Operating Systems

Process Interaction

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What do you already know?

Let's go to the survey again:
`https://pingo.coactum.de/977183`

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- Which OS components are involved in process switching?

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- Which OS components are involved in process switching?
- Which property can be used as scheduling criteria?

What do you already know?

Let's go to the survey again:
https://pingo.coactum.de/977183

- Which OS components are involved in process switching?
- Which property can be used as scheduling criteria?
- Which formula is correct?

Agenda

- Process Interaction
- Inter-Processes Communication (IPC)
- Process Synchronization
- Process Cooperation

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Why do processes need to interact?

Interprocess Communication (IPC)

- In many cases processes do **not** operate isolated on separated data
- Processes will often...
  - **call** each other,
  - **wait** for each other, or
  - **coordinate** with each other

$\Longrightarrow$ They must interact with each other

Interprocess Communication (IPC)

- In many cases processes do **not** operate isolated on separated data
- Processes will often. . .
  - **call** each other,
  - **wait** for each other, or
  - **coordinate** with each other

$\Longrightarrow$ They must interact with each other

- Important questions regarding interprocess communication (IPC):
  - How can a process transmit information to other processes?
  - How can multiple processes access shared resources?

Communicating Threads

What about threads?

Communicating Threads

What about threads?

- Essentially threads are facing the same problems and challenges
- However, the solutions can often be simpler because threads operate in the same address space

Critical Sections

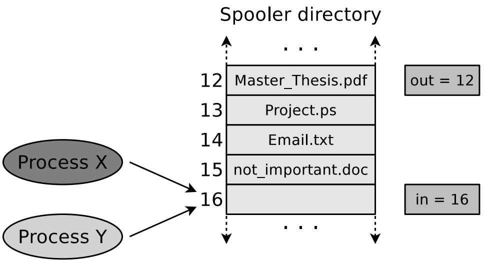
- If multiple processes access **shared resources**, i.e., common data, they contain critical sections
  - Only one process may enter this section at a time ($\Rightarrow$ it must be protected against concurrent access)
  - It appears as an atomic operation to the outside
  - **Uncritical sections**: The processes do not access shared data or carry out only read operations on shared data
- The OS must provide mechanisms for mutual exclusion

Race Condition

- If the process' behaviour depends on the order of multiple code paths, it is called a race condition
  - The result of a process depends on the order or timing of other events
  - Frequent reason for bugs, which are hard to locate and fix
- **Problem**: The occurrence of the symptoms depends on different events
  - The symptoms may be different or disappear with each test run
- Race conditions can be avoided with the **semaphore** concept ($\Longrightarrow$ slide 58)

Critical Sections – Example: Print Spooler

Process X		Process Y
`next_free_slot = in;` (Result: 16)		
	Process switch	
		`next_free_slot = in;` (Result: 16) `Store record in next_free_slot;` (Result: 16) `in = next_free_slot + 1;` (Result: 17)
	Process switch	
`Store record in next_free_slot;` (Result: 16) `in = next_free_slot + 1;` (Result: 17)		

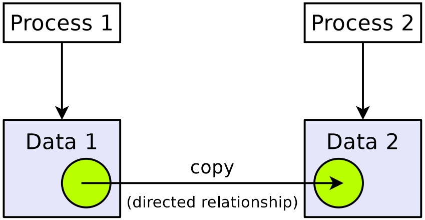


- The spooling directory is consistent
  - But the entry of **process Y** was overwritten by **process X** and got lost
- Such a situation is called **race condition**

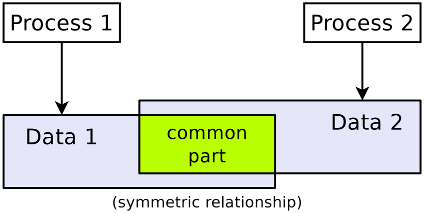
Communication vs. Cooperation

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

Communication
(= explicit data transport)



Cooperation
(= access to common data)



- **Communication** and **cooperation** base on **synchronization**

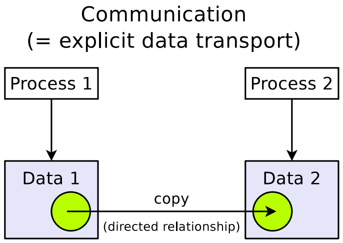
Agenda

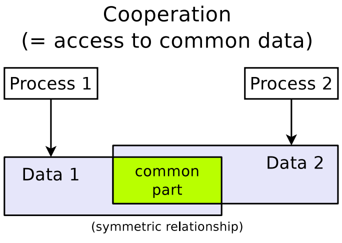
- Process Interaction
- Inter-Processes Communication (IPC)
- Process Synchronization
- Process Cooperation

How can processes communi-
cate?

