

Parallel Programming

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Lecture 07

B3B36PRG – C Programming Language

Overview of the Lecture

- Part 1 – Introduction to Parallel Programming
 - Introduction
 - Parallel Processing
 - Semaphores
 - Shared Memory
 - Messages
 - Parallel Computing using GPU

Part I Part 1 – Introduction to Parallel Programming

Parallel Programming

- The idea of parallel programming comes from the 60s with the first multi-program and pseudo-parallel systems
- Parallelism
 - Hardware based – true hardware parallelism of multiprocessor systems
 - Software based – pseudo-parallelism
- Pseudo-parallelism – A program with parallel constructions may run in pseudo-parallel environment on single or multi-processor systems

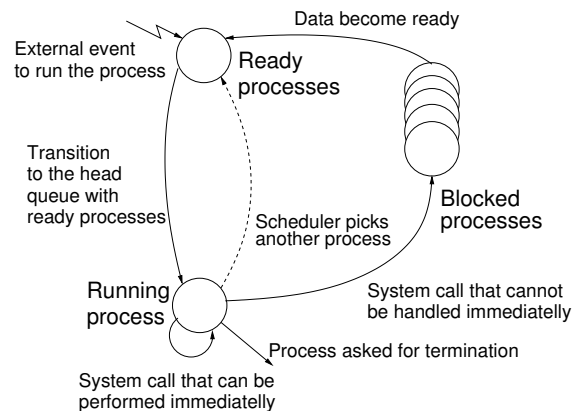
Motivation Why to Deal with Parallel Programming

- Increase computational power
 - Having multi-processor system we can solve the computational problem faster
- Efficient usage of the computational power
 - Even a running program may wait for data
 - E.g., a usual program with user-interaction typically waits for the user input
- Simultaneous processing of many requests
 - Handling requests from individual clients in client/server architecture

Process – Executed Program

- Process is executed program running in a dedicated memory space
- Process is an entity of the Operating System (OS) that is schedule for independent execution
- Process is usually in one of three basic states:
 - Executing – currently running on the processor (CPU)
 - Blocked – waiting for the periphery
 - Waiting – waiting for the processor
- A process is identified in the OS by its identifier, e.g., PID
- Scheduler of the OS manage running processes to be allocated to the available processors

Process States



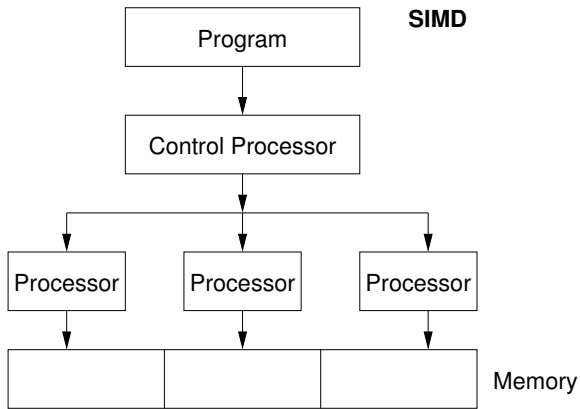
Multi-processor Systems

- Multi-processor systems allow true parallelism
- It is necessary to synchronize processors and support data communication
 - Resources for activity synchronization
 - Resources for communication between processors (processes)

Possible Architectures for Parallel Executions

- Control of individual instructions
 - SIMD – Single-Instruction, Multiple-Data – same instructions are simultaneously performed on different data.
 - “Processors” are identical and run synchronously
 - E.g., “Vectorization” such as MMX, SSE, 3DNow!, and AVX, etc.
 - MIMD – Multiple-Instruction, Multiple-Data – processors run independently and asynchronously
- Memory Control Access
 - Systems with shared memory – central shared memory
E.g., multi-core CPUs
 - Systems with distributed memory – each processor has its memory
E.g., computational grids

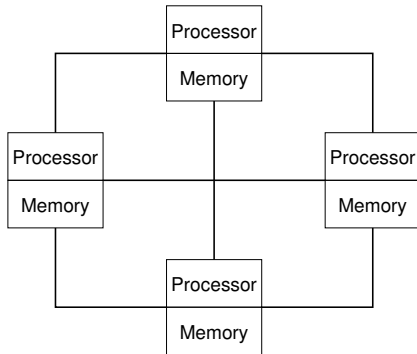
SIMD – Single-Instruction, Multiple-Data



SIMD

Memory

Systems with Distributive Memory



- There is not a problem with exclusive access to the memory
- It is necessary to address communication between the processors

