

# Concurrent Systems

*Nebenläufige Systeme*

## VII. Semaphore

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# Agenda

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Preface

Fundamentals

Classification

Characteristics

Implementation

Data Structures

Functions

Mutex

Summary



# Outline

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- discussion on **abstract concepts** as to unilateral and multilateral synchronisation, thus, partial and mutual exclusion
  - with the **general semaphore** as a measure that supports both
  - while the **binary semaphore** was/is intended to support the latter, only



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- comprehensive differentiation of **semaphore** and **mutex**
  - in terms of the mutual exclusion aspect only, computer science folklore is right in stating disparities between the general variant and a mutex
  - but one have to be much more precise and argue with caution as far as the binary alternative is concerned



# Subject Matter

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## Hint (Methods v. Implementation/Object)

*A **binary semaphore** is a valid implementation of one of the many “mutex methods”, but not that restrictive as a “mutex object” need to be.*



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- elaboration of various implementation aspects regarding both types of semaphore as well as mutex as an object

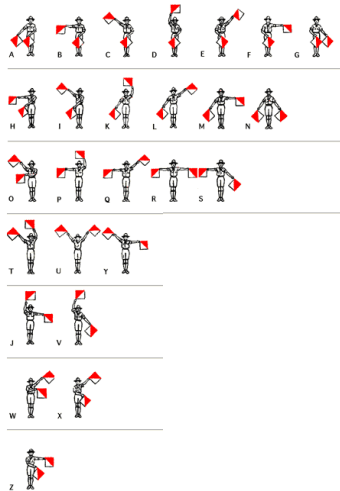




(Ger.) *Signalmast, Formsignal*





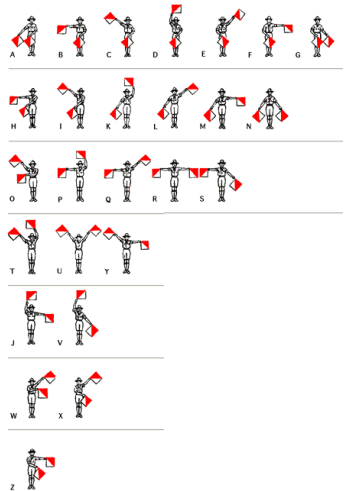


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- also referred to as **counting semaphore** (Ger. *zählender Semaphor*)



## Elementary Operations

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- insensitive to the distinction between binary and general semaphore is the definition of two **intrinsic primitives** [1]:

**P** abbr. for (Hol.) *prolaag*; a.k.a. *down*, *wait*, or *acquire*, resp.

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  - P abbr. for (Hol.) *prolaag*; a.k.a. *down*, *wait*, or *acquire*, resp.
    - decreases<sup>1</sup> the value of the semaphore by 1:
      - i iff the resulting value would be non-negative [2, p. 29]
      - ii non-constraining [3, p. 345]
    - blocks the process iff the value is or was, resp., 0 before decrease
      - blocking processes are put on a **waitlist** associated with each semaphore

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## Hint (Waitlist)

*The **queuing discipline** rivals with planning decisions of the process scheduler and, thus, may be the cause of critical **interference**.*

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- **multilateral synchronisation** [5, p. 15] of interacting processes
  - the critical section is considered as a **non-preemptable reusable resource** that needs to be allocated indivisibly to a process to be usable correctly
  - in logical respect, the process having completed  $P$  on semaphore  $S$  is the only one being authorised to complete  $V$  on  $S$

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  - $V$  must come before  $P$



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### Hint (Mutex (cf. p. 14/15))

A *mutex* is a **binary semaphore** that incorporates an **explicit check for authorisation** to release a critical section in the moment of  $V$ .





