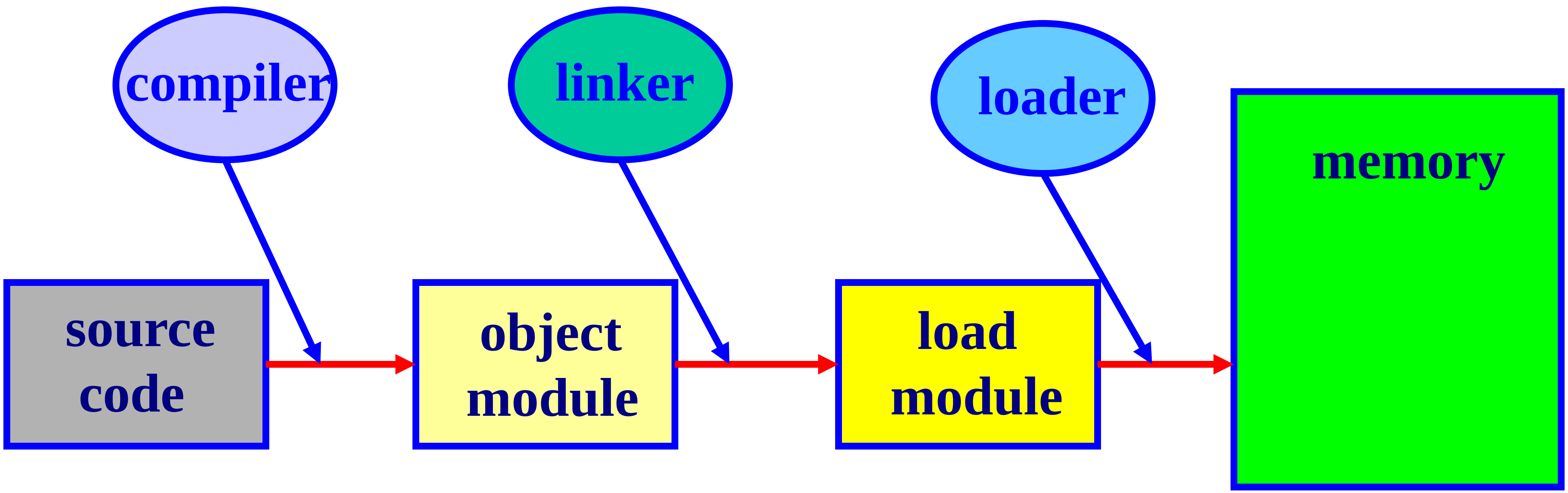
Part II
Processes and Threads
Process Basics

Program testing can be used to show the presence of bugs,
but never to show their absence

Edsger W. Dijkstra

From Compilation to Execution

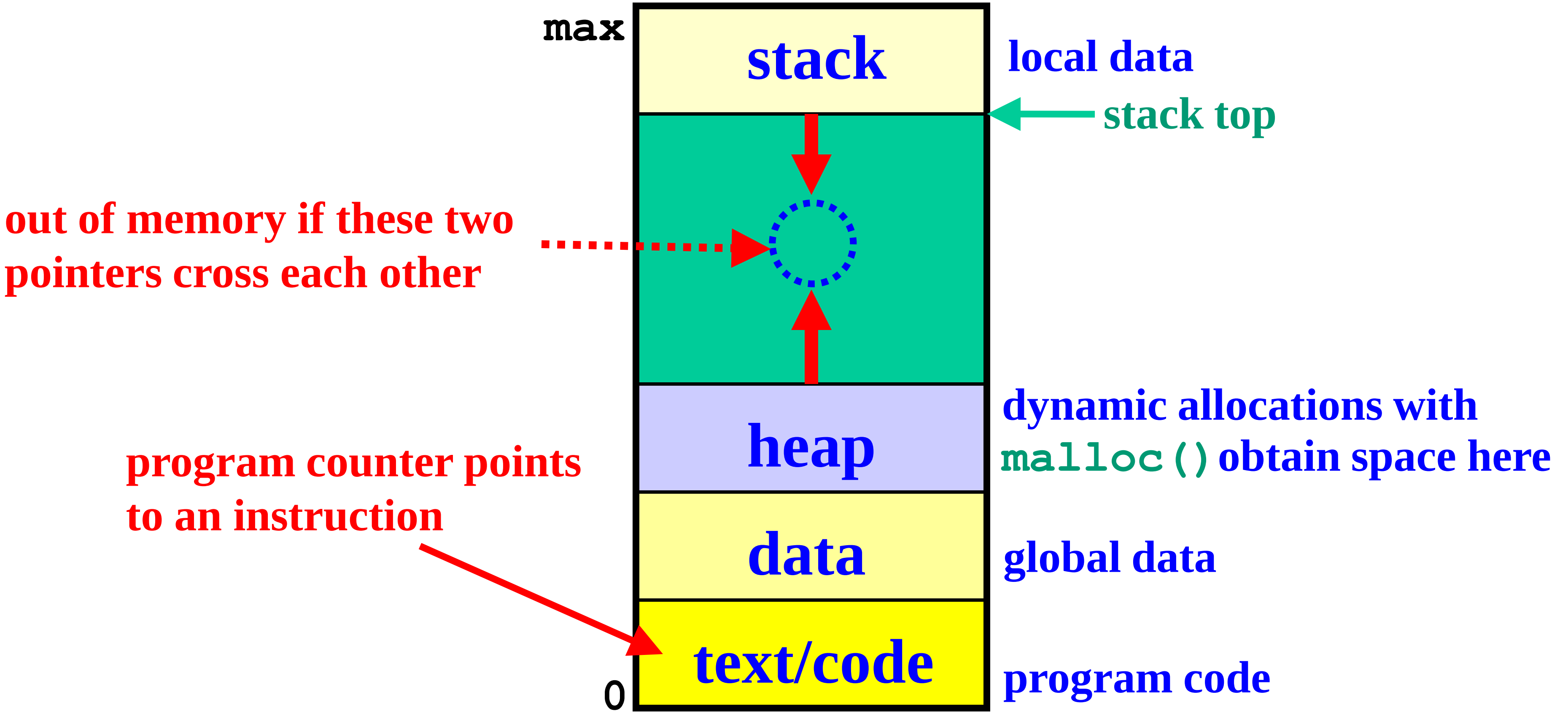
- A compiler compiles source files to `.o` files.
- A linker links `.o` files and other libraries together, producing a binary executable (e.g., `a.out`).
- A loader loads a binary executable into memory for execution.



What Is a Process?