Communication of Processes

- Types of IPC
  - Files
  - Signals/Flags
  - Shared Memory
  - Message Queues
  - Pipes
  - Sockets





Files

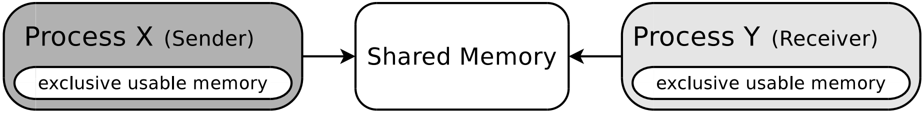
- A resource stored in the → **file system** which can be accessed by multiple processes
- **Linux**
  - File descriptors represent file handles
  - Part of the **POSIX** API
  - Per default every process owns three file descriptors (`stdin`, `stdout`, and `stderr`)
  - File descriptors can be used for, e.g., reading, writing, seeking, or truncating a file
- **RIOT**
  - Virtual File System (VFS) may be implemented by various backends
  - Not all IoT devices provide persistent memory
  - If available, persistent memory is often realized on flash memory → wear leveling is required

Signals and Flags

- Notify another process about the occurrence of an event
- **Linux**
  - **POSIX** signals
  - Standardized messages to trigger a certain behaviour
  - The receiver process gets interrupted
  - If a signal is unhandled by the receiver, it will terminate
- **RIOT**
  - Thread flags
  - The receiver needs to wait for a flag
  - Optional kernel feature
  - Notify threads of conditions in a race-free and allocation-less way

Shared Memory

- **IPC** via **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 *mapped* in the address space of multiple processes
- Coordination (→ **synchronization**) between the processes accessing the shared memory is required

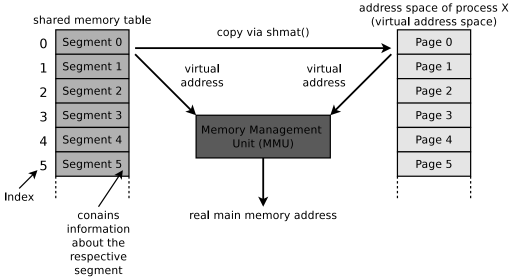


RIOT

Since most microcontrollers do not provide a → **MMU** all processes can typically access all memory regions . . .

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
- Shared memory objects are accessed similar to files



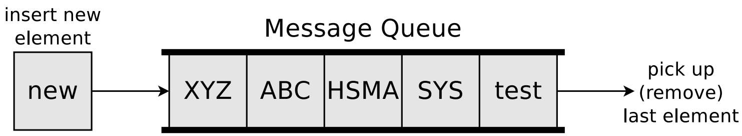
- A shared memory segment is always addressed via its index number in the shared memory table

- **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

Message Queues

- Are linked lists with messages
- Operate according to the **FIFO** principle
- Processes can store data inside and picked 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

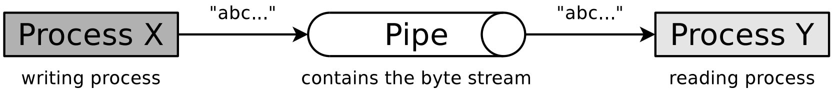


Message Queues

- **Linux**
  - **POSIX** and System V message queues
  - Queues are named and can be shared via this name between processes
  - Message have priorities
- **RIOT**
  - Kernel messages and mailboxes
  - Optional feature
  - Blocking and non-blocking API available
  - A thread may create a message buffer for queuing
  - Mailboxes can be accessed by multiple processes

Anonymous Pipes (1/2)