Example of Parallel Processing Realized by Compiler 1/2

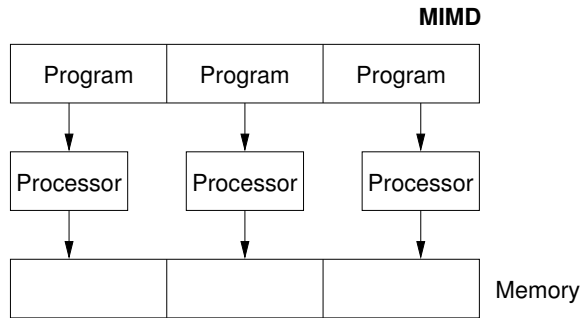
Example – Array Multiplication

```

1 #include <stdlib.h>
2
3 #define SIZE 30000000
4
5 int main(int argc, char *argv[])
6 {
7     int i;
8     int *in1 = (int*)malloc(SIZE*sizeof(int));
9     int *in2 = (int*)malloc(SIZE*sizeof(int));
10    int *out = (int*)malloc(SIZE*sizeof(int));
11    for (i = 0; i < SIZE; ++i) {
12        in1[i] = i;
13        in2[i] = 2 * i;
14    }
15    for (i = 0; i < SIZE; ++i) {
16        out[i] = in1[i] * in2[i];
17        out[i] = out[i] - (in1[i] + in2[i]);
18    }
19    return 0;
20 }

```

MIMD – Multiple-Instruction, Multiple-Data



MIMD

Memory

The Role of the Operating System (OS)

- OS provides hardware abstraction layer – encapsulate HW and separate the user from the particular hardware architecture (true/pseudo parallelism)
- OS is responsible for synchronization of running processes
- OS provides user interfaces (system calls):
 - To **create** and destroy processes
 - To **manage** processes and processors
 - To **schedule** processors on available processors
 - To control access to **shared memory**
 - Mechanisms for inter-process **communication** (IPC)
 - Mechanisms for processes **synchronization**

Example of Parallel Processing Realized by Compiler 2/2

Example 1

```

1 icc compute.c
2 time ./a.out
3
4 real 0m0.562s
5 user 0m0.180s
6 sys 0m0.384s

```

Example 2

```

1 icc -m SSE compute.c; time ./a.out
2 compute.c(8) : (col. 2) remark: LOOP WAS
3 VECTORIZED.
4 real 0m0.542s
5 user 0m0.136s
6 sys 0m0.408s

```

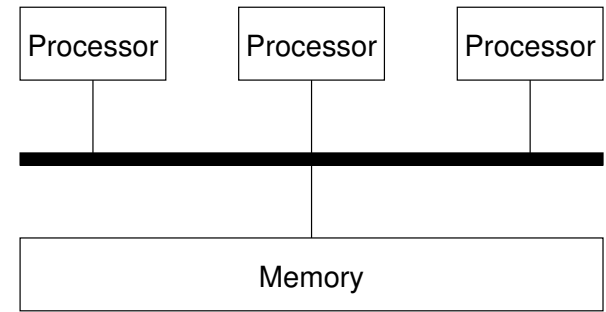
Example 3

```

1 icc -parallel compute.c; time ./a.out
2 compute.c(12) : (col. 2) remark: LOOP WAS AUTO-
3 PARALLELIZED.
4 real 0m0.702s
5 user 0m0.484s
6 sys 0m0.396s

```

Systems with Shared Memory



- Processors communicate using shared memory space
- Processors may also synchronize their activities, i.e., granting exclusive access to the memory

Parallel Processing and Programming Languages

- Regarding parallel processing programming languages can be divided into
 - Without explicit support for parallelism – possible mechanisms of parallel processing
 - Parallel processing is realized by compiler and operating system
 - Parallel constructions are explicitly marked for the compiler
 - Parallel processing is performed by OS system calls
 - With explicit support for parallelism

Example – Open MP – Matrix Multiplication 1/2

- Open Multi-Processing (OpenMP) - application programming interface for multi-platform shared memory multiprocessing

<http://www.openmp.org>

- We can instruct the compiler by macros for parallel constructions
 - E.g., parallelization over the outside loop for the *i* variable

```

1 void multiply(int n, int a[n][n], int b[n][n], int c[n][n])
2 {
3     int i;
4     #pragma omp parallel private(i)
5     #pragma omp for schedule (dynamic, 1)
6     for (i = 0; i < n; ++i) {
7         for (int j = 0; j < n; ++j) {
8             c[i][j] = 0;
9             for (int k = 0; k < n; ++k) {
10                c[i][j] += a[i][k] * b[k][j];
11            }
12        }
13    }
14 }

```

lec07/demo-omp-matrix.c

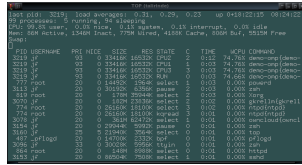
Squared matrices of the same dimensions are used for simplicity.

