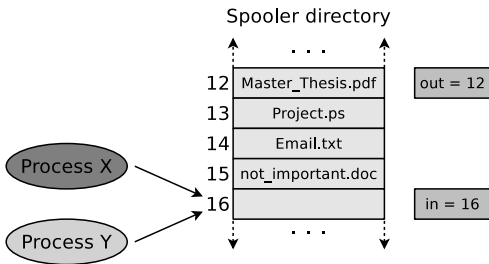
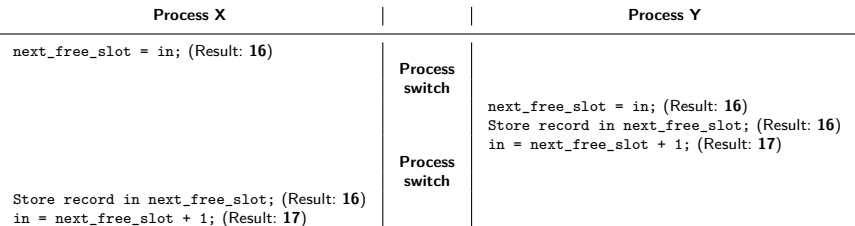


Critical Sections – Example: Print Spooler



- The spooling directory is consistent
 - But the entry of **process Y** was overwritten by **process X** and got lost
- Such a situation is called **race condition**

Therac-25: Race Condition with tragic Result (1/2)

- Therac-25 is a linear particle accelerator for the radiation therapy of cancer tumors
- Mid-1980s: In the United States some accidents happened because of poor programming and quality assurance
 - Some patients got an up to 100 times increased radiation dose



Image source: Google image search.
Frequently shown picture in this context.
(author and license: unknown)

An Investigation of the Therac-25 Accidents. Nancy Leveson, Clark S. Turner. IEEE Computer, Vol. 26, No. 7, July 1993, S.18-41
http://courses.cs.vt.edu/~cs3604/lib/Therac_25/Therac_1.html

Therac-25: Race Condition with tragic Result (2/2)

- A race condition („Texas-Bug“) led to incorrect settings of the device and consequently to increased radiation doses.
 - The control process did not synchronize correctly with the user interface process
 - The error occurred only during a quick input correction (time window: 8 seconds) by the user
 - During testing the error did not occur because experience (routine) was required to operate the device this fast

The Worst Computer Bugs in History: Race conditions in Therac-25:

<https://www.bugsnag.com/blog/bug-day-race-condition-therac-25>

„Once the data entry phase was marked complete, the magnet setting phase began. However, if a specific sequence of edits was applied in the Data Entry phase during the 8 second magnet setting phase, the setting was not applied to the machine hardware, due to the value of the completion variable. The UI would then display the wrong mode to the user, who would confirm the potentially lethal treatment.“

Other interesting sources

https://www-dssz.informatik.tu-cottbus.de/information/slides_studis/ss2009/mehner_RisikoComputer_zs09.pdf

Killer Bug. Therac-25: Quick-and-Dirty: <https://www.viva64.com/en/b/0438/>

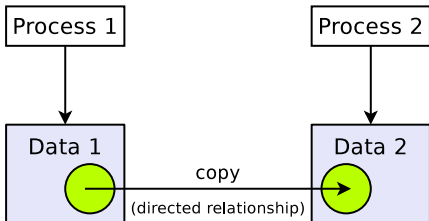
Killed by a machine: The Therac-25: <https://hackaday.com/2015/10/26/killed-by-a-machine-the-therac-25/>

Communication vs. Cooperation

- Interprocess communication has 2 aspects:
 - Functional aspect: **communication** and **cooperation**
 - Temporal aspect: **synchronization**

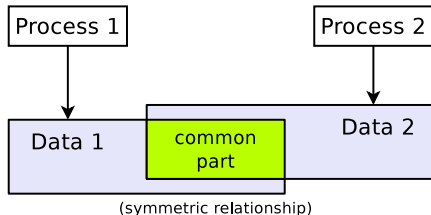
Communication

(= explicit data transport)



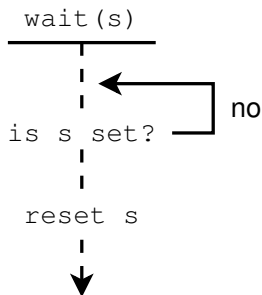
Cooperation

(= access to common data)



- _____

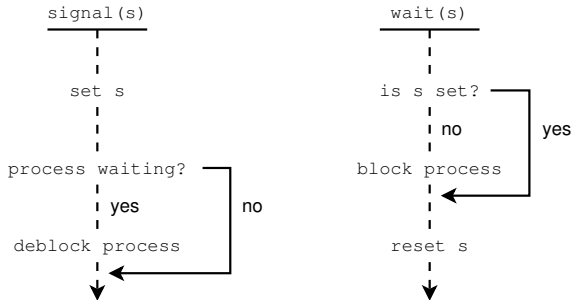
Most Simple Form of Signaling (Busy Waiting)



- The figure shows **busy waiting** at the signal variable `s`
 - The signal variable can be located in a local file, for example
 - Drawback: CPU resources are wasted, because the `wait` operation occupies the processor at regular intervals
- This technique is also called **spinlock** or **polling**

Signal and Wait

- Better concept: Blocking of process P_B until process P_A has finished section **X**
 - Advantage: No CPU resources are wasted
 - Drawback: Only a single process can wait
 - In literature, this technique is also called **passive waiting**



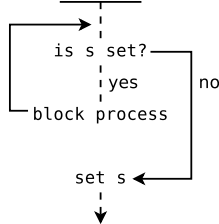
One way to specify in Linux an execution order with passive waiting, is by using the function `sigsuspend`. Thereby a process blocks itself until another process sends it an appropriate signal (usually `SIGUSR1` or `SIGUSR2`) with the command `kill` (or the system call of the same name) and in this way signals that it should continue working.

Alternative system calls and function calls by which a process can block itself until it is woken up again by a system call are `pause` and `sleep`

-
- The diagram illustrates the implementation of a semaphore using two mutexes and two condition variables. It is divided into three parts:
- Process 1 and Process 2:** Two processes, Process 1 and Process 2, are shown. Each process has a vertical timeline with two critical sections: `lock(s)` and `unlock(s)`. Process 1's critical sections are labeled `X` and `Y`, and Process 2's are labeled `Y` and `X`. Arrows indicate that both processes can access both critical sections, but they must do so in a mutually exclusive manner.
 - Reset and Deblock:** A flowchart showing the logic for resetting the semaphore. It starts with `unlock(s)`, followed by `reset s`. A loop checks `process waiting?`. If `yes`, it executes `deblock process`. If `no`, it loops back.
 - Lock and Block:** A flowchart showing the logic for locking the semaphore. It starts with `lock(s)`, followed by a loop checking `is s set?`. If `yes`, it executes `set s`. If `no`, it executes `block process` and loops back.