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    - i a **consumable resource** in the form of any data of any number
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    - in the end, the data store will have to be deallocated and, thus, made available again by the “data consumer”
- from this it follows that  $P$  and  $V$  applied to the same semaphore  $S$  must have to be accomplishable by different processes, normally
  - which makes the big difference to a binary semaphore or mutex, resp.



```
1 semaphore_t data = {0};
2
3 void producer() {
4     for (;;) {
5         /* data released */
6         V(&data);
7     }
8 }
9
10 void consumer() {
11     for (;;) {
12         P(&data);
13         /* data acquired */
14     }
15 }
```

- default value is 0
    - $P$  must block out only if there is no data
    - $V$  indicates more data
  - calling sequence
    - $V$  must be actable independent of  $P$
    - in order to complete,  $P$  depends on  $V$
- ↪ beware of an **overflow** of the values margin



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```

- usually, producer and consumer are different interacting processes
  - in case of one and the same process, the number of a completed  $V$  must exceed the number of a completed  $P$  in order to prevent deadlock
  - $\#V > \#P$ , which implies a path  $V \rightarrow P$  (i.e.,  $V$  “happens before”  $P$ )

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```
1 semaphore_t store = {N};
2
3 void producer() {
4     for (;;) {
5         P(&store);
6         /* store acquired */
7     }
8 }
9
10 void consumer() {
11     for (;;) {
12         /* store released */
13         V(&store);
14     }
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```

- default value is  $N \geq 0$ 
    - $P$  must block out only if there is no store
    - $V$  indicates more store
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- as to interacting processes in the line of producer and consumer, the same applies as mentioned before:  $\#V > \#P$
- in other cases:  $\#V \leq \#P$ , must be completed by the same process

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## Hint (Bounded Buffer)

*A means of managing an unlimited number of consumable resources on the basis of a limited number of reusable resources.*



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8     }                                     16     }
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```

- indisputable classic in cooperation and communication of processes
  - simply a merge of the semaphore use pattern discussed as before
  - **transverse application** of  $P$  and  $V$  to a pair of general semaphores



## Hint

*Checking **authorisation** for release of a critical section in that very moment is improper for a general semaphore, optional for a binary semaphore, and may be demanded for a mutex (cf. p. 15).*



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- a **mutex object** ensures that the release of critical section CS will succeed only for the process having acquired CS
  - by extending a binary semaphore,  $P$  will have to record and  $V$  will have to check ownership of CS



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- improper
- $P$  and  $V$  on a **general semaphore** must be accomplishable in particular also by different processes
  - this is prevented by a mutex object—but not by a mutex



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- basically, a **binary semaphore** may be implemented by a general semaphore  $S$ , with  $S \leq 1 \Rightarrow$  never a mutex object
  - values  $S > 1$  must be prevented either by the use pattern or by the implementation of  $P$  and  $V$





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- if **authorisation fails**, the process attempting to release CS should be aborted—in kernel mode, the computing system must be halted. . .



## Hint (Computer Science Folklore)

*A semaphore can be released by any process.*

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<sup>2</sup>see also p. 36



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- incomplete or rough, if not broad-bush, phrase that must be regarded with suspicion—one have to distinguish between semaphore types<sup>2</sup>
  - strictly, essence of this phrase is **requirement** for a general semaphore
  - strictly as well, it is merely an **option** for a binary semaphore
    - in logical respect, a binary semaphore cannot be released by any process
    - in physical respect, this however is not a must for any implementation

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- a phrase that is slanted towards only one aspect as to the leastwise twofold non-uniform common understanding about a mutex:
  - i a category of **methods** for ensuring mutual exclusion *or*
  - ii the **implementation** of one of these methods in terms of an **object**<sup>2</sup>

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    - P – if no further process is ready to run, the **idle loop** becomes active
      - in that case, the blocking process likewise may fade to the **idle process**
      - thus, doing without a dedicated **idle-process instance** and context switch



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    - √ – if there is a waiting process, it will be set “ready to run” (cf. [9, p. 28])
    - in that case, **priority violation**<sup>3</sup> must be prevented (scheduling discipline!)
    - thus, the current process may defer to a prior-ranking one: context switch

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<sup>3</sup>If at least one of the processes on the waitlist is of higher-priority than the current process but will not become “ready to run” or allocated the processor.



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      - thus, doing without a dedicated **idle-process instance** and context switch
    - $V$  – if there is a **waiting process**, it will be set “ready to run” (cf. [9, p. 28])
      - in that case, **priority violation**<sup>3</sup> must be prevented (scheduling discipline!)
      - thus, the current process may defer to a prior-ranking one: context switch
  - all this makes  $P$  and  $V$  programs of the operating system machine level

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<sup>3</sup>If at least one of the processes on the waitlist is of higher-priority than the current process but will not become “ready to run” or allocated the processor.