Example – Open MP – Matrix Multiplication 2/2

- Comparison of matrix multiplication with 1000×1000 matrices using OpenMP on iCore5 (2 cores with HT)

```

1 gcc -std=c99 -O2 -o demo-omp demo-omp-matrix.c -fopenmp
2 ./demo-omp 1000
3 Size of matrices 1000 x 1000 naive
4   multiplication with 0(n^3)
5 c1 == c2: 1
6 Multiplication single core 9.33 sec
7 Multiplication multi-core 4.73 sec
8
9 export OMP_NUM_THREADS=2
10 ./demo-omp 1000
11 Size of matrices 1000 x 1000 naive
12   multiplication with 0(n^3)
13 c1 == c2: 1
14 Multiplication single core 9.48 sec
15 Multiplication multi-core 6.23 sec
    
```



lec07/demo-omp-matrix.c

Languages with Explicit Support for Parallelism

- It has support for creation of new processes
 - Running process create a copy of itself
 - Both processes execute the identical code (copied)
 - The **parent** process and **child** process are distinguished by the process identifier (PID)
 - The code segment is explicitly linked with the new process
 - Regardless how new process is created – the most important is
 - Does the parent process stops its execution till the end of the child process
 - Is the memory shared by the child and parent processes
 - Granularity of the processes – parallelism ranging from the level of the instructions to the parallelism of programs

Parallelism – Statement Level

Example – parbegin-parend block

```

parbegin
  S1;
  S2;
  ...
  Sn;
parend
    
```

- Statement S_1 are S_n executed in parallel
- Execution of the main program is interrupted until all statements S_1 to S_n are terminated
- Statement S_1 are S_n executed in parallel

Example – doparallel

```

1 for i = 1 to n doparallel {
2   for j = 1 to n do {
3     c[i,j] = 0;
4     for k = 1 to n do {
5       c[i,j] = c[i,j] + a[i,k]*b[k,j];
6     } } }
    
```

Parallel execution of the outer loop over all i

E.g., OpenMP in C

Parallelism – Procedure Level

- A procedure is coupled with the execution process

```

...
procedure P;
pid xpid = newprocess(P);
...
killprocess(xpid);
    
```

- P is a procedure and x_{pid} is a process identifier

- Assignment of the procedure/function to the process at the declaration

```
PID xpid process(P).
```

- The process is created at the creation of the variable x
- The process is terminated at the end of x or sooner

E.g., Threads (pthreads) in C

Parallelism – Program (Process) Level

- A new process can be only a whole program
- A new program is created by a system call, which creates a complete copy of itself including all variable and data at the moment of the call

Example - Creating a copy of the process by fork system call

```

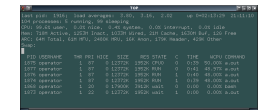
1 if (fork() == 0) {
2   /* code executed by the child process */
3 } else {
4   /* code executed by the parent process */
5 }
    
```

E.g., fork() in C

Example – fork()

```

1 #define NUMPROCS 4
2 for (int i = 0; i < NUMPROCS; ++i) {
3   pid_t pid = fork();
4   if (pid == 0) {
5     compute(i, n);
6     exit(0);
7   } else {
8     printf("Child %d created\n", pid);
9   }
10 }
11 printf("All processes created\n");
12 for (int i = 0; i < NUMPROCS; ++i) {
13   pid_t pid = wait(&r);
14   printf("Wait for pid %d return: %d\n",
15         pid, r);
16 }
17 void compute(int myid, int n)
18 {
19   printf("Process myid %d start
20     computing\n", myid);
21   ...
22   printf("Process myid %d
23     finished\n", myid);
24 }
    
```



```

clang demo-fork.c && ./a.out
Child 2049 created
Process myid 0 start computing
Child 2050 created
Process myid 1 start computing
Process myid 2 start computing
Child 2051 created
Child 2052 created
Process myid 3 start computing
All processes created
Process myid 1 finished
Process myid 0 finished
Wait for pid 2050 return: 0
Process myid 3 finished
Process myid 2 finished
Wait for pid 2049 return: 0
Wait for pid 2051 return: 0
Wait for pid 2052 return: 0
    
```

Semaphore

- E.W.Dijkstra – semaphore is a mechanism to synchronize parallel processes with shared memory
- Semaphore is an integer variable with the following operations

- InitSem - initialization

- Wait $\begin{cases} S > 0 - S = S - 1 \\ \text{otherwise} - \text{suspend execution of the calling process} \end{cases}$

- Signal $\begin{cases} \text{awake a waiting process if such process exists} \\ \text{otherwise} - S = S + 1 \end{cases}$

- Semaphores can be used to control access to a shared resources
 - $S < 0$ – shared resource is in use. The process asks for the access to the resources and waits for its release
 - $S > 0$ – shared resource is available. The process releases the resource

The value of the semaphore can represent the number of available resources.

