Concurrent Systems

Nebenläufige Systeme

VII. Semaphore

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December 13, 2016

Agenda

Outline

Subject Matter

- 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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Hint (Methods v. Implementation/Entity)

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

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

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(Ger.) *Gemeinsprache*, *Redensart*

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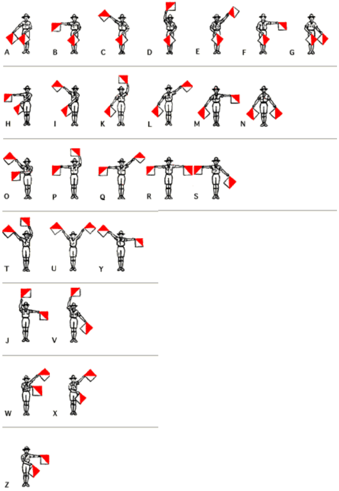

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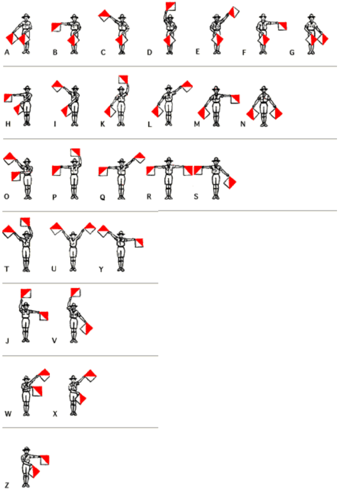

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The semaphores are essentially non-negative integers; when only used to solve the mutual exclusion problem, the range of their values will even be restricted to "0" and "1". [2, p. 28]

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

Elementary Operations

- 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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  - decreases[1] 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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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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    - 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.

Consumable Resource


```
semaphore_t data = {0};

void producer() {
    for (;;) {
        /* data released */
        V(&data);
    }
}

void consumer() {
    for (;;) {
        P(&data);
        /* data acquired */
    }
}
```

- 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*

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- usually, producer and consumer are <u>different</u> 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)

Reusable Resource

```
semaphore_t store = {N};

void producer() {
    for (;;) {
        P(&store);
        /* store acquired */
    }
}

void consumer() {
    for (;;) {
        /* store released */
        V(&store);
    }
}
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- default value is $N \geq 0$
  - P must block out only if there is no 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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- 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

Semaphore v. Mutex I

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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*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).*

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

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Hint (Computer Science Folklore)

A semaphore can be released by any process.

[2] see also p. 38

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A semaphore can be released by any process.

- incomplete or rough, if not broad-bush, phrase that must be regarded with suspicion—one have to distinguish between semaphore types[2]
  - 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 may not 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 **entity**[2]

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    P
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[3] 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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  - all this makes P and V programs of the operating system machine level

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  - all this makes P and V programs of the operating system machine level
- 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

[3]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.

Hierarchic Placement

- 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***
      - 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***[3] 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
- 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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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.

Indivisible Operation I

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

```
void prolaag(semaphore_t *sema) {
    if (!claim(sema))   /* at the moment, unavailable */
        sleep(&sema->wand);
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  - whereat *claim* decreases and *unban* increases the value of the semaphore according to binary or general, resp., characteristic[4]

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- but, assuming that the presence of simultaneous processes is possible, this implementation shows a **race condition** $\leadsto$ ***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

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Indivisible Operation II

- *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*

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void prolaag(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

- as a process will have to block inside a critical section, **deregulation of protection** is indispensable for the period the process is blocked

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- protection of the P/V pair against simultaneous processes sharing a semaphore follows either the blocking or non-blocking paradigm

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blocking
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↪ coming right up next in this lecture (cf. p. 22*ff.*)

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- problem-specific construction of P and V

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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
  - this is because completion of V also opens the door for any process, not only for a process having been blocked at the semaphore
  - $\hookrightarrow$ if applicable, aroused processes have to **retry claiming**: `if` $\mapsto$ `while`

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  - ↪ if applicable, aroused processes 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

Semaphore Data Type

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typedef volatile struct wand {
    lock_t clue;            /* protects P or V, resp. */
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↪ becoming acquainted with other wands is content of future lectures...

P and *V* Safeguarded


```
void prolaag(semaphore_t *sema) {
    enter(&sema->wand);        /* avert overlapped P or V */
    lodge(sema);               /* raise claim to proceed */
    when (!avail(sema))        /* check for process delay */
        sleep(&sema->wand);    /* await wakeup signal */
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void verhoog(semaphore_t *sema) {
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- exercise caution in the analysis of these program statements:
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  - 11–12 ▪ if applicable, search for sleepers happens unconditionally
    - in case of (i) logical waitlist and (ii) strict binary semaphore

Acquire and Release Semaphore I

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

```
inline int lodge(semaphore_t *sema) {
    return 42;
}

inline bool avail(semaphore_t *sema) {
    return (sema->gate == 0) ? false : !(sema->gate = 0);
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- also note the persisting sensitivity to simultaneous processes: *avail*
  - use within a safeguarded program section is assumed...

