

Concurrent Systems

Nebenläufige Systeme

VIII. Monitor

Wolfgang Schröder-Preikschat

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Outline

Preface

Fundamentals

Mutual Exclusion
Condition Variable
Signalling Semantics

Implementation

Data Structures
Use Case
Operations

Summary



Agenda

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Subject Matter

- discussion on **abstract concepts** as to “a shared variable and the set of meaningful operations on it” [7, p. 121]:
 - monitor** ■ a *language notation*, initially denoted by **critical region** [6, 7]
 - associates a set of procedures with a shared variable
 - enables a compiler to:
 - i check that only these procedures are carried out on that variable
 - ii ensure that the respective operations exclude each other in time
 - condition** ■ 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
- 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
- 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]
 - 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]
- yet, the subject matter is beyond programming-language constructs
 - 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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Class Concept Expanded by Coordination

- key aspect is to facilitate solely indirect access to shared variables by means of **monitor procedures**
 - 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 \rightsquigarrow *lockout* simultaneous processes
 - on behalf of the occupying process, at return the **procedure epilogue** releases the monitor again \rightsquigarrow *proceed* locked processes, if any
 - 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 abnormality¹
 - 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 used¹

¹Thinking of a multi-language system.



Intentional Process Delay

- multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit
 - Hansen** ■ proposed to attach a shared variable to an *event* [6, p. 577]
 - with *cause* and *await* as intrinsic functions for event signalling
 - Hoare** ■ proposed a non-attached *condition variable* [12, p. 550]
 - with *wait* and *signal* as intrinsic functions for condition handling
- in operating-system terms, per variable an **event queue** of processes waiting by reason of a certain condition
 - sticking point is how the event queue is being acted upon
 - Hansen** ■ all processes can be transferred to the monitor waitlist (*cause*)
 - suggests that the former take priority over the latter [7, p. 118]
 - remodels his idea to a *single-process waitlist* [8, 9]: **all \equiv one**
 - Hoare** ■ exactly one out of the waiting processes is selected (*signal*)
 - decrees that the chosen one is immediately resumed [12, p. 550]
 - but signalling is non-effective (void) if no process would be waiting on it
- in this spirit, the **signalling convention** makes the wide difference and affects structuring of monitor-based non-sequential programs [13]



- 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
 - urgent wait**
 - join **preferential queue** and leave the monitor
 - resume one signalled process (first come, first served)
 - re-enter the monitor, enjoy priority over entrant processes
 - return**
 - leave the monitor and resume the single signalled process
 - continue**
 - carry on holding the monitor, keep inside the procedure
 - resume all signalled processes (one at a time) at return
- 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)
- a main issue is the **control transfer** between signaller and signallee

Waiting inside a monitor

Without leaving the monitor, another process is unable to signal.



- consequence for the **ownership structure** of monitor and signaller:
 - change**
 - signal and wait, urgent wait, or return
 - keep**
 - signal and continue or automatic signalling
- with an **indivisible change** in ownership a signallee has guarantee on the still effective invalidation of its waiting condition:
 - 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
 - ↪ **while** (!condition), wait: **tolerant to false signalisation**
 - 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
 - ↪ **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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Fundamental Data Types I

- abstraction for **mutual exclusion** of monitor-procedure executions:


```

1 typedef struct monitor {
2     semaphore_t mutex; /* initial {1} */
3 #ifdef __FAME_MONITOR_SIGNAL_RETURN__
4     bool elide; /* leave monitor locked */
5 #endif
6 #ifdef __FAME_MONITOR_SIGNAL_URGENT_WAIT__
7     lineup_t prime; /* urgent waiting signallers */
8 #endif
9 } monitor_t;
            
```

 - mandatory feature is a *binary semaphore*
 - further attributes as optional feature, depending on **signalling semantics**

- data type used for keeping track of **waiting processes**:

```

1 typedef struct lineup {
2     int count; /* number of waiting processes */
3     semaphore_t event; /* wait-for event: initial {0} */
4 } lineup_t;
            
```



- abstraction for **condition synchronisation** of interacting processes:

```

1 typedef struct condition {
2     monitor_t *guard; /* surrounding monitor */
3     lineup_t queue; /* event awaiting list */
4 #ifdef __FAME_MONITOR_SIGNAL_WAIT__
5     lineup_t prime; /* urgent waiting signallers */
6 #endif
7 } condition_t;

