, numBytes, cudaMemcpyHostToDevice);

// Execute kernel
increment_gpu<<< N/blockSize, blockSize>>>(d_A, b);

// copy back data from device to host
cudaMemcpy(h_A, d_A, numBytes, cudaMemcpyDeviceToHost);

// Free device memory
cudaFree(d_A);
```

```
int main() {
  float *a = new float[N*N];
  float *b = new float[N*N];
  float *c = new float[N*N];

  for ( int i = 0; i < N*N; ++i ) {
   a[i] = 1.0f; b[i] = 3.5f; }

  float *ad, *bd, *cd;
  const int size = N*N*sizeof(float);
  cudaMalloc( (void**)&ad, size );
  cudaMalloc( (void**)&bd, size );
  cudaMalloc( (void**)&cd, size );

  cudaMemcpy( ad, a, size, cudaMemcpyHostToDevice );
  cudaMemcpy( bd, b, size, cudaMemcpyHostToDevice );

  dim3 dimBlock( blocksize, blocksize );
  dim3 dimGrid( N/dimBlock.x, N/dimBlock.y );
  add_matrix<<<dimGrid, dimBlock>>>( ad, bd, cd, N );

  cudaMemcpy( c, cd, size, cudaMemcpyDeviceToHost );

  cudaFree( ad ); cudaFree( bd ); cudaFree( cd );
  delete[] a; delete[] b; delete[] c;
  return EXIT_SUCCESS;
}
```

OpenACC

- A spin-off activity from OpenMP ARB for supporting accelerators such as GPGPU

- NVIDIA, Cray Inc., the Portland Group (PGI), and CAPS enterprise

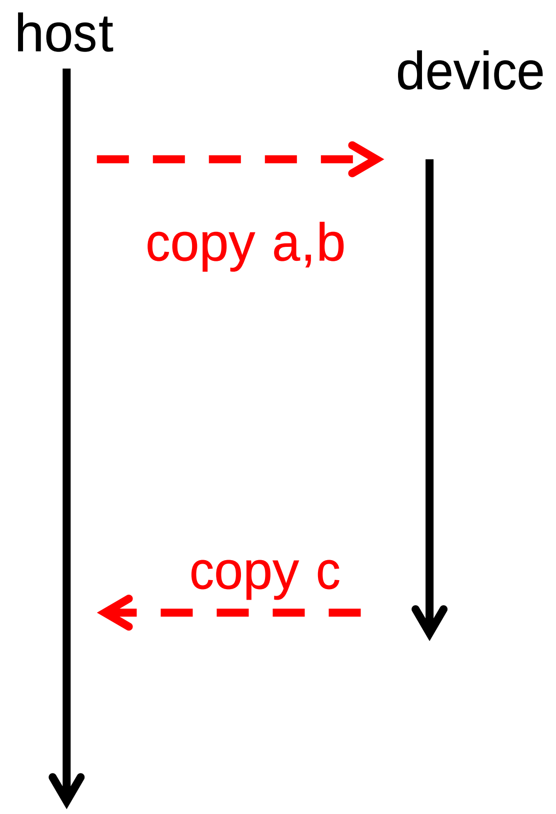
- Directive to specify the code offloaded to GPU.

OpenACC®
DIRECTIVES FOR ACCELERATORS

A simple example

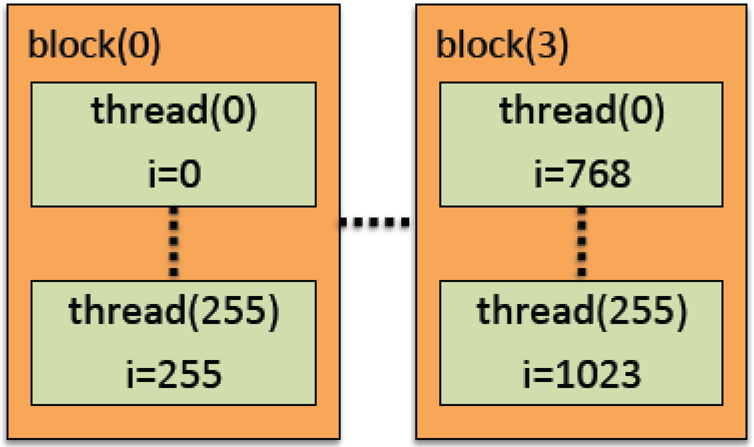
direction	copy	copyin	copyout
Host->device	○	○	
Device->Host	○		○