- Pipes can be **anonymous** or **named** (see slide 23)
- An **anonymous pipe**...
  - A buffered unidirectional communication channel between two processes (⇒ simplex FIFO)
  - One process accesses the write end, the other the read end of the pipe
    - ⇒ If communication in both directions shall be possible at the same time two pipes are necessary
  - Has a limited capacity and can block on both ends:
    - If the pipe is filled $\Longrightarrow$ the writing process gets blocked
    - If the Pipe is empty $\Longrightarrow$ the reading process gets blocked



Anonymous Pipes (2/2)

- In Linux pipes are created with the system call `pipe()`
  - The kernel creates an $\longrightarrow$ *inode* and two **file descriptors** (*handles*)
  - Processes access the access identifiers with `read()` and `write()` system calls (or standard library functions) similar to files
- 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: `lsof | grep pipe`

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)

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

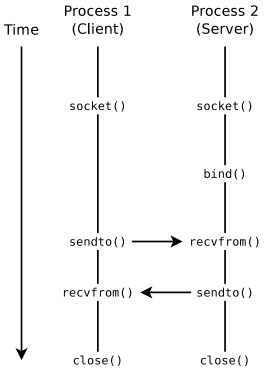
Using Sockets

- 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`

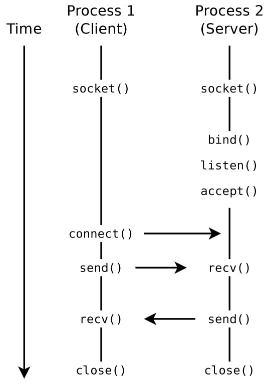
Examples of Interprocess communication via sockets (TCP and UDP) in Linux can be found on the website of this course

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`)

Comparison of Communication Systems

	Shared Memory	Message Queues	(anon./named) Pipes	Sockets
Scheme	Memory-based	Message-based	Stream-based	Message-based
Bidirectional	yes	no	no	yes
Platform independent	no	no	no	yes
Processes relation required	no	no	for anon. pipes	no
Common address space required	yes	yes	yes	no
Bound to a process	no	on	yes	yes
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 $\Longrightarrow$ comfortable
  - Can be used in distributed systems without a shared memory
  - Better portability of applications

Storage can be integrated via network connections

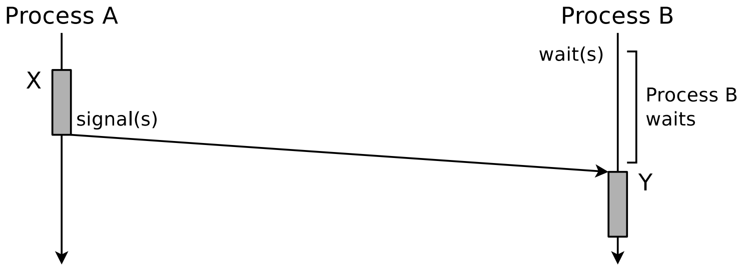
- This allows memory-based communication between processes on different independent systems
- The problem of synchronizing the accesses also exists here

Agenda

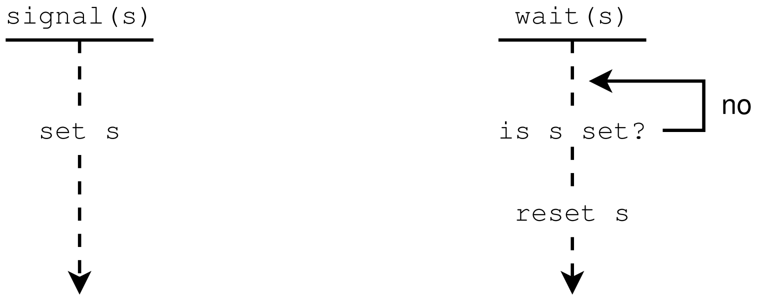
What is required if process P_A needs to process X before process P_B can do Y?