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Process 1



sigsuspend, kill, pause and sleep

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Locking and Unlocking Processes in Linux (2/2)

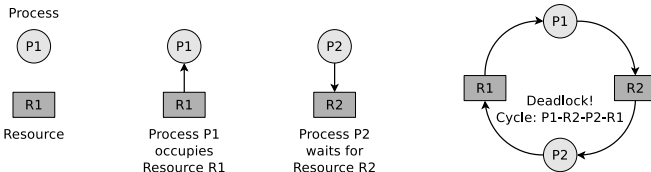
- Alternative 2: A local file serves as a locking mechanism for mutual exclusion
 - Each process verifies before entering its critical section whether it can open the file exclusively
 - e.g. with the system call `open` or the standard library function `fopen`
 - If this is not the case, it must pause for a certain time (e.g. with the system call `sleep`) and then try again (**busy waiting**).
 - Alternatively, it can pause itself with `sleep` or `pause` and hope that the process that has already opened the file unblocks it with a signal at the end of its critical section (**passive waiting**)

Summary: Difference between Signaling and Blocking

- **Signaling** specifies the execution order
Example: Execute section X of process P_A before section Y of P_B
- **Blocking / Locking** secures critical sections
The execution order of the critical sections of the processes is not specified! It is just ensured that the execution of critical sections does not overlap

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- The relations of processes and resources can be visualized using directed graphs
- In this way, deadlocks can also be modeled
 - The nodes of a resource graph are:
 - **Processes:** Are shown as circles
 - **Resources:** Are shown as rectangles
 - An edge from a process to a resource means:
 - The process is blocked because it waits for the resource
 - An edge from a resource to a process means:
 - The process occupies the resource



A good description of resource graphs provides the book **Betriebssysteme – Eine Einführung**, Uwe Baumgarten, Hans-Jürgen Siegart, 6th Edition, Oldenbourg Verlag (2007), Chapter 6

Deadlock Detection with Matrices

- One drawback of deadlock detection with resource graphs is that only individual resources can be represented with it
 - If multiple copies (instances) of a resource exist, then graphs are not suited for the visualisation and detection of deadlocks
 - If multiple copies of a resource exist, a matrices-based algorithm can be used, which requires 2 vectors and 2 matrices
- We specify 2 vectors
 - **Existing resource vector**
 - Indicates the number of existing resources of each class
 - **Available resource vector**
 - Indicates the number of free resources of each class
- Additionally 2 matrices are required
 - **Current allocation matrix**
 - Indicates, which resources are currently occupied by the processes
 - **Request matrix**
 - Indicates, which resource the processes would like to occupy

Deadlock Detection with Matrices – Example (2/2)

- If process 3 finished execution, it deallocates its resources

Available resource vector = $\begin{pmatrix} 2 & 2 & 2 & 0 \end{pmatrix}$

$$\text{Request matrix} = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ - & - & - & - \end{bmatrix}$$

- 2 resources of class 1 are available
- 2 resources of class 2 are available
- 2 resources of class 3 are available
- No resources of class 4 are available
- If process 2 finished execution, it deallocates its resources

- Process 1 is blocked, because no free resources of class 4 exist
- **Process 2 is not blocked**

Available resource vector = $\begin{pmatrix} 4 & 2 & 2 & 1 \end{pmatrix}$

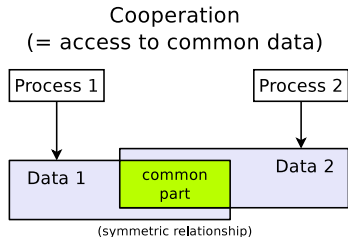
$$\text{Request matrix} = \begin{bmatrix} 2 & 0 & 0 & 1 \\ - & - & - & - \\ - & - & - & - \end{bmatrix}$$

- **Process 1 is not blocked** \Rightarrow no deadlock in this example

Conclusion about Deadlocks

- Sometimes it is tolerated that deadlocks can occur
 - What matters is how important a system is
 - A deadlock, which statistically occurs every 5 years, is not a problem in a system, which crashes because of hardware failures or other software problems one time per week
- Deadlock detection is complicated and causes overhead
- In all operating systems, deadlocks can occur:
 - Full process table
 - No more new processes can be created
 - Maximum number of inodes allocated
 - No new files or directories can be created
- The probability that this happens is low, but $\neq 0$
 - Such potential deadlocks are accepted because an occasional deadlock is not as troublesome as the otherwise necessary restrictions (e.g. only 1 running process, only 1 open file, more overhead)

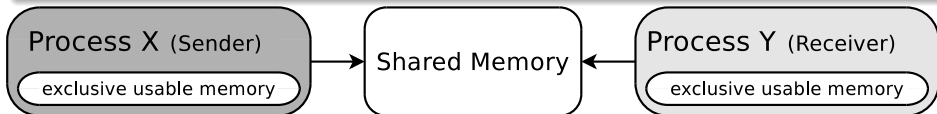
- Shared Memory
- Message Queues
- Pipes
- Sockets



Shared Memory

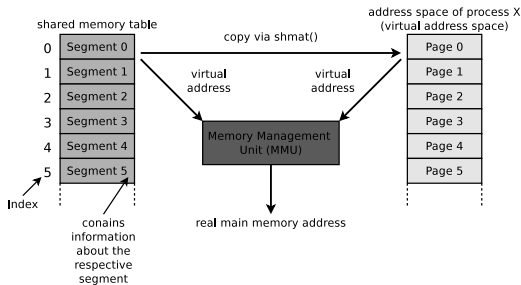
- Interprocess communication via a shared memory is also called **memory-based communication**
- **Shared memory segments** are memory areas, which can be accessed by multiple processes
 - These memory areas are located in the address space of multiple processes
- The processes need to coordinate the access operations by themselves and ensure that their memory requests are mutually exclusive
 - A receiver process, cannot read data from the shared memory, before the sender process has finished its current write operation
 - If access operations are not coordinated carefully \implies inconsistencies

In all other forms of interprocess communication, the operating system takes care about the synchronization of the access operations



Shared Memory in Linux/UNIX

- Linux/UNIX operating systems contain a **shared memory table**, which contains information about the existing shared memory segments
 - This information includes: Start address in memory, size, owner (username and group) and privileges



- A shared memory segment is always addressed via its index number in the shared memory table

- Advantage: A shared memory segment which is not attached to a process, is not erased by the operating system automatically

When the operating system is rebooted, the shared memory segments and their contents are lost

Working with Shared Memory (System V vs. POSIX)

Linux/UNIX operating systems provide 4 system calls for working with shared memory

- `shmget()`: Create a shared memory segment or access an existing one
- `shmat()`: Attach a shared memory segment to a process
- `shmdt()`: Detach a shared memory segment from a process
- `shmctl()`: Request status information (e.g. privileges) of a shared memory segment, modify or erase it
- The command `ipcs` provides information about existing shared memory segments (System V)

One example of working with shared memory segments in Linux can be found on the website of this course

- Some developers prefer the System V API and Others the POSIX API. ...