Semaphores Implementation

- Operations with a semaphore must be atomic
 - The processor cannot be interrupted during execution of the operation
- Machine instruction *TestAndSet* reads and stores a content of the addressed memory space and set the memory to a non-zero value
- During execution of the *TestAndSet* instructions the processor holds the system bus and access to the memory is not allowed for any other processor

Usage of Semaphores

- Semaphores can be utilized for defining a **critical sections**
- Critical sections is a part of the program where exclusive access to the shared memory (resources) must be guaranteed

Example of critical section protected by a semaphore

```

InitSem(S,1);
Wait(S);
/* Code of the critical section */
Signal(S);
    
```

- Synchronization of the processes using semaphores

Example of synchronization of processes

```

/* process p */
InitSem(S,0)
Wait(S); ...
exit();

/* process q */
Signal(S);
exit();
    
```

Process p waits for termination of the process q

Example – Semaphore 1/4 (System Calls)

- Semaphore is an entity of the Operating System (OS)

```

1 #include <sys/types.h>
2 #include <sys/ipc.h>
3 #include <sys/sem.h>
4
5 /* create or get existing set of semaphores */
6 int semget(key_t key, int nsems, int flag);
7
8 /* atomic array of operations on a set of semaphores */
9 int semop(int semid, struct sembuf *array, size_t nops);
10
11 /* control operations on a set of semaphores */
12 int semctl(int semid, int semnum, int cmd, ...);

```

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Example – Semaphore 4/4 (Slave Process)

```

1 int main(int argc, char* argv[])
2 {
3     struct sembuf sem;
4     int id = semget(1000, 1, 0);
5     int r;
6     if (id != -1) {
7         sem.sem_num = 0; // add the slave
8         sem.sem_op = 1; // to the "pool" of resources
9         sem.sem_flg = 0;
10        printf("Increase semaphore value (add resource)\n");
11        r = semop(id, &sem, 1);
12        sem.sem_op = 0;
13        printf("Semaphore value is %d\n", semctl(id, 0, GETVAL, 0));
14        printf("Wait for semaphore value 0\n");
15        r = semop(id, &sem, 1);
16        printf("Done\n");
17    }
18    return 0;
19 }

```

lec07/sem-master.c

- The IPC entities can be listed by `ipcs`
- ```

clang sem-master.c -o sem-master
clang sem-slave.c -o sem-slave

```

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## Example – Shared Memory 1/4 (Write)

- Write a line read from stdin to the shared memory

```

1 #include <sys/types.h>
2 #include <sys/ipc.h>
3 #include <sys/shm.h>
4 #include <stdio.h>
5
6 #define SIZE 512
7
8 int main(int argc, char *argv[])
9 {
10 char *buf;
11 int id;
12 if ((id = shmget(1000, SIZE, IPC_CREAT | 0666)) != -1)
13 {
14 if ((buf = (char*)shmat(id, 0, 0))) {
15 fgets(buf, SIZE, stdin);
16 shmdt(buf);
17 }
18 }
19 return 0;

```

lec07/shm-write.c

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## Example – Semaphore 2/4 (Synchronization Protocol)

- Example when the main (master) process waits for two other processes (slaves) become ready
  - Master process suspend the execution and waits for two other processes slaves become ready
  - Slave processes then wait to be released by the master process

- Proposed synchronization "protocol"

- Define our way to synchronize the processes using the system semaphores
- Slave process increments semaphore by 1
- Slave process waits the semaphore become 0 and then it is terminated
- Master process waits for two slave processes and decrements the semaphore about 2
  - It must also ensure the semaphore value is not 0; otherwise slaves would be terminated prematurely
- We need to use the atomic operations with the semaphore

lec07/sem-master.c lec07/sem-slave.c

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## Issues with Semaphores

- The main issues are arising from a wrong usage
- Typical mistakes are:
  - Wrongly identified a critical section
  - Process may block by multiple calls of `Wait(S)`.
  - E.g., the **deadlock** issues may arise from situations like

## Example – Deadlock

```

/* process 1*/ /* process 2*/
Wait(S1); Wait(S2);
Wait(S2); Wait(S1);
Signal(S2); Signal(S1);
Signal(S1); Signal(S2);
... ...

