

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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Subject Matter

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 - explanation of various styles: Hansen, Hoare, Concurrent Pascal, Mesa
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 - according to this, schematic representation of implementation variants
- demonstrate basic functions of a fictitious (language) run-time system



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 - 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]



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 - 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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 - 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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 - only constructs beyond the **frame of reference** may force abnormality¹
 - 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 used¹

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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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 - wait ■ join monitor **entrance queue** and leave the monitor
 - resume all signalled processes (one at a time)
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return ■ leave the monitor and resume the single signalled process



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- 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)



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

```
1 typedef struct monitor {
2     semaphore_t mutex; /* initial {1} */
3 #ifdef __FAME_MONITOR_SIGNAL_URGENT_WAIT__
4     lineup_t urgent; /* urgent waiting signallers */
5 #endif
6 } monitor_t;
7
8 typedef struct condition {
9     monitor_t *guard; /* enclosing monitor */
10    lineup_t event; /* signal-awaiting processes */
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- data type used for keeping track of **waiting processes** (cf. p. 18):

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



```
1 extern void lockout(monitor_t*); /* enter monitor */
2 extern void proceed(monitor_t*); /* leave monitor */
3
4 extern void watch(condition_t*); /* wait on signal */
5 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
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 - 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:

```
1 #include "monitor.h"
2
3 #define BUF_SIZE 80
4
5 typedef struct buffer {
6     condition_t space;      /* control of reusables */
7     condition_t data;      /* control of consumables */
8     char store[BUF_SIZE];  /* reusable resource */
9     unsigned in, out;      /* store housekeeping */
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- instantiation of the necessary monitor and condition variables:

```
1 static monitor_t storehouse = {1}; /* monitor is free */
2 static buffer_t buffer = {          /* actual buffer */
3     {&storehouse}, {&storehouse}   /* link to monitor */
4 };
```



- 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



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

```
1 char get() {
2     char item;
3
4     lockout(&storehouse);    /* procedure prologue */
5     {
6         while (buffer.count == 0) watch(&buffer.data);
7
8         item = buffer.store[buffer.out];
9         buffer.out = (buffer.out + 1) % BUF_SIZE;
10        buffer.count -= 1;
11
12        spark(&buffer.space);
13    }
14    proceed(&storehouse);    /* procedure epilogue */
15
16    return item;
17 }
```

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



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

```
1 typedef struct event { } event_t;;
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3 extern void catch(event_t*);      /* expect event */
4 extern int  coast();              /* wait for event */
5 extern int  await(event_t*);     /* catch & coast */
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- i non-effective in case of cooperative scheduling, otherwise
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 - iii notifies event sensibility to potential signalers (*cause*)
- ensures that a process in running state is detectable by *cause*



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await ■ blocks the process on the specified event (i.e., signalled 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
- await** ■ blocks the process on the specified event (i.e., signalled by *cause*)
- cause** ■ unblocks processes (tentatively) waiting on the specified event



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

```
1 typedef struct event { } event_t;;
2
3 extern void catch(event_t*);      /* expect event */
4 extern int  coast();              /* wait for event */
5 extern int  await(event_t*);     /* catch & coast */
6 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*)

- 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 (i.e., signalled by *cause*)

cause ■ unblocks processes (tentatively) waiting on the specified event

- based on this abstraction, **waitlist operations** can be composed next



```
1 inline void brace(lineup_t *this) {
2     this->count++;           /* one more delaying */
3     catch(&this->crowd);     /* ready to block/continue */
4 }
5
6 inline void shift(lineup_t *this) {
7     coast();                /* conditionally block */
8     this->count--;          /* one less delaying */
9 }
10
11 inline void defer(lineup_t *this) {
12     this->count++;           /* one more delaying */
13     await(&this->crowd);     /* unconditionally block */
14     this->count--;          /* one less delaying */
15 }
16
17 inline int level(lineup_t *this) {
18     return this->count;     /* number delayed procs. */
19 }
```



```
1  inline int avail(lineup_t *this) {
2      if (this->count > 0)                /* any delayed? */
3          cause(&this->crowd);           /* yes, unblock */
4      return this->count;
5  }
6
7  inline int evoke(lineup_t *this) {
8      int count = this->count;            /* save state */
9      if (count > 0)                     /* any delayed? */
10         admit(elect(&this->crowd));    /* yes, seize CPU */
11     return count;
12 }
```



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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.]
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- 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



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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