```
#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];
   }
 }
}
}
```



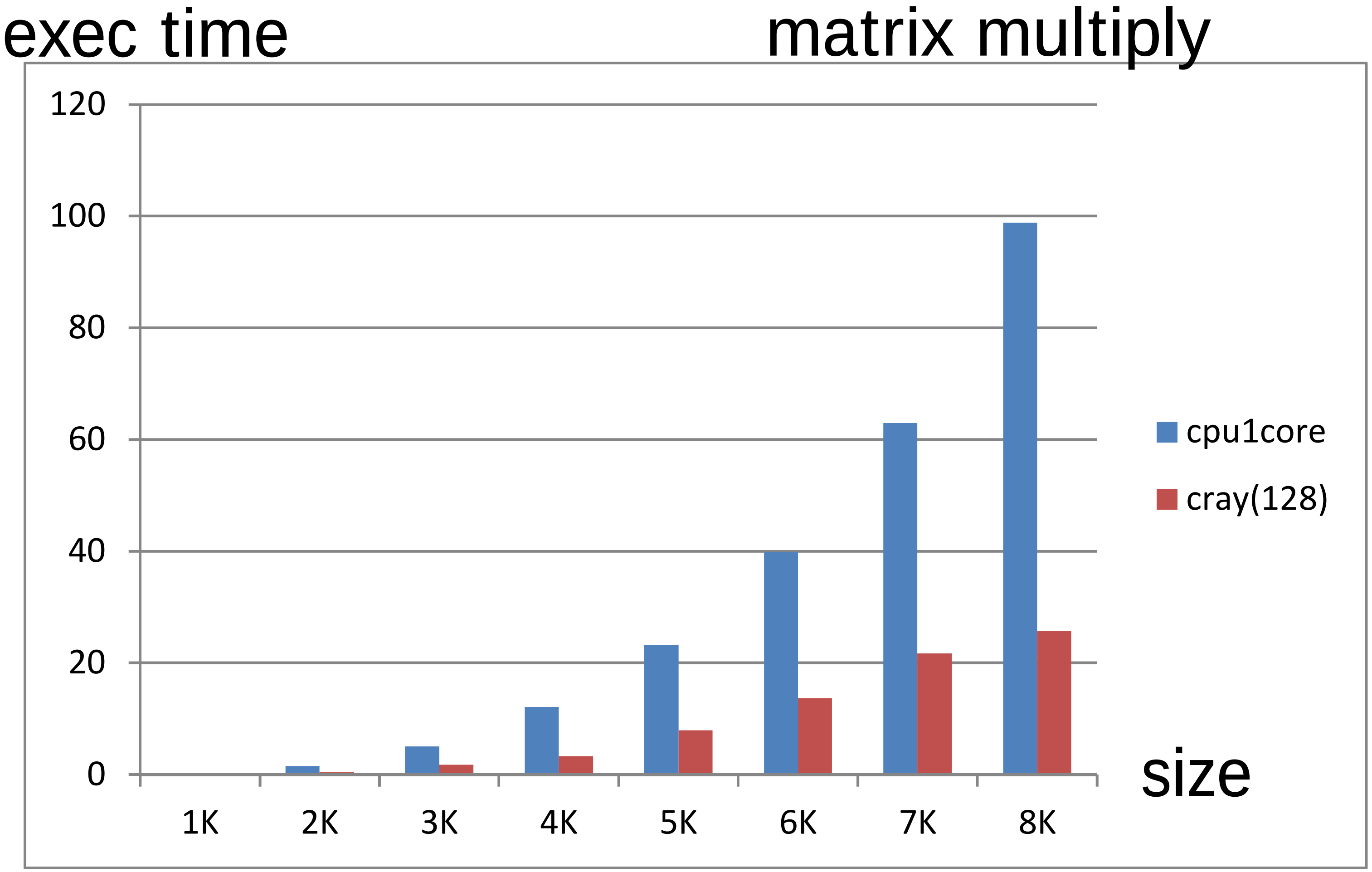
execute iterations like CUDA kernel

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;
    }
  }
}
```