C function calls for working with POSIX shared memory segments (some defined in the header file `mman.h`)

- `shm_open()`: Create a shared memory segment or access an existing one
- `ftruncate()`: Specify the size of a shared memory segment
- `mmap()`: Attach a shared memory segment to a process
- `munmap()`: Detach a shared memory segment from a process
- `close()`: Close the descriptor of a shared memory segment Speichersegmente schließen
- `shm_unlink()`: Erase a segment
- In Linux, POSIX shared memory segments can be found in the `/dev/shm` directory

One example of working with POSIX shared memory segments in Linux can be found on the website of this course

Create a (System V) Shared Memory Segment (in C)

```
1 #include <sys/ipc.h>
2 #include <sys/shm.h>
3 #include <stdio.h>
4 #define MAXMEMSIZE 20
5
6 int main(int argc, char **argv) {
7     int shared_memory_id = 12345;
8     int returncode_shmget;
9
10    // Create shared memory segment or access an existing one
11    // IPC_CREAT = create a shared memory segment, if it does not still exist
12    // 0600 = Access privileges for the new message queue
13    returncode_shmget = shmget(shared_memory_id, MAXMEMSIZE, IPC_CREAT | 0600);
14
15    if (returncode_shmget < 0) {
16        printf("Unable to create the shared memory segment.\n");
17        perror("shmget");
18    } else {
19        printf("The shared memory segment has been created.\n");
20    }
21 }
```

```
$ ipcs -m
----- Shared Memory Segments -----
key          shmid      owner          perms          bytes          nattch          status
0x00003039  56393780      bnc            600            20             0
$ printf "%d\n" 0x00003039          # Convert from hexadecimal to decimal
12345
```

Attach a (System V) Shared Memory Segment (in C)

```

1 #include <sys/types.h>
2 #include <sys/ipc.h>
3 #include <sys/shm.h>
4 #include <stdio.h>
5 #define MAXMEMSIZE 20
6
7 int main(int argc, char **argv) {
8     int shared_memory_id = 12345;
9     int returncode_shmget;
10    char *sharedmempointer;
11
12    // Create shared memory segment or access an existing one
13    returncode_shmget = shmget(shared_memory_id, MAXMEMSIZE, IPC_CREAT | 0600);
14    ...
15
16    // Attach shared memory segment
17    sharedmempointer = shmat(returncode_shmget, 0, 0);
18    if (sharedmempointer==(char *)-1) {
19        printf("Unable to attach the shared memory segment.\n");
20        perror("shmat");
21    } else {
22        printf("The shared memory segment has been attached %p\n", sharedmempointer);
23    }
24 }
25 }

```

```
$ ipcs -m
```

```
----- Shared Memory Segments -----
```

key	shmid	owner	perms	bytes	nattch	status
0x00003039	56393780	bnc	600	20	1	

1. *Journal of the American Medical Association*, 1997; 277: 1039-1043.

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Detach a (System V) Shared Memory Segment (in C)

```

1 #include <sys/types.h>
2 #include <sys/ipc.h>
3 #include <sys/shm.h>
4 #include <stdio.h>
5 #define MAXMEMSIZE 20
6
7 int main(int argc, char **argv) {
8     int shared_memory_id = 12345;
9     int returncode_shmget;
10    int returncode_shmdt;
11    char *sharedmempointer;
12
13    // Create shared memory segment or access an existing one
14    returncode_shmget = shmget(shared_memory_id, MAXMEMSIZE, IPC_CREAT | 0600);
15    ...
16
17    // Attach the shared memory segment
18    sharedmempointer = shmat(returncode_shmget, 0, 0);
19    ...
20
21    // Detach the shared memory segment
22    returncode_shmdt = shmdt(sharedmempointer);
23    if (returncode_shmdt < 0) {
24        printf("Unable to detach the shared memory segment.\n");
25        perror("shmdt");
26    } else {
27        printf("The shared memory segment has been detached.\n");
28    }
29 }
30 }

```

Erase a (System V) Shared Memory Segment (in C)

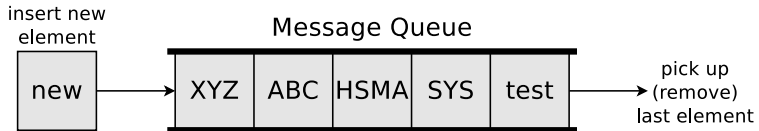
```

1 #include <sys/types.h>
2 #include <sys/ipc.h>
3 #include <sys/shm.h>
4 #include <stdio.h>
5 #define MAXMEMSIZE 20
6
7 int main(int argc, char **argv) {
8     int shared_memory_id = 12345;
9     int returncode_shmget;
10    int returncode_shmctl;
11    char *sharedmempointer;
12
13    // Create shared memory segment or access an existing one
14    returncode_shmget = shmget(shared_memory_id, MAXMEMSIZE, IPC_CREAT | 0600);
15    ...
16
17    // Erase shared memory segment
18    returncode_shmctl = shmctl(returncode_shmget, IPC_RMID, 0);
19    if (returncode_shmctl == -1) {
20        printf("Unable to erase the shared memory segment.\n");
21        perror("semctl");
22    } else {
23        printf("The shared memory segment has been erased.\n");
24    }
25 }
26 }

```


Message Queues

- Are linked lists with messages
- Operate according to the FIFO principle
- Processes can store data inside and pick them up from there
- Benefit: Even after the termination of the process, which created the message queue, the data inside the message queue stays available



Linux/UNIX operating systems provide 4 system calls for working with message queues (System V)

- `msgget()`: Create a message queue or access an existing one
- `msgsnd()`: Write message into message queues (\Rightarrow send operation)
- `msgrcv()`: Read message from message queues (\Rightarrow receive operation)
- `msgctl()`: Request status information (e.g. privileges) of a message queue, modify or erase it
- The command `ipcs` provides information about existing System V message queues

Create (System V) Message Queues (in C)

```

1 #include <stdlib.h>
2 #include <sys/types.h>
3 #include <sys/ipc.h>
4 #include <stdio.h>
5 #include <sys/msg.h>
6
7 int main(int argc, char **argv) {
8     int returncode_msgget;
9
10    // Create message queue or access an existing one
11    // IPC_CREAT => create a message queue, if it does not still exist
12    // 0600 = Access privileges for the new message queue
13    returncode_msgget = msgget(12345, IPC_CREAT | 0600);
14    if(returncode_msgget < 0) {
15        printf("Unable to create the message queue.\n");
16        exit(1);
17    } else {
18        printf("The message queue 12345 with the ID %i has been created.\n",
19               returncode_msgget);
20    }
21 }

```

```
$ ipcs -q
----- Message Queues -----
key      msqid      owner      perms      used-bytes   messages
0x00003039 98304      bnc        600         0             0

$ printf "%d\n" 0x00003039      # Convert from hexadecimal to decimal
12345
```

```

1 #include <stdlib.h>
2 #include <sys/types.h>
3 #include <sys/ipc.h>
4 #include <stdio.h>
5 #include <sys/msg.h>
6 #include <string.h>                                // This header file is required for strcpy()
7
8 struct msgbuf {                                     // Template of a buffer for msgsnd and msgrcv
9     long mtype;                                     // Message type
10    char mtext[80];                                  // Send buffer
11 } msg;
12
13 int main(int argc, char **argv) {
14     int returncode_msgget;
15
16     // Create message queue or access an existing one
17     returncode_msgget = msgget(12345, IPC_CREAT | 0600);
18     ...
19
20     msg.mtype = 1;                                   // Specify the message type
21     strcpy(msg.mtext, "Testnachricht");              // Write the message into the send buffer
22
23     // Write a message into the message queue
24     if (msgsnd(returncode_msgget, &msg, strlen(msg.mtext), 0) == -1) {
25         printf("Unable to write the message into the message queue.\n");
26         exit(1);
27     }
28 }