Signaling

- Used to specify an execution order
- **Example**: Section **X** of process P_A must be executed before section **Y** of process P_B
  - The `signal` operation signals that process P_A has finished section **X**
  - Perhaps, process P_B must wait for the signal of process P_A



Most Simple Form of Signaling (Busy Waiting)

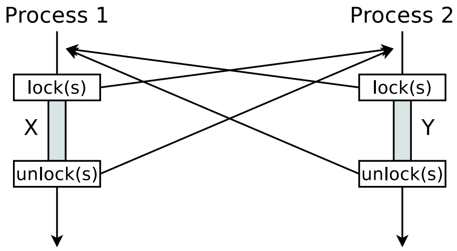


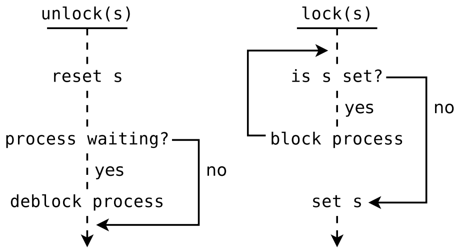
- The figure shows busy waiting at the signal variable `s`
  - The signal variable can be located in a local file, for example
  - **Drawback:** CPU resources are wasted, because the `wait` operation occupies the processor at regular intervals
- This technique is also called spinlock or polling

What can be done if the order of execution is not important?

Locking

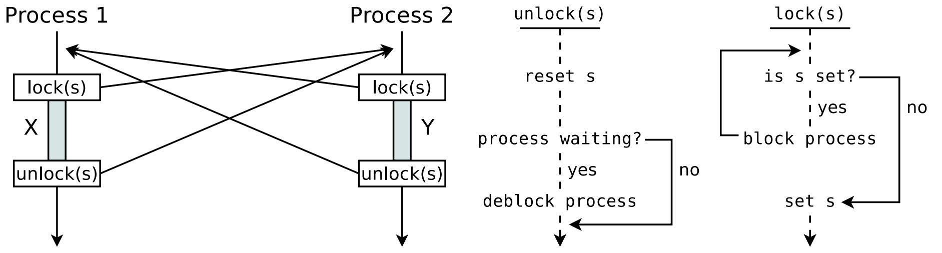
- In order to protect **critical sections**, i.e., no overlap in their execution, locking can be used
- In contrast to **signaling** the execution order is not specified
- The necessary operations are `lock` and `unlock`





- **Example**: Critical Sections **X** of process P_A and **Y** of process P_B

Locking in Linux via Signals



Useful system calls and standard library function to call the operations `lock` and `unlock` in Linux

`sigsuspend`, `kill`, `pause` and `sleep`

- **Alternative 1**: Implementation of **locking** with the **signals** `SIGSTOP` (No. 19) and `SIGCONT` (No. 18)
  - With `SIGSTOP` a process can be stopped
  - With `SIGCONT` a process can be resumed

Locking and Unlocking Processes in Linux (2/2)

- **Alternative 2**: A file is used for locking
  - 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 Locking

- **Signaling** specifies the execution order
  Example: Execute section X of process P_A before section Y of P_B
- **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

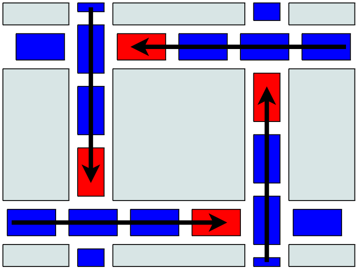
What may go wrong?

Problems caused by Locking

- **Starvation**
  - If a process does never remove a lock, the other processes need to wait infinitely long for the release

Problems caused by Locking

- **Starvation**
  - If a process does never remove a lock, the other processes need to wait infinitely long for the release
- **Deadlock**
  - If several processes wait for resources, locked by each other, they lock each other mutually
  - Because all processes, which are involved in the deadlock, must wait forever, no one can initiate an event that resolves the situation



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Conditions for Deadlock Occurrence

System Deadlocks. E. G. Coffman, M. J. Elphick, A. Shoshani. Computing Surveys, Vol. 3, No. 2, June 1971, P.67-78
http://people.cs.umass.edu/~mcorner/courses/691J/papers/TS/coffman_deadlocks/coffman_deadlocks.pdf

- A deadlock situation can arise if these conditions are all fulfilled
  - **Mutual exclusion**
    - At least one resource is either occupied by exactly one process or is available $\Longrightarrow$ non-sharable resource

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    - A process, which currently occupies at least one resource, requests additional resources which are being held by another process

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  - **Circular wait**
    - A cyclic chain of processes exists
    - Each process requests a resource that the next process in the chain occupies.