```

- mandatory features are:
 - a suitable link to the surrounding monitor object
 - a queue for processes expecting cancellation of their waiting condition
- further attributes as optional feature, depending on **signalling semantics**
- a condition variable is usually required for each waiting condition
 - their definition is part of the non-sequential program
 - as well as the typically problem-specific formulation of this condition



```

1 extern void occupy(monitor_t*); /* enter monitor */
2 extern void vacate(monitor_t*); /* leave monitor */
3
4 extern void comply(condition_t*); /* wait on signal */
5 extern void cancel(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 `occupy` and `vacate` will be automatically generated as part of the pro- and epilogue of the respective monitor procedure
 - similarly, calls to `comply` and `cancel` will be generated for the corresponding applications of condition variables
 - in addition, instances of type `monitor` and `condition` are 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



Consolidating Example I

- a bounded buffer is controlled by a **pair** of condition variables:

```

1 #include "monitor.h"
2
3 #define BUF_SIZE 80
4
5 typedef struct buffer {
6     condition_t space; /* control of reusables */
7     condition_t data; /* control of consumables */
8     char store[BUF_SIZE]; /* reusable resource */
9     unsigned in, out; /* store housekeeping */
10    unsigned count; /* wait/signal condition */
11 } buffer_t;

```

- instantiation of the necessary monitor and condition variables:

```

1 static monitor_t storehouse = {1}; /* monitor is free */
2 static buffer_t buffer = {
3     {&storehouse}, {&storehouse} /* link to monitor */
4 };

```



Consolidating Example II

- handmade monitor procedure to put one item into the buffer:

```

1 void put(char item) {
2     occupy(&storehouse); /* procedure prologue */
3     {
4         while (buffer.count == BUF_SIZE)
5             comply(&buffer.space); /* await event */
6
7         buffer.store[buffer.in] = item;
8         buffer.in = (buffer.in + 1) % BUF_SIZE;
9         buffer.count += 1;
10
11        cancel(&buffer.data); /* cause event */
12    }
13    vacate(&storehouse); /* procedure epilogue */
14 }

```

- 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:

```

1 char get() {
2     char item;
3
4     occupy(&storehouse);    /* procedure prologue */
5     {
6         while (buffer.count == 0) comply(&buffer.data);
7
8         item = buffer.store[buffer.out];
9         buffer.out = (buffer.out + 1) % BUF_SIZE;
10        buffer.count -= 1;
11
12        cancel(&buffer.space);
13    }
14    vacate(&storehouse);    /* procedure epilogue */
15
16    return item;
17 }

```

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

- 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]
- some reflect **improvements** as proposed by Hoare [12, p. 551, 1.–4.]
 - starting point was the strict approach of *signal and urgent wait* monitor
 - here, the discussion is in the order as to increasing complexity/overhead
- as indicated by the data type (cf. p. 12), the designs presented next are typical for an approach using **semaphores**
 - note that signalling is non-effective if no process is waiting on it (cf. p. 8)
 - this requires caution when using semaphores, as *V* leaves a signal trace
 - *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

Signal and Continue

```

1 void occupy(monitor_t *this) { P(&this->mutex); }
2
3 void vacate(monitor_t *this) { V(&this->mutex); }
4
5 void comply(condition_t *this) {
6     this->queue.count++;    /* sign-in process */
7     vacate(this->guard);    /* release monitor */
8     P(&this->queue.event);    /* delay process */
9     occupy(this->guard);    /* re-acquire monitor */
10    this->queue.count--;    /* sign-out process */
11 }
12
13 void cancel(condition_t *this) {
14     if (this->queue.count > 0) /* any registered? */
15         V(&this->queue.event); /* continue one */
16 }

```

- as comply needs to release the monitor before delaying the process, a potential **race condition** must be prevented

- still within the monitor, accounting for registered processes

Signal and Return

```

1 void occupy(monitor_t *this) { P(&this->mutex); }
2
3 void vacate(monitor_t *this) {
4     if (this->elide) this->elide = false;
5     else V(&this->mutex);
6 }
7
8 void comply(condition_t *this) {
9     this->queue.count++;    /* sign-in process */
10    vacate(this->guard);    /* release monitor */
11    P(&this->queue.event);    /* delay process */
12    this->queue.count--;    /* sign-out process */
13 }
14
15 void cancel(condition_t *this) {
16     if (this->queue.count > 0) { /* any registered? */
17         this->elide = true;    /* leave locked */
18         V(&this->queue.event); /* continue complier */
19     }
20 }

```