```

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Result of writing a Message into a Message Queue

- Before...

```
$ ipcs -q
----- Message Queues -----
key          msqid          owner          perms          used-bytes      messages
0x00003039  98304          bnc            600            0               0
```

- Afterwards...

```
$ ipcs -q
----- Message Queues -----
key          msqid          owner          perms          used-bytes      messages
0x00003039  98304          bnc            600            80              1
```

Pick a Message from a (System V) Message Queue (in C)

```

1 #include <stdlib.h>
2 #include <sys/types.h>
3 #include <sys/ipc.h>
4 #include <stdio.h>
5 #include <sys/msg.h>
6 #include <string.h>           // This header file is required for strcpy()
7 struct msgbuf {              // Template of a buffer for msgsnd and msgrcv
8     long mtype;               // Message type
9     char mtext[80];           // Send buffer
10 } msg;
11
12 int main(int argc, char **argv) {
13     int returncode_msgget, returncode_msgrcv;
14     msg receivebuffer;        // Create a receive buffer
15
16     // Create message queue or access an existing one
17     returncode_msgget = msgget(12345, IPC_CREAT | 0600)
18
19     msg.mtype = 1;            // Pick the first message of type 1
20     // MSG_NOERROR => The message will be truncated when it is too long
21     // IPC_NOWAIT  => Do not block the process if no message exists
22     returncode_msgrcv = msgrcv(returncode_msgget, &msg, sizeof(msg.mtext), msg.mtype,
23                               MSG_NOERROR | IPC_NOWAIT);
24     if (returncode_msgrcv < 0) {
25         printf("Unable to pick a message from the message queue.\n");
26         perror("msgrcv");
27     } else {
28         printf("This message was picked from the message queue: %s\n", msg.mtext);
29         printf("The received message is %i characters long.\n", returncode_msgrcv);
30     }
31 }

```

Erase a (System V) Message Queue (in C)

```

1 #include <stdlib.h>
2 #include <sys/types.h>
3 #include <sys/ipc.h>
4 #include <stdio.h>
5 #include <sys/msg.h>
6
7 int main(int argc, char **argv) {
8     int returncode_msgget;
9     int returncode_msgctl;
10
11     // Create message queue or access an existing one
12     returncode_msgget = msgget(12345, IPC_CREAT | 0600);
13     ...
14
15     // Erase message queue
16     returncode_msgctl = msgctl(returncode_msgget, IPC_RMID, 0);
17     if (returncode_msgctl < 0) {
18         printf("Unable to erase the message queue with the ID %i.\n", returncode_msgget);
19         perror("msgctl");
20         exit(1);
21     } else {
22         printf("The message queue with the ID %i has been erased.\n", returncode_msgget);
23     }
24     exit(0);
25 }

```

One example of working with System V message queues in Linux can be found on the website of this course

Message Queues in Linux (System V vs. POSIX)

- The functions described so far for working with message queues are part of the **System V** interface
- Some developers prefer the System V API and Others the POSIX API... ٩(ツ)𐌹

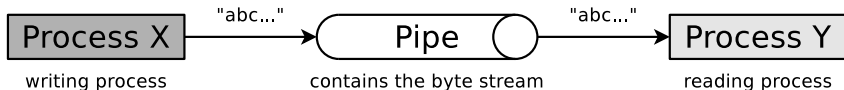
C function calls for POSIX message queue specified in the header file `mqueue.h`

- `mq_open()`: Create a message queue or access an existing one
- `mq_send()`: Write (send) a message into a message queue. Blocking function
- `mq_timedsend()`: Write (send) a message into a message queue. Blocking instruction with a timeout
- `mq_receive()`: Read (receive) a message from a message queue. Blocking instruction
- `mq_timedreceive()`: Read (receive) a message from a message queue. Blocking instruction with a timeout
- `mq_getattr()`: Request the attributes of a message queue. These are: number of messages in the queue, maximum message size, maximum number of messages...
- `mq_setattr()`: Modify the attributes of a message queue
- `mq_notify()`: Notify the process as soon as a message is available
- `mq_close()`: Close a message queue
- `mq_unlink()`: Erase a message queue
- POSIX message queues are created In Linux in the folder `/dev/mqueue`

One example of working with POSIX message queues in Linux can be found on the website of this course

Anonymous Pipes (1/2)

- Pipes can be **anonymous pipes** or **named pipes** (see slide 44)
- An **anonymous pipe**...
 - is a buffered unidirectional communication channel between 2 processes
 - If communication in both directions shall be possible at the same time, 2 pipes are necessary – one for each communication direction
 - operates according to the FIFO principle
 - has a limited capacity
 - Pipe = filled \implies the writing process gets blocked
 - Pipe = empty \implies the reading process gets blocked
 - is created with the system call `pipe()`
 - During this process, the kernel of the operating system creates an Inode (\implies slide set 6) and 2 file descriptors (*handles*)
 - Processes access the access identifiers with `read()` and `write()` system calls (or standard library functions) for reading data from or writing data into the pipe



Anonymous Pipes (2/2)

- When child processes are created with `fork()`, the child processes also inherit access to the file descriptors
- **Anonymous pipes** allow process communication only between closely related processes
 - Only processes, which are closely related via `fork()` can communicate with each other via anonymous pipes
 - If the last process, which has access to an anonymous pipe, terminates, the pipe gets erased by the operating system

Overview of the pipes in Linux/UNIX: `lsuf` | `grep pipe`

Anonymous Pipe Example (in C) – Part 1/2

You can monitor the anonymous pipe in Linux/UNIX via `lsuf -n -P | grep <PID>` and inside the directory `/proc/<PID>/fd`

```

1 #include <stdio.h>
2 #include <unistd.h>
3 #include <stdlib.h>
4
5 void main() {
6     int pid_of_child;
7     // Create handles for the pipe to read (testpipe[0]) and write (testpipe[1])
8     int testpipe[2];
9
10    // Create anonymous pipe testpipe
11    if (pipe(testpipe) < 0) {
12        printf("Unable to create the anonymous pipe.\n");
13        // Terminate process
14        exit(1);
15    } else {
16        printf("Created the anonymous pipe testpipe.\n");
17    }
18
19    // Create a child process
20    pid_of_child = fork();
21
22    if (pid_of_child < 0) {
23        perror("Unable to create the child process!\n");
24        // Terminate process
25        exit(1);
26    }

```

Anonymous Pipe Example (in C) – Part 2/2

```

27 // Parent process
28 if (pid_of_child > 0) {
29     printf("Parent process: PID: %i\n", getpid());
30     // Block the read channel of the anonymous pipe testpipe
31     close(testpipe[0]);
32     char message[] = "Testnachricht";
33     // Write the message into the write channel of the anonymous pipe
34     write(testpipe[1], &message, sizeof(message));
35 }
36
37 // Child process
38 if (pid_of_child == 0) {
39     printf("Child process: PID: %i\n", getpid());
40     // Block the write channel of the anonymous pipe testpipe
41     close(testpipe[1]);
42     // Create a receive buffer (80 bytes capacity)
43     char puffer[80];
44     // Read the message from the read channel of the anonymous pipe
45     read(testpipe[0], puffer, sizeof(puffer));
46     printf("Received: %s\n", puffer);
47 }
48 }