- **When the OS runs a program (i.e., a binary executable), this program is loaded into memory and the control is transferred to this program's first instruction. Then, the program runs.**
- ***A process is a program in execution*.**
- **A process is more than a program, because a process has a program counter, stack, data section, code section, etc (i.e., the runtime stuffs).**
- **Moreover, multiple processes may be associated with one program (e.g., run the same program, say `a.out`, multiple times at the same time).**

Process Space

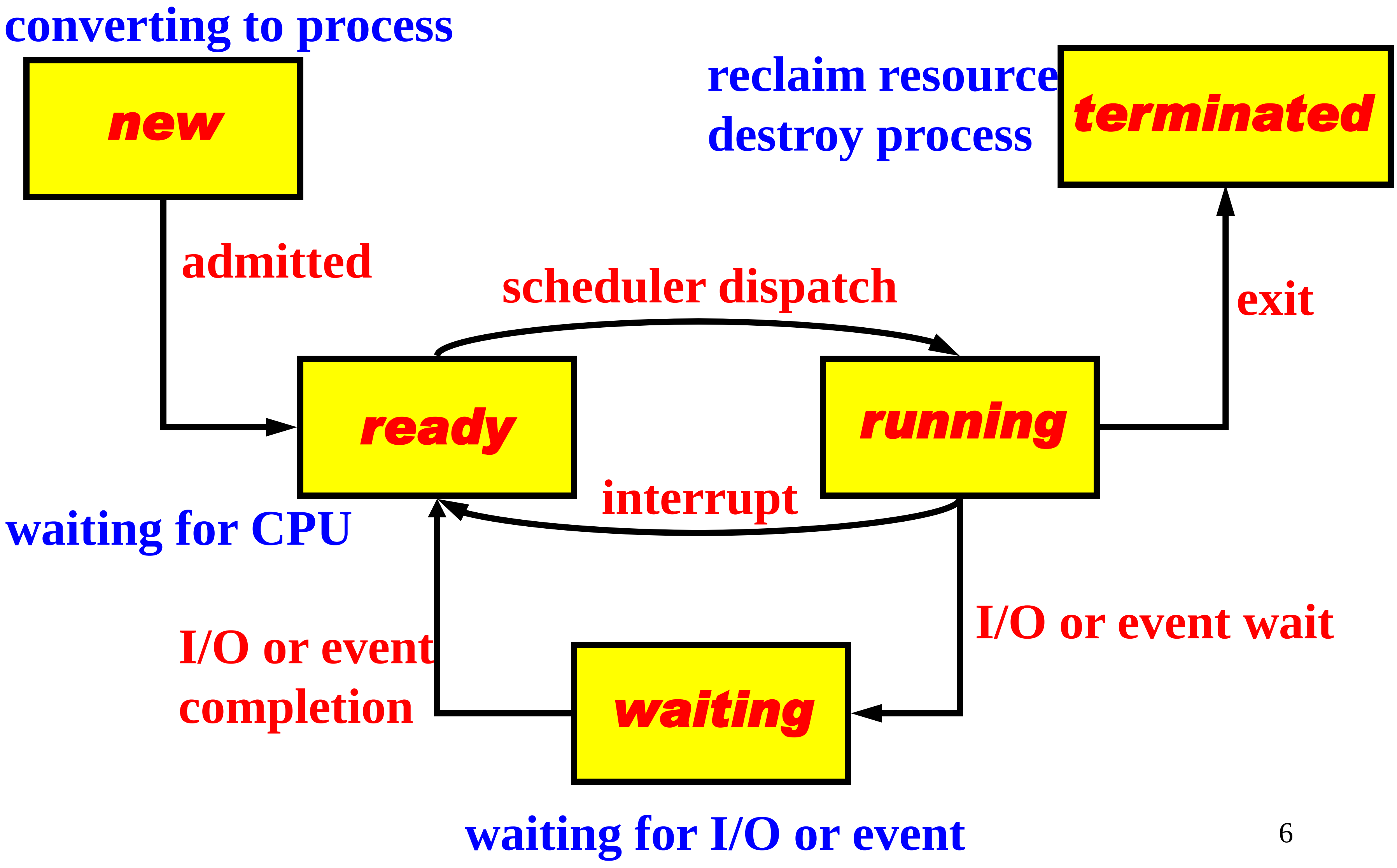


Process States

At any moment, a process can be in one of the five states: new, running, waiting, ready and terminated.

- ***New*: The process is being created**
- ***Running*: The process is executing on a CPU**
- ***Waiting*: The process is waiting for some event to occur (e.g., waiting for I/O completion)**
- ***Ready*: The process has everything but the CPU. It is waiting to be assigned to a processor.**
- ***Terminated*: The process has finished execution.**

Process State Diagram



Process Representation in OS

pointer	process state
process ID	
program counter	
registers	
scheduling info	
memory limits	
list of open files	
⋮	

- Each process is assigned a unique number, the ***process ID***.
- Process info are stored in a table, the ***process control block*** (***PCB***).
- These PCBs are chained into a number of lists. For example, all processes in the ready state are in the ***ready queue***.

Process Scheduling: 1/2

- **Since the number of processes may be larger than the number of available CPUs, the OS must maintain maximum CPU utilization.**
- **To determine which process can do what, processes are chained into a number of scheduling queues.**
- **For example, in addition to the ready queue, each event may have its own scheduling queue (*i.e.*, waiting queue).**