Performance of OpenACC code



Remarks

- GPGPU is a good solution for apps which can be parallelized for GPU.
  - It can be very good esp. when the app fits into one GPU.
  - If the apps needs more than one GPU, the cost of communication will kill performance.

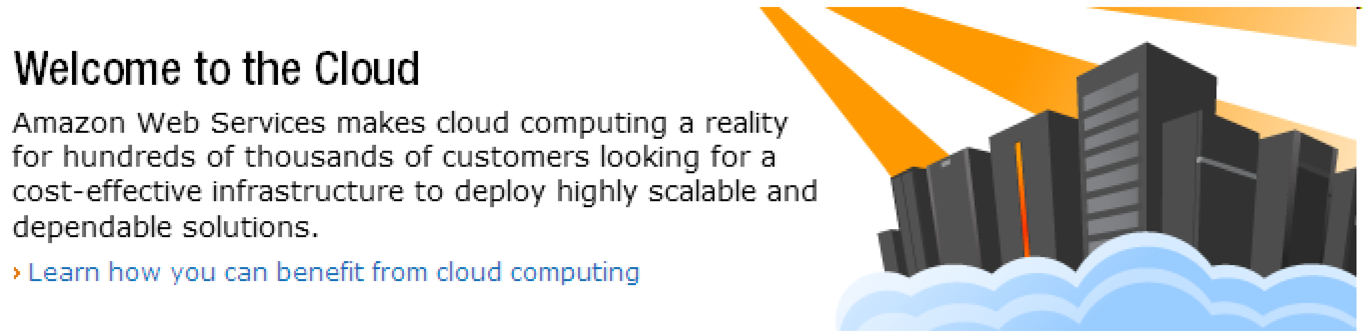
- Programming in CUDA is still difficult …
  - Performance tuning, memory layout …
  - OpenACC will help you!

Cloud Computing

- Only required amount of CPU and storage can be used anytime from anywhere via network
  - Availability, throughput, reliability
  - Manageability
- No need to procure, maintain, and update computers
- Large-scale distributed data processing by MapReduce
  - Loosely coupled data intensive computing
  - Can be a standard parallel language other than MPI

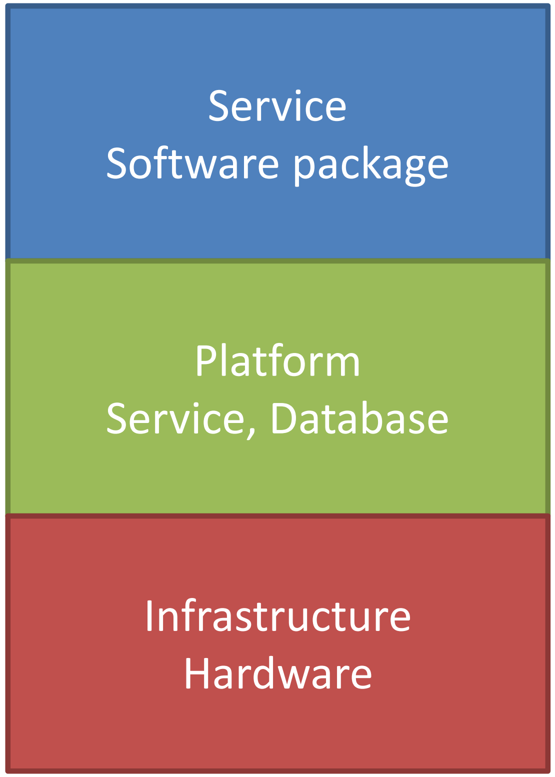
Amazon Web Services (2002)