- the **standby position** of a process within  $P$  is passive, normally
  - “blocks the” or “unblocks a”, resp. (cf. p. 8), process means rescheduling
  - if so, both may also entail context switching—“may” because:
    - $P$  – if no further process is ready to run, the **idle loop** becomes active
      - in that case, the blocking process likewise may fade to the **idle process**
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- $P$  and  $V$  relies on **process management** of the operating system
  - one have to put the current process asleep and get a sleeping process up
  - in functional terms, however,  $P$  and  $V$  need not be system calls
  - in non-functional terms,  $P$  and  $V$  should be close to the **scheduler**
    - by settling  $P$  and  $V$  in the address space of the operating-system kernel *or*
    - by making scheduler functions available through “strawweight” system calls

---

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## Waitlist Association

---

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    - to block, a **blocked-on mark** is stored in the process descriptor
    - to unblock, a process-table walk looks for that mark
    - ↪ constant ( $P$ ) and variable but bounded above ( $V$ ) run-time
    - ↪ blocked-on mark is a “magic” address, no extra attributes





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**physical**

- to block, the process descriptor joins a **queue data structure**
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  - a characteristic by means of which **priority violation** will be prevented
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## Hint (Process-Table Walk—Conformance to Scheduling)

*Part of the scheduler, lookup function to locate a process descriptor on the basis of the blocked-on mark as search key.*



- in the absence of simultaneous processes, the implementation of a semaphore could be as simple as follows:

```
1 void prolaag(semaphore_t *sema) {
2     if (!claim(sema))    /* at the moment, unavailable */
3         sleep(&sema->wand);
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5
6 void verhoog(semaphore_t *sema) {
7     if (unban(sema))    /* as from now, available */
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- whereat *claim* decreases and *unban* increases the value of the semaphore according to binary or general, resp., characteristic<sup>4</sup>

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- whereat *claim* decreases and *unban* increases the value of the semaphore according to binary or general, resp., characteristic<sup>4</sup>
- but, assuming that the presence of simultaneous processes is possible, this implementation shows a **race condition**  $\rightsquigarrow$  **lost wakeup**
  - 3 ■ while going to sleep, i.e. being “sleepy”, the process gets delayed
  - 7–8 ■ but in good faith of a sleeper, the “sleepy” process may be missed

<sup>4</sup>The implementation of these helper functions will be revealed later.



- $P$  and  $V$  itself constitute a **critical section**, likewise, that must be protected in order to function correctly
  - protection should be constructed **per semaphore instance**, not  $P/V$

```
1 void prolaag(semaphore_t *sema) {
2     atomic *sema = {
3         if (!claim(sema))
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5     }
6 }
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8 void verhoog(semaphore_t *sema) {
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### Deadlock Prevention

Provided that protection of the critical section on the  $P$  side is not deregulated, the  $V$  side will never complete and, thus, will never cause unblocking of a process:

- the right location for deregulation is *sleep*
- after the process was marked sleeping





- protection of the  $P/V$  pair against simultaneous processes sharing a semaphore follows either the blocking or non-blocking paradigm
  - blocking
    - inhibit FLIH<sup>5</sup>, postpone SLIH<sup>5</sup>, or lock process
    - problem-specific construction of an **enter/leave** pair
  - non-blocking
    - fall back on the elementary operations of the ISA level
    - problem-specific construction of  $P$  and  $V$

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<sup>5</sup>abbr. for *first- or second-level interrupt handling*, resp.



