Concurrent Systems

*Nebenläufige Systeme*

VIII. Monitor

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— Selbststudium —
Agenda

Preface

Fundamentals
  Mutual Exclusion
  Condition Variable
  Signalling Semantics

Implementation
  Data Structures
  Use Case
  Operations

Summary
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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

**monitor** enables a compiler to:

- check that only these procedures are carried out on that variable
- ensure that the respective operations exclude each other in time

**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

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  - too low level, programmers must keep track of all calls to $P$ and $V$
  - although different, used for both uni- and multilateral synchronisation
Motivation

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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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- 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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  - inspired by SIMULA 67 [4, 3]
  - first implemented in Concurrent Pascal [9]
  - 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.
Outline

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- Mutual Exclusion
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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 \( \rightsarrow \textit{lockout} \) simultaneous processes
- on behalf of the occupying process, at return the procedure epilogue releases the monitor again \( \rightsarrow \textit{proceed} \) locked processes, if any
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- only infinite loops or hardware failures may prevent epilogue execution
- only constructs beyond the frame of reference may force abnormality$^1$

---

$^1$Thinking of a multi-language system.
Class Concept Expanded by Coordination

- key aspect is to facilitate solely **indirect access** to shared variables by means of **monitor procedures**
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  - in logical respect, deadlocks due to programmed absence of unblocking of critical sections are impossible

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- 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

\(^1\)Thinking 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.
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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.

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.

A sticking point is how the event queue is being acted upon.

Hansen suggests that all processes can be transferred to the monitor waitlist (cause).

Hoare suggests that the former take priority over the latter [7, p. 118]

Remodels his idea to a single-process waitlist [8, 9]:

All ≡ one process of the waiting processes is selected (signal).

Hoare 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].
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- in this spirit, the **signalling convention** makes the wide difference and affects structuring of monitor-based non-sequential programs [13]
explicit signal operation assumed
Signalling Conventions

explicit signal operation assumed, **signal-and-**$\phi$, with $\phi$ 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

- **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)
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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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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
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- consequence for the **ownership structure** of monitor and signaller:
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  - 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
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    - makes re-evaluation of the waiting condition necessary

  - while (!condition), wait: tolerant to false signalisation
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  **urgent wait**

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  - 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

  \[ \text{if} (!\text{condition}), \text{wait: intolerant to false signalisation} \]

  **return** ditto
Atomicity of Control Transfer

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

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  ⇔ 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-awaiting processes */
} condition_t;
Fundamental Data Types

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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

Functional Interface

```c
extern void lockout(monitor_t*); /* enter monitor */
extern void proceed(monitor_t*); /* leave monitor */
extern void watch(condition_t*); /* wait on signal */
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

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

```c
typedef struct event { } event_t;

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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 */
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**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**
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**:
  1. non-effective in case of cooperative scheduling, otherwise
  2. inhibits preemption or dispatching (SMP), resp., or
  3. 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
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- **coast** ensures that a process in running state is detectable by **cause**
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- **await** blocks the process on the specified event (i.e., signalled by **cause**)

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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;
}
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
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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
- 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
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]

some reflect
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starting point was the strict approach of
signal and urgent wait
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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
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note that signalling is non-effective if no process is waiting on it (cf. p. 8)
leaves a signal trace
always has an effect: at least it increases the semaphore value
lightweight and efficient monitor operation benefits from
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from language- to system-level run-time system to operating system
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  - note that signalling is non-effective if no process is waiting on it (cf. p. 8)
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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
Signal and Continue

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

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void watch(condition_t *this) {
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void spark(condition_t *this) {
    if (!avail(&this->event)) /* no watcher waiting? */
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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

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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 signallee was detected
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void watch(condition_t *this) {
    brace(&this->event); /* prepare to release */
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    shift(&this->event); /* release processor */
}

void spark(condition_t *this) {
    if (evoke(&this->event)) /* signallee done! */
        lockout(this->guard); /* re-enter monitor */
}
Signal and Wait

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

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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 signallee, 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
Signal and Urgent Wait 1

Monitor Entrance/Exit

1

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

2

3

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

4

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 their own operation in favor of processes pending for event handling.

Urgent processes caused events recently and want to be resumed, expressly.

The indicator of urgent waiting processes is a counter by means of which the number of process blockings is registered.
### Signal and Urgent Wait I

Monitor Entrance/Exit

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    if (avail(&this->event)) /* watcher waiting? */
        defer(&this->guard->urgent); /* urgent wait */
}

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
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
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Process States and State Transitions

cf. [17, p. 27]

- start
- ready
- seize
- running
- yield
- cease
- blocked
- await

ready $\leftrightarrow$ running
running $\rightarrow$ blocked
blocked $\rightarrow$ ready

- wait ($\leftarrow$), scheduler ($\leftrightarrow$)
- urgent wait
- all, iff effective signalling (i.e., waiting signallee)
Process States and State Transitions

### Diagram:

- **Ready**
  - Start
  - Seize
  - Yield
- **Running**
  - Cease
- **Blocked**
  - Cause
  - Await
  - Coast
- **Pending**
  - Cause
  - Catch
  - Blocks

### States and Transitions:

- **Ready ↔ Running**
  - Wait (←), Scheduler (↔)

- **Running → Blocked**
  - Urgent Wait

- **Blocked → Ready**
  - All, Iff **Effective Signalling** (i.e., Waiting Signallee)

- **Running ↔ Pending**
  - All (→), Signallee Released Monitor (←)

- **Pending → Blocked**
  - All, No Overlap of Signaller and Signallee

---

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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 signallees)
- all (→), signallees released monitor (←)
- all, no overlap of signaller and signallees
Outline

Preface

Fundamentals
  Mutual Exclusion
  Condition Variable
  Signalling Semantics

Implementation
  Data Structures
  Use Case
  Operations

Summary
Résumé

- 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]
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*In: Yeh, R. T. (Hrsg.) ; Ramamoorthy, C. V. (Hrsg.): Proceedings of the 2nd International Conference on Software Engineering (ICSE ’76).*


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]