Concurrent Systems

Nebenläufige Systeme

VIII. Monitor

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January 7, 2021

Agenda

Outline

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

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]
- 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.

Outline

Class Concept Expanded by Coordination

- key aspect is to facilitate solely <u>indirect access</u> 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 ⇝ *lockout* simultaneous processes
    - on behalf of the occupying process, at return the procedure epilogue releases the monitor again ⇝ *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[1]
  - 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]

[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 — <u>all</u> processes <u>can</u> 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]: <u>all</u> ≡ <u>one</u>
  - Hoare — exactly <u>one</u> out of the waiting processes <u>is</u> 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

cf. [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.

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
  - 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

Outline

Fundamental Data Types I

Semaphore-based

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

```
typedef struct monitor {
    semaphore_t mutex;  /* initial {1} */
#ifdef __FAME_MONITOR_SIGNAL_RETURN__
    bool elide;         /* leave monitor locked */
#endif
#ifdef __FAME_MONITOR_SIGNAL_URGENT_WAIT__
    lineup_t prime;     /* urgent waiting signallers */
#endif
} 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**:

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

Fundamental Data Types II

Event signalling

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

```
typedef struct condition {
    monitor_t *guard;    /* surrounding monitor */
    lineup_t queue;      /* event awaiting list */
#ifdef __FAME_MONITOR_SIGNAL_WAIT__
    lineup_t prime;      /* urgent waiting signallers */
#endif
} condition_t;
```

  - mandatory features are:
    - a suitable ink 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

Monitor Procedures

Functional Interface

```
extern void occupy(monitor_t*);      /* enter monitor */
extern void vacate(monitor_t*);      /* leave monitor */

extern void comply(condition_t*);    /* wait on signal */
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

Bounded Buffer

- 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 = {           /* actual buffer */
    {&storehouse}, {&storehouse}     /* link to monitor */
};
```


Consolidating Example II

Bounded-Buffer Fill

- 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

Consolidating Example III

Bounded-Buffer Empty

- handmade monitor procedure to get one item out of the buffer:

```
char get() {
    char item;

    occupy(&storehouse);    /* procedure prologue */
    {
        while (buffer.count == 0) comply(&buffer.data);

        item = buffer.store[buffer.out];
        buffer.out = (buffer.out + 1) % BUF_SIZE;
        buffer.count -= 1;

        cancel(&buffer.space);
    }
    vacate(&storehouse);    /* procedure epilogue */

    return item;
}
```

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

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 **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

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

void vacate(monitor_t *this) { V(&this->mutex); }

void comply(condition_t *this) {
    this->queue.count++;         /* sign-in process */
    vacate(this->guard);         /* release monitor */
    P(&this->queue.event);       /* delay process */
    occupy(this->guard);         /* re-acquire monitor */
    this->queue.count--;         /* sign-out process */
}

void cancel(condition_t *this) {
    if (this->queue.count > 0)   /* any registered? */
        V(&this->queue.event);   /* continue one */
}
```

- 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

Combined Final Action

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

void vacate(monitor_t *this) {
    if (this->elide) this->elide = false;
    else V(&this->mutex);
}

void comply(condition_t *this) {
    this->queue.count++;            /* sign-in process */
    vacate(this->guard);            /* release monitor */
    P(&this->queue.event);          /* delay process */
    this->queue.count--;            /* sign-out process */
}

void cancel(condition_t *this) {
    if (this->queue.count > 0) {/* any registered? */
        this->elide = true;         /* leave locked */
        V(&this->queue.event);      /* continue complier */
    }
}
```

Signal and Wait

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

void vacate(monitor_t *this) { V(&this->mutex); }

void comply(condition_t *this) {
    this->queue.count++;        /* sign-in process */
    vacate(this->guard);        /* release monitor */
    P(&this->queue.event);      /* delay process */
    this->queue.count--;        /* sign-out process */
    V(&this->prime.event);      /* urgent continue */
}

void cancel(condition_t *this) {
    if (this->queue.count > 0) {/* any registered? */
        V(&this->queue.event);  /* continue one */
        P(&this->prime.event);  /* urgent delay */
        occupy(this->guard);    /* re-acquire monitor */
    }
}
```