```

```

$ gcc anonymous_pipe_example.c -o anonymous_pipe_example
$ ./anonymous_pipe_example
Created the anonymous pipe testpipe.
Parent process: PID: 394769
Child process: PID: 394770
Received: Testnachricht

```

Named Pipes

- Processes, which are not closely related with each other, can communicate via **named pipes**
 - These pipes can be accessed by using their names
 - They are created in C by: `mkfifo("<pathname>", <permissions>)`
 - Any process, which knows the name of a pipe, can use the name to access the pipe and communicate with other processes
- The operating system ensures **mutual exclusion**
 - At any time, only a single process can access a pipe
- Named pipes are not erased automatically by the operating system (unlike anonymous pipes)

Named Pipe Example (in C) – Part 1/4

```

1  #include <stdio.h>
2  #include <unistd.h>
3  #include <stdlib.h>
4  #include <fcntl.h>
5  #include <sys/stat.h>
6
7  void main() {
8      int pid_of_child;
9
10     // Create named pipe
11     if (mkfifo("testfifo", 0666) < 0) {
12         printf("Unable to create the named pipe.\n");
13         exit(1);
14     } else {
15         printf("Created the named pipe testfifo.\n");
16     }
17
18     // Create a child process
19     pid_of_child = fork();
20
21     if (pid_of_child < 0) {
22         perror("Unable to create the child process!\n");
23         exit(1);
24     }

```

The function call creates a file system entry named `testfifo` in the current directory. The first letter in the output of the `ls` command shows that `testfifo` is a named pipe.

```
$ ls -la testfifo
```

```
prw-r--r-- 1 bnc bnc 0 1. Feb 10:15 testfifo
```

Named Pipe Example (in C) – Part 2/4

```

25 // Parent process
26 if (pid_of_child > 0) {
27     printf("Parent process: PID: %i\n", getpid());
28
29     // Create the file descriptor (handle) for the pipe
30     int fd;
31
32     // Specify the message to be transferred
33     char message[] = "Testnachricht";
34
35     // Open the named pipe for writing
36     fd = open("testfifo", O_WRONLY);
37
38     // Write the message into the pipe
39     write(fd, &message, sizeof(message));
40
41     // Close the named pipe
42     close(fd);
43 }

```

Named Pipe Example (in C) – Part 3/4

```

44 // Child process
45 if (pid_of_child == 0) {
46     printf("Child process: PID: %i\n", getpid());
47
48     // Create the file descriptor (handle) for the pipe
49     int fd;
50     // Create a receive buffer
51     char puffer[80];
52
53     // Open the named pipe for reading
54     fd = open("testfifo", O_RDONLY);
55
56     // Read the message from the pipe
57     read(fd, puffer, sizeof(puffer));
58     printf("Received: %s\n", puffer);
59
60     // Close the named pipe
61     close(fd);
62
63     // Erase the named pipe
64     if (unlink("testfifo") < 0) {
65         printf("Unable to erase the named pipe.\n");
66         exit(1);
67     } else {
68         printf("The named pipe has been erased.\n");
69     }
70 }
71 }

```

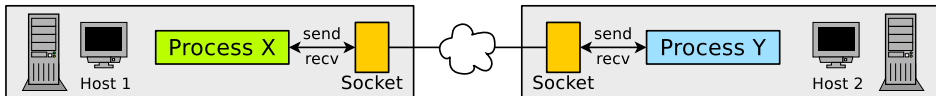
Named Pipe Example (in C) – Part 4/4

```
$ gcc named_pipe_example.c -o named_pipe_example
$ ./named_pipe_example
Created the named pipe testfifo.
Parent process: PID: 395415
Child process: PID: 395416
Received: Testnachricht
The named pipe has been erased.
```

You can monitor the named pipe in Linux/UNIX via `ls -l | grep <PID>` and inside the directory `/proc/<PID>/fd`

Sockets

- Full duplex-ready alternative to pipes and shared memory
 - Allow interprocess communication in distributed systems
- An user process can request a socket from the operating system and afterwards send and receive data via the socket
 - The operating system maintains all used sockets and the related connection information



- Ports are used for the communication via sockets
 - Port numbers are randomly assigned during connection establishment
 - Port numbers are assigned randomly by the operating system
 - Exceptions are port numbers of well-known applications, such as HTTP (80) SMTP (25), Telnet (23), SSH (22), FTP (21),...
- Sockets can be used in a blocking (synchronous) and non-blocking (asynchronous) way

Different Types of Sockets

- **Connectionless sockets (= datagram sockets)**
 - Use the Transport Layer protocol UDP
 - Advantage: Better data rate as with TCP
 - Reason: Lesser overhead for the protocol
 - Drawback: Segments may arrive in wrong sequence or may get lost
- **Connection-oriented sockets (= stream sockets)**
 - Use the Transport Layer protocol TCP
 - Advantage: Better reliability
 - Segments cannot get lost
 - Segments always arrive in the correct sequence
 - Drawback: Lower data rate as with UDP
 - Reason: More overhead for the protocol

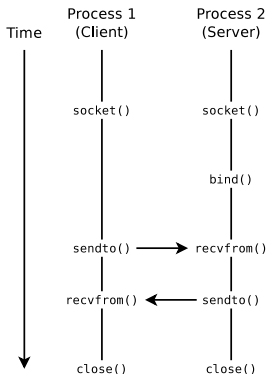
Using Sockets

- Almost all major operating systems support sockets
 - Advantage: Better portability of applications
- Functions for communication via sockets:
 - Creating a Socket:
`socket()`
 - Binding a socket to a port number and making it ready to receive data:
`bind()`, `listen()`, `accept()` and `connect()`
 - Sending/receiving messages via the socket:
`send()`, `sendto()`, `recv()` and `recvfrom()`
 - Closing eines Socket:
`shutdown()` or `close()`

Overview of the sockets in Linux/UNIX: `netstat -n` or `lsof | grep socket`

Examples of Interprocess communication via sockets (TCP and UDP) in Linux can be found on the website of this course

Connection-less Communication via Sockets – UDP



• Client

- Create socket (`socket`)
- Send (`sendto`) and receive data (`recvfrom`)
- Close socket (`close`)

• Server

- Create socket (`socket`)
- Bind socket to a port (`bind`)
- Send (`sendto`) and receive data (`recvfrom`)
- Close socket (`close`)

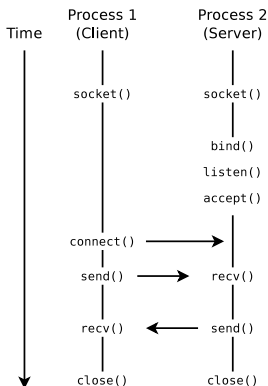
Connection-oriented Communication via Sockets – TCP

• Client

- Create socket (`socket`)
- Connect client with server socket (`connect`)
- Send (`send`) and receive data (`recv`)
- Close socket (`close`)