Process Scheduling: 2/2

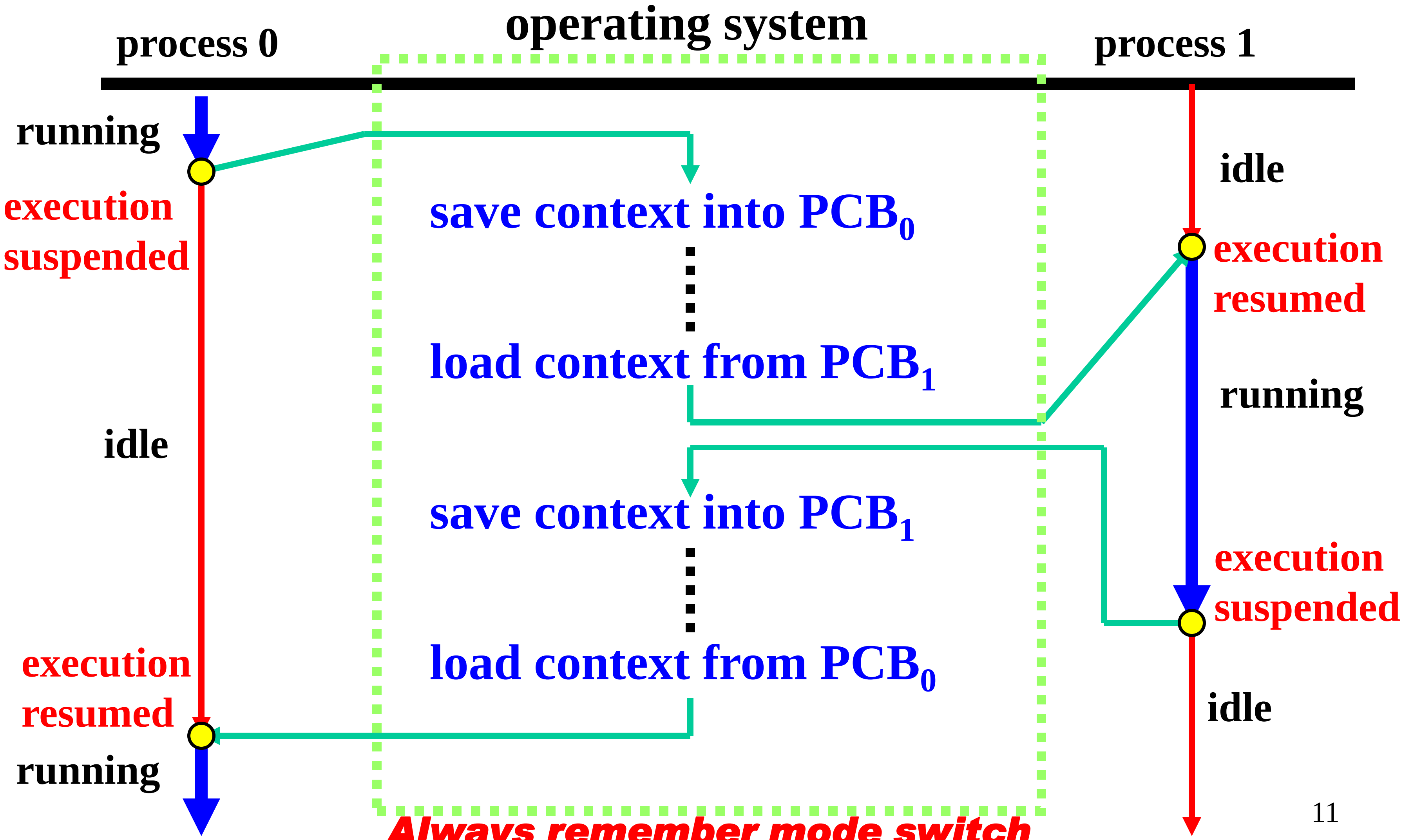
- **The ready queue, which may be organized into several sub-queues, has all processes ready to run.**
- **The OS has a *CPU scheduler*.**
- **When a CPU is free, the CPU scheduler looks at the ready queue, picks a process, and resumes it.**
- **The way of picking a process from the ready queue is referred to as *scheduling policy*.**
- **Scheduling policy is unimportant to this course because we *cannot make any assumption* about it.**

Context Switch: 1/2

- **What is a process context?** **The *context* of a process includes process ID, process state, the values of CPU registers, the program counter, and other memory/file management information (i.e., execution environment).**
- **What is a context switch?** **After the CPU scheduler selects a process and before allocates CPU to it, the CPU scheduler must**
  - **save the context of the currently running process,**
  - **put it back to the ready queue or waiting state,**
  - **load the context of the selected process, and**
  - **go to the saved program counter.**

mode switching may be needed

Context Switch: 2/2



Always remember mode switch

Operations on Processes

- There are three commonly seen operations:
  - **Process Creation**: Create a new process. The newly created is the child of the original. Unix uses `fork()` to create new processes.
  - **Process Termination**: Terminate the execution of a process. Unix uses `exit()`.
  - **Process Join**: Wait for the completion of a child process. Unix uses `wait()`.
- `fork()`, `exit()` and `wait()` are system calls.

Some Required Header Files

- **Before you use processes, include header files `sys/types.h` and `unistd.h`.**
- **`sys/types.h` has all system data types, and `unistd.h` declares standard symbolic constants and types.**

```
#include  <sys/types.h>
#include  <unistd.h>
```

The fork() System Call

- **The purpose of `fork()` is to create a child process. The creating and created processes are the parent and child, respectively.**
- **`fork()` does not require any argument!**
- **If the call to `fork()` is successful, Unix creates an identical but separate address space for the child process to run.**
- **Both processes start running with the instruction following the `fork()` system call.**

fork() Return Values

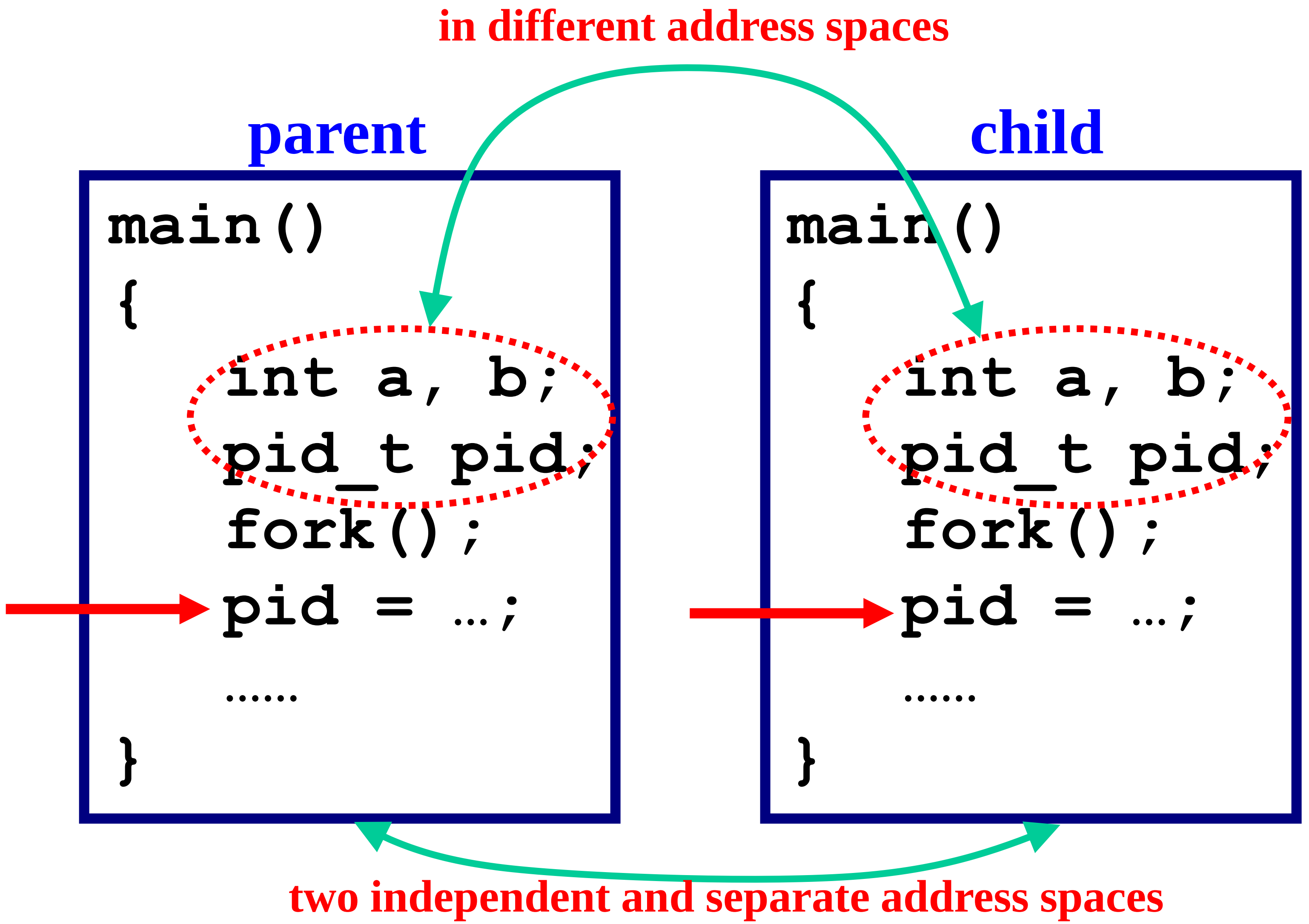
- A negative value means the creation of a child process was unsuccessful.
- A zero means the process is a child.
- Otherwise, `fork()` returns the process ID of the child process. The ID is of type `pid_t`.
- Function `getpid()` returns the process ID of the caller.
- Function `getppid()` returns the parent's process ID. If the calling process has no parent, `getppid()` returns `1`.