- On-demand elastic infrastructure managed by web services
  - Elastic Compute Cloud (EC2)
    - Web service that provides resizable compute capacity
  - Simple Storage Service (S3)
    - Simple web service I/F to store and retrieve data
  - Elastic Block Store (EBS)
    - Block level storage used by EC2 in the same AZ
    - Automatically replicate within the same AZ
    - Point-in-time snapshots can be persisted to S3
- Region and Availability Zone



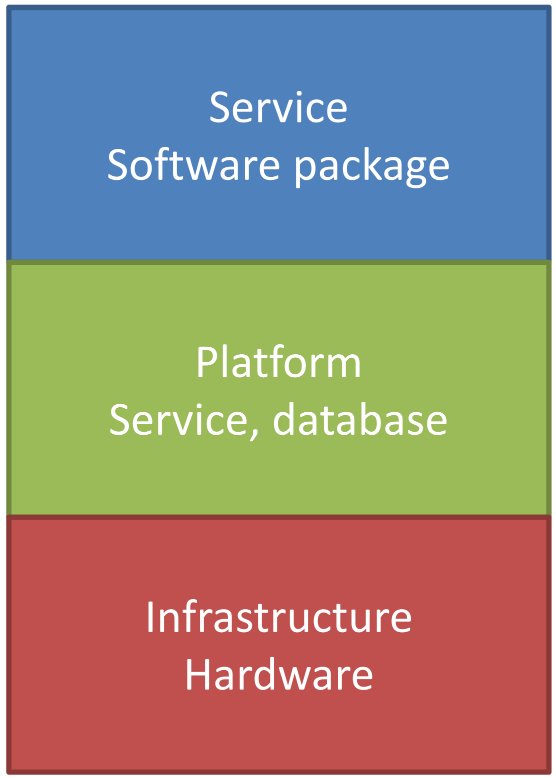
Taxonomy of Cloud

- SaaS (Software as a Service)
  - Google Apps (Gmail, …), CRM
  - Microsoft Online Services
- PaaS (Platform as a Service)
  - Development of Web apps
    - Force.com
    - Google App Engine
- IaaS (Infrastructure as a Service)
  - Amazon EC2, S3
  - Microsoft Azure