```

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## Example – Shared Memory 2/4 (Read)

- Read a line from the shared memory and put it to the stdout

```

1 #include <sys/types.h>
2 #include <sys/shm.h>
3 #include <stdio.h>
4
5 #define SIZE 512
6
7 int main(int argc, char *argv[])
8 {
9 int id;
10 char *buf;
11 if ((id = shmget(1000, 512, 0)) != -1) {
12 if ((buf = (char*)shmat(id, 0, 0))) {
13 printf("mem:%s\n", buf);
14 }
15 shmdt(buf);
16 } else {
17 fprintf(stderr, "Cannot access to shared memory!\n");
18 }
19 return 0;
20 }

```

lec07/shm-read.c

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## Example – Semaphore 3/4 (Master Process)

```

1 int main(int argc, char* argv[])
2 {
3 struct sembuf sem[2]; // structure for semaphore atomic operations
4 int id = semget(1000, 1, IPC_CREAT | 0666); // create semaphore
5 if (id != -1) {
6 int r = semctl(id, 0, SETVAL, 0) == 0;
7
8 sem[0].sem_num = 0; // operation to acquire semaphore
9 sem[0].sem_op = -2; // once its value will be >= 2
10 sem[0].sem_flg = 0; // representing two slaves are ready
11
12 sem[1].sem_num = 0; // the next operation in the atomic set
13 sem[1].sem_op = 2; // of operations increases the value of
14 sem[1].sem_flg = 0; // the semaphore about 2
15
16 printf("Wait for semvalue >= 2\n");
17 r = semop(id, sem, 2); // perform all operations atomically
18 printf("Press ENTER to set semaphore to 0\n");
19 getchar();
20 r = semctl(id, 0, SETVAL, 0) == 0; // set the value of semaphore
21 r = semctl(id, 0, IPC_RMID, 0) == 0; // remove the semaphore
22 }
23 return 0;
24 }

```

lec07/sem-master.c

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## Shared Memory

- Labeled part of the memory accessible from different processes
- OS service provided by system calls

## Example of System Calls

```

1 /* obtain a shared memory identifier */
2 int shmget(key_t key, size_t size, int flag);
3
4 /* attach shared memory */
5 void* shmat(int shmid, const void *addr, int flag);
6
7 /* detach shared memory */
8 int shmdt(const void *addr);
9
10 /* shared memory control */
11 int shmctl(int shmid, int cmd, struct shmid_ds *buf);

```

- OS manages information about usage of shared memory
- OS also manages permissions and access rights

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## Example – Shared Memory 3/4 (Demo)

- Use `shm-write` to write a text string to the shared memory
- Use `shm-read` to read data (string) from the shared memory
- Remove shared memory segment  
`ipcrm -M 1000`
- Try to read data from the shared memory

```

1 % clang -o shm-write shm-write.c 1 % clang -o shm-read shm-read.c
2 % ./shm-write 2 % ./shm-read
3 Hello! I like programming in C! 3 mem:Hello! I like programming in
 C!
 4
5 % ./shm-read 5 mem:Hello! I like programming in
6 mem:Hello! I like programming in 6 C!
7 7
8 % ipcrm -M 1000 8 % ipcrm -M 1000
9 % ./shm-read 9 % ./shm-read
10 Cannot access to shared memory! 10 Cannot access to shared memory!

```

lec07/shm-write.c lec07/shm-read.c

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## Example – Shared Memory 4/4 (Status)

- A list of accesses to the shared memory using `ipcs` command

```

1 after creating shared memory segment and before writing the text
2 m 65539 1000 --rw-rw-rw- jf jf jf jf
 no-entry 22:18:48 512 1239 1239 22:18:48
3
4 after writing the text to the shared memory
5 m 65539 1000 --rw-rw-rw- jf jf jf jf
 0 512 1239 1239 22:18:48
6 22:19:37 22:18:48
7 after reading the text
8 m 65539 1000 --rw-rw-rw- jf jf jf jf
 0 512 1239 1260 22:20:07
9 22:20:07 22:18:48

```

## Sensing Messages and Queues of Messages

- Processes can communicate using messages send/received to/from system messages queues
- Queues are entities of the OS with defined system calls

## Example of System Calls

```

1 #include <sys/types.h>
2 #include <sys/ipc.h>
3 #include <sys/msg.h>
4
5 /* Create a new message queue */
6 int msgget(key_t key, int msgflg);
7
8 /* Send a message to the queue -- block/non-block (IPC_NOWAIT) */
9 int msgsnd(int msqid, const void *msgp, size_t msgsz, int msgflg);
10
11 /* Receive message from the queue -- block/non-block (IPC_NOWAIT) */
12 int msgrcv(int msqid, void *msgp, size_t msgsz, long msgtyp, int msgflg);
13
14 /* Control operations (e.g., destroy) the message queue */
15 int msgctl(int msqid, int cmd, struct msqid_ds *buf)

```

Another message passing system can be implemented by a user library, e.g., using network communication.