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    - $\hookrightarrow$ will be forced to *sleep*
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Hint (erroneous rouse)

Caused by misuse of V or by forced and uncontrolled unblocking of a process that went to sleep in P. Both are programming errors: the former at (semaphore) application level, the latter at system level.

Special Process Management


```
inline void sleep(wand_t *wand) {
    catch(&wand->wait); /* disclose process to V */
    leave(wand);        /* allow P or V */
    coast();            /* take a break */
    enter(wand);        /* apply for return to P */
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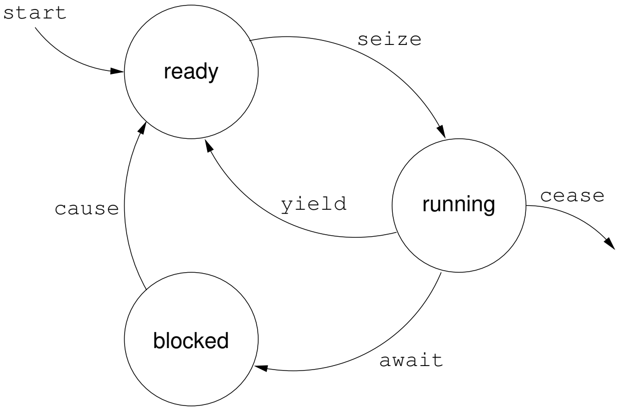
Hint (Idle State (cf. p. 16 and p. 39))

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.

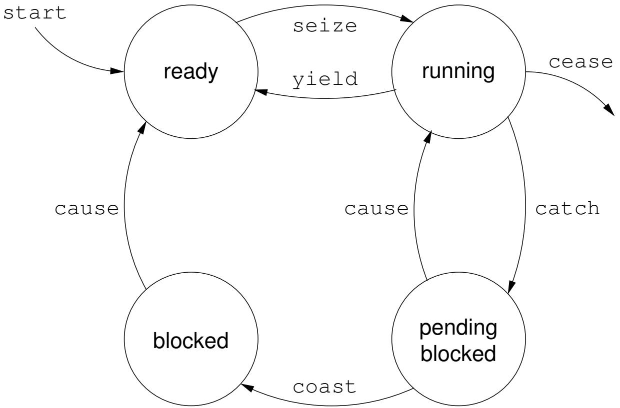
Process States and State Transitions

cf. [9, p. 27]



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

Process States and State Transitions cf. [9, p. 27]



- 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

Semaphore Gatekeeper (Ger.) *Schrankenwärter, Türhüter*

- 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:

```
inline void enter(wand_t *wand) {
    lock(&wand->clue);
}

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partial
- processor **multiplexing** $\rightsquigarrow$ interrupt control

mutual
- processor **multiplication** $\rightsquigarrow$ process lock, see example above

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  mutual
  - processor **multiplication** $\rightsquigarrow$ process lock, see example above
- 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

Specialisation of a Binary Semaphore

- 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[6]

[6] At kernel level, the handle is the pointer to the process descriptor of the process instance. At user level, it is the process identification.

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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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- a corresponding **data type** may be laid out as follows:

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

[6] At kernel level, the handle is the pointer to the process descriptor of the process instance. At user level, it is the process identification.

Acquire and Release Mutex

```c
extern void panic(char*) __attribute__ ((noreturn));

void acquire(mutex_t *mutex) {
    P(&mutex->sema);              /* lockout */
    mutex->link = being(ONESELF);   /* register owner */
}

void release(mutex_t *mutex) {
    if (mutex->link != being(ONESELF)) /* it's not me! */
        panic("unauthorised release of mutex");

    mutex->link = 0;              /* deregister owner */
    V(&mutex->sema);              /* unblock */
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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

Résumé

- 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/entity):

Hint

A ***binary semaphore*** *is a valid implementation of one of the many "mutex methods", but not that restrictive as a "mutex entity" 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:

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Constrict concurrency to no more than what is absolutely necessary.

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

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Extent of Critical Section

Binary Semaphore devoid of Waitlist[7]

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```
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
  - 6: point at process structure
  - 7: define blocked-on mark
  - 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 ☺

[7] Take a sledgehammer to crack a nut...

Semaphore v. Mutex III

cf. p. 14/15

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 entity 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

Idle State

cf. p. 28

- principle pattern of a scheduler function to block a process
  - called by *coast* (cf. p. 27) 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. 27)