Parallel Programming

Jan Faigl

Department of Computer Science
Faculty of Electrical Engineering
Czech Technical University in Prague

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

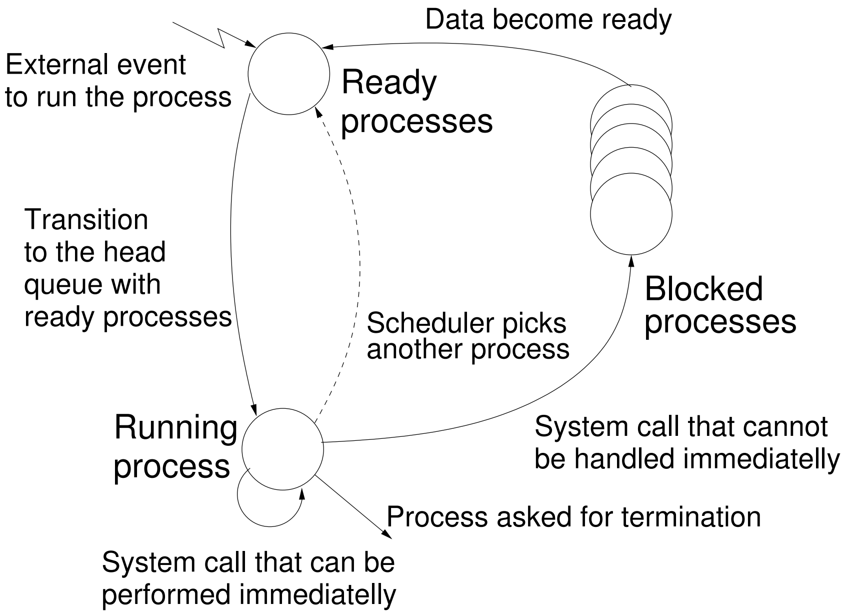
Motivation Why to Deal with Parallel Programming

- 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)

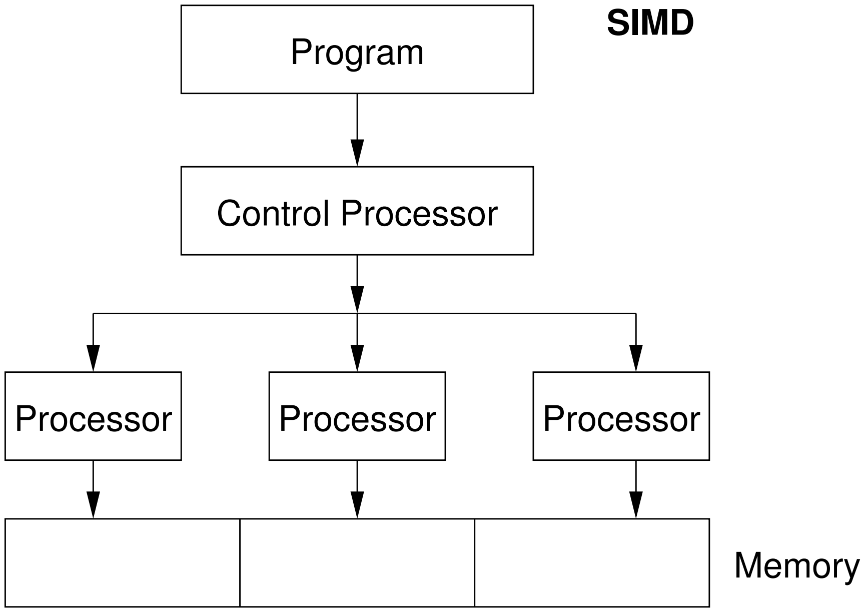
Possible Architectures for Parallel Executions

- 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 ar 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