## Example – Messages Passing 1/4 (Synchronization, Master)

- Two processes are synchronized using messages
  - The `master` process waits for the message from the `slave` process
  - The master process informs slave to solve the task
  - The slave process informs master about the solution
  - The master process sends message about termination

## Example of master process 1/2

```

1 struct msgbuf {
2 long mtype;
3 char mtext[SIZE];
4 };
5
6 int main(int argc, char *argv[])
7 {
8 struct msgbuf msg;
9 int id = msgget(KEY, IPC_CREAT | 0666);
10 int r;
11 if (id != -1) {

```

## Example – Messages Passing 2/4 (Master)

## Example of master process 2/2

```

1 msg.mtype = 3; //type must be > 0
2 printf("Wait for other process \n");
3 r = msgrcv(id, &msg, SIZE, 3, 0);
4 printf("Press ENTER to send work\n");
5 getchar();
6 strcpy(msg.mtext, "Do work");
7 msg.mtype = 4; //work msg is type 4
8 r = msgsnd(id, &msg, sizeof(msg.mtext), 0);
9 fprintf(stderr, "msgsnd r:%d\n", r);
10 printf("Wait for receive work results\n", r);
11 msg.mtype = 5;
12 r = msgrcv(id, &msg, sizeof(msg.mtext), 5, 0);
13 printf("Received message:%s\n", msg.mtext);
14 printf("Press ENTER to send exit msg\n");
15 getchar();
16 msg.mtype = EXIT_MSG; //I choose type 10 as exit msg
17 r = msgsnd(id, &msg, 0, 0);
18 }
19 return 0;
20 }

```

lec07/msg-master.c

## Example – Messages Passing 3/4 (Slave)

```

1 int main(int argc, char *argv[])
2 {
3 ...
4 msg.mtype = 3;
5 printf("Inform main process\n");
6 strcpy(msg.mtext, "I'm here, ready to work");
7 r = msgsnd(id, &msg, sizeof(msg.mtext), 0);
8 printf("Wait for work\n");
9 r = msgrcv(id, &msg, sizeof(msg.mtext), 4, 0);
10 printf("Received message:%s\n", msg.mtext);
11 for (i = 0; i < 4; i++) {
12 sleep(1);
13 printf(".");
14 fflush(stdout);
15 } //do something useful
16 printf("Work done, send wait for exit\n");
17 strcpy(msg.mtext, "Work done, wait for exit");
18 msg.mtype = 5;
19 r = msgsnd(id, &msg, sizeof(msg.mtext), 0);
20 msg.mtype = 10;
21 printf("Wait for exit msg\n");
22 r = msgrcv(id, &msg, SIZE, EXIT_MSG, 0);
23 printf("Exit message has been received\n");

```

lec07/msg-slave.c

## Example – Messages Passing 4/4 (Demo)

- Execute the master process
- Execute the slave process
- Perform the computation
- Remove the created message queue identified by the `msgid`

```

 #define KEY 1000
1 % clang msg-master.c -o master 1 % clang msg-slave.c -o slave
2 % ./master 2 % ./slave
3 Wait for other process 3 Inform main process
4 Slave msg received, press ENTER 4 Wait for work
 to send work msg 5 Received message:Do work
5 ...done 6 ...done
6 msgsnd r:0 7 Work done, send wait for exit
7 Wait for receive work results 8 Wait for exit msg
8 Received message:I'm going to 9 Exit message has been received
 wait for exit msg 10 %ipcs -q
9 Press ENTER to send exit msg 11 Message Queues:
10 12 T ID KEY MODE OWNER GROUP
11 %ipcrm -Q 1000 13 q 65536 1000 -rw-rw- jf jf
12 %ipcrm -Q 1000 14 %
13 ipcrm: msgq(1000): : No such
 file or directory
 lec07/msg-master.c lec07/msg-slave.c
14 %

```

## Massive parallelism using graphics cards

- Image rendering performed pixel-by-pixel can be easily parallelized
- Graphics Processing Units (GPU) has similar (or even higher) degree of integration with the main processors (CPU)
- They have huge number of parallel processors

*E.g., GeForce GTX 1060 ~ 1280 cores*

- The computational power can also be used in another applications
  - Processing stream of data (SIMD instructions - processors).
  - GPGPU - General Purpose computation on GPU
    - <http://www.gpgpu.org>
    - OpenCL (Open Computing Language) – GPGPU abstract interface
    - CUDA - Parallel programming interface for NVIDIA graphics cards
      - [http://www.nvidia.com/object/cuda\\_home.html](http://www.nvidia.com/object/cuda_home.html)

## Computational Power (2008)

- What is the reported processor computational power?
- Graphics (stream) processors

|                  |               |
|------------------|---------------|
| CSX700           | 96 GigaFLOPs  |
| Cell             | 102 GigaFLOPs |
| GeForce 8800 GTX | 518 GigaFLOPs |
| Radeon HD 4670   | 480 GigaFLOPs |

