Concurrent Systems

Nebenlaufige Systeme

VIII. Monitor

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Agenda

Preface

Fundamentals
   Mutual Exclusion
   Condition Variable
   Signalling Semantics

Implementation
   Data Structures
   Use Case
   Operations

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discussion on **abstract concepts** as to “a shared variable and the set of meaningful operations on it” [7, p. 121]:

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- a *language notation*, initially denoted by **critical region** [6, 7]
- associates a set of procedures with a shared variable
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- one or more special variables that do “not have any stored value accessible to the program” [12, p. 550]  
- used to indicate and control a particular wait mode  
- for the respective process inside the monitor
Subject Matter

- discussion on **abstract concepts** as to “a shared variable and the set of meaningful operations on it” [7, p. 121]:
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- in functional terms, get to know “monitor” as fundamental means of synchronisation independent of linguistic features
  - explanation of various styles: Hansen, Hoare, Concurrent Pascal, Mesa
  - according to this, schematic representation of implementation variants
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In functional terms, get to know “monitor” as fundamental means of synchronisation independent of linguistic features:

- Explanation of various styles: Hansen, Hoare, Concurrent Pascal, Mesa
- According to this, schematic representation of implementation variants
- Demonstrate basic functions of a fictitious (language) run-time system
for all advantages, semaphores are to be approached with caution:
- too low level, programmers must keep track of all calls to $P$ and $V$
- although different, used for both uni- and multilateral synchronisation
Motivation

Semaphore Considered Harmful

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out of it, various design and languages concepts originated:
- **secretary** idea for structuring control of sharing [5, p. 135–136]
- **critical region** mutual exclusive use of a shared variable [6]
- **event variable** a shared variable associated with an event queue [6]
- **path expressions** synchronisation rules within type definitions [2]
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- **path expressions** synchronisation rules within type definitions [2]
- **monitor** class-like synchronised data type [7, 12, 14]
- inspired by SIMULA 67 [4, 3]
- first implemented in Concurrent Pascal [9]
- comes in a characteristic of many kinds [1, 10]
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  - event variable
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  - monitor

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  - synchronisation rules within type definitions [2]
  - class-like synchronised data type [7, 12, 14]
    - inspired by SIMULA 67 [4, 3]
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    - comes in a characteristic of many kinds [1, 10]

however, the concept is beyond a programming-language construct
  - it is fundamental for system programming and system-level operation

**Hint (Monitor [7, p. 121])**

The purpose of a monitor is to control the scheduling of resources among individual processes according to a certain policy.
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Summary
key aspect is to facilitate solely indirect access to shared variables by means of monitor procedures
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- by definition, these procedures have to execute by **mutual exclusion**
  - on behalf of the calling process, the **procedure prologue** applies for exclusive occupation of the monitor \(\rightsimeq\) **lockout** simultaneous processes
  - on behalf of the occupying process, at return the **procedure epilogue** releases the monitor again \(\rightsimeq\) **proceed** locked processes, if any
Class Concept Expanded by Coordination

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  - usually, a compiler is in charge of ejecting the procedure pro- and epilogue
    - only infinite loops or hardware failures may prevent epilogue execution
    - only constructs beyond the frame of reference may force abnormality\(^1\)

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in logical respect, deadlocks due to programmed absence of unblocking of critical sections are impossible

accordingly, instructions for synchronisation are cross-cutting concern of the monitor and no longer of the whole non-sequential program

particularly, instructions to protect critical sections are not made explicit
given that foreign-language synchronisation primitives cannot be used\(^1\)

---

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Intentional Process Delay

- multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit.
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Hansen
- Proposed to attach a shared variable to an event [6, p. 577]
- With *cause* and *await* as intrinsic functions for event signalling.

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Fundamentals – Condition Variable
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in this spirit, the **signalling convention** makes the wide difference and affects structuring of monitor-based non-sequential programs [13]
Signalling Conventions

- explicit signal operation assumed
explicit signal operation assumed, **signal-and-φ**, with φ indicating the behaviour of the signalling process as follows:

- **wait**
  - join monitor **entrance queue** and leave the monitor
  - resume all signalled processes (one at a time)
  - re-enter the monitor, compete against all processes
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- explicit signal operation assumed, **signal-and-**\( \phi \), with \( \phi \) indicating the behaviour of the signalling process as follows:

  - **urgent wait**
    - join **preferential queue** and leave the monitor
    - resume one signalled process (first come, first served)
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explicit signal operation assumed, **signal-and-φ**, with φ indicating the behaviour of the signalling process as follows:

- **return** leave the monitor and resume the single signalled process

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Fundamentals – Signalling Semantics
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- in case of absence of a signal primitive, signalling may still happen:
  - **automatic**
    - leave the monitor and re-evaluate waiting conditions
    - if so, resume no longer waiting processes (one at a time)
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**Waiting inside a monitor**

Without leaving the monitor, another process is unable to signal.
Atomicity of Control Transfer

consequence for the *ownership structure* of monitor and signaller:

- **change**
  - signal and wait, urgent wait, or return
- **keep**
  - signal and continue or automatic signalling
Atomicity of Control Transfer

- consequence for the **ownership structure** of monitor and signaller:
  - change
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- with an **indivisible change** in ownership a signallee has guarantee on the still effective invalidation of its waiting condition

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  - **wait**
    - only for one out of possibly many signalled processes
    - if applicable, the order of process resumption is undefined
    - a resumed signallee may change the condition for the others
    - makes re-evaluation of the waiting condition necessary

  $\iff$ **while** (!condition), wait: tolerant to false signalisation

Atomicity of Control Transfer

- consequence for the **ownership structure** of monitor and signaller:
  - change  ■ signal and wait, urgent wait, or return
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- with an **indivisible change** in ownership a signallee has guarantee on the still effective invalidation of its waiting condition:

  **urgent wait**  ■ exactly for the single signalled process
  ■ by definition, the process to be resumed is predetermined
  ■ no other process can re-establish the waiting condition
  ■ makes re-evaluation of the waiting condition unnecessary
  $$\text{if} \; (!\text{condition}), \text{wait}: \text{intolerant to false signalisation}$$

  **return**  ■ *ditto*
consequence for the **ownership structure** of monitor and signaller:

- **change** signal and wait, urgent wait, or return
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  - makes re-evaluation of the waiting condition unnecessary

  ↔ if (!condition), wait: intolerant to false signalisation

- **return** ditto

keeping ownership by the signaller means fewer context switches and, thus, less background noise but higher (signal) allocation latency
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Summary
typedef struct monitor {
    semaphore_t mutex; /* initial {1} */
#ifdef __FAME_MONITOR_SIGNAL_URGENT_WAIT__
    lineup_t urgent;  /* urgent waiting signallers */
#endif
} monitor_t;

typedef struct condition {
    monitor_t *guard; /* enclosing monitor */
    lineup_t event;  /* signal-等待ing processes */
} condition_t;
Fundamental Data Types

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typedef struct condition {
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    lineup_t event; /* signal-awaiting processes */
} condition_t;

Data type used for keeping track of waiting processes (cf. p. 18):

typedef struct lineup {
    int count; /* number of waiting processes */
    event_t crowd; /* wait-for event */
} lineup_t;
Monitor Procedures

1. extern void lockout (monitor_t *); /* enter monitor */
2. extern void proceed (monitor_t *); /* leave monitor */
3. extern void watch (condition_t *); /* wait on signal */
4. extern void spark (condition_t *); /* signal condition */

Consider these operations an additional run-time system element for a compiler of a “concurrent C-like” programming language:

- Calls to lockout and proceed will be automatically generated as part of the pro- and epilogue of the respective monitor procedure.
- Similarly, calls to watch and spark will be generated for the corresponding applications of condition variables.
- In addition, instances of type monitor and condition will be automatically ejected, too, by the code generation process of such a compiler.
Monitor Procedures

Functional Interface

1. `extern void lockout(monitor_t *); /* enter monitor */`
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Consider these operations an additional **run-time system** element for a compiler of a “concurrent C-like” programming language:

- Calls to `lockout` and `proceed` will be automatically generated as part of the pro- and epilogue of the respective monitor procedure.
- Similarly, calls to `watch` and `spark` will be generated for the corresponding applications of condition variables.
- In addition, instances of type `monitor` and `condition` will be automatically ejected, too, by the code generation process of such a compiler.