Program

Control Processor

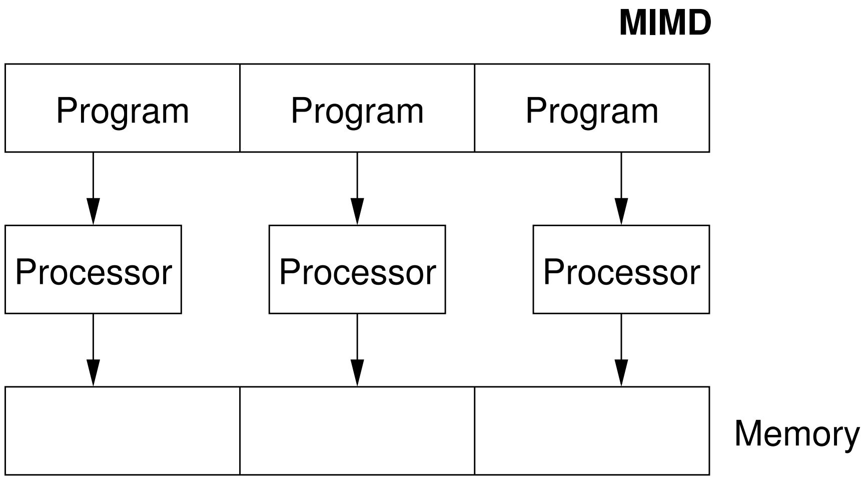
Processor

Processor

Processor

Memory

MIMD – Multiple-Instruction, Multiple-Data



MIMD

Program

Program

Program

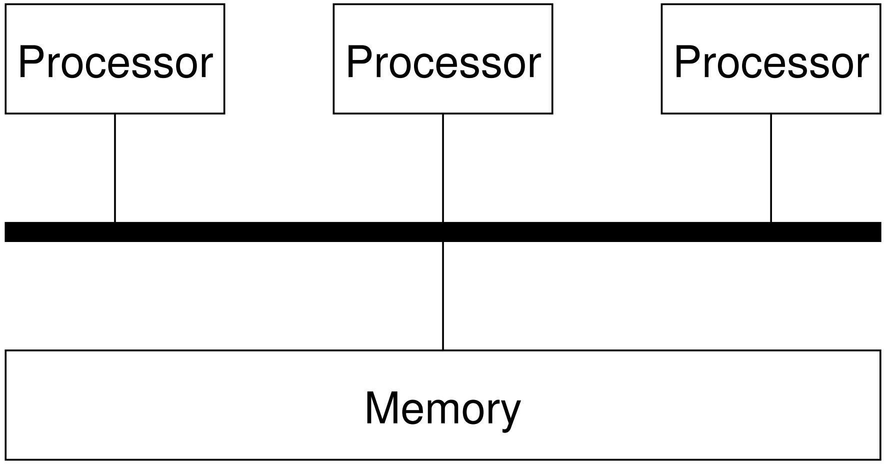
Processor

Processor

Processor

Memory

Systems with Shared Memory



Processor

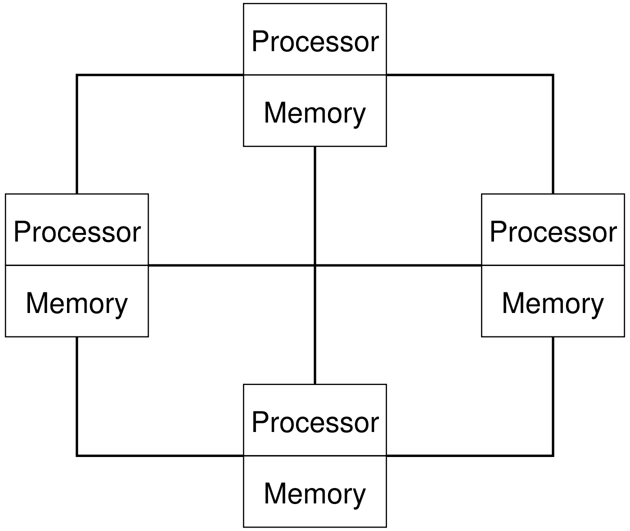
Processor

Processor

Memory

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

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

Parallel Processing and Programming Languages

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

Example of Parallel Processing Realized by Compiler 1/2

Example – Array Multiplication

```c
#include <stdlib.h>

#define SIZE 30000000

int main(int argc, char *argv[])
{
   int i;
   int *in1 = (int*)malloc(SIZE*sizeof(int));
   int *in2 = (int*)malloc(SIZE*sizeof(int));
   int *out = (int*)malloc(SIZE*sizeof(int));
   for (i = 0; i < SIZE; ++i) {
      in1[i] = i;
      in2[i] = 2 * i;
   }
   for (i = 0; i < SIZE; ++i) {
      out[i] = in1[i] * in2[i];
      out[i] = out[i] - (in1[i] + in2[i]);
   }
   return 0;
}
```