```
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     avail(&this->event);          /* try signal process */
13 }
```



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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

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2
3 void proceed(monitor_t *this) { V(&this->mutex); }
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5 void watch(condition_t *this) {
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11 void spark(condition_t *this) {
12     if (!avail(&this->event))     /* no watcher waiting? */
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14 }
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Signal and Return

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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



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9 }
10
11 void spark(condition_t *this) {
12     if (evoke(&this->event))     /* signallee done! */
13         lockout(this->guard);    /* re-enter monitor */
14 }
```



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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



```
1 void lockout(monitor_t *this) { P(&this->mutex); }
2
3 void proceed(monitor_t *this) {
4     if (!avail(&this->urgent)) /* no urgent waiting */
5         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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1 void lockout(monitor_t *this) { P(&this->mutex); }
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 - i the re-entrance waitlist (*urgent*), but only in case of urgent processes
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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



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5 }
6
7 void spark(condition_t *this) {
8     if (avail(&this->event))      /* watcher waiting? */
9         defer(&this->guard->urgent); /* urgent wait */
10 }
```



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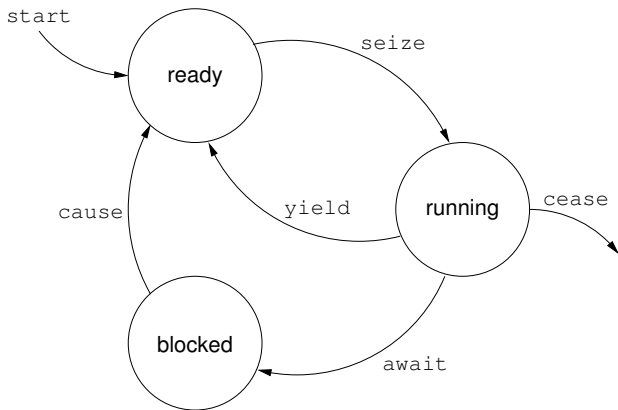
- as the case may be, *spark* makes the current process urgent waiting
 - a **preferential queue** (Ger. *Vorzugswarteschlange*) is used to this end
 - *defer* results in a process switch from line 9 to line 4, back and forth
 - from *spark* to *shift*, out of *watch*, and back to *spark* at monitor exit



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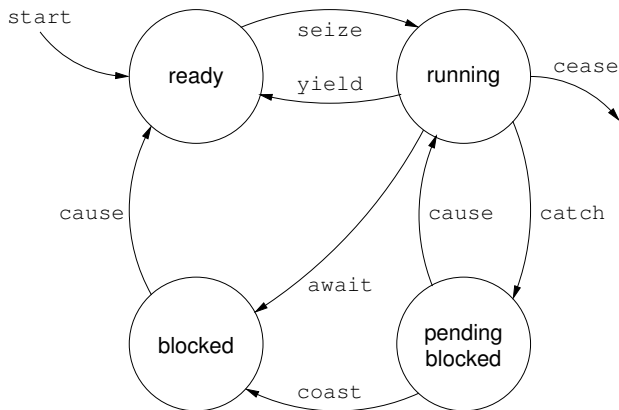
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 - *defer* results in a process switch from line 9 to line 4, back and forth
 - from *spark* to *shift*, out of *watch*, and back to *spark* at monitor exit
- urgent waiting processes keep *proceed* off from unlocking the monitor
 - when the monitor owner returns or blocks, an urgent process resumes
 - as a consequence, the monitor should not be protected by a **mutex**





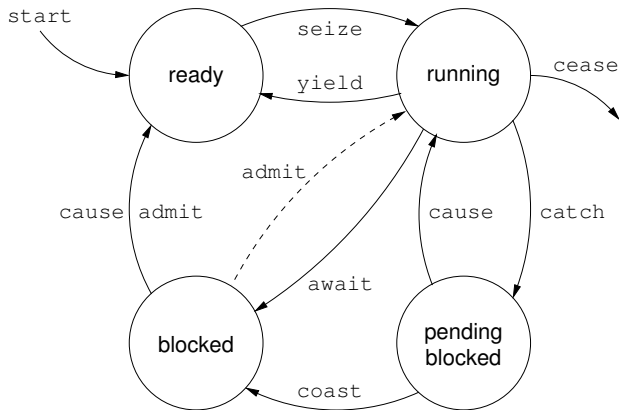
- **ready** ↔ **running** ■ wait (←), scheduler (↔)
- running** → **blocked** ■ urgent wait
- blocked** → **ready** ■ all, iff *effective signalling* (i.e., waiting signallee)





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- 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





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

Preface

Fundamentals

- Mutual Exclusion

- Condition Variable

- Signalling Semantics

Implementation

- Data Structures

- Use Case

- Operations

Summary



- 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]

```
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*:

```
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]