Before the Execution of fork()

parent

```
main()
{
    int a, b;
    pid_t pid
    fork();
    pid = …;
    ……
}
```

After the Execution of fork()



Example 1: 1/2

fork-1.c

```
#include  <stdio.h>
#include  <string.h>
#include  <sys/types.h>
#include  <unistd.h>

void main(void)
{
   pid_t  MyID, ParentID;
   int    i;
   char   buf[100];

   fork();                     // create a child process
   MyID     = getpid();        // get my process ID
   ParentID = getppid();       // get my parent's process ID
   for (i = 1; i <= 200; i++) {
      sprintf(buf, "From MyID=%ld, ParentID=%ld, i=%3d\n",
                   MyID, ParentID, i);
      write(1, buf, strlen(buf));   // why don't we
   }                                //     use printf?
}
```

this is stdout

Example 1: 2/2

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```
From MyID = 19087, ParentID = 19004, i = 193
From MyID = 19088, ParentID = 19087, i =  88
From MyID = 19087, ParentID = 19004, i = 194
From MyID = 19088, ParentID = 19087, i =  89
From MyID = 19087, ParentID = 19004, i = 195
From MyID = 19088, ParentID = 19087, i =  90
From MyID = 19087, ParentID = 19004, i = 196
From MyID = 19088, ParentID = 19087, i =  91
From MyID = 19087, ParentID = 19004, i = 197
From MyID = 19088, ParentID = 19087, i =  92
From MyID = 19087, ParentID = 19004, i = 198
From MyID = 19088, ParentID = 19087, i =  93
From MyID = 19087, ParentID = 19004, i = 199
From MyID = 19088, ParentID = 19087, i =  94
From MyID = 19087, ParentID = 19004, i = 200
From MyID = 19088, ParentID = 19087, i =  95
From MyID = 19088, ParentID = 19087, i =  96
From MyID = 19088, ParentID = 19087, i =  97
From MyID = 19088, ParentID = 19087, i =  98
From MyID = 19088, ParentID = 19087, i =  99
From MyID = 19088, ParentID = 19087, i = 100
From MyID = 19088, ParentID = 19087, i = 101
From MyID = 19088, ParentID = 19087, i = 102
From MyID = 19088, ParentID = 19087, i = 103
```

Processes 19087 and 19088 run concurrently

Parent: 19087
Child : 19088

19004
↓
19087
↓
19088

Parent 19087's parent is 19004, the shell that executes `fork-1`

fork(): A Typical Use

```
main(void)
{
  pid_t pid;

  pid = fork();
  if (pid < 0)
    printf("Oops!");
  else if (pid == 0)
    child();
  else // pid > 0
    parent();
}
```

```
void child(void)
{
  int i;
  for (i=1; i<=10; i++)
    printf(" Child:%d\n", i);
  printf("Child done\n");
}

void parent(void)
{
  int i;
  for (i=1; i<=10; i++)
    printf("Parent:%d\n", i);
  printf("Parent done\n");
}
```

we use `printfs` here to save space.

Before the Execution of fork()

parent

pid = ?

```
main(void)
{
   pid = fork();
   if (pid == 0)
      child();
   else
      parent();
}

void child(void)
{ ...... }

void parent(void)
{ ...... }
```

After the Execution of fork() 1/2

parent

pid=123

```
main(void)
{
   pid = fork();
   if (pid == 0)
      child();
   else
      parent();
}

void child(void)
{ ...... }

void parent(void)
{ ...... }
```

child

pid = 0

```
main(void)
{
   pid = fork();
   if (pid == 0)
      child();
   else
      parent();
}

void child(void)
{ ...... }

void parent(void)
{ ...... }
```

in two different address spaces

After the Execution of fork() 2/2

parent

pid=123

```
main(void)
{
  pid = fork();
  if (pid == 0)
    child();
  else
    parent();
}

void child(void)
{ ...... }

void parent(void)
{ ...... }
```

child

pid = 0

```
main(void)
{
  pid = fork();
  if (pid == 0)
    child();
  else
    parent();
}

void child(void)
{ ...... }

void parent(void)
{ ...... }
```

Example 2: 1/2

fork-2.c

force the child to print after the parent terminates

```
#include .........          // child exits first
void main(void)
{
   pid_t  pid;

   pid = fork();
   if (pid == 0) {              // child here
      printf("   From child %ld: my parent is %ld\n",
                          getpid(), getppid());
      sleep(5);
      printf("   From child %ld 5 sec later: parent %ld\n",
                          getpid(), getppid());
   }
   else {                       // parent here
      sleep(2);
      printf("From parent %ld: child %ld, parent %ld\n",
                   getpid(), pid, getppid());
      printf("From parent: done!\n");
   }
}
```

Example 2: 2/2

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```
HILBERT:/home/csdept/shene/CS3331/03-Process(41) fork-2
    From child 19292: my parent is 19291
From parent 19291: my child is 19292, my parent is 19004
From parent: done!
    From child 19292 5 sec later: my parent is 1
```

Orphan children have a new parent `init`, the Unix process that spawns all processes

while parent is still running

19004

parent 19291

child 19292

parent terminated

1

1 is the ID of `init`, the Unix process that spawns all processes

child 19292

19004 is the shell process that executes 19291

Example 3: 1/2

fork-3.c

```
#include   ......    // separate address spaces

void  main(void)
{
   pid_t  pid;
   char   out[100];
   int    i = 10, j = 20;

   if ((pid = fork()) == 0) {    // child here
      i = 1000; j = 2000;        // child changes values
      sprintf(out, "   From child: i=%d, j=%d\n", i, j);
      write(1, out, strlen(out));
   }
   else {                        // parent here
      sleep(3);
      sprintf(out, "From parent: i=%d, j=%d\n", i, j);
      write(1, out, strlen(out));
   }
}
```

this is equivalent to

```
pid = fork();
if (pid == 0)  ...
```

force the parent to print after the child terminated

Example 3: 2/2

```
HILBERT:/home/csdept/shene/CS3331/03-Process(46) fork-3
   From child: i = 1000, j = 2000
From parent: i = 10, j = 20
HILBERT:/home/csdept/shene/CS3331/03-Process(47)
```

child changes `i` and `j` to 1000 and 2000 from 10 and 20, respectively

parent's `i` and `j` are not affected because parent and child have independent and separate address space

The wait() System Call

- **The `wait()` system call blocks the caller until *one of its child processes* exits or a signal is received.**
- **`wait()` takes a pointer to an integer variable and returns the process ID of the completed process. If no child process is running, `wait()` returns `-1`.**
- **Some flags that indicate the completion status of the child process are passed back with the integer pointer.**

How to Use wait()?