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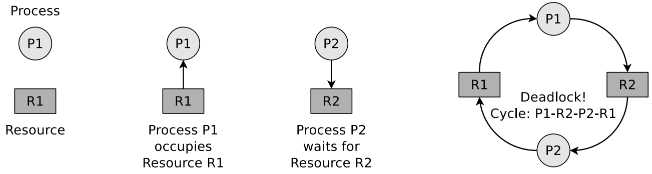
  - **Circular wait**
    - A cyclic chain of processes exists
    - Each process requests a resource that the next process in the chain occupies.
- Only if **all** of these conditions are fulfilled a deadlock occurs

Resource Graphs

- 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


Process
P1
R1
Resource
P1
R1
Process P1 occupies Resource R1
P2
R2
Process P2 waits for Resource R2
P1
R1
R2
P2
Deadlock!
Cycle: P1-R2-P2-R1

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

Deadlock Detection with Matrices

Limitations of deadlock detection with resource graphs

Only individual resources (i.e., no copies) can be represented

- If multiple copies of a resource exist, an algorithm based on matrices can be used
- We specify two 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 two 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 (1/2)

Source of the example: Tanenbaum. Moderne Betriebssysteme. Pearson. 2009

Existing resource vector $= \begin{pmatrix} 4 & 2 & 3 & 1 \end{pmatrix}$

- Four resources of class 1 exist
- Two resources of class 2 exist
- Three resources of class 3 exist
- One resource of class 4 exist

Available resource vector $= \begin{pmatrix} 2 & 1 & 0 & 0 \end{pmatrix}$

- Two resources of class 1 are available
- One resource of class 2 is available
- No resources of class 3 are available
- No resources of class 4 are available

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- Two resources of class 1 are available
- One resource of class 2 is available
- No resources of class 3 are available
- No resources of class 4 are available

Current allocation matrix $= \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$

- Process 1 occupies one resource of class 3
- Process 2 occupies two resources of class 1 and one resource of class 4
- Process 3 occupies one resource of class 2 and two resources of class 3

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

- Process 1 is blocked, because no free resources of class 4 exist
- Process 2 is blocked, because no free resources of class 3 exist
- Process 3 is not blocked

Deadlock Detection with Matrices – Example (2/2)

- If process 3 finished execution, it deallocates its resources

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

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

- Two resources of class 1 are available
- Two resources of class 2 are available
- Two resources of class 3 are available
- No resources of class 4 are available

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

- If process 2 finished execution, it deallocates its resources

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

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

- Process 1 is not blocked $\Longrightarrow$ no deadlock in this example

Conclusion about Deadlocks

- 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 > 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)

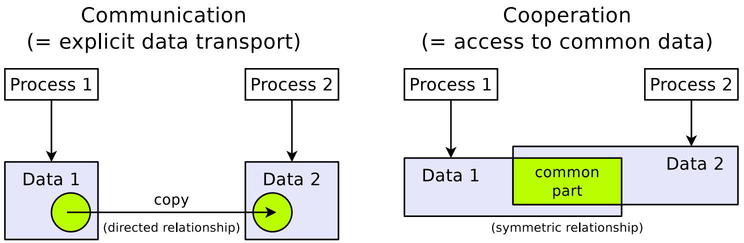
Sometimes it is tolerated that deadlocks can occur

A deadlock which statistically occurs every five years is not a problem in a system which crashes because of hardware failures or other software problems one time per week

Agenda

Cooperation

- Cooperation
  - Semaphor
  - Mutex



Semaphore

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- First published in 1965 by **Edsger W. Dijkstra**

Cooperating sequential processes. Edsger W. Dijkstra (1965)

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

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- May allow multiple processes accessing the critical section

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Semaphore Access Operations (1/3)