Example of Parallel Processing Realized by Compiler 2/2

Example 1

```
icc compute.c
time ./a.out

real 0m0.562s
user 0m0.180s
sys  0m0.384s
```

Example 2

```
icc -msse compute.c; time ./a.out
compute.c(8) : (col. 2) remark: LOOP WAS
     VECTORIZED.

real 0m0.542s
user 0m0.136s
sys  0m0.408s
```

Example 3

```
icc -parallel  compute.c; time ./a.out
compute.c(12) : (col. 2) remark: LOOP WAS AUTO-
     PARALLELIZED.

real 0m0.702s
user 0m0.484s
sys  0m0.396s
```

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

```
void multiply(int n, int a[n][n], int b[n][n], int c[n][n])
{
   int i;
#pragma omp parallel private(i)
#pragma omp for schedule (dynamic, 1)
   for (i = 0; i < n; ++i) {
      for (int j = 0; j < n; ++j) {
         c[i][j] = 0;
         for (int k = 0; k < n; ++k) {
            c[i][j] += a[i][k] * b[k][j];
         }
      }
   }
}
```

lec07/demo-omp-matrix.c

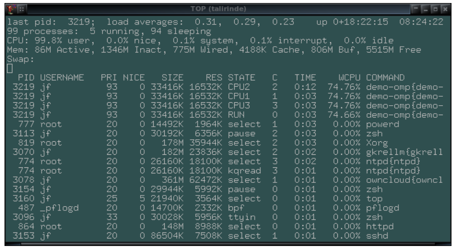
Squared matrices of the same dimensions are used for simplicity.

Example – Open MP – Matrix Multiplication 2/2

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

```
gcc -std=c99 -O2 -o demo-omp demo-omp-matrix.c -fopenmp
./demo-omp 1000
Size of matrices 1000 x 1000 naive
          multiplication with O(n^3)
c1 == c2: 1
Multiplication single core 9.33 sec
Multiplication  multi-core 4.73 sec

export OMP_NUM_THREADS=2
./demo-omp 1000
Size of matrices 1000 x 1000 naive
          multiplication with O(n^3)
c1 == c2: 1
Multiplication single core 9.48 sec
Multiplication  multi-core 6.23 sec
```



```
last pid:  3219;  load averages:  0.31,  0.29,  0.23    up 0+18:22:15  08:24:22
99 processes:  5 running, 94 sleeping
CPU: 99.8% user,  0.0% nice,  0.1% system,  0.1% interrupt,  0.0% idle
Mem: 86M Active, 1346M Inact, 775M Wired, 4188K Cache, 806M Buf, 5515M Free
Swap:

  PID USERNAME    PRI NICE   SIZE    RES STATE   C   TIME    WCPU COMMAND
 3219 jf           93    0 33416K 16532K CPU2    2   0:12  74.76% demo-omp{demo-
 3219 jf           93    0 33416K 16532K CPU1    1   0:03  74.76% demo-omp{demo-
 3219 jf           93    0 33416K 16532K CPU3    3   0:03  74.76% demo-omp{demo-
 3219 jf           93    0 33416K 16532K RUN     0   0:03  74.66% demo-omp{demo-
  777 root         20    0 14492K  1964K select  1   0:03   0.00% powerd
 3113 jf           20    0 30192K  6356K pause   2   0:03   0.00% zsh
  819 root         20    0   178M 35944K select  2   0:03   0.00% Xorg
 3070 jf           20    0   182M 23836K select  2   0:02   0.00% gkrellm{gkrell
  774 root         20    0 26160K 18100K select  3   0:02   0.00% ntpd{ntpd}
  774 root         20    0 26160K 18100K kqread  3   0:01   0.00% ntpd{ntpd}
 3078 jf           20    0   361M 62472K select  1   0:01   0.00% owncloud{owncl
 3154 jf           20    0 29944K  5992K pause   0   0:01   0.00% zsh
 3160 jf           25    5 21940K  3564K select  0   0:01   0.00% top
  487 _pflogd      20    0 14700K  2332K bpf     0   0:01   0.00% pflogd
 3096 jf           33    0 30028K  5956K ttyin   0   0:01   0.00% zsh
  864 root         20    0   148M  8988K select  0   0:01   0.00% httpd
 3153 jf           20    0 86504K  7508K select  1   0:01   0.00% sshd
```

