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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Outline

Subject Matter

- discussion on **abstract concepts** as to “a shared variable and the set of meaningful operations on it” [7, p. 121]:

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- demonstrate basic functions of a fictitious (language) run-time system

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    - comes in a characteristic of many kinds [1, 10]

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	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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  - 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]

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- in this spirit, the **signalling convention** makes the wide difference and affects structuring of monitor-based non-sequential programs [13]

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cf. [13]

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Waiting inside a monitor

Without leaving the monitor, another process is unable to signal.

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    - if applicable, the order of process resumption is undefined
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  - 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

```
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 */
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- data type used for keeping track of **waiting processes** (cf. p. 18):

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

Monitor Procedures

```
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
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  - 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

- 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 */
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- 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

- handmade monitor procedure to put one item into the buffer:

```
1  void put(char item) {
2      lockout(&storehouse);    /* procedure prologue */
3      {
4          while (buffer.count == BUF_SIZE)
5              watch(&buffer.space);
6
7          buffer.store[buffer.in] = item;
8          buffer.in = (buffer.in + 1) % BUF_SIZE;
9          buffer.count += 1;
10
11         spark(&buffer.data);
12     }
13     proceed(&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

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

```
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 */
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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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`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`
- 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)

Event Queue

- 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
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- blocks the process on the specified event (signalled by `cause`)

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

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`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->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. */
}
```

Waitlist Operations II

```
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;
}
```

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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" <u>and</u>
- 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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  - 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

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  - 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

```
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 */
}
```

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}
```

- 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

Signal and Return

```
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 */
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}

void spark(condition_t *this) {
    if (!avail(&this->event))     /* no watcher waiting? */
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}
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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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void lockout(monitor_t *this) { P(&this->mutex); }

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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

```
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 */
}
```

Signal and Wait

```
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))      /* signallee done! */
13         lockout(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 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

Signal and Urgent Wait I

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

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

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- 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

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- 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

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  - 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

```
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 */
}
```

Signal and Urgent Wait II


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1  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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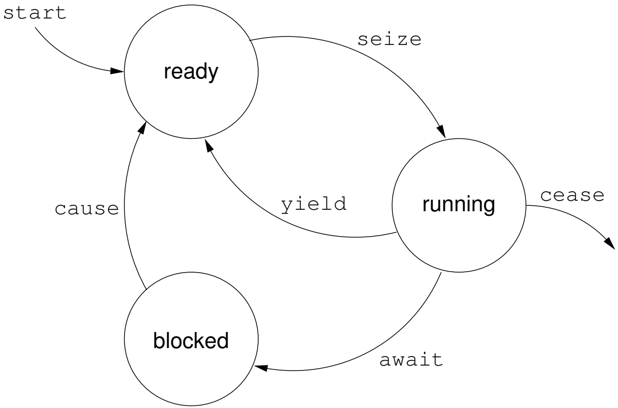
  - `defer` results in a process switch from line 9 to line 4, back and forth
    - from `spark` to `shift`, out of `watch`, and back to `spark` at monitor exit
- urgent waiting processes `proceed` with monitor locked (cf. p. 24)
  - when the monitor owner returns or blocks, an urgent process resumes
  - as a consequence, the monitor should not be protected by a **mutex**

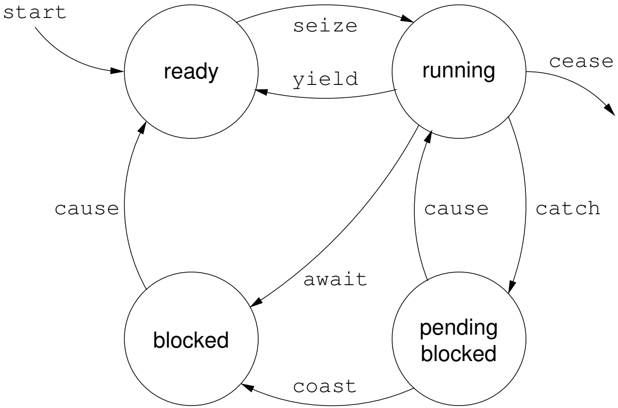
Process States and State Transitions

cf. [17, p. 27]



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

Process States and State Transitions



- ready $\leftrightarrow$ running ▪ wait ($\leftarrow$), scheduler ($\leftrightarrow$)
  running $\rightarrow$ blocked ▪ urgent wait
  blocked $\rightarrow$ ready ▪ all, iff *effective signalling* (i.e., waiting signallee)
  running $\leftrightarrow$ pending ▪ all ($\rightarrow$), signallee released monitor ($\leftarrow$)
  pending $\rightarrow$ blocked ▪ all, no overlap of signaller and signallee

Process States and State Transitions

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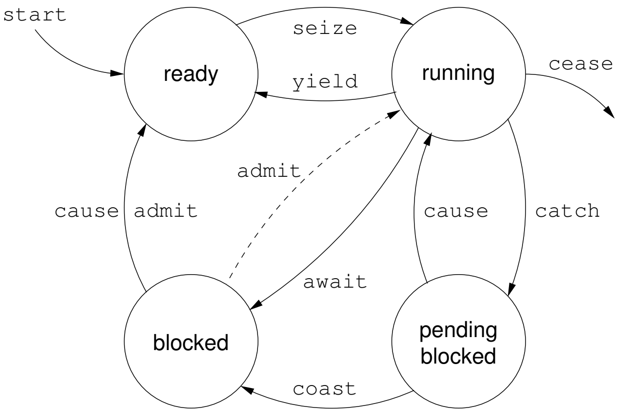

- ready $\leftrightarrow$ running
  - wait ($\leftarrow$), scheduler ($\leftrightarrow$)
- running $\leftrightarrow$ blocked
  - urgent wait ($\rightarrow$), wait ($\leftarrow$, iff *full preemptive*)
- blocked $\rightarrow$ ready
  - all, iff *effective signalling* (i.e., waiting signallee)
- running $\leftrightarrow$ pending
  - all ($\rightarrow$), signallee released monitor ($\leftarrow$)
- pending $\rightarrow$ blocked
  - all, no overlap of signaller and signallee

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

- 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() { lockout(&sluice); };
    ~atomic() { proceed(&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]