- **Wait for an unspecified child process:**

```
wait(&status);
```

- **Wait for a number, say `n`, of unspecified child processes:**

```
for (i = 0; i < n; i++)
    wait(&status);
```

- **Wait for a specific child process whose ID is known:**

```
while (pid != wait(&status))
    ;
```

wait() System Call Example

```
void main(void)
{
   pid_t pid, pid_child;
   int   status;

   if ((pid = fork()) == 0)  // child here
      child();
   else {                    // parent here
      parent();
      pid_child = wait(&status);
   }
}
```

The exec() System Calls

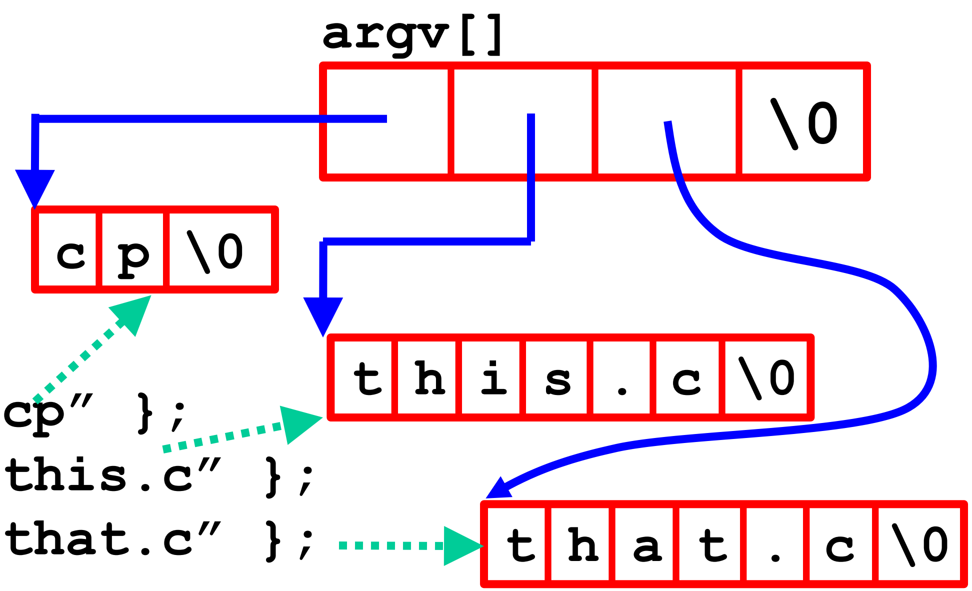
- A newly created process may run a different program rather than that of the parent.
- This is done using the `exec` system calls. We will only discuss `execvp()`:

```
int execvp(char *file, char *argv[]);
```

  - `file` is a `char` array that contains the name of an executable file
  - `argv[]` is the argument passed to your main program
  - `argv[0]` is a pointer to a string that contains the program name
  - `argv[1]`, `argv[2]`, … are pointers to strings that contain the arguments

execvp() : An Example 1/2

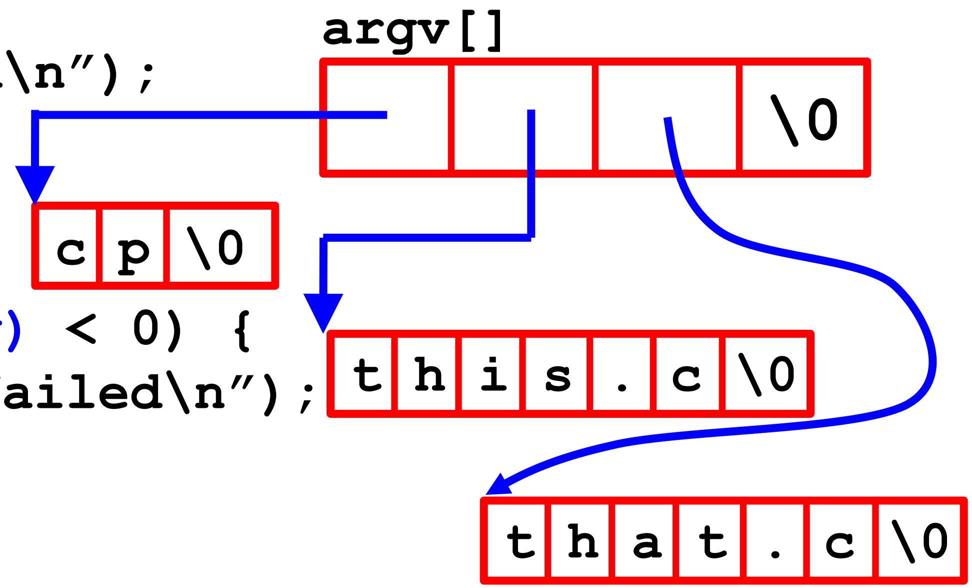
```
#include  <stdio.h>
#include  <unistd.h>

void main(void)
{
  char    prog[] = { “cp” };
  char    in[]   = { “this.c” };
  char    out[]  = { “that.c” };
  char    *argv[4];
  int     status;
  pid_t   pid;

  argv[0] = prog;  argv[1] = in;
  argv[2] = out;   argv[3] = ‘\0’;
```