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
  $S_1$;
  $S_2$;
  ...
  $S_n$
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

```
for i = 1 to n doparalel {
   for j = 1 to n do {
      c[i,j] = 0;
      for k = 1 to n do {
         c[i,j] = c[i,j] + a[i,k]*b[k,j];
} } }
```

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 x_{pid} = newprocess(P);

  ...

  killprocess(x_{pid});

  - P is a procedure and x_{pid} is a process identifier
- Assignment of the procedure/function to the process at the declaration

  `PID` x_{pid} `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

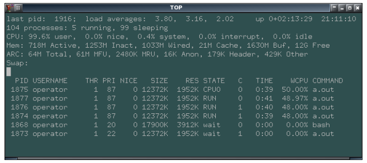
```c
if (fork() == 0) {
   /* code executed by the child process */
} else {
   /* code executed by the parent process */
}
```

E.g., `fork()` *in C*

Example – `fork()`

```c
#define NUMPROCS 4
for (int i = 0; i < NUMPROCS; ++i) {
   pid_t pid = fork();
   if (pid == 0) {
      compute(i, n);
      exit(0);
   } else {
      printf("Child %d created\n", pid);
   }
}
printf("All processes created\n");
for (int i = 0; i < NUMPROCS; ++i) {
   pid_t pid = wait(&r);
   printf("Wait for pid %d return: %d\n",
     pid, r);
}
void compute(int myid, int n)
{
   printf("Process myid %d start
         computing\n", myid);
   ...
   printf("Process myid %d
         finished\n", myid);
}
```

lec07/demo-fork.c



```
TOP
last pid:  1916;  load averages:  3.80,  3.16,  2.02     up 0+02:13:29  21:11:10
104 processes: 5 running, 99 sleeping
CPU: 99.6% user,  0.0% nice,  0.4% system,  0.0% interrupt,  0.0% idle
Mem: 718M Active, 1253M Inact, 1033M Wired, 21M Cache, 1630M Buf, 12G Free
ARC: 64M Total, 61M MFU, 2480K MRU, 16K Anon, 179K Header, 429K Other
Swap:

  PID USERNAME    THR PRI NICE   SIZE    RES STATE   C   TIME    WCPU COMMAND
 1875 operator      1  87    0 12372K  1952K CPU0    0   0:39  50.00% a.out
 1877 operator      1  87    0 12372K  1952K RUN     0   0:41  48.97% a.out
 1876 operator      1  87    0 12372K  1952K RUN     1   0:40  48.00% a.out
 1874 operator      1  87    0 12372K  1952K RUN     1   0:39  48.00% a.out
 1868 operator      1  20    0 17900K  3912K wait    0   0:00   0.00% bash
 1873 operator      1  22    0 12372K  1952K wait    1   0:00   0.00% a.out
```

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

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>

/* create or get existing set of semphores */
int semget(key_t key, int nsems, int flag);

/* atomic array of operations on a set of semphores */
int semop(int semid, struct sembuf *array, size_t nops);

/* control operations on a st of semaphores */
int semctl(int semid, int semnum, int cmd, ...);
```

Example – Semaphore 2/4 (Synchronization Protocol)

- Example when the main (master) process waits for two other processes (slaves) become ready
  1. *Master* process suspend the execution and waits for two other processes *slaves* become ready
  2. *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 fro 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

Example – Semaphore 3/4 (Master Process)