Signal and Urgent Wait I

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

void vacate(monitor_t *this) {
    if (this->prime.count > 0)  /* urgent waiting? */
        V(&this->prime.event);  /* yes, continue that */
    else
        V(&this->mutex);        /* no, release 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 (`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

```c
void comply(condition_t *this) {
    this->queue.count++;        /* sign-in process */
    vacate(this->guard);        /* release monitor */
    P(&this->queue.event);      /* deleay process */
    this->queue.count--;        /* sign-out process */
}

void cancel(condition_t *this) {
    if (this->queue.count > 0) {     /* any registered? */
        this->guard->prime.count++; /* sign-in urgent */
        V(&this->queue.event);       /* continue queued */
        P(&this->guard->prime.event);  /* urgent wait */
        this->guard->prime.count--; /* sign-out urgent */
    }
}
```

- 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)

Outline

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-pogramming 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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Monitor Entry/Exit Revisited

C ↦ C++

- 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]

```
class atomic {
    static monitor_t sluice;
public:
     atomic() { occupy(&sluice); };
    ~atomic() { vacate(&sluice); };
};
```

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

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

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

Fundamental Data Types

Event-queue based

- 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**:

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


Event Queue

Classical Technique for Monitor Implementation

- 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 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

Waitlist Operations I


```
inline void brace(lineup_t *this) {
    this->count++;              /* one more delaying */
    catch(&this->event);        /* 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->event);        /* unconditionally block */
    this->count--;              /* one less delaying */
}

inline int level(lineup_t *this) {
    return this->count;         /* number delayed procs. */
}
```


Waitlist Operations II


```
inline int avail(lineup_t *this) {
    if (this->count > 0)                  /* any delayed? */
        cause(&this->event);              /* 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->event));       /* 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" <u>and</u>
    ▪ makes the elected process (signallee) available to the processor

Signal and Continue

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

void vacate(monitor_t *this) { V(&this->mutex); }

void comply(condition_t *this) {
    brace(&this->queue);            /* prepare to release */
    vacate(this->guard);            /* release monitor */
    shift(&this->queue);            /* release processor */
}

void cancel(condition_t *this) {
    avail(&this->queue);            /* try signal process */
}
```

- 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

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

void vacate(monitor_t *this) { V(&this->mutex); }

void comply(condition_t *this) {
    brace(&this->queue);            /* prepare to release */
    vacate(this->guard);            /* release monitor */
    shift(&this->queue);            /* release processor */
}

void cancel(condition_t *this) {
    if (!avail(&this->queue))       /* no watcher waiting? */
        vacate(this->guard);        /* release monitor */
}
```

- 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

Signal and Wait

Combined Monitor Waitlist

```
 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:
  - 12
    - 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
  - 13
    - accordingly, the signaller must make sure to **relock** the monitor

Signal and Urgent Wait I

Monitor Entrance/Exit

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

void vacate(monitor_t *this) {
    if (!avail(&this->prime))    /* no urgent waiting */
        V(&this->mutex);         /* release 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 (`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

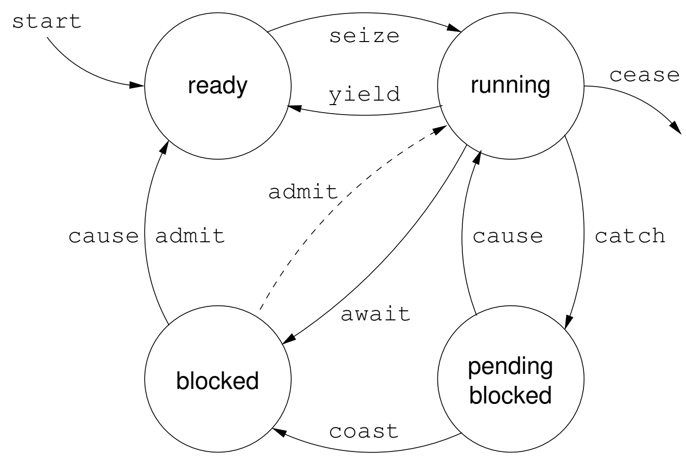
Condition Handling

```
 1  void comply(condition_t *this) {
 2      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 — wait (←), scheduler (↔)
- running ↔ blocked — urgent wait (→), wait (←, iff *full preemptive*)
- 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