```

1 void occupy(monitor_t *this) { P(&this->mutex); }
2
3 void vacate(monitor_t *this) { V(&this->mutex); }
4
5 void comply(condition_t *this) {
6     this->queue.count++;           /* sign-in process */
7     vacate(this->guard);           /* release monitor */
8     P(&this->queue.event);         /* delay process */
9     this->queue.count--;           /* sign-out process */
10    V(&this->prime.event);         /* urgent continue */
11 }
12
13 void cancel(condition_t *this) {
14     if (this->queue.count > 0) { /* any registered? */
15         V(&this->queue.event);    /* continue one */
16         P(&this->prime.event);    /* urgent delay */
17         occupy(this->guard);     /* re-acquire monitor */
18     }
19 }

```



```

1 void occupy(monitor_t *this) { P(&this->mutex); }
2
3 void vacate(monitor_t *this) {
4     if (this->prime.count > 0) /* urgent waiting? */
5         V(&this->prime.event); /* yes, continue that */
6     else
7         V(&this->mutex);      /* no, release monitor */
8 }

```

- in contrast to the solutions discussed before, **exit** from the monitor needs to check two waitlists for pending processes
 - i the re-entrance waitlist (prime), 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
 - urgent processes caused events, recently, and want be resumed, expressly
- indicator of urgent waiting processes is a counter by means of which the number of process blockings is registered



Signal and Urgent Wait II

Condition Handling

```

1 void comply(condition_t *this) {
2     this->queue.count++;           /* sign-in process */
3     vacate(this->guard);           /* release monitor */
4     P(&this->queue.event);         /* delay process */
5     this->queue.count--;           /* sign-out process */
6 }
7
8 void cancel(condition_t *this) {
9     if (this->queue.count > 0) { /* any registered? */
10        this->guard->prime.count++; /* sign-in urgent */
11        V(&this->queue.event);     /* continue queued */
12        P(&this->guard->prime.event); /* urgent wait */
13        this->guard->prime.count--; /* sign-out urgent */
14    }
15 }

```

- as the case may be, comply makes the current process urgent waiting
 - a **preferential queue** (Ger. *Vorzugswarteschlange*) is used to this end
- urgent waiting processes proceed with monitor locked (cf. p. 22)



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- 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 un-interruptible operations in assembly language. [11, p. 31]

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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]

```

1 class atomic {
2     static monitor_t sluice;
3 public:
4     atomic() { occupy(&sluice); };
5     ~atomic() { vacate(&sluice); };
6 };

```

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

```

1 int64_t inc64(int64_t *i) {
2     atomic inc; return *i + 1;
3 }

```

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



- abstractions for **mutual exclusion** of monitor-procedure executions and for **condition synchronisation** of interacting processes

- both remain syntactically identical, but not semantically
- in the given example they are reused (cf. p. 12)
 - here, however, without forced long jumps to “signal and return”
 - a certain programming convention is adopted instead (cf. p. 36)
- the main change is the list of waiting processes. . .

- data type used for keeping track of **waiting processes**:

```

1 typedef struct lineup {
2     int count;           /* number of waiting processes */
3     event_t event;      /* wait-for event */
4 } lineup_t;

```



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

```

1 typedef struct event { } event_t;;
2
3 extern void catch(event_t*);    /* expect event */
4 extern int  coast();           /* wait for event */
5 extern int  await(event_t*);    /* catch & coast */
6 extern int  cause(event_t*);    /* signal event */

```

- 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 signallers (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 (signalled by cause)

- cause** unblocks processes (tentatively) waiting on the specified event

- based on this abstraction, **waitlist operations** can be composed next



```

1 inline void brace(lineup_t *this) {
2     this->count++;           /* one more delaying */
3     catch(&this->event);     /* ready to block/continue */
4 }
5
6 inline void shift(lineup_t *this) {
7     coast();                /* conditionally block */
8     this->count--;          /* one less delaying */
9 }
10
11 inline void defer(lineup_t *this) {
12     this->count++;          /* one more delaying */
13     await(&this->event);    /* unconditionally block */
14     this->count--;          /* one less delaying */
15 }
16
17 inline int level(lineup_t *this) {
18     return this->count;     /* number delayed procs. */
19 }

```



