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

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Summary
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
Motivation

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]

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**

- 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 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

---

\(^1\)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

- 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]
  - remolds his idea to a *single-process waitlist* [8, 9]: \textbf{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]
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

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

\[
\text{wait: tolerant to false signalisation} \quad \iff \quad \text{while (!condition), wait: tolerant to false signalisation}
\]

- 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

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

- 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

```c
typedef struct monitor {
    semaphore_t mutex; /* initial {1} */
#else __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;

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

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

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

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

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;

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;

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

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

- `coast` ensures that a process in running state is detectable by `cause`
  - if the process was not yet detected by `cause`, blocks on the event
  - otherwise, clears the catch state and keeps the process running

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

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

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
therefore, 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

```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
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
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)) /* signallee done! */
        lockout(this->guard); /* re-enter 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:

- 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
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))   /* 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**
Process States and State Transitions

cf. [17, p. 27]

ready ↔ running
running ↔ blocked
blocked → ready
running ↔ pending
pending → blocked

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