Concurrent Systems

Nebenläufige Systeme

VIII. Monitor

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Agenda

Preface

Fundamentals
  Mutual Exclusion
  Condition Variable
  Signalling Semantics

Implementation
  Data Structures
  Use Case
  Operations

Summary
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Summary
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
- critical region
- event variable
- path expressions
- monitor
  - 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]
  - synchronisation rules within type definitions [2]
  - 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.
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 $\leadsto \textit{lockout}$ simultaneous processes
- on behalf of the occupying process, at return the *procedure epilogue* releases the monitor again $\leadsto \textit{proceed}$ 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 abnormality

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

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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]: \( \text{all} \equiv \text{one} \)
    - 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].
Signalling Conventions

- 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

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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

- 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
  - **return**: ditto

- **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

- keeping ownership by the signaller means fewer context switches and, thus, less background noise but higher (signal) allocation latency
Outline

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  Condition Variable
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  Operations

Summary
Fundamental Data Types

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-waiting 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

### 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

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;

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:

```
typedef struct event { } event_t;
```

- `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` 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
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;
}

- 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 **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 **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
- 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

#### Code Snippet

```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 */
}
```

- **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); }

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 */
}

■ 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

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)) /* signalleee done! */
        lockout(this->guard); /* re-enter monitor */
}

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

12   ■ 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

13   ■ 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:

- the re-entrance waitlist (**urgent**), 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
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**
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
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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

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**Hansen**

*In practice, monitors would, of course, be implemented by uninterruptible operations in assembly language.* [11, p. 31]
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handmade monitor procedures are prone to absence of unblocking the monitor before return: \textit{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 \textit{atomic} instance implicitly performs \textit{proceed}:

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

- a technique that is also known as the \textbf{scoped locking} pattern [15]