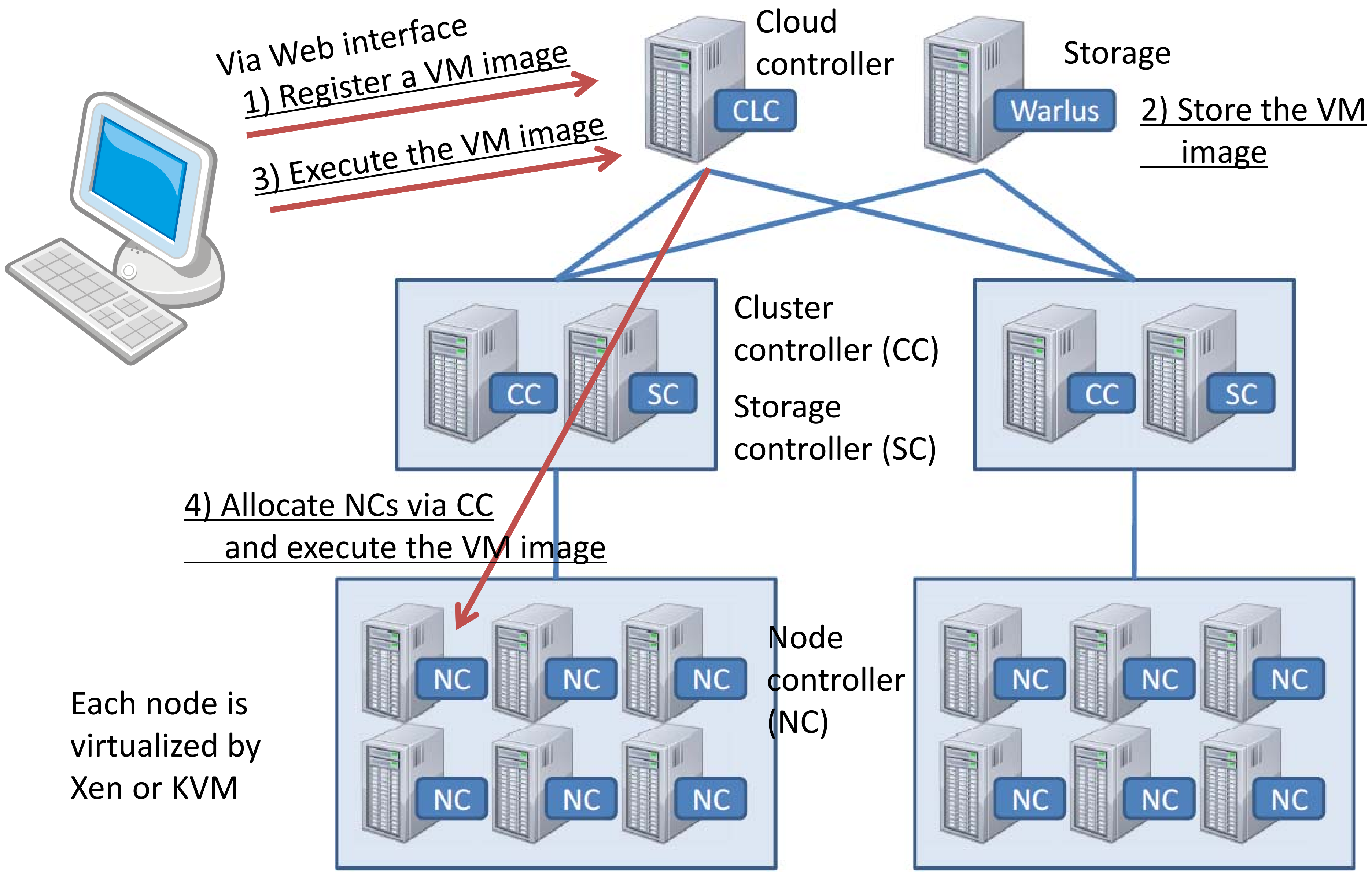


Cloud technology

- SaaS (Software as a Service)
  - Web 2.0
- PaaS (Platform as a Service)
  - Web API
  - Web Service
    - XML, WSDL, SOAP/REST
- IaaS (Infrastructure as a Service)
  - Virtual machine (Xen, KVM)
  - Virtualization of harddisk, storage and network



Example of IaaS: Eucalyptus [2009 Nurmi]



Storage system in cloud

- Availability, reliability
- Amazon Web Services
  - S3, EBS
  - Can construct any (file) system that uses block device
    - HDFS (using EBS) for Elastic MapReduce
  - Difficult to construct a system beyond Availability Zone and Region
- Google App Engine
  - Utilize GFS and BigTable

Summary of cloud computing

- Resources in cloud computing
  - Inexpensive, always available, reliable, high performance
  - Easy to maintain
- Realized by virtualization and web interface
- No need to procure, maintain, and update computers
- If required, more resources can be obtained by cloud

MapReduce (2004)