// see next slide

execvp() : An Example 2/2

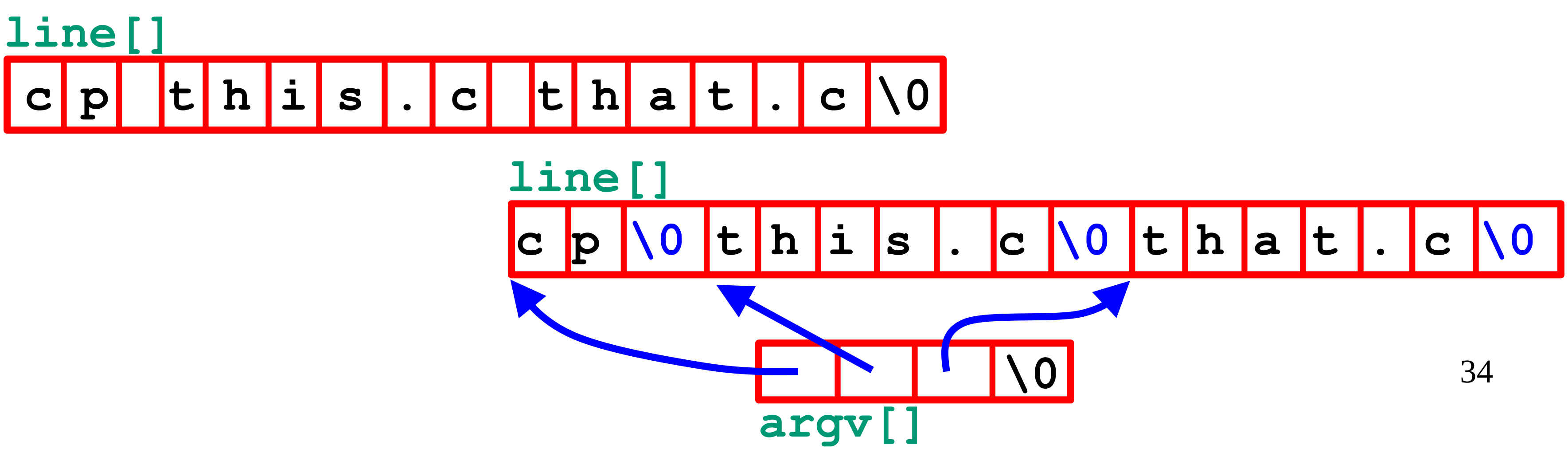
```
if ((pid = fork()) < 0) {
     printf(“fork() failed\n”);
     exit(1);
  }
  else if (pid == 0)
     if (execvp(prog, argv) < 0) {
         printf(“execvp() failed\n”);
         exit(1);
     }
  else
     wait(&status);
}
```



execute program cp

A Mini-Shell: 1/3

```
void parse(char *line, char **argv)
{
    while (*line != '\0') { // not EOLN
        while (*line == ' ' || *line == '\t' || *line == '\n')
            *line++ = '\0';   // replace white spaces with 0
        *argv++ = line;       // save the argument position
        while (*line != '\0' && *line ! =' '
                             && *line!='\t' && *line != '\n')
            line++;           // skip the argument until ...
    }
    *argv = '\0';             // mark the end of argument list
}
```



A Mini-Shell: 2/3

```
void execute(char **argv)
{
   pid_t pid;
   int status;
   if ((pid = fork()) < 0) { // fork a child process
      printf("*** ERROR: forking child process failed\n");
      exit(1);
   }
   else if (pid == 0) {       // for the child process:
      if (execvp(*argv, argv) < 0) { // execute the command
         printf("*** ERROR: exec failed\n");
         exit(1);
      }
   }
   else {                     // for the parent:
      while (wait(&status) != pid) // wait for completion
         ;
   }
}
```

A Mini-Shell: 3/3

```
void main(void)
{
   char line[1024];  // the input line
   char *argv[64];   // the command line argument

   while (1) {       // repeat until done ....
      printf("Shell -> "); // display a prompt
      gets(line);    // read in the command line
      printf("\n");
      parse(line, argv);  // parse the line
      if (strcmp(argv[0], "exit") == 0) // is it an "exit"?
         exit(0);    // exit if it is
      execute(argv); // otherwise, execute the command
   }
}
```

Don't forget that `gets()` is risky! Use `fgets()` instead.

What is Shared Memory?

- **The parent and child processes are run in independent and separate address spaces. All processes, parent and children included, do not share anything.**
- **A shared memory segment is a piece of memory that can be allocated and attached to an address space. Processes that have this memory segment attached will have access to it.**
- **But, race conditions can occur!**

Procedure for Using Shared Memory

- **Find a *key*. Unix uses this key for identifying shared memory segments.**
- **Use `shmget()` to allocate a shared memory.**
- **Use `shmat()` to attach a shared memory to an address space.**
- **Use `shmdt()` to detach a shared memory from an address space.**
- **Use `shmctl()` to deallocate a shared memory.**

Keys: 1/2

- To use shared memory, include the following:

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

- A key is a value of type `key_t`. There are three ways to generate a key:
  - Do it yourself
  - Use function `ftok()`
  - Ask the system to provide a private key.

Keys: 2/2

- **Do it yourself:**

```
key_t    SomeKey;
SomeKey = 1234;
```

- **Use `ftok()` to generate one for you:**

```
key_t = ftok(char *path, int ID);
```

  - `path` **is a path name (e.g., `"./"`)**
  - `ID` **is an integer (e.g., `'a'`)**
  - **Function `ftok()` returns a key of type `key_t`:**

```
SomeKey = ftok("./", 'x');
```

- **Keys are global entities. If other processes know your key, they can access your shared memory.**
- **Ask the system to provide a private key with `IPC_PRIVATE`.**

Ask for a Shared Memory: 1/4

- **Include the following:**

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

- **Use `shmget()` to request a shared memory:**

```
shm_id = shmget(
   key_t  key,     /* identity key    */
   int    size,    /* memory size     */
   int    flag);   /* creation or use */
```

- **`shmget()` returns a shared memory ID.**
- **The flag, for our purpose, is either `0666` (rw) or `IPC_CREAT | 0666`. Yes, `IPC_CREAT`.**

Ask for a Shared Memory: 2/4

- **The following creates a shared memory of size `struct Data` with a private key `IPC_PRIVATE`. This is a creation (`IPC_CREAT`) with read and write permission (`0666`).**

```
struct Data { int a; double b; char x; };
int            ShmID;

ShmID = shmget(
         IPC_PRIVATE,  /* private key */
         sizeof(struct Data), /* size */
         IPC_CREAT | 0666);/* cr & rw */
```