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- more detailed analysis of the “atomic” version of  $P$  reveals another problem: **overtaking** of an aroused process
  - upon return from *sleep* a formerly blocked process may complete  $P$  by mistake, joining a process in the critical section to be protected by  $P$
  - note that completion of  $V$  also opens the door for any process, not only for a process having been blocked at the semaphore
  - ↪ aroused processes will have to **retry claiming**: `if`  $\mapsto$  `while`

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  - ↪ aroused processes will have to **retry claiming**: **if** ↪ **while**
- not least, concurrency had to be constricted to no more than what is absolutely necessary: reflect on *claim/sleep* and *unban/rouse*

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# Outline

---

Preface

Fundamentals

Classification

Characteristics

Implementation

Data Structures

Functions

Mutex

Summary



# Semaphore Data Type

---

```
1 typedef volatile struct semaphore {
2     int gate;           /* value: binary or general */
3     wand_t wand;      /* protective shield */
4 } semaphore_t;
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- purpose of “wand” (Ger. *Zauberstab*) is to **safeguard** the semaphore operations in various respect
  - i protect  $P$  and  $V$  against simultaneous processes
  - ii give leeway for protection variants (cf. p. 20)



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- a wand that takes care of **mutual exclusion** techniques as presented in the previous lecture could be the following:

```
1 typedef volatile struct wand {
2     lock_t clue;       /* protects P or V, resp. */
3     event_t wait;     /* list of sleeping processes */
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→ becoming acquainted with other wands is content of future lectures...



```
1 void prolaag(semaphore_t *sema) {
2     enter(&sema->wand);      /* avert overlapped P or V */
3     while (!claim(sema))    /* acquire semaphore */
4         sleep(&sema->wand); /* await wakeup signal */
5     leave(&sema->wand);     /* allow P or V */
6 }
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8 void verhoog(semaphore_t *sema) {
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10    if (unban(sema))        /* release semaphore */
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12    else                    /* no sleeping process... */
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- exercise caution in the analysis of these program statements:
  - 3–4 ■ takes care of the overtaking-problem as to aroused processes
  - 10–11 ■ in case of (i) logical waitlist and (ii) strict binary semaphore, the search for sleeping processes happens unconditionally
    - in that particular case, there is no direct indication of sleepers



# Acquire and Release Semaphore

- load/store-based implementation for a **binary semaphore**:

```
1 inline bool claim(semaphore_t *sema) {  
2     return (sema->gate == 0) ? false : (sema->gate = 1);  
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- enumerator-based implementation for a **general semaphore**:

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1 inline bool claim(semaphore_t *sema) {
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- note that both variants are sensitive to simultaneous processes
  - use within a safeguarded program section is assumed...





```
1 inline void sleep(wand_t *wand) {
2     catch(&wand->wait); /* disclose process to V */
3     leave(wand);       /* allow P or V */
4     coast();           /* take a break */
5     enter(wand);       /* apply for return to P */
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8 inline void rouse(wand_t *wand) {
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- constrict concurrency to no more than what is absolutely necessary:
  - 2 ■ endorse interest of the current process of upcoming dormancy
  - 3 ■ soon dormant process was made known, deregulate  $P$  safeguard
  - 4 ■ transition to dormant state: rescheduling, context switch or idleness
  - 5 ■ apply for return to safeguarded  $P$
  - 9 ■ dormant processes could be available, deregulate  $V$  safeguard
  - 10 ■ annulment of dormant state: rescheduling, context switch



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- catch* ■ exists in two variants, depending on the waitlist model (cf. p 17):
- i store of a blocked-on mark in the process descriptor *or*
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- coast* ■ blocks the current process, reschedules the processor, and either performs a context switch or runs through the idle loop
- manipulates a shared data structure (ready list)
  - performs the queuing function of the queue-based *catch*
- eventually returns when the blocking condition was nullified



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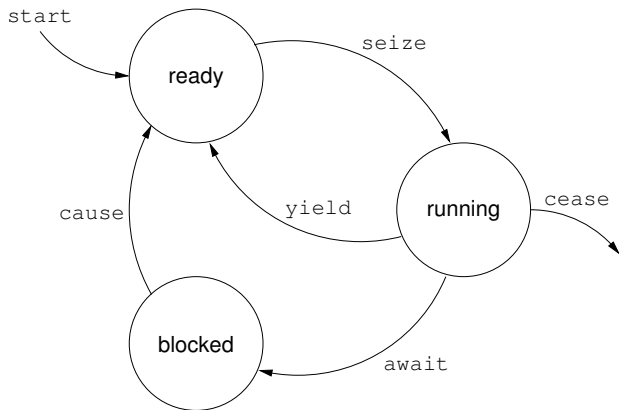
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### Hint (Idle State (cf. p. 16 and p. 37))

*The last process blocked may find itself on the ready list. Same may happen to the “sleepy process” as coast runs deregulated to P/V.*

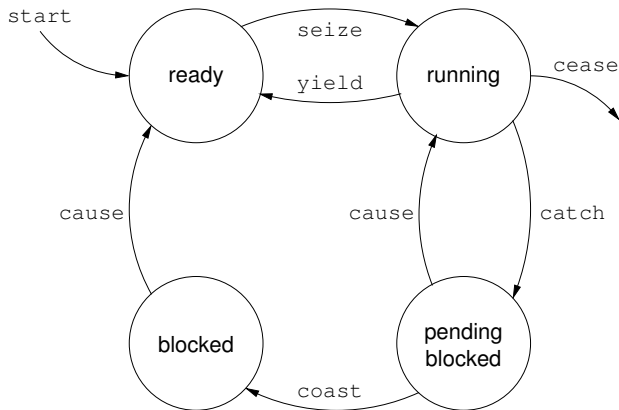






- **ready** ↔ **running** ■ scheduler
- blocked** → **ready** ■ iff *effective signalling* ( $V$ ), i.e., waiting process
- running** → **blocked** ■  $P$ , intermediate step needed: prevent *lost wakeup*





- **ready** ↔ **running** ■ scheduler
- blocked** → **ready** ■ iff *effective signalling* ( $V$ ), i.e., waiting process
- running** ↔ **pending** ■ doze ( $P \rightarrow$ ), *effective signalling* ( $\leftarrow V$ )
- pending** → **blocked** ■ deep sleep ( $P$ ), no overlapping  $V$



- as there is no single solution to protect  $P$  and  $V$  adequately, the wand attribute symbolises intention to application orientation
  - depending on the mode of operation or use case, the wand acts differently
  - assuming that processing elements are not multiplexed [7, p. 5], then:

```
1 inline void enter(wand_t *wand) {
2     lock(&wand->clue);
3 }
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5 inline void leave(wand_t *wand) {
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- wand capability depends on the “type of exclusion” in relation to the required characteristics of the operating system machine level:
  - partial** ■ processor **multiplexing**  $\rightsquigarrow$  interrupt control
  - mutual** ■ processor **multiplication**  $\rightsquigarrow$  process lock, see example above



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- combination of both is optional, not mandatory, and problem-specific
  - depends on the degree of parallelism (a) allowed for by the application use case and (b) made possible by the ISA level





```

1      ...
2      movl  16(%esp), %edi
3      leal  4(%edi), %esi
4      jmp   LBB0_2
5  LBB0_1:
6      movl  _life, %eax
7      movl  %esi, 4(%eax)
8      movl  %esi, (%esp)
9      calll _unlock
10     calll _coast
11  LBB0_2:
12     movl  %esi, (%esp)
13     calll _lock
14     cmpl  $0, (%edi)
15     je    LBB0_1
16     movl  $1, (%edi)
17     movl  %esi, (%esp)
18     calll _unlock
19     ...

```

- let the sequence of instructions within  $P$  be as follows:
  - 2 ■ point at semaphore
  - 3 ■ point at lock structure
  - address is blocked-on mark
  - 12–13 ■ apply for  $P$  protection
  - 14–15 ■ check binary semaphore  $S_b$
  - 16–18 ■ unoccupied, take  $S_b$ 
    - quit  $P$  protection, done
    - 5 ■ occupied,  $S_b$  already taken
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    - 8–9 ■ deregulate  $P$  protection
    - 10 ■ fall asleep, dream about  $V$



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    - 8–9 ■ deregulate  $P$  protection
    - 10 ■ fall asleep, dream about  $V$
  - locking overhead when unoccupied
    - net worth of about 5 instructions ☹
- ↪ non-blocking synchronisation ☺

<sup>6</sup>Take a sledgehammer to crack a nut...