```c
int main(int argc, char* argv[])
{
   struct sembuf sem[2]; // structure for semaphore atomic operations
   int id = semget(1000, 1, IPC_CREAT | 0666); // create semaphore
   if (id != -1) {
      int r = semctl(id, 0, SETVAL, 0) == 0;

      sem[0].sem_num = 0;  // operation to acquire semaphore
      sem[0].sem_op = -2;  // once its value will be >= 2
      sem[0].sem_flg = 0;  // representing two slaves are ready

      sem[1].sem_num = 0;  // the next operation in the atomic set
      sem[1].sem_op = 2;   // of operations increases the value of
      sem[1].sem_flg = 0;  // the semaphore about 2

      printf("Wait for semvalue >= 2\n");
      r = semop(id, sem, 2); // perform all operations atomically
      printf("Press ENTER to set semaphore to 0\n");
      getchar();
      r = semctl(id, 0, SETVAL, 0) == 0; // set the value of semaphore
      r = semctl(id, 0, IPC_RMID, 0) == 0; // remove the semaphore
   }
   return 0;
}
```

lec07/sem-master.c

Example – Semaphore 4/4 (Slave Process)

```c
int main(int argc, char* argv[])
{
   struct sembuf sem;
   int id = semget(1000, 1, 0);
   int r;
   if (id != -1) {
      sem.sem_num = 0; // add the slave
      sem.sem_op = 1;  // to the "pool" of resources
      sem.sem_flg = 0;
      printf("Increase semafore value (add resource)\n");
      r = semop(id, &sem, 1);
      sem.sem_op = 0;
      printf("Semaphore value is %d\n", semctl(id, 0, GETVAL, 0));
      printf("Wait for semaphore value 0\n");
      r = semop(id, &sem, 1);
      printf("Done\n");
   }
   return 0;
}
```

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
```

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);
...                           ...
```

Shared Memory

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

Example of System Calls

```c
/* obtain a shared memory identifier */
int shmget(key_t key, size_t size, int flag);

/* attach shared memory */
void* shmat(int shmid, const void *addr, int flag);

/* detach shared memory */
int shmdt(const void *addr);

/* shared memory control */
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

Example – Shared Memory 1/4 (Write)

- Write a line read from stdin to the shared memory

```c
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/shm.h>
#include <stdio.h>

#define SIZE 512

int main(int argc, char *argv[])
{
   char *buf;
   int id;
   if ((id = shmget(1000, SIZE, IPC_CREAT | 0666)) != -1)
     {
      if ( (buf = (char*)shmat(id, 0, 0)) ) {
         fgets(buf, SIZE, stdin);
         shmdt(buf);
      }
   }
   return 0;
}
```

lec07/shm-write.c

Example – Shared Memory 2/4 (Read)

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

```c
#include <sys/types.h>
#include <sys/shm.h>
#include <stdio.h>

#define SIZE 512

int main(int argc, char *argv[])
{
   int id;
   char *buf;
   if ((id = shmget(1000, 512, 0)) != -1) {
      if ((buf = (char*)shmat(id, 0, 0)) ) {
         printf("mem:%s\n", buf);
      }
      shmdt(buf);
   } else {
      fprintf(stderr, "Cannot access to shared memory!\n");
   }
   return 0;
}
```

lec07/shm-read.c

Example – Shared Memory 3/4 (Demo)

1. Use shm-write to write a text string to the shared memory
2. Use shm-read to read data (string) from the shared memory
3. Remove shared memory segment

   ipcrm -M 1000
4. Try to read data from the shared memory

```
% clang -o shm-write shm-write.c
% ./shm-write
Hello! I like programming in C!
```

```
% clang -o shm-read shm-read.c
% ./shm-read
mem:Hello! I like programming in
      C!

% ./shm-read
mem:Hello! I like programming in
      C!

% ipcrm -M 1000
% ./shm-read
Cannot access to shared memory!
```