Further improvements [12, p. 551] are imaginable to also better reflect the different signalling semantics.
a bounded buffer is controlled by a pair of condition variables:

```c
#include "monitor.h"

#define BUF_SIZE 80

typedef struct buffer {
    condition_t space; /* control of reusables */
    condition_t data; /* control of consumables */
    char store[BUF_SIZE]; /* reusable resource */
    unsigned in, out; /* store housekeeping */
    unsigned count; /* wait/signal condition */
} buffer_t;
```
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instantiation of the necessary monitor and condition variables:

static monitor_t storehouse = {1}; /* monitor is free */
static buffer_t buffer = {
    &storehouse, &storehouse /* link to monitor */
};
handmade monitor procedure to put one item into the buffer:

```c
void put(char item) {
    lockout(&storehouse); /* procedure prologue */
    {
        while (buffer.count == BUF_SIZE)
            watch(&buffer.space);

        buffer.store[buffer.in] = item;
        buffer.in = (buffer.in + 1) % BUF_SIZE;
        buffer.count += 1;

        spark(&buffer.data);
    }
    proceed(&storehouse); /* procedure epilogue */
}
```

2–3   ■ monitor entrance, usually to be generated by a compiler
4–11  ■ body of monitor procedure, to be programmed by a human
12–13 ■ monitor exit, usually to be generated by a compiler
handmade monitor procedure to get one item out of the buffer:

```c
char get() {
    char item;

    lockout(&storehouse); /* procedure prologue */
    {
        while (buffer.count == 0) watch(&buffer.data);

        item = buffer.store[buffer.out];
        buffer.out = (buffer.out + 1) % BUF_SIZE;
        buffer.count -= 1;

        spark(&buffer.space);
    }
    proceed(&storehouse); /* procedure epilogue */

    return item;
}
```

- monitor entrance and exit and body of monitor procedure as before
Event Queue

Classical Technique for Monitor Implementation

A classic monitor implementation on **event queue** basis is considered:

```c
typedef struct event { } event_t;

extern void catch(event_t*); /* expect event */
extern int coast(); /* wait for event */
extern int await(event_t*); /* catch & coast */
extern int cause(event_t*); /* signal event */
```

- Catch makes the process unsusceptible against lost wakeup:
  - i) non-effective in case of cooperative scheduling, otherwise
  - ii) inhibits preemption or dispatching (SMP), resp., or
  - iii) notifies event sensibility to potential signalers (cause)

Ensures that a process in running state is detectable by cause:
- Coast if the process was not yet detected by cause, blocks on the event otherwise, clears the catch state and keeps the process running.
- Await blocks the process on the specified event (i.e., signalled by cause).

Cause unblocks processes (tentatively) waiting on the specified event based on this abstraction, waitlist operations can be composed next.
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extern void catch(event_t*);  /* expect event */
extern int coast();            /* wait for event */
extern int await(event_t*);    /* catch & coast */
extern int cause(event_t*);    /* signal event */
```

- **catch** makes the process unsusceptible against **lost wakeup**:
  - i. non-effective in case of cooperative scheduling, otherwise
  - ii. inhibits preemption or dispatching (SMP), resp., or
  - iii. notifies event sensibility to potential signalers (**cause**)

- **coast** if the process was not yet detected by **cause**, blocks on the event
  - otherwise, clears the catch state and keeps the process running

- **await** blocks the process on the specified event (i.e., signalled by **cause**)

a classic monitor implementation on **event queue** basis is considered:

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typedef struct event { } event_t;
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**catch** makes the process unsusceptible against **lost wakeup**:

- non-effective in case of cooperative scheduling, otherwise
- inhibits preemption or dispatching (SMP), resp., or
- notifies event sensibility to potential signalers (**cause**)

**coast** ensures that a process in running state is detectable by **cause**

- if the process was not yet detected by **cause**, blocks on the event
- otherwise, clears the catch state and keeps the process running

**await** blocks the process on the specified event (i.e., signalled by **cause**)

**cause** unblocks processes (tentatively) waiting on the specified event
a classic monitor implementation on **event queue** basis is considered:

```c
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extern void catch(event_t*);    /* expect event */
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- **catch** makes the process unsusceptible against **lost wakeup**:
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- **coast** if the process was not yet detected by **cause**, blocks on the event otherwise, clears the catch state and keeps the process running