• Server

- Create socket (`socket`)
- Bind socket to a port (`bind`)
- Make socket ready to receive (`listen`)
 - Set up a queue for connection requests.
Specifies the number of connection requests, which can be stored in the queue
- Server accepts connections (`accept`)
 - Fetch the first connection request from the queue
- Send (`send`) and receive data (`recv`)
- Close socket (`close`)

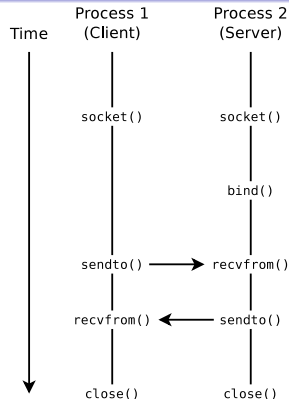


Sockets via UDP – Example (Server)

```

1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <string.h>
4  #include <sys/socket.h>
5  #include <netinet/in.h>
6  #include <unistd.h>
7  #include <arpa/inet.h>
8
9  int main(int argc, char *argv[]) {
10     int sd, adresse_laenge;
11     char puffer[1024] = { 0 };
12     struct sockaddr_in adresse, client_adresse;
13     memset(&adresse, 0, sizeof(adresse));
14     memset(&client_adresse, 0, sizeof(client_adresse));
15     adresse.sin_family = AF_INET;
16     adresse.sin_addr.s_addr = INADDR_ANY;
17     adresse.sin_port = htons(atoi(argv[1]));
18
19     sd = socket(AF_INET, SOCK_DGRAM, 0);
20     bind(sd, (struct sockaddr *) &adresse, sizeof(adresse));
21     adresse_laenge = sizeof(client_adresse);
22     rcvfrom(sd, (char *)puffer, sizeof(puffer), 0,
23             (struct sockaddr *) &client_adresse, &adresse_laenge);
24     printf("Empfangene Nachricht: %s\n", puffer);
25     char antwort[]="Server: Nachricht empfangen.\n";
26     sendto(sd, (const char *)antwort, sizeof(antwort), 0,
27            (struct sockaddr *) &client_adresse, adresse_laenge);
28     close(sd);
29     exit(0);
30 }

```



```

$ gcc udp_server.c -o udp_server
$ ./udp_server 50002

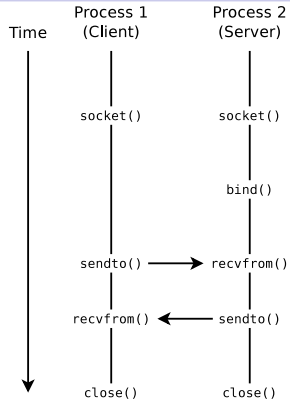
```

Sockets via UDP – Example (Client)

```

1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <string.h>
4 #include <sys/socket.h>
5 #include <netinet/in.h>
6 #include <unistd.h>
7 #include <arpa/inet.h>
8
9 int main(int argc, char *argv[]) {
10     int sd, adresse_laenge;
11     char puffer[1024] = { 0 };
12     struct sockaddr_in adresse;
13     memset(&adresse, 0, sizeof(adresse));
14     adresse.sin_family = AF_INET;
15     adresse.sin_port = htons(atoi(argv[2]));
16     adresse.sin_addr.s_addr = inet_addr(argv[1]);
17
18     sd = socket(AF_INET, SOCK_DGRAM, 0);
19     printf("Bitte Nachricht eingeben: ");
20     fgets(puffer, sizeof(puffer), stdin);
21     adresse_laenge = sizeof(adresse);
22     sendto(sd, (const char *)puffer, strlen(puffer), 0,
23             (struct sockaddr *) &adresse, adresse_laenge);
24     memset(puffer, 0, sizeof(puffer));
25     recvfrom(sd, (char *)puffer, sizeof(puffer), 0,
26              (struct sockaddr *) &adresse, &adresse_laenge);
27     printf("%s\n", puffer);
28     close(sd);
29     exit(0);
30 }

```



```
$ gcc udp_client.c -o udp_client
$ ./udp_client 127.0.0.1 50002
Bitte Nachricht eingeben: Test
Server: Nachricht empfangen.
```

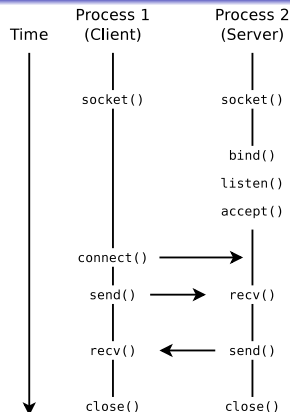
```
$ ./udp_server 50002
Empfangene Nachricht: Test
```

Sockets via TCP – Example (Server)

```

1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <string.h>
4 #include <sys/socket.h>
5 #include <netinet/in.h>
6 #include <unistd.h>
7 #include <arpa/inet.h>
8
9 int main(int argc, char *argv[]) {
10     int sd, fd, adresse_laenge;
11     char puffer[1024] = { 0 };
12     struct sockaddr_in adresse;
13     memset(&adresse, 0, sizeof(adresse));
14     adresse.sin_family = AF_INET;
15     adresse.sin_addr.s_addr = INADDR_ANY;
16     adresse.sin_port = htons(atoi(argv[1]));
17
18     sd = socket(AF_INET, SOCK_STREAM, 0);
19     bind(sd, (struct sockaddr *) &adresse, sizeof(adresse));
20     listen(sd, 5);
21     adresse_laenge = sizeof(adresse);
22     fd = accept(sd, (struct sockaddr *) &adresse, &adresse_laenge);
23     read(fd, puffer, sizeof(puffer));
24     printf("Empfangene Nachricht: %s\n", puffer);
25     char antwort[]="Server: Nachricht empfangen.\n";
26     write(fd, antwort, sizeof(antwort));
27     close(fd);
28     close(sd);
29     exit(0);
30 }

```



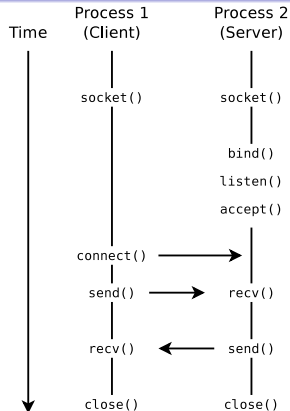
```
$ gcc tcp_server.c -o tcp_server
$ ./tcp_server 50003
```


Sockets via TCP – Example (Client)

```

1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <string.h>
4 #include <sys/socket.h>
5 #include <netinet/in.h>
6 #include <unistd.h>
7 #include <arpa/inet.h>
8
9 int main(int argc, char *argv[]) {
10     int sd;
11     char puffer[1024] = { 0 };
12     struct sockaddr_in adresse;
13     memset(&adresse, 0, sizeof(adresse));
14     adresse.sin_family = AF_INET;
15     adresse.sin_port = htons(atoi(argv[2]));
16     adresse.sin_addr.s_addr = inet_addr(argv[1]);
17
18     sd = socket(AF_INET, SOCK_STREAM, 0);
19     connect(sd, (struct sockaddr *) &adresse, sizeof(adresse));
20
21     printf("Bitte Nachricht eingeben: ");
22     fgets(puffer, sizeof(puffer), stdin);
23     write(sd, puffer, strlen(puffer));
24     memset(puffer, 0, sizeof(puffer));
25     read(sd, puffer, sizeof(puffer));
26     printf("%s\n", puffer);
27
28     close(sd);
29     exit(0);
30 }