*Peak catalogue values*

- Main processors :

|                               |              |
|-------------------------------|--------------|
| Phenom X4 9950 (@2.6 GHz)     | 21 GigaFLOPs |
| Core 2 Duo E8600 (@3.3 GHz)   | 22 GigaFLOPs |
| Cure 2 Quad QX9650 (@3.3 GHz) | 35 GigaFLOPs |
| Cure 2 Quad QX9650 (@3.3 GHz) | 35 GigaFLOPs |
| Core i7 970 (@3.2 GHz)        | 42 GigaFLOPs |

*Test linpack 32-bit*

- Is the reported power really achievable?
- How about other indicators

*(float vs double)*

*E.g., computational power / power consumption*

- CSX700 has typical power consumption around 9W

## CUDA

- NVIDIA Compute Unified Device Architecture.
- Extension of the C to access to the parallel computational units of the GPU
- Computation (**kernel**) is executed by the GPU
- Kernel is performed in parallel using available computational units
- Host** - Main processor (process)
- Device** - GPU
- Data must be in the memory accessible by the GPU

*Host memory → Device memory*

- The result (of the computation) is stored in the GPU memory

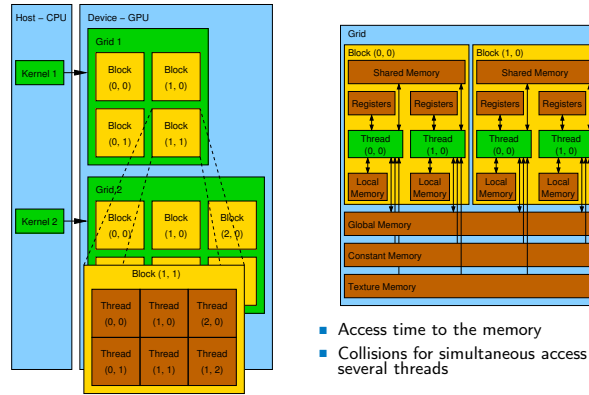
*Host memory ← Device memory*

## CUDA – Computational Model

- Kernel (computation) is divided into blocks
- Each block represent a parallel computation of the part of the result  
*E.g., a part of the matrix multiplication*
- Each block consists of computational threads
- Parallel computations are synchronization within the block
- Blocks are organized into the **grid**.
- Scalability is realized by dividing the computation into blocks

*Blocks may not be necessarily computed in parallel. Based on the available number of parallel units, particular blocks can be computed sequentially.*

## CUDA – Grid, Blocks, Threads, and Memory Access



## CUDA – Example – Matrix Multiplication 1/8

- NVIDIA CUDA SDK - Version 2.0, matrixMul.
- Simple matrix multiplication
  - $C = A \cdot B$ ,
  - Matrices have identical dimensions  $n \times n$ ,
  - where  $n$  is the multiple of the block size
- Comparison
  - naive implementation in C ( $3 \times$  for loop),
  - naive implementation in C with matrix transpose
  - CUDA implementation
- Hardware
  - CPU - Intel Core 2 Duo @ 3 GHz, 4 GB RAM,
  - GPU - NVIDIA G84 (GeForce 8600 GT), 512 MB RAM.

## CUDA – Example – Matrix Multiplication 2/8

### Naive implementation

```
1 void simple_multiply(const int n,
2 const float *A, const float *B, float *C)
3 {
4 for (int i = 0; i < n; ++i) {
5 for (int j = 0; j < n; ++j) {
6 float prod = 0;
7 for (int k = 0; k < n; ++k) {
8 prod += A[i * n + k] * B[k * n + j];
9 }
10 C[i * n + j] = prod;
11 }
12 }
13 }
```

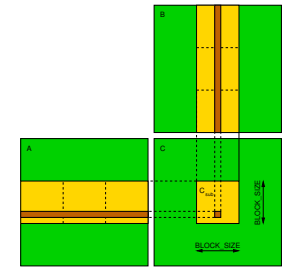
## CUDA – Example – Matrix Multiplication 3/8

### Naive implementation with transpose

```
1 void simple_multiply_trans(const int n,
2 const float *a, const float *b, float *c)
3 {
4 float *bT = create_matrix(n);
5 for (int i = 0; i < n; ++i) {
6 bT[i*n + i] = b[i*n + i];
7 for (int j = i + 1; j < n; ++j) {
8 bT[i*n + j] = b[j*n + i];
9 bT[j*n + i] = b[i*n + j];
10 }
11 }
12 for (int i = 0; i < n; ++i) {
13 for (int j = 0; j < n; ++j) {
14 float tmp = 0;
15 for (int k = 0; k < n; ++k) {
16 tmp += a[i*n + k] * bT[j*n + k];
17 }
18 c[i*n + j] = tmp;
19 }
20 }
21 free(bT);
22 }
```

## CUDA – Example – Matrix Multiplication 4/8

- CUDA – computation strategy
  - Divide matrices into blocks
  - Each block computes a single sub-matrix  $C_{sub}$
  - Each thread of the individual blocks computes a single element of  $C_{sub}$