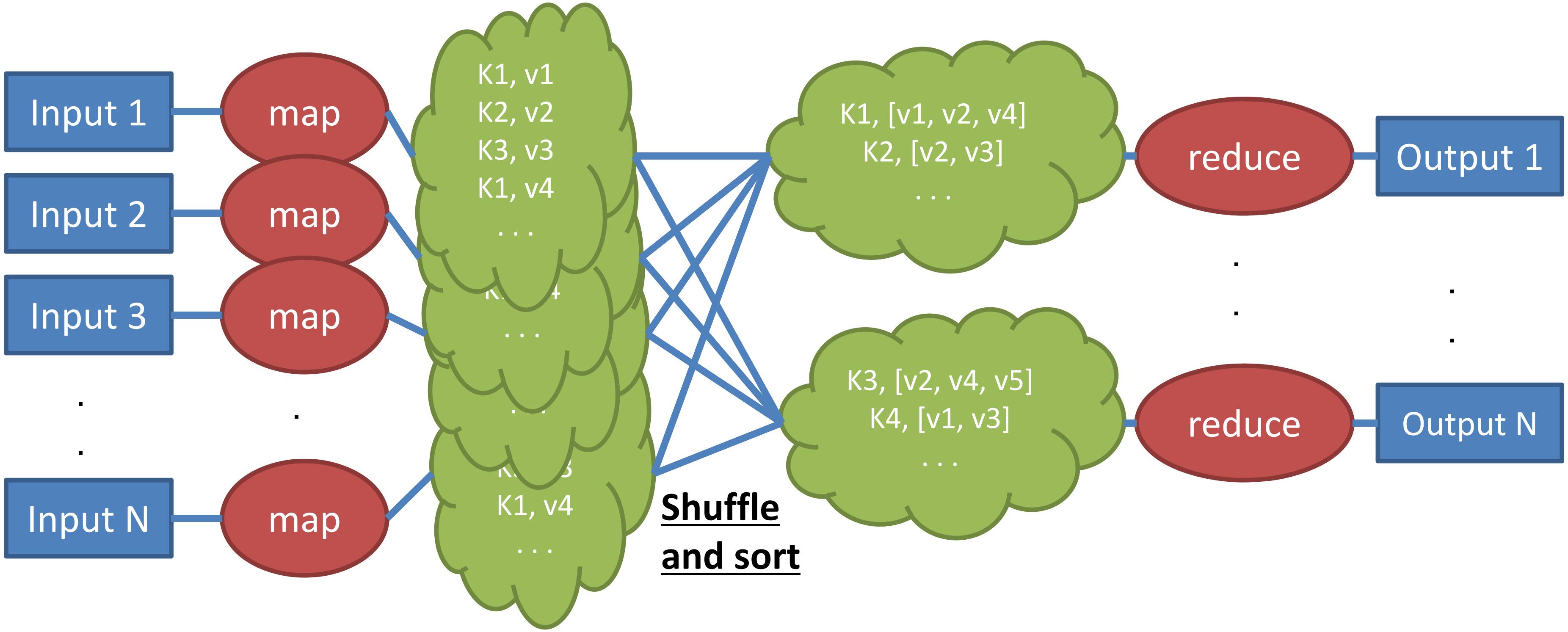
- **Programming model and runtime for data processing on large-scale cluster**
- A user specifies map and reduce functions
- Runtime system does
  - Automatically parallelize
  - Manage machine failure
  - Schedule jobs to efficiently exploit disk and network

Background

- Google requires to process
  - Inverted index
  - Various graph expression of Web documents
  - Number of pages that each host crawls
  - Set of the hottest query in a day
    - from large amount of crawled documents and Web request logs using hundreds to thousands of compute nodes
- Large amount of codes for parallelization, data distribution, error handing are required
- These hide original code for computation

New abstraction (1)

- Describes only required computation
- Runtime library hides complicated processes including parallelization, fault handling, data distribution, load balancing
- Most computation has the following same pattern



New abstraction (2)

- A functional model of user-supplied map and reduce operations enables
  - Easy parallelization of large-scale computation
  - To run failed tasks again for fault tolerance

- Simple but powerful interface
- It enables high-performance computation on large-scale cluster by auto-parallelization and auto-distribution

Comments on MapReduce

- MapReduce programming model has been successfully used at Google for many different purposes
  - Easy to use
  - It hides details of parallelization, fault tolerance, locality optimization and load balancing
  - A large variety of problems are easily expressible
  - Scales to large clusters of machines comprising thousands of machines
- It can be obtained by restricting the programing model