```



```
$ gcc tcp_client.c -o tcp_client
$ ./tcp_client 127.0.0.1 50003
Bitte Nachricht eingeben: Test
Server: Nachricht empfangen.
```

```
$ ./tcp_server 50003
Empfangene Nachricht: Test
```

Comparison of Communication Systems

	Shared Memory	Message Queues	(anon./named) Pipes	Sockets
Sort of communication	Memory-based	Message-based	Message-based	Message-based
Bidirectional	yes	no	no	yes
Platform independent	no	no	no	yes
Processes must be related with each other	no	no	for anon. pipes	no
Communication over computer boundaries	no	no	no	yes
Remain intact without a bound process	yes	yes	no	no
Automatic synchronization	no	yes	yes	yes

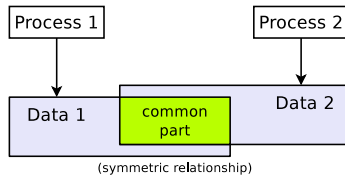
- Advantages of message-based communication versus memory-based communication:
 - The operating system takes care about the synchronization of accesses
⇒ comfortable
 - Can be used in distributed systems without a shared memory
 - Better portability of applications

Storage can be integrated via network connections

- This allows memory-based communication between processes on different independent systems
- The problem of synchronizing the accesses also exists here

- Semaphore
- Mutex

Cooperation
(= access to common data)



Semaphore

- In order to protect (lock) critical sections, not only the already discussed locks can be used, but also **semaphores**
- 1965: Published by Edsger W. Dijkstra
- A semaphore is a counter lock **S** with operations **P(S)** and **V(S)**
 - **V** comes from the dutch *verhogen* = raise
 - **P** comes from the dutch *proberen* = try (to reduce)
- The **access operations are atomic** \implies can not be interrupted (indivisible)
- May allow multiple processes accessing the critical section
 - In contrast to semaphores, can locks (\implies slide 14) only be used to allow a single process entering the critical section at the same time

Cooperating sequential processes. *Edsger W. Dijkstra* (1965)

<https://www.cs.utexas.edu/~EWD/ewd01xx/EWD123.PDF>

Semaphore Access Operations (1/3)

A Semaphore consists of 2 Data Structures

- **COUNT:** An **integer, non-negative counter variable**.
Specifies how many processes can pass the semaphore now without getting blocked
 - A waiting room for the processes, which **wait** until they are allowed to pass the semaphore
The processes are in blocked state until they are transferred into ready state by the operating system when the semaphore allows to access the critical section
-
- **Initialization:** First, a new semaphore is created or an existing one is opened
 - For a new semaphore, the counter variable is initialized at the beginning with a non-negative initial value

```
1 // apply the INIT operation on semaphore SEM
2 SEM.INIT(unsigned int init_value) {
3
4     // initialize the variable COUNT of Semaphor SEM
5     // with a non-negative initial value
6     SEM.COUNT = init_value;
7 }
```

Image Source: Carsten Vogt

- ```
1 SEM.P() {
2 // if the counter variable = 0, the process becomes blocked
3 if (SEM.COUNT == 0)
4 < block >
5
6 // if the counter variable is > 0, the counter variable
7 // is decremented immediately by 1
8 SEM.COUNT = SEM.COUNT - 1;
9 }
```

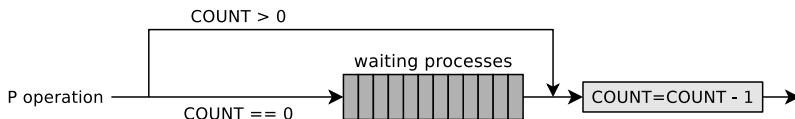
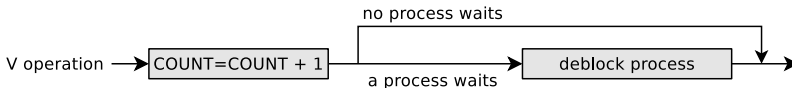


Image Source: Carsten Vogt

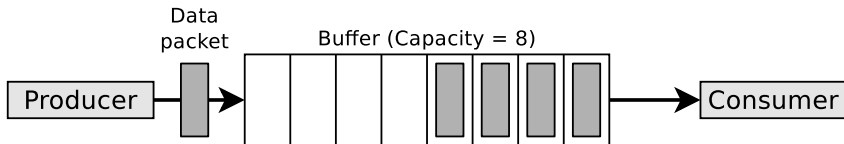
- If processes are in the waiting room, one process gets deblocked
- The process, which just got deblocked, continues its P operation and first reduces the counter variable

```
1 SEM.V() {
2 // counter variable = counter variable + 1
3 SEM.COUNT = SEM.COUNT + 1;
4
5 // if processes are in the waiting room, one gets deblocked
6 if (< SEM waiting room is not empty >)
7 < deblock a waiting process >
8 }
```



# Producer/Consumer Example (1/3)

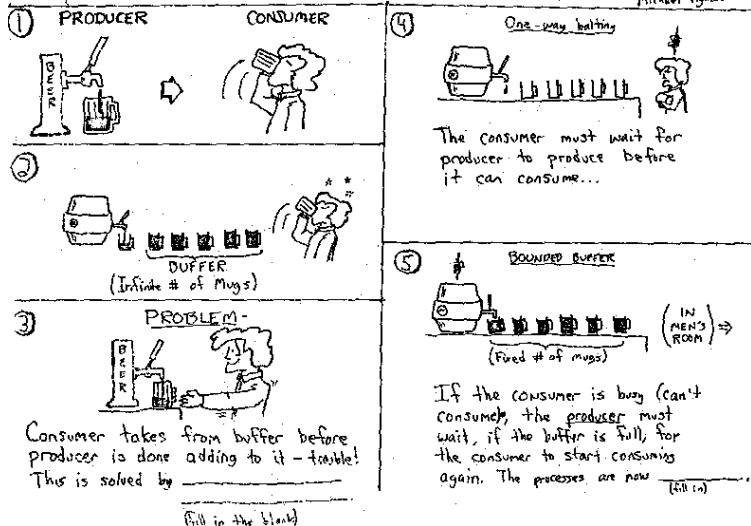
- A producer sends data to a consumer
- A buffer with limited capacity is used to minimize the waiting times of the consumer
- Data is placed into the buffer by the producer and the consumer removes data from the buffer
- Mutual exclusion is mandatory in order to avoid inconsistencies
- Buffer = full  $\implies$  producer must be blocked
- Buffer = empty  $\implies$  consumer must be blocked





### A GRAPHIC EXAMPLE OF THE PRODUCER/CONSUMER PROBLEM

Michael Vignaro



Source: Kenneth Baclawski (Northeastern University in Boston), Image source: Michael Vigneau (license: unknown)

<http://www.ccs.neu.edu/home/kenb/tutorial/example.gif>





Image Source: Carsten Vogt

- 
- Diagram illustrating the structure of a semaphore table:
- The **Semaphore table** is indexed by **Group number** (0, 1, 2, 3, ..., n).
  - Each entry in the table (e.g., 0, 1, 2, 3) points to a specific semaphore group.
  - The semaphore groups are organized as follows:
    - Group 0:  $S_{00}, S_{01}, S_{02}, S_{03}, S_{04}, S_{05}$
    - Group 1:  $S_{10}, S_{11}$
    - Group 2:  $S_{20}, S_{21}, S_{22}$
    - Group 3:  $S_{30}, S_{31}, S_{32}, S_{33}, S_{34}$
  - The entry  $n$  is labeled **empty**.
  - A bracket under the semaphores  $S_{30}$  through  $S_{34}$  is labeled **Semaphore group**.
  - An arrow pointing to  $S_{22}$  is labeled **individual semaphore**.
  - The label **Semaphore number within the group** points to the indices 0 through 5 above the first group.