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

Example – Shared Memory 4/4 (Status)

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

```
after creating shared memory segment and before writing the text
m        65539         1000 --rw-rw-rw-    jf    jf    jf    jf
              1          512         1239          1239 22:18:48
    no-entry 22:18:48

after writing the text to the shared memory
m        65539         1000 --rw-rw-rw-    jf    jf    jf    jf
              0          512         1239          1239 22:18:48
    22:19:37 22:18:48

after reading the text
m        65539         1000 --rw-rw-rw-    jf    jf    jf    jf
              0          512         1239          1260 22:20:07
    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

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/msg.h>

/* Create a new message queue */
int msgget(key_t key, int msgflg);

/* Send a message to the queue -- block/non-block (IPC_NOWAIT) */
int msgsnd(int msqid, const void *msgp, size_t msgsz, int msgflg);

/* Receive message from the queue -- block/non-block (IPC_NOWAIT) */
int msgrcv(int msqid, void *msgp, size_t msgsz, long msgtyp, int msgflg);

/* Control operations (e.g., destroy) the message queue */
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
  1. The `master` process waits for the message from the `slave` process
  2. The master process informs slave to solve the task
  3. The slave process informs master about the solution
  4. The master process sends message about termination

Example of `master` process 1/2

```
struct msgbuf {
   long mtype;
   char mtext[SIZE];
};

int main(int argc, char *argv[])
{
   struct msgbuf msg;
   int id = msgget(KEY, IPC_CREAT | 0666);
   int r;
   if (id != -1) {
```

Example – Messages Passing 2/4 (Master)

Example of `master` process 2/2

```
      msg.mtype = 3; //type must be > 0
      printf("Wait for other process \n");
      r = msgrcv(id, &msg, SIZE, 3, 0);
      printf("Press ENTER to send work\n");
      getchar();
      strcpy(msg.mtext, "Do work");
      msg.mtype = 4; //work msg is type 4
      r = msgsnd(id, &msg, sizeof(msg.mtext), 0);
      fprintf(stderr, "msgsnd r:%d\n",r);
      printf("Wait for receive work results\n",r);
      msg.mtype = 5;
      r = msgrcv(id, &msg, sizeof(msg.mtext), 5, 0);
      printf("Received message:%s\n", msg.mtext);
      printf("Press ENTER to send exit msg\n");
      getchar();
      msg.mtype = EXIT_MSG; //I choose type 10 as exit msg
      r = msgsnd(id, &msg, 0, 0);
   }
   return 0;
}
```

`lec07/msg-master.c`

Example – Messages Passing 3/4 (Slave)

```c
int main(int argc, char *argv[])
{
   ...
   msg.mtype = 3;
   printf("Inform main process\n");
   strcpy(msg.mtext, "I'm here, ready to work");
   r = msgsnd(id, &msg, sizeof(msg.mtext), 0);
   printf("Wait for work\n");
   r = msgrcv(id, &msg, sizeof(msg.mtext), 4, 0);
   printf("Received message:%s\n", msg.mtext);
   for (i = 0; i < 4; i++) {
     sleep(1);
     printf(".");
     fflush(stdout);
   } //do something useful
   printf("Work done, send wait for exit\n");
   strcpy(msg.mtext, "Work done, wait for exit");
   msg.mtype = 5;
   r = msgsnd(id, &msg, sizeof(msg.mtext), 0);
   msg.mtype = 10;
   printf("Wait for exit msg\n");
   r = msgrcv(id, &msg, SIZE, EXIT_MSG, 0);
   printf("Exit message has been received\n");
```

lec07/msg-slave.c

Example – Messages Passing 4/4 (Demo)

1. Execute the master process
2. Execute the slave process
3. Perform the computation
4. Remove the created message queue identified by the **msgid**

#define KEY 1000

ipcrm -Q 1000

```
% clang msg-master.c -o master
% ./master
Wait for other process
Slave msg received, press ENTER
     to send work msg

msgsnd r:0
Wait for receive work results
Received message:I'm going to
     wait for exit msg
Press ENTER to send exit msg