Ask for a Shared Memory: 3/4

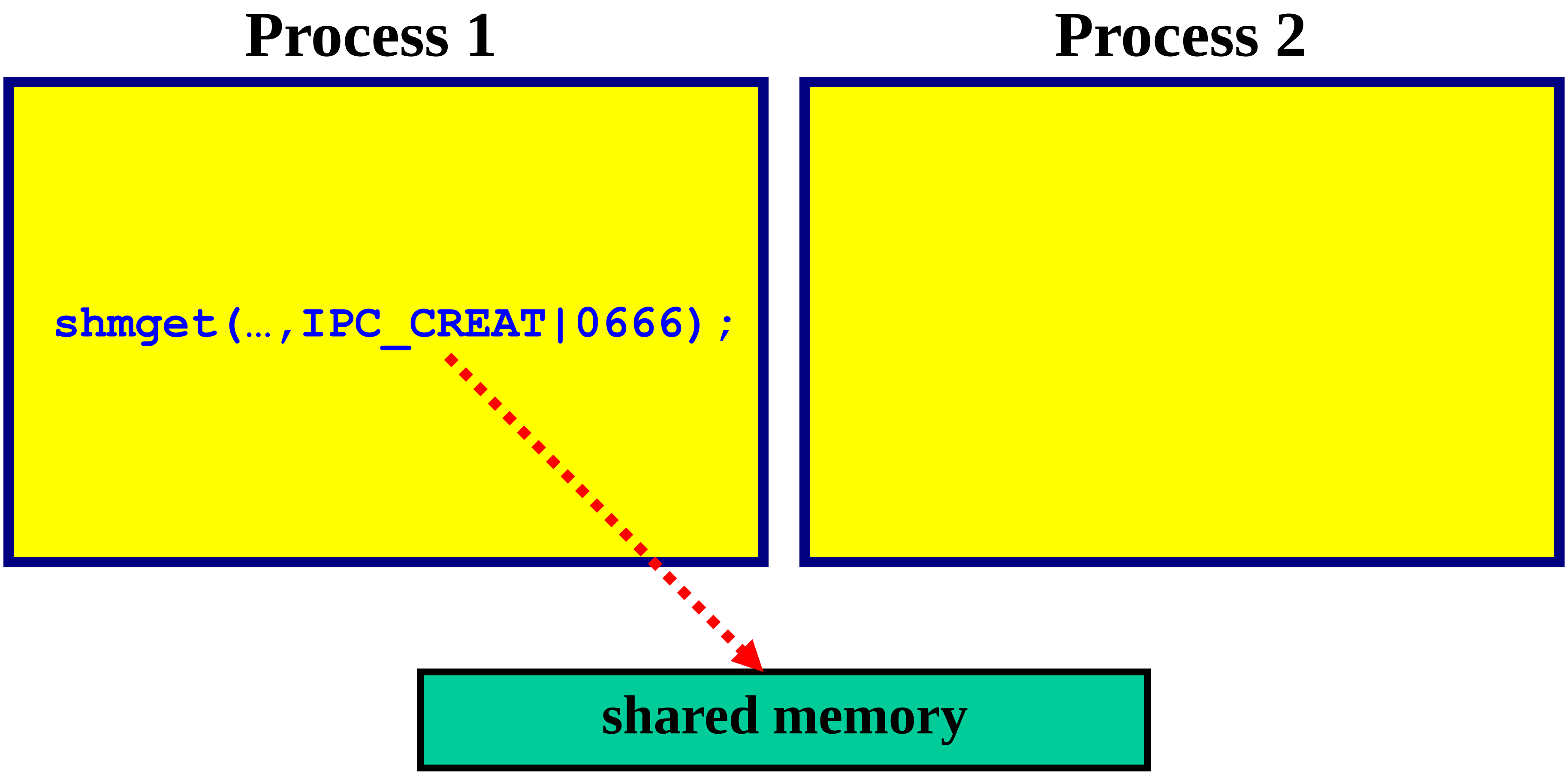
- **The following creates a shared memory with a key based on the current directory:**

```
struct Data { int a; double b; char x;};
int     ShmID;
key_t   Key;

Key = ftok(".//", 'h');
ShmID = shmget(
          Key,              /* a key */
          sizeof(struct Data),
          IPC_CREAT | 0666);
```

Ask for a Shared Memory: 4/4

- **When asking for a shared memory, the process that creates it uses `IPC_CREAT | 0666` and processes that access a created one use `0666`.**
- **If the return value is negative (Unix convention), the request was unsuccessful, and no shared memory is allocated.**
- ***Create a shared memory before its use!***

After the Execution of *shmget()*



Shared memory is allocated; but, is not part of the address space

Attaching a Shared Memory: 1/3

- Use `shmat()` to attach an existing shared memory to an address space:

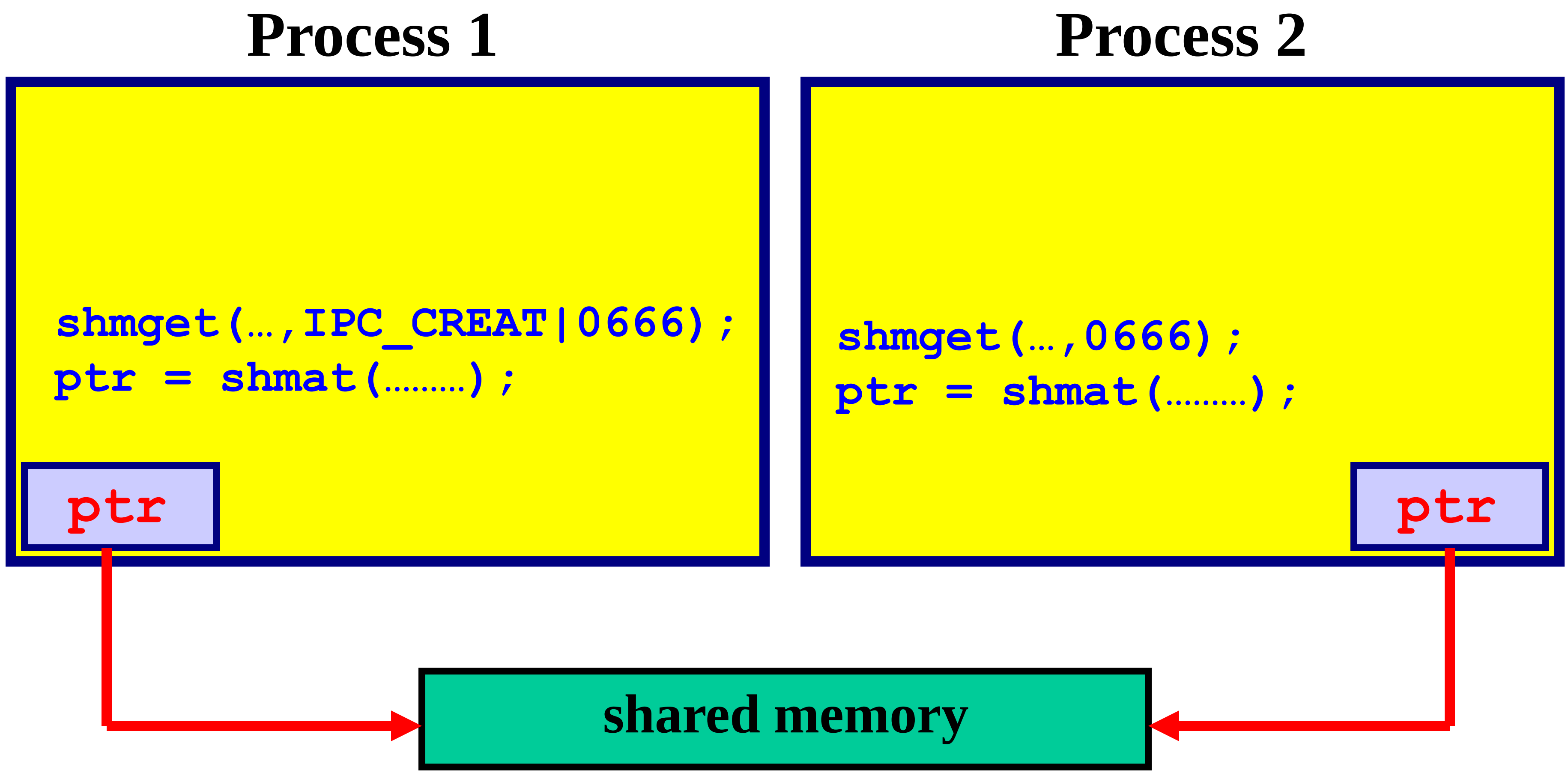
```
shm_ptr = shmat(
    int  shm_id, /* ID from shmget() */
    char *ptr,   /* use NULL here    */
    int  flag);  /* use 0 here       */
```

- `shm_id` is the shared memory ID returned by `shmget()`.
- Use `NULL` and `0` for the second and third arguments, respectively.
- `shmat()` returns a `void` pointer to the memory. If unsuccessful, it returns a negative integer.