## CUDA – Example – Matrix Multiplication 5/8

### CUDA – Implementation – main function

```
1 void cuda_multiply(const int n,
2 const float *hostA, const float *hostB, float *hostC)
3 {
4 const int size = n * n * sizeof(float);
5 float *devA, *devB, *devC;
6
7 cudaMalloc((void**)&devA, size);
8 cudaMalloc((void**)&devB, size);
9 cudaMalloc((void**)&devC, size);
10
11 cudaMemcpy(devA, hostA, size, cudaMemcpyHostToDevice);
12 cudaMemcpy(devB, hostB, size, cudaMemcpyHostToDevice);
13
14 dim3 threads(BLOCK_SIZE, BLOCK_SIZE); // BLOCK_SIZE == 16
15 dim3 grid(n / threads.x, n / threads.y);
16
17 // Call kernel function matrixMul
18 matrixMul<<grid, threads>>(n, devA, devB, devC);
19
20 cudaMemcpy(hostC, devC, size, cudaMemcpyDeviceToHost);
21
22 cudaFree(devA);
23 cudaFree(devB);
24 cudaFree(devC);
25 }
```

## CUDA – Example – Matrix Multiplication 6/8

### CUDA implementation – kernel function

```
1 __global__ void matrixMul(int n, float* A, float* B, float* C) {
2 int bx = blockIdx.x; int by = blockIdx.y;
3 int tx = threadIdx.x; int ty = threadIdx.y;
4 int aBegin = n * BLOCK_SIZE * by; //beginning of sub-matrix in the block
5 int aEnd = aBegin + n - 1; //end of sub-matrix in the block
6 float Csub = 0;
7 for (
8 int a = aBegin, b = BLOCK_SIZE * bx;
9 a <= aEnd;
10 a += BLOCK_SIZE, b += BLOCK_SIZE * n
11) {
12 __shared__ float As[BLOCK_SIZE][BLOCK_SIZE]; // shared memory within
13 __shared__ float Bs[BLOCK_SIZE][BLOCK_SIZE]; // the block
14 As[ty][tx] = A[a + n * ty + tx]; // each thread reads a single element
15 Bs[ty][tx] = B[b + n * ty + tx]; // of the matrix to the memory
16 __syncthreads(); // synchronization, sub-matrix in the shared memory
17
18 for (int k = 0; k < BLOCK_SIZE; ++k) { // each thread computes
19 Csub += As[ty][k] * Bs[k][tx]; // the element in the sub-matrix
20 }
21 __syncthreads();
22 }
23 int c = n * BLOCK_SIZE * by + BLOCK_SIZE * bx;
24 C[c + n * ty + tx] = Csub; // write the results to memory
25 }
```

## CUDA – Example – Matrix Multiplication 7/8

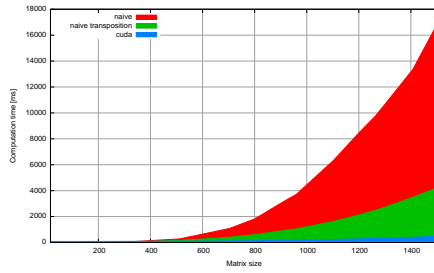
- CUDA source codes

### Example – Dedicated source file cuda\_func.cu

- Declaration of the external function  
extern "C" { // declaration of the external function (cuda kernel)  
void cuda\_multiply(const int n, const float \*A, const float \*B, float \*C); }
- Compile the CUDA code to the C++ code  
1 nvcc --cuda cuda\_func.cu -o cuda\_func.cc
- Compilation of the cuda\_func.cu.cc file using standard compiler

## CUDA – Example – Matrix Multiplication 8/8

Computational time (in milliseconds)



| N   | Naive | Transp. | CUDA | N    | Naive | Transp. | CUDA |
|-----|-------|---------|------|------|-------|---------|------|
| 112 | 2     | 1       | 81   | 704  | 1083  | 405     | 122  |
| 208 | 11    | 11      | 82   | 1104 | 6360  | 1628    | 235  |
| 304 | 35    | 33      | 84   | 1264 | 9763  | 2485    | 308  |

■ Matlab 7.6.0 (R2008a):  
 n=1104; A=rand(n,n); B=rand(n,n); tic; C=A\*B; toc  
 Elapsed time is 0.224183 seconds.

## Summary of the Lecture

## Topics Discussed

- Introduction to Parallel Programming
  - Ideas and main architectures
  - Program and process in OS
- Parallel processing
- Synchronization and Inter-Process Communication (IPC)
  - Semaphores
  - Messages
  - Shared memory
- Parallel processing on graphics cards
  
- **Next: Multithreading programming**