- given the concept of a binary semaphore, implementation of a **mutex** is straightforward and, absolutely, no black magic:
  - a mutex data structure is composed of two parts:
    - i a binary semaphore used to actually protect the critical section *and*
    - ii a handle that uniquely identifies the process having acquired the mutex<sup>7</sup>

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  - given such a structure, let the following two functions be defined:
    - acquire** – performs the  $P$  and registers the current process as owner
    - release** – conditionally unregisters the owner and performs the  $V$ 
      - in case of a wrong owner, the current process or kernel, resp., panics

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      - in case of a wrong owner, the current process or kernel, resp., panics
- a corresponding **data type** may be laid out as follows:

```
1 typedef volatile struct mutex {
2     semaphore_t sema;    /* binary semaphore */
3     process_t *link;    /* owning process or 0 */
4 } mutex_t;
```

---

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## Acquire and Release Mutex

```
1 extern void panic(char*) __attribute__((noreturn));
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3 void acquire(mutex_t *mutex) {
4     P(&mutex->sema);          /* lockout */
5     mutex->link = being(ONESELF); /* register owner */
6 }
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8 void release(mutex_t *mutex) {
9     if (mutex->link != being(ONESELF)) /* it's not me! */
10        panic("unauthorised release of mutex");
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12     mutex->link = 0;          /* deregister owner */
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  - presumably, the non-sequential program contains a **software fault** (bug)
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  - returning an error code is no option, as one cannot rely on error checking
  - any other than “raising a non-maskable exception” is a botch job...



# Outline

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Preface

Fundamentals

- Classification

- Characteristics

Implementation

- Data Structures

- Functions

- Mutex

Summary



- fundamental concept for cooperation and communication
  - binary and general/counting semaphore, intrinsic primitives  $P$  and  $V$
  - correlation to unilateral and multilateral synchronisation
  - differentiation as to mutex (methods v. implementation/object):

## Hint

*A binary semaphore is a valid implementation of one of the many "mutex methods", but not that restrictive as a "mutex object" need to be.*

*↳ Hierarchic placement at operating system machine level*

- characteristics important in functional and non-functional terms
  - logical or physical waitlist, conformance to the scheduling discipline
  - deregulation of the protection of  $P$  against simultaneous processes
  - further shallows such as overtaking of unblocked processes in  $P$ :

## Hint

*Constrict concurrency to no more than what is absolutely necessary.*

*not least, basic approaches and sketches of an implementation...*





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## Commonalities and differences as to their possible **internal states**.

- general semaphore  $S_g$ :
  - positive ■  $N > 0$  processes will complete  $P(S_g)$  without blocking
  - zero ■  $P(S_g)$  will block the running process on the waitlist of  $S_g$
  - negative ■  $P(S_g)$  will block the running process on the waitlist of  $S_g$ 
    - $|N|$  processes are blocked on the waitlist of  $S_g$
- binary semaphore  $S_b$ :
  - not taken ■ exactly one process will complete  $P(S_b)$  without blocking
    - the very process becomes **logical owner** of  $S_b$
  - taken ■  $P(S_b)$  will block the running process on the waitlist of  $S_b$ 
    - $V(S_b)$  should be performed only by the logical owner of  $S_b$
- mutex object  $M$ : let  $A$  be *acquire* and let  $R$  be *release*
  - not owned ■ exactly one process will complete  $A(M)$  without blocking
    - the very process becomes **physical owner** of  $M$
  - owned ■  $A(M)$  will block the running process on the waitlist of  $M$ 
    - $R(M)$  can succeed only for the physical owner of  $M$



- principle pattern of a scheduler function to block a process
  - called by *coast* (cf. p.25) and other functions to pause computation

```
1 void block() {
2     process_t *next, *self = being(ONESELF);
3
4     while (!(next = elect(hoard(READY))))
5         relax();                /* no ready to run... */
6
7     if (next != self) {         /* must relinquish */
8         self->state = BLOCKED; /* vacate processor */
9         seize(next);          /* resume elected */
10    }
11    self->state = RUNNING;     /* occupy processor */
12 }
```

- 4 ■ choose next process to be dispatched to the processor
- 5 ■ ready list is empty, so the running process fades to the idle process
- 7 ■ as the case may be, the running process may be allowed to continue:
  - i the idle/running process found itself ready-to-run on the ready list *or*
  - ii the running process, sent to sleep due to  $P$ , was roused due to  $V$  (p.25)