Attaching a Shared Memory: 2/3

```
struct Data { int a; double b; char x;};
int     ShmID;
key_t   Key;
struct Data *p;

Key = ftok("./", 'h');
ShmID = shmget(Key, sizeof(struct Data),
              IPC_CREAT | 0666);
p = (struct Data *) shmat(ShmID, NULL, 0);
if ((int) p < 0) {
   printf("shmat() failed\n"); exit(1);
}
p->a = 1; p->b = 5.0; p->x = '.';
```

Attaching a Shared Memory: 3/3



Now processes can access the shared memory

Detaching/Removing Shared Memory

- To detach a shared memory, use

```
shmdt(shm_ptr);
```

`shm_ptr` is the pointer returned by `shmat()`.

- After a shared memory is detached, it is still there. You can attach and use it again.
- To remove a shared memory, use

```
shmctl(shm_ID, IPC_RMID, NULL);
```

`shm_ID` is the shared memory ID returned by `shmget()`. After a shared memory is removed, it no longer exists.

Communicating with a Child: 1/2

```
void main(int argc, char *argv[])
{
  int   ShmID, *ShmPTR, status;
  pid_t pid;

  ShmID = shmget(IPC_PRIVATE,4*sizeof(int),IPC_CREAT|0666);
  ShmPTR = (int *) shmat(ShmID, NULL, 0);
  ShmPTR[0] = getpid();         ShmPTR[1] = atoi(argv[1]);
  ShmPTR[2] = atoi(argv[2]);    ShmPTR[3] = atoi(argv[3]);
  if ((pid = fork()) == 0) {
     Child(ShmPTR);
     exit(0);
  }
  wait(&status);
  shmdt((void *) ShmPTR);  shmctl(ShmID, IPC_RMID, NULL);
  exit(0);
}
```

parent's process ID here

Communicating with a Child: 2/2

```
void Child(int  SharedMem[])
{
   printf("%d %d %d %d\n",  SharedMem[0],
        SharedMem[1], SharedMem[2], SharedMem[3]);
}
```

- ***Why are*** `shmget()` ***and*** `shmat()` ***not needed in the child process?***

Communicating Among Separate Processes: 1/5

- **Define the structure of a shared memory segment as follows:**

```
#define  NOT_READY  (-1)
#define  FILLED     (0)
#define  TAKEN      (1)

struct Memory {
   int  status;
   int  data[4];
};
```

Communicating Among Separate Processes: 2/5

The "Server"

Prepare for a shared memory

```
int main(int argc, char *argv[])
{
   key_t              ShmKEY;
   int                ShmID, i;
   struct Memory      *ShmPTR;

   ShmKEY = ftok("./", 'x');
   ShmID = shmget(ShmKEY, sizeof(struct Memory),
                  IPC_CREAT | 0666);
   ShmPTR = (struct Memory *) shmat(ShmID, NULL, 0);
```

Communicating Among Separate Processes: 3/5

shared memory not ready

filling in data

```
    ShmPTR->status = NOT_READY;

    ShmPTR->data[0] = getpid();
    for (i = 1; i < 4; i++)
       ShmPTR->data[i] = atoi(argv[i]);

    ShmPTR->status = FILLED;
    while (ShmPTR->status != TAKEN)
       sleep(1);  /* sleep for 1 second */
    printf("My buddy is %ld\n", ShmPTR->data[0]);
    shmdt((void *) ShmPTR);
    shmctl(ShmID, IPC_RMID, NULL);
    exit(0);
}
```

wait until the data is taken

detach and remove shared memory

Communicating Among Separate Processes: 4/5

The "Client"

prepare for shared memory

```
int main(void)
{
   key_t            ShmKEY;
   int              ShmID;
   struct Memory    *ShmPTR;

   ShmKEY=ftok(“./”, ‘x’);
   ShmID = shmget(ShmKEY, sizeof(struct Memory), 0666);
   ShmPTR = (struct Memory *) shmat(ShmID, NULL, 0);
   while (ShmPTR->status != FILLED)
      ;
   printf(“%d %d %d %d\n”, ShmPTR->data[0],
      ShmPTR->data[1], ShmPTR->data[2], ShmPTR->data[3]);
   ShmPTR->data[0] = getpid();
   ShmPTR->status = TAKEN;
   shmdt((void *) ShmPTR);
   exit(0);
}
```

Communicating Among Separate Processes: 5/5

- The "server" must run first to prepare a shared memory.
- Run the server in one window, and run the client in another a little later.
- Or, run the server as a background process. Then, run the client in the foreground later:

```
server 1 3 5 &
client
```

- This version uses busy waiting.
- One may use Unix semaphores for mutual exclusion.

Important Notes: 1/3

- **If you do not remove your shared memory segments (e.g., program crashes before the execution of `shmctl()`), they will be in the system forever until the system is shut down. This will degrade the system performance.**
- **Use the `ipcs` command to check if you have shared memory segments left in the system.**
- **Use the `ipcrm` command to remove your shared memory segments.**

Important Notes: 2/3

- To see existing shared memory segments in the system, use `ipcs -m`, where `m` means shared memory.
- The following is a snapshot on `wopr`:

```
shene@wopr:~
[shene@wopr ~]$ ipcs -m

------ Shared Memory Segments --------
key        shmid      owner      perms      bytes      nattch     status
0x78181367 1573912576 machoudh   666        12         0
0x7817433c 1336737793 hyunjik    666        204        0
0x78181363 1575583746 machoudh   666        12         0
0x7818132a 1577582595 machoudh   666        12         0
0x781813da 1579515908 machoudh   666        12         0
0x6b179e35 1612414981 mswillia   666        20         0
0x6b18b8b0 1909686278 machoudh   666        40         0
0x7918299c 1910013959 machoudh   666        92         0

[shene@wopr ~]$
```

Important Notes: 3/3

- To remove a shared memory, use the `ipcrm` command as follows:
  - `ipcrm –M` shm-key
  - `ipcrm –m` shm-ID
- You have to be the owner (or super user) to remove a shared memory.

The End