%ipcrm -Q 1000
%ipcrm -Q 1000
ipcrm: msqs(1000): : No such
     file or directory
%
```

```
% clang msg-slave.c -o slave
% ./slave
Inform main process
Wait for work
Received message:Do work
....done
Work done, send wait for exit
Wait for exit msg
Exit message has been received
%ipcs -q
Message Queues:
T ID    KEY  MODE     OWNER GROUP
q 65536 1000 -rw-rw- jf    jf
%
```

lec07/msg-master.c lec07/msg-slave.c

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`

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?

  (float vs double)
- How about other indicators

  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

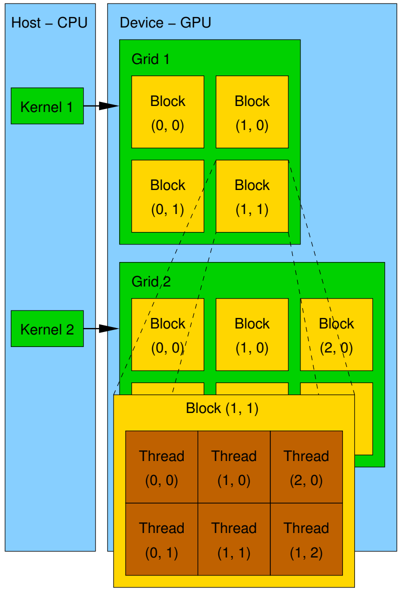
CUDA – Computational Model

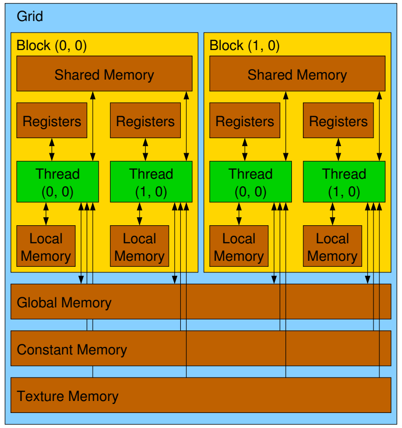
- Kernel (computation) is divided into blocks
- Each block represent a parallel computation of the part of the result

  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





- Access time to the memory
- Collisions for simultaneous access of several threads

CUDA – Example – Matrix Multiplication 1/8

- NVIDIA CUDA SDK - Version 2.0, `matrixMul`.
- Simple matrix multiplication
  - $\boldsymbol{C} = \boldsymbol{A} \cdot \boldsymbol{B}$,
  - Matrices have identical dimensions $n \times n$,
  - where n is the multiple of the block size
- Comparison
  - naive implementation in C (3× *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

```
void simple_multiply(const int n,
      const float *A, const float *B, float *C)
{
  for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
      float prod = 0;
      for (int k = 0; k < n; ++k) {
        prod += A[i * n + k] * B[k * n + j];
      }
      C[i * n + j] = prod;
    }
  }
}
```

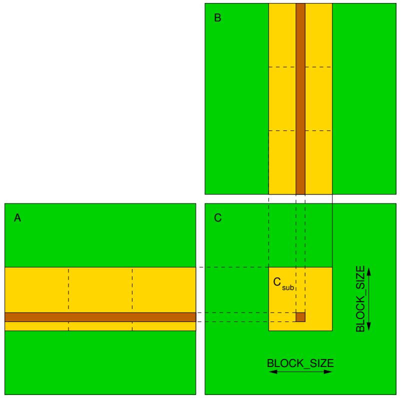
CUDA – Example – Matrix Multiplication 3/8

Naive implementation with transpose

```
void simple_multiply_trans(const int n,
      const float  *a,  const float *b, float  *c)
{
  float * bT = create_matrix(n);
  for (int i = 0; i < n; ++i) {
    bT[i*n + i] = b[i*n + i];
    for (int j = i + 1; j < n; ++j) {
      bT[i*n + j] = b[j*n + i];
      bT[j*n + i] = b[i*n + j];
    }
  }
  for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
      float tmp = 0;
      for (int k = 0; k < n; ++k) {
        tmp += a[i*n + k] * bT[j*n + k];
      }
      c[i*n + j] = tmp;
    }
  }
  free(bT);
}
```

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

