Concurrent Systems

Nebenläufige Systeme

VIII. Monitor

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December 11, 2018
Agenda

Preface

Fundamentals
  Mutual Exclusion
  Condition Variable
  Signalling Semantics

Implementation
  Data Structures
  Use Case
  Operations

Summary
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- used to indicate and control a particular wait mode
- for the respective process inside the monitor
Subject Matter

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  ■ explanation of various styles: Hansen, Hoare, Concurrent Pascal, Mesa
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- 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
  - critical region
  - event variable
  - path expressions

  - idea for structuring control of sharing [5, p. 135–136]
  - mutual exclusive use of a shared variable [6]
  - a shared variable associated with an event queue [6]
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- **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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- 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]

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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key aspect is to facilitate solely indirect access to shared variables by means of monitor procedures.
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- On behalf of the calling process, the *procedure prologue* applies for exclusive occupation of the monitor \(\leadsto lockout\) simultaneous processes.  
- On behalf of the occupying process, at return the *procedure epilogue* releases the monitor again \(\leadsto proceed\) locked processes, if any.
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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  - 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

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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

\(^{1}\)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

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. The 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 process. 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].
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Signalling Conventions

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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

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.
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**urgent wait**

- join **preferential queue** and leave the monitor
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  - **return** leave the monitor and resume the single signalled process
explicit signal operation assumed, *signal-and*-φ, with φ indicating the behaviour of the signalling process as follows:

continue
- carry on holding the monitor, keep inside the procedure
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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**
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  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
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  **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*
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  - keep
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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-awaiting processes */
}

condition_t;
Fundamental Data Types

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typedef struct condition {
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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;
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` are automatically ejected, too, by the code generation process of such a compiler
Monitor Procedures

Functional Interface

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` 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.
a bounded buffer is controlled by a pair of condition variables:

```
#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;
```
a bounded buffer is controlled by a pair of condition variables:

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} buffer_t;

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 */
}
```

- **monitor entrance**, usually to be generated by a compiler
- **body** of monitor procedure, to be programmed by a human
- **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;

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

typedef struct event { } event_t ;

extern void catch (event_t *); /* expect 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 signallers (cause)

ensures that a process in running state is detectable by cause
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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 signallers (**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
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 */
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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]
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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
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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
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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 */
}
null
Signal and Return

1. `void lockout(monitor_t *this) { P(&this->mutex); }`
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   brace(&this->event); /* prepare to release */
   proceed(this->guard); /* release monitor */
   shift(&this->event); /* release processor */
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4. `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]
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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
Signal and Wait

Combined Monitor Waitlist

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

2.

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

4.

5. `void watch(condition_t *this) {
   6. brace(&this->event); /* prepare to release */
   7. proceed(this->guard); /* release monitor */
   8. shift(&this->event); /* release processor */
   9. }

10.

11. `void spark(condition_t *this) {
   12. if (evoke(&this->event)) /* signallees done! */
   13.     lockout(this->guard); /* re-enter monitor */
   14. }

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

in case of a pending signallees, 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
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
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.

Urgent processes caused events, recently, and want to be resumed, expressly. Indicator of urgent waiting processes is a counter by means of which the number of process blockings is registered.
in contrast to the solutions discussed before, **exit** from the monitor needs to check two waitlists for pending processes:

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void spark(condition_t *this) {
    if (avail(&this->event))   /* watcher waiting? */
        defer(&this->guard->urgent);   /* urgent wait */
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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
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- 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 proceed with monitor locked (cf. p. 24)
- 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

- **start**: ready
- **seize**: ready → running
- **yield**: running → blocked
- **await**: blocked → ready
- **cease**: running

**State Transitions**

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

- **wait (←)**, scheduler (↔)
- **urgent wait**
- **all, iff effective signalling** (i.e., waiting signallee)

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

- **ready ↔ running**
  - wait (←), scheduler (↔)
  - urgent wait

- **running → blocked**
  - all, iff *effective signalling* (i.e., waiting signallee)

- **blocked → ready**
  - all (→), signallee released monitor (←)

- **running ↔ pending**
  - all, no overlap of signaller and signallee

- **pending → blocked**

---

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Implementation – Operations  
26
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)
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- all, no overlap of signaller and signallee
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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Reference List I


In: Communications of the ACM 9 (1966), Sept., Nr. 9, S. 671–678

In: Acta Informatica 1 (1971), S. 115–138


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]

```c++
1 class atomic {
2    static monitor_t sluice;
3 public:
4    atomic() { lockout(&sluice); }
5    ~atomic() { proceed(&sluice); }
6};
```

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

```c++
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]