- `semget()`: Create new semaphore or a group of semaphores or open an existing semaphore
- `semctl()`: Request or modify the value of an existing semaphore or of a semaphore group or erase a semaphore
- `semop()`: Carry out P and V operations on semaphores
- Information about existing semaphores (**System V**) provides the command `ipcs`

This program creates a child process. The parent process and the child process both try to print characters in the command line interface (critical section). Each process may print only one character at a time. Two semaphores are used to ensure mutual exclusion

Helpful documentation of `semget`

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```

52 // Einen Kindprozess erzeugen
53 pid_des_kindess = fork();
54
55 // Kindprozess
56 if (pid_des_kindess == 0) {
57 for (int i=0;i<5;i++) {
58 semop(returncode_semget2, &p_operation, 1); // P-Operation Semaphore 54321
59 // Kritischer Abschnitt (Anfang)
60 printf("B");
61 sleep(1);
62 // Kritischer Abschnitt (Ende)
63 semop(returncode_semget1, &v_operation, 1); // V-Operation Semaphore 12345
64 }
65 exit(0);
66 }
67
68 // Elternprozess
69 if (pid_des_kindess > 0) {
70 for (int i=0;i<5;i++) {
71 semop(returncode_semget1, &p_operation, 1); // P-Operation Semaphore 12345
72 // Kritischer Abschnitt (Anfang)
73 printf("A");
74 sleep(1);
75 // Kritischer Abschnitt (Ende)
76 semop(returncode_semget2, &v_operation, 1); // V-Operation Semaphore 54321
77 }
78 }

```

Helpful documentation of `semop`

<https://www.nt.th-koeln.de/fachgebiete/inf/diplom/semwork/unix/semop/semop.html>

```

79 // Warten auf die Beendigung des Kindprozesses
80 wait(NULL);
81
82 printf("\n");
83
84 // Semaphorgruppe 12345 entfernen
85 returncode_semctl = semctl(returncode_semget1, 0, IPC_RMID, 0);
86 if (returncode_semctl < 0) {
87 printf("Die Semaphorgruppe %i konnte nicht entfernt werden.\n", returncode_semget1);
88 exit(1);
89 } else {
90 printf("Die Semaphorgruppe mit ID %i und Key %i wurde entfernt.\n", returncode_semget1, sem_key1);
91 }
92
93 // Semaphorgruppe 54321 entfernen
94 returncode_semctl = semctl(returncode_semget2, 0, IPC_RMID, 0);
95 if (returncode_semctl < 0) {
96 printf("Die Semaphorgruppe %i konnte nicht entfernt werden.\n", returncode_semget2);
97 exit(1);
98 } else {
99 printf("Die Semaphorgruppe mit ID %i und Key %i wurde entfernt.\n", returncode_semget2, sem_key2);
100 }
101
102 exit(0);
103 }

```

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```
$ gcc semaphore_beispiel_systemv.c -o semaphore_beispiel_systemv
$./semaphore_beispiel_systemv
Wert der Semaphore mit ID 98362 und Key 12345: 1
Wert der Semaphore mit ID 98363 und Key 54321: 0
ABABABABAB
Die Semaphorgruppe mit ID 98362 und Key 12345 wurde entfernt.
Die Semaphorgruppe mit ID 98363 und Key 54321 wurde entfernt.
```

```
$ printf "%d\n" 0x00003039 # Convert from hexadecimal to decimal
12345
$ printf "%d\n" 0x0000d431
54321
```

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# Semaphores in Linux (System V vs. POSIX)

- The concept of protecting critical sections described so far is also called **system V semaphores** in the literature
- Some developers prefer the System V API and Others the POSIX API... 🤔

C function calls of the POSIX semaphores specified in the header file `semaphore.h`

- `sem_init()`: Create a new **unnamed** semaphore and thereby specify the initial value
- `sem_open()`: Create a new **named** semaphore and thereby specify the initial value
- `sem_post()`: Increment the value of a semaphore (V operation)
- `sem_wait()`: Decrement the value of a semaphore (P operation). Blocking operation
- `sem_trywait()`: Decrement the value of a semaphore (P operation). Non-blocking operation
- `sem_timedwait()`: Decrement the value of a semaphore (P operation). Blocking operation but with a timeout
- `sem_getvalue()`: Request the value of a semaphore
- `sem_destroy()`: Erase an **unnamed** semaphore
- `sem_close()`: Close a **named** semaphore
- `sem_unlink()`: Erase a **named** semaphore
- Named POSIX semaphores are created in Linux in the folder `/dev/shm` with names of the form `sem.<name>`

One example of working of working with named POSIX semaphores in Linux can be found on the website of this course

# Mutexes

- If the Semaphore-feature of counting is not required, a simplified alternative, the mutex can be used instead
  - **Mutexes** (derived from **Mutual Exclusion**) are used to protect critical sections, which are allowed to be accessed by only **a single process** at any given moment
    - Mutexes can only have 2 states: **occupied** and **not occupied**
    - Mutexes have the same functionality as **binary semaphores**

Several implementations of the mutex concept exist

- **C standard library:** `mtx_init`, `mtx_unlock („V operation“)`, `mtx_lock („P operation“)`, `mtx_trylock`, `mtx_timedlock`, `mtx_destroy`
- **POSIX threads:** `pthread_mutex_init`, `pthread_mutex_unlock`, `pthread_mutex_lock`, `pthread_mutex_trylock`, `pthread_mutex_timedlock`, `pthread_mutex_destroy`
- **C standard library (Sun/Oracle Solaris):** `mutex_init`, `mutex_unlock`, `mutex_lock`, `mutex_trylock`, `mutex_destroy`

- Focus: Cooperation of threads of a process (intra-process synchronization)
  - Cooperation of processes (inter-process synchronization) is not always possible and if, then via a shared memory segment (System V or POSIX)

## Monitor and erase IPC Objects

- Information about existing (**System V**) shared memory segments, (**System V**) message queues and (**System V**) semaphores provides the command `ipcs`
- The easiest way to erase such shared memory segments, message queues and semaphores from the command line is the command `ipcrm`

```
ipcrm [-m shmids] [-q msgids] [-s semids]
 [-M shmkeys] [-Q msgkeys] [-S semkeys]
```

- **POSIX** memory segments and **POSIX** semaphores can be inspected and manually erased in the directory `/dev/shm`
- **POSIX** message queues can be inspected and manually erased in the directory `/dev/mqueue`