- **await** blocks the process on the specified event (i.e., signalled by **cause**) based on this abstraction, **waitlist operations** can be composed next
inline void brace(lineup_t *this) {
    this->count++; /* one more delaying */
    catch(&this->crowd); /* ready to block/continue */
}

inline void shift(lineup_t *this) {
    coast(); /* conditionally block */
    this->count--; /* one less delaying */
}

inline void defer(lineup_t *this) {
    this->count++; /* one more delaying */
    await(&this->crowd); /* unconditionally block */
    this->count--; /* one less delaying */
}

inline int level(lineup_t *this) {
    return this->count; /* number delayed procs. */
}
inline int avail(lineup_t *this) {
    if (this->count > 0) /* any delayed? */
        cause(&this->crowd); /* yes, unblock */
    return this->count;
}

inline int evoke(lineup_t *this) {
    int count = this->count; /* save state */
    if (count > 0) /* any delayed? */
        admit(elect(&this->crowd)); /* yes, seize CPU */
    return count;
}
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    if (this->count > 0) /* any delayed? */
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note that evoke forces a process switch within a still locked monitor
as the case may be, the resuming process then unlocks the monitor
consequently, the monitor should not be protected by a mutex object
inline int avail(lineup_t *this) {
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}

Note that `evoke` forces a process switch within a still locked monitor:
- As the case may be, the resuming process then unlocks the monitor.
- Consequently, the monitor should not be protected by a `mutex` object.

Thereafter, a cut-through to basic process management is appropriate:
- **elect** selects the next process, if any, from the specified waitlist.
- **admit** books the current process (signaller) “ready to run” and makes the elected process (signallee) available to the processor.
Signalling Semantics

as has been foreshadowed by a **configuration option** (cf. p. 12):

- signal and continue  ■ Mesa-style [14]
- signal and return   ■ Hansen-style as to Concurrent Pascal [8, 9]
- signal and wait     ■ Hansen-style as originally proposed [7]
- signal and urgent wait ■ Hoare-style [12]
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- as indicated by the data type (cf. p. 12), the designs presented next are typical for an approach using **event queues**
  - note that signalling is non-effective if no process is waiting on it (cf. p. 8)
  - this excludes the use of semaphores, as *V* leaves a signal trace
    - *V* always has an effect: at least it increases the semaphore value
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    - $V$ always has an effect: at least it increases the semaphore value

- lightweight and efficient monitor operation benefits from **cross-layer optimisation** in constructive means
  - from language- to system-level run-time system to operating system
void lockout(monitor_t *this) { P(&this->mutex); }

void proceed(monitor_t *this) { V(&this->mutex); }

void watch(condition_t *this) {
  brace(&this->event); /* prepare to release */
  proceed(&this->guard); /* release monitor */
  shift(&this->event); /* release processor */
}

void spark(condition_t *this) {
  avail(&this->event); /* try signal process */
}
Signal and Continue

```c
void lockout(monitor_t *this) { P(&this->mutex); }

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}

void spark(condition_t *this) {
    avail(&this->event); /* try signal process */
}
```

as `watch` needs to release the monitor before releasing the processor, a potential **race condition** must be prevented

- `brace` notifies upcoming blocking of the current process to the system
- this is to assure the current process of progress guarantee as soon as the monitor was released and another process is enabled to `spark` a signal
Signal and Return

```c
void lockout(monitor_t *this) { P(&this->mutex); }

void proceed(monitor_t *this) { V(&this->mutex); }

void watch(condition_t *this) {
    brace(&this->event); /* prepare to release */
    proceed(this->guard); /* release monitor */
    shift(&this->event); /* release processor */
}

void spark(condition_t *this) {
    if (!avail(&this->event)) /* no watcher waiting? */
        proceed(this->guard); /* release monitor */
}
```
Signal and Return

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void lockout(monitor_t *this) { P(&this->mutex); }

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```

- calling `spark` must be the **final action** within a monitor procedure
- similar to the `continue` statement of Concurrent Pascal [9, p. 205]
Signal and Return

void lockout(monitor_t *this) { P(&this->mutex); }  

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- calling `spark` must be the **final action** within a monitor procedure
- similar to the `continue` statement of Concurrent Pascal [9, p. 205]
- otherwise, the signaller could proceed inside an unlocked monitor if no signallees was detected
void lockout(monitor_t *this) { P(&this->mutex); }

void proceed(monitor_t *this) { V(&this->mutex); }

void watch(condition_t *this) {
    brace(&this->event); /* prepare to release */
    proceed(this->guard); /* release monitor */
    shift(&this->event); /* release processor */
}

void spark(condition_t *this) {
    if (evoke(&this->event)) /* signallees done! */
        lockout(this->guard); /* re-enter monitor */
}
void lockout(monitor_t *this) {
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void watch(condition_t *this) {
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}

as the case may be, the signaller blocks on a condition variable:

— in case of a pending signalleee, the signaller interrupts execution
— a process switch inside the looked monitor takes place (cf. p.19)
— in the further course, another process unlocks/releases the monitor

— accordingly, the signaller must make sure to relock the monitor
void lockout(monitor_t *this) { P(&this->mutex); }

void proceed(monitor_t *this) {
    if (!avail(&this->urgent)) /* no urgent waiting */
        V(&this->mutex); /* release monitor */
}
void lockout(monitor_t *this) { P(&this->mutex); }

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in contrast to the solutions discussed before, **exit** from the monitor needs to check two waitlists for pending processes:

i. the re-entrance waitlist (**urgent**), but only in case of urgent processes

ii. the entrance waitlist (**mutex**), else
void lockout(monitor_t *this) { P(&this->mutex); }

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- By definition, urgent processes interrupted own operation in favour of processes pending for event handling
- **Urgent processes caused events, recently, and want be resumed, expressly**
in contrast to the solutions discussed before, exit from the monitor needs to check two waitlists for pending processes:

i the re-entrance waitlist (urgent), but only in case of urgent processes
ii the entrance waitlist (mutex), else

by definition, urgent processes interrupted own operation in favour of processes pending for event handling

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indicator of urgent waiting processes is a counter by means of which the number of process blockings is registered
void watch(condition_t *this) {
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}

void spark(condition_t *this) {
    if (avail(&this->event))    /* watcher waiting? */
        defer(&this->guard->urgent);   /* urgent wait */
}
void watch(condition_t *this) {
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as the case may be, spark makes the current process urgent waiting

- a preferential queue (Ger. Vorzugswarteschlange) is used to this end
- defer results in a process switch from line 9 to line 4, back and forth
- from spark to shift, out of watch, and back to spark at monitor exit
void watch(condition_t *this) {
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- a **preferential queue** (Ger. Vorzugswarteschlange) is used to this end
- defer results in a process switch from line 9 to line 4, back and forth from spark to shift, out of watch, and back to spark at monitor exit
- urgent waiting processes keep proceed off from unlocking the monitor
- when the monitor owner returns or blocks, an urgent process resumes
- as a consequence, the monitor should not be protected by a **mutex**
Process States and State Transitions

- ready ↔ running
- running → blocked
- blocked → ready

- wait (←), scheduler (↔)
- urgent wait
- all, iff effective signalling (i.e., waiting signallee)
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- all (→), signallee released monitor (←)
- all, no overlap of signaller and signallee

cf. [17, p. 27]
Process States and State Transitions

cf. [17, p. 27]

- ready ↔ running
- running ↔ blocked
- blocked → ready
- running ↔ pending
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- wait (←), scheduler (↔)
- urgent wait (→), wait (←, iff full preemptive)
- all, iff effective signalling (i.e., waiting signallee)
- all (→), signallee released monitor (←)
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Preface

Fundamentals
   Mutual Exclusion
   Condition Variable
   Signalling Semantics

Implementation
   Data Structures
   Use Case
   Operations

Summary
in linguistic terms, a monitor is a language notation for a critical region and one or more associated shared variables
- a shared class [7, p. 226–232], inspired by SIMULA 67 [3]
- linked with event queues [6] or condition variables [12], resp.
- differentiated by several signalling semantics and conventions [13]

in operating-system terms, a monitor is a means of control of the scheduling of resources among interacting processes
- mutual-exclusive use of non-preemptable reusable resources
- coordinated use of consumable resources according to a causal chain

in system-programming terms, a monitor can be readily implemented by a binary semaphore and event queues
- note that a mutex is to be rejected for the signal and wait variants

Hansen

In practice, monitors would, of course, be implemented by uninterruptible operations in assembly language. [11, p. 31]
Résumé

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handmade monitor procedures are prone to absence of unblocking the monitor before return: `proceed` is missing or will never be executed

object constructors/destructors find a remedy [16, p. 220, Sec. 6.1.4]

```cpp
class atomic {
    static monitor_t sluice;

public:
    atomic() { lockout(&sluice); }
    ~atomic() { proceed(&sluice); }
};
```

exit from the scope of an `atomic` instance implicitly performs `proceed`:

```cpp
int64_t inc64(int64_t *i) {
    atomic inc; return *i + 1;
}
```

a technique that is also known as the `scoped locking` pattern [15]