```
void cuda_multiply(const int n,
      const float *hostA, const float *hostB, float *hostC)
{
 const int size = n * n * sizeof(float);
 float *devA, *devB, *devC;

 cudaMalloc((void**)&devA, size);
 cudaMalloc((void**)&devB, size);
 cudaMalloc((void**)&devC, size);

 cudaMemcpy(devA, hostA, size, cudaMemcpyHostToDevice);
 cudaMemcpy(devB, hostB, size, cudaMemcpyHostToDevice);

 dim3 threads(BLOCK_SIZE, BLOCK_SIZE);  // BLOCK_SIZE == 16
 dim3 grid(n / threads.x, n /threads.y);

 // Call kernel function matrixMul
 matrixMul<<<grid, threads>>>(n, devA, devB, devC);

 cudaMemcpy(hostC, devC, size, cudaMemcpyDeviceToHost);

 cudaFree(devA);
 cudaFree(devB);
 cudaFree(devC);
}
```

CUDA – Example – Matrix Multiplication 6/8

CUDA implementation – kernel function

```
__global__ void matrixMul(int n, float* A, float* B, float* C) {
   int bx = blockIdx.x; int by = blockIdx.y;
   int tx = threadIdx.x; int ty = threadIdx.y;
   int aBegin = n * BLOCK_SIZE * by;  //beginning of sub-matrix in the block
   int aEnd = aBegin + n - 1; //end of sub-matrix in the block
   float Csub = 0;
   for (
         int a = aBegin, b = BLOCK_SIZE * bx;
         a <= aEnd;
         a += BLOCK_SIZE, b += BLOCK_SIZE * n
       ) {
      __shared__ float As[BLOCK_SIZE][BLOCK_SIZE]; // shared memory within
      __shared__ float Bs[BLOCK_SIZE][BLOCK_SIZE]; // the block
      As[ty][tx] = A[a + n * ty + tx]; // each thread reads a single element
      Bs[ty][tx] = B[b + n * ty + tx]; // of the matrix to the memory
      __syncthreads(); // synchronization, sub-matrix in the shared memory

      for (int k = 0; k < BLOCK_SIZE; ++k) { // each thread computes
         Csub += As[ty][k] * Bs[k][tx]; // the element in the sub-matrix
      }
      __syncthreads();
   }
   int c = n * BLOCK_SIZE * by + BLOCK_SIZE * bx;
   C[c + n * ty + tx] = Csub; // write the results to memory
}
```

CUDA – Example – Matrix Multiplication 7/8

- CUDA source codes

Example – Dedicated source file cuda_func.cu

1. 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);
}
```

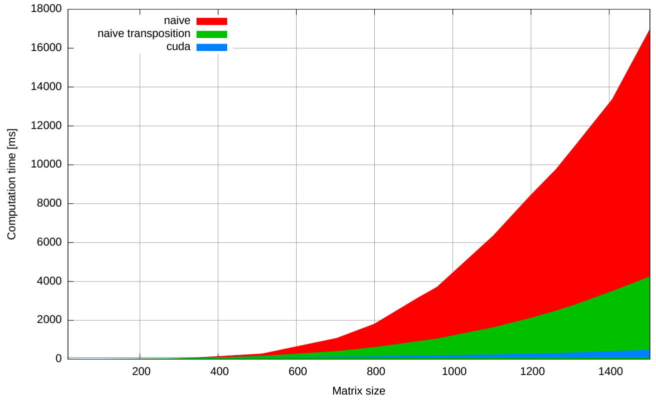
2. Compile the CUDA code to the C++ code

```
nvcc --cuda cuda_func.cu -o cuda_func.cu.cc
```

3. 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
- Sychronization and Inter-Process Communication (IPC)
  - Semaphores
  - Messages
  - Shared memory
- Parallel processing on graphics cards

- Next: Multithreading programming