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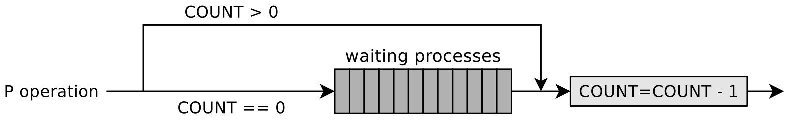
```
// apply the INIT operation on semaphore SEM
SEM.INIT(unsigned int init_value) {
    // initialize the variable COUNT of Semaphor SEM
    // with a non-negative initial value
    SEM.COUNT = init_value;
}
```

Semaphore Access Operations (2/3)

Image Source: Carsten Vogt

- **P operation** (*reduce*): It checks the value of the counter variable
  - If the value is 0, the process becomes blocked
  - If the value > 0, it is reduced by 1

```
SEM.P() {
    // if the counter variable = 0, the process becomes blocked
    if (SEM.COUNT == 0)
    < block >
    // if the counter variable is > 0, the counter variable
    // is decremented immediately by 1
    SEM.COUNT = SEM.COUNT - 1;
}
```

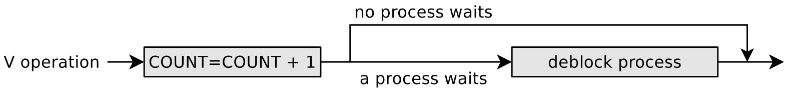


Semaphore Access Operations (3/3)

Image Source: Carsten Vogt

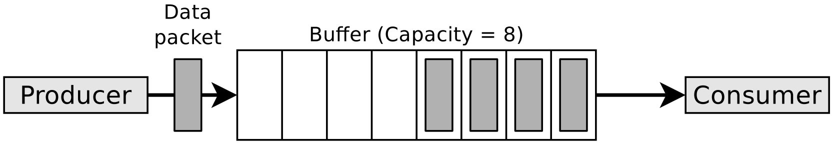
- **V operation** (*raise*): It first increases the counter variable by value 1
  - If processes are in the waiting room, one process gets unblocked
  - The process, which just got unblocked, continues its P operation and first reduces the counter variable

```
SEM.V() {
    // counter variable = counter variable + 1
    SEM.COUNT = SEM.COUNT + 1;
    // if processes are in the waiting room, one gets unblocked
    if ( < SEM waiting room is not empty > )
    < unblock a waiting process >
}
```

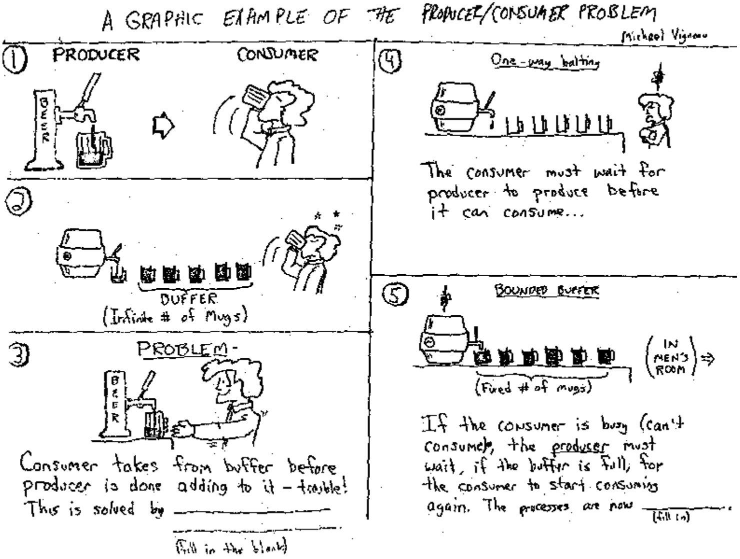


Producer/Consumer Example (1/3)

- 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



- If the buffer is full $\Longrightarrow$ producer must be blocked
- If the buffer is empty $\Longrightarrow$ consumer must be blocked


A GRAPHIC EXAMPLE OF THE PRODUCER/CONSUMER PROBLEM
Michael Vigneau
① PRODUCER
CONSUMER
BEER
② BUFFER (Infinite # of Mugs)
③ PROBLEM -
BEER
Consumer takes from buffer before producer is done adding to it - trouble!
This is solved by ____________
(Fill in the blank)
④ One-way halting
The consumer must wait for producer to produce before it can consume...
⑤ BOUNDED BUFFER
(Fixed # of mugs)
(IN MEN'S ROOM)
If the consumer is busy (can't consume), the producer must wait, if the buffer is full, for the consumer to start consuming again. The processes are now ________.
(fill in)