```

1 inline int avail(lineup_t *this) {
2     if (this->count > 0)    /* any delayed? */
3         cause(&this->event); /* yes, unblock */
4     return this->count;
5 }
6
7 inline int evoke(lineup_t *this) {
8     int count = this->count; /* save state */
9     if (count > 0)          /* any delayed? */
10        admit(elect(&this->event)); /* yes, seize CPU */
11    return count;
12 }

```

- 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
- thereto, 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



Signal and Continue

```

1 void occupy(monitor_t *this) { P(&this->mutex); }
2
3 void vacate(monitor_t *this) { V(&this->mutex); }
4
5 void comply(condition_t *this) {
6     brace(&this->queue);    /* prepare to release */
7     vacate(this->guard);    /* release monitor */
8     shift(&this->queue);    /* release processor */
9 }
10
11 void cancel(condition_t *this) {
12     avail(&this->queue);    /* try signal process */
13 }

```

- as comply 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 signal



Signal and Return

```

1 void occupy(monitor_t *this) { P(&this->mutex); }
2
3 void vacate(monitor_t *this) { V(&this->mutex); }
4
5 void comply(condition_t *this) {
6     brace(&this->queue);    /* prepare to release */
7     vacate(this->guard);    /* release monitor */
8     shift(&this->queue);    /* release processor */
9 }
10
11 void cancel(condition_t *this) {
12     if (!avail(&this->queue)) /* no watcher waiting? */
13         vacate(this->guard); /* release monitor */
14 }

```

- calling cancel 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 signallee was detected



```

1 void occupy(monitor_t *this) { P(&this->mutex); }
2
3 void vacate(monitor_t *this) { V(&this->mutex); }
4
5 void comply(condition_t *this) {
6     brace(&this->queue);           /* prepare to release */
7     vacate(this->guard);           /* release monitor */
8     shift(&this->queue);           /* release processor */
9 }
10
11 void cancel(condition_t *this) {
12     if (evoke(&this->queue))       /* signallee done! */
13         occupy(this->guard);       /* re-enter monitor */
14 }

```

- as the case may be, the signaller blocks on a condition variable:
 - in case of a pending signallee, the signaller interrupts execution
 - a process switch inside the locked monitor takes place (cf. p. 34)
 - in the further course, another process unlocks/releases the monitor
 - accordingly, the signaller must make sure to **relock** the monitor



```

1 void occupy(monitor_t *this) { P(&this->mutex); }
2
3 void vacate(monitor_t *this) {
4     if (!avail(&this->prime))     /* no urgent waiting */
5         V(&this->mutex);           /* release monitor */
6 }

```

- in contrast to the solutions discussed before, **exit** from the monitor needs to check two waitlists for pending processes:
 - the re-entrance waitlist (prime), but only in case of urgent processes
 - the entrance waitlist (mutex), else
- 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
- indicator of urgent waiting processes is a counter by means of which the number of process blockings is registered



Signal and Urgent Wait II

Condition Handling

```

1 void comply(condition_t *this) {
2     brace(&this->queue);           /* prepare to release */
3     vacate(this->guard);           /* release monitor */
4     shift(&this->queue);           /* release processor */
5 }
6
7 void cancel(condition_t *this) {
8     if (avail(&this->queue))       /* watcher waiting? */
9         defer(&this->guard->prime); /* urgent wait */
10 }

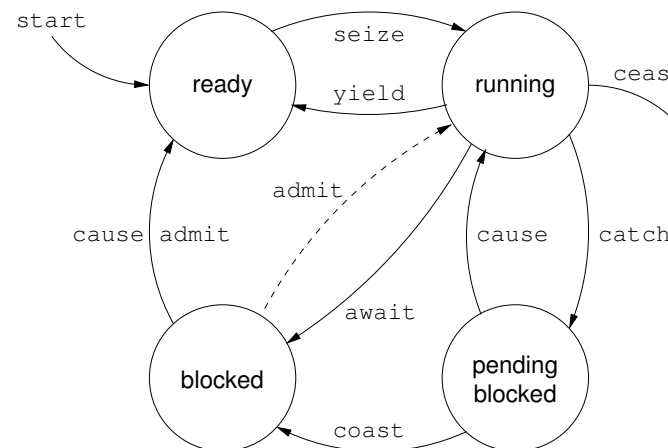
```

- as the case may be, cancel 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 cancel to shift, out of comply, and back to cancel at monitor exit
- urgent waiting processes proceed with monitor locked (cf. p. 38)
 - 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

cf. [17, p. 27]



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