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

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

Producer/Consumer Example (2/3)

- Three semaphores are used to synchronize access to the buffer
  - `empty`
  - `filled`
  - `mutex`
- The semaphores `filled` and `empty` are used in opposite to each other
  - `empty` counts the number of empty locations in the buffer and its value is reduced by the producer (P operation) and raised by the consumer (V operation)
    - `empty` $= 0 \Longrightarrow$ buffer is completely filled $\Longrightarrow$ producer is blocked
  - `filled` counts the number of data packets (occupied locations) in the buffer and its value is raised by the producer (V operation) and reduced by the consumer (P operation)
    - `filled` $= 0 \Longrightarrow$ buffer is empty $\Longrightarrow$ consumer is blocked
- The semaphore `mutex` is used to ensure for the mutual exclusion

Binary Semaphores

- Binary semaphores are initialized with value 1 and ensure that 2 or more processes cannot simultaneously enter their critical sections
- Example: The semaphore `mutex` from the producer/consumer example

Producer/Consumer Example (3/3)

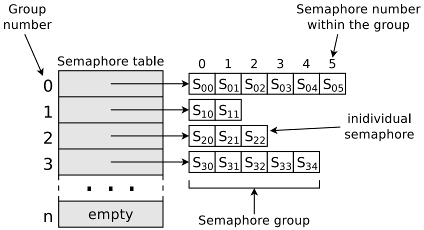
```
typedef int semaphore;          // semaphores are of type integer
semaphore filled = 0;           // counts the number of occupied locations in the buffer
semaphore empty  = 8;           // counts the number of empty locations in the buffer
semaphore mutex  = 1;           // controls access to the critial sections
void producer (void) {
    int data;
    while (TRUE) {                  // infinite loop
        createDatapacket(data);     // create data packet
        P(empty);                   // decrement the empty locations counter
        P(mutex);                   // enter the critical section
        insertDatapacket(data);     // write data packet into the buffer
        V(mutex);                   // leave the critical section
        V(filled);                  // increment the occupied locations counter
    }
}
void consumer (void) {
    int data;
    while (TRUE) {                  // infinite loop
        P(filled);                  // decrement the occupied locations counter
        P(mutex);                   // enter the critical section
        removeDatapacket(data);     // pick data packet from the buffer
        V(mutex);                   // leave the critical section
        V(empty);                   // increment the empty locations counter
        consumeDatapacket(data);    // consume data packet
    }
}
```

Semaphores in Linux (System V)

Image Source: Carsten Vogt

- The semaphore concept of Linux differs from the Dijkstra concept
  - The counter variable can be incremented or decremented with a P or V operation by more than value 1
  - Multiple access operations on different semaphores can be carried out in an atomic way

- Linux systems maintain a semaphore table, which contains references to arrays of semaphores
  - Individual semaphores are addressed using the table index and the position in the group


Group number
Semaphore number within the group
Semaphore table
0 1 2 3 4 5
0
1
2
3
n
empty
S_{00} S_{01} S_{02} S_{03} S_{04} S_{05}
S_{10} S_{11}
S_{20} S_{21} S_{22}
S_{30} S_{31} S_{32} S_{33} S_{34}
inidividual semaphore
Semaphore group

Linux/UNIX operating systems provide three system calls for working with *System V* semaphores

- `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`

Mutexes

- If the Semaphore feature of counting is not required a simplified alternative, the **mutex** can be used instead
  - **Mutexes** (derived from **Mut**ual **Ex**clusion) 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 two 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`

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 shmid] [-q msqid] [-s semid]
[-M shmkey] [-Q msgkey] [-S semkey]
```

- **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`

You should now be able to answer the following questions:

- What are **critical sections** and **race conditions**?
- What is **synchronization**?
- How can critical sections be secured via **blocking**?
- Which problems are described by (**starvation** and **deadlocks**)?
- How does **deadlock detection with matrices** work?
- What are different options to implement **communication** between processes?
- How can critical sections be protected via **semaphores** (and **mutex**)?