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

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Fundamentals
  Mutual Exclusion
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Summary
discuss 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
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:
      1. check that only these procedures are carried out on that variable
      2. ensure that the respective operations exclude each other in time

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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

- **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
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

- 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

- 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
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

**condition**
- one or more special variables that do “not have any stored value accessible to the program” [12, p. 550]
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in functional terms, get to know “monitor” as fundamental means of synchronisation independent of linguistic features

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
Motivation

for all advantages, semaphores are to be approached with caution

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]
for all advantages, semaphores are to be approached with caution

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]
Motivation

for all advantages, semaphores are to be approached with caution

out of it, various design and languages concepts originated

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

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Summary
key aspect is to facilitate solely indirect access to shared variables by means of monitor procedures
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 $\leadsto$ lockout simultaneous processes
  - on behalf of the occupying process, at return the procedure epilogue releases the monitor again $\leadsto$ proceed locked processes, if any
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

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

\footnote{Thinking of a multi-language system.}
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**

usually, a compiler is in charge of ejecting the procedure pro- and epilogue

in logical respect, deadlocks due to programmed absence of unblocking of critical sections are impossible
key aspect is to facilitate solely indirect access to shared variables by means of monitor procedures

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
Intentional Process Delay

- multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit.
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.
Intentional Process Delay

multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit

**Hoare**
- proposed a non-attached *condition variable* [12, p. 550]
- with *wait* and *signal* as intrinsic functions for condition handling
Intentional Process Delay

- Multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit.

- 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.
Intentional Process Delay

- Multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit.

- In operating-system terms, per variable an **event queue** of processes waiting by reason of a certain condition.

  **Hansen**
  - All processes can be transferred to the monitor waitlist (**cause**) and suggests that the former take priority over the latter [7, p. 118].
Intentional Process Delay

- multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit

- in operating-system terms, per variable an **event queue** of processes waiting by reason of a certain condition

**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]: all ≡ one
Intentional Process Delay

- Multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit.

- In operating-system terms, per variable an **event queue** of processes waiting by reason of a certain condition.

  **Hoare**

  - Exactly **one** out of the waiting processes is selected (**signal**).
  - Decrees that the chosen one is immediately resumed [12, p. 550].

© wosch, thoenig  CS (WS 2019/20, LEC 8)  Fundamentals – Condition Variable
Intentional Process Delay

- multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit

- in operating-system terms, per variable an **event queue** of processes waiting by reason of a certain condition

  **Hansen**  ■ all processes can be transferred to the monitor waitlist (**cause**)  

  **Hoare**  ■ exactly one out of the waiting processes is selected (**signal**)  

  ■ but signalling is non-effective (void) if no process would be waiting on it
Intentional Process Delay

multilateral (blocking) synchronisation is implicit basis of a monitor, but **unilateral synchronisation** needs to be made explicit.

in operating-system terms, per variable an **event queue** of processes waiting by reason of a certain condition.

**Hansen**
- all processes can be transferred to the monitor waitlist (**cause**)  

**Hoare**
- exactly one out of the waiting processes is selected (**signal**)  

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
Signalling Conventions

- explicit signal operation assumed, *signal-and-*$\phi$*, with $\phi$ 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
Signalling Conventions

- explicit signal operation assumed, \textit{signal-and-}Φ, with Φ indicating the behaviour of the signalling process as follows:

\textbf{urgent wait}  
- join \textbf{preferential queue} and leave the monitor
- resume one signalled process (first come, first served)
- re-enter the monitor, enjoy priority over entrant processes
Signalling Conventions

- explicit signal operation assumed, **signal-and-\(\phi\)**, with \(\phi\) indicating the behaviour of the signalling process as follows:

- **return**: leave the monitor and resume the single signalled process
explicit signal operation assumed, **signal-and-ϕ**, with ϕ indicating the behaviour of the signalling process as follows:

### continue
- carry on holding the monitor, keep inside the procedure
- resume all signalled processes (one at a time) at return
Signalling Conventions

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)
Signalling Conventions

cf. [13]

- explicit signal operation assumed, **signal-and-φ**

- a main issue is the **control transfer** between signaller and signallee
Signalling Conventions

explicit signal operation assumed, **signal-and-\( \phi \)**

a main issue is the **control transfer** between signaller and signalleee

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

> Keep ownership by the signaller means fewer context switches and, thus, less background noise but higher (signal) allocation latency.
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 signalle has guarantee on the still effective invalidation of its waiting condition
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

  $$\leftrightarrow \text{while} (!\text{condition}), \text{wait: tolerant to false signalisation}$$
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:

  **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

  ![Condition](https://via.placeholder.com/150)

  → if (!condition), wait: **intolerant to false signalisation**
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 signallees has guarantee on the still effective invalidation of its waiting condition:
  - wait ■ only for one out of possibly many signalled processes

urgent wait ■ exactly for the single signalled process

return ■ *ditto*
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

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

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

```c
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*
Semaphore-based abstraction for mutual exclusion of monitor-procedure executions:

```c
typedef struct monitor {
    semaphore_t mutex; /* initial */
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    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:

```c
typedef struct lineup {
    int count; /* number of waiting processes */
    semaphore_t event; /* wait-for event: initial */
} lineup_t;
```
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
Consider these operations an additional **run-time system** element for a compiler of a “concurrent C-like” programming language.

```c
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 */
```
Monitor Procedures

Functional Interface

1. extern void occupy(monitor_t*);  /* enter monitor */
2. extern void vacate(monitor_t*);  /* leave monitor */
3. /* additional code */
4. extern void comply(condition_t*); /* wait on signal */
5. 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
Monitor Procedures

1. `extern void occupy(monitor_t*); /* enter monitor */`
2. `extern void vacate(monitor_t*); /* leave monitor */`
3. `extern void comply(condition_t*); /* wait on signal */`
4. `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.

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;
```
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    unsigned in, out;     /* store housekeeping */
    unsigned count;        /* wait/signal condition */
} buffer_t;
```

instantiation of the necessary monitor and condition variables:

```c
static monitor_t storehouse = {1};    /* monitor is free */
static buffer_t buffer = {
    &storehouse,  /* actual buffer */
    &storehouse,  /* link to monitor */
};
```
Consolidating Example II

Bounded-Buffer Fill

handmade monitor procedure to put one item into the buffer:

```c
void put(char item) {
    occupy(&storehouse);    /* procedure prologue */
    {
        while (buffer.count == BUF_SIZE)
            comply(&buffer.space);  /* await event */

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

        cancel(&buffer.data);    /* cause event */
    }
    vacate(&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;

    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 leaves a signal trace 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.
Signalling Semantics

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- signal and continue  ■ Mesa-style [14]
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- 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
Signalling Semantics

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  - signal and continue  ■ Mesa-style [14]
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- 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
Signalling Semantics

- as has been foreshadowed by a **configuration option** (cf. p. 12):
  - signal and continue  ■ Mesa-style [14]
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  - signal and urgent wait  ■ Hoare-style [12]

- as indicated by the data type (cf. p. 12), the designs presented next are typical for an approach using **semaphores**

- lightweight and efficient monitor operation benefits from **cross-layer optimisation** in constructive means
  ■ from language- to system-level run-time system to operating system
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 */
}
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
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 */
  }
}
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 */
}
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
void occupy(monitor_t *this) { P(&this->mutex); }

task (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

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
Signal and Urgent Wait I

Monitor Entrance/Exit

1. void occupy(monitor_t *this) { P(&this->mutex); }
2.
3. void vacate(monitor_t *this) {
4.     if (this->prime.count > 0) /* urgent waiting? */
5.         V(&this->prime.event); /* yes, continue that */
6.     else
7.         V(&this->mutex); /* no, release monitor */
8. }

In contrast to the solutions discussed before, **exit** from the monitor needs to check two waitlists for pending processes:

- By definition, urgent processes interrupted own operation in favour of processes pending for event handling.
- Indicator of urgent waiting processes is a counter by means of which the number of process blockings is registered.
`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->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
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->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)
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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.

Hansen

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FAU Erlangen-Nürnberg, 2014 (Lecture Slides), Kapitel 3
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:**

```c
typedef struct lineup {
    int count;  /* number of waiting processes */
    event_t event;  /* wait-for event */
} lineup_t;
```
a classic monitor implementation on **event queue** basis is considered:

```c
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:

1. **non-effective** in case of cooperative scheduling, otherwise
2. inhibits preemption or dispatching (SMP), resp., or
3. notifies event sensibility to potential signallers (*cause*)

*coast* ensures that a process in running state is detectable by *cause*

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

typedef struct event { } event_t;

catch(void) makes the process unsusceptible against **lost wakeup**:

i. non-effective in case of cooperative scheduling, otherwise

ii. inhibits preemption or dispatching (SMP), resp., or

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ensures that a process in running state is detectable by cause
a classic monitor implementation on **event queue** basis is considered:

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typedef struct event { } event_t;

extern void catch(event_t*); /* expect event */
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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)

catch 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
Event Queue

Classical Technique for Monitor Implementation

A classic monitor implementation on event queue basis is considered:

define struct event { } event_t;

catch (event_t*) /* expect event */
coast () /* wait for event */
await (event_t*) /* catch & coast */
cause (event_t*) /* signal event */

**catch** makes the process unsusceptible against *lost wakeup*:

1. Non-effective in case of cooperative scheduling, otherwise
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extern void catch(event_t*);  /* expect event */
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**await** blocks the process on the specified event (signalled by **cause**)

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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
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. */
}
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;
}
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 \texttt{mutex} object
Waitlist Operations II

Control of Unblocking

```
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” and
    makes the elected process (signallee) available to the processor
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 */
}
Signal and Continue

```c
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

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

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

define
void comply(condition_t *this) {
  brace(&this->queue);    /* prepare to release */
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}

define
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]
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? */
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}

■ 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
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 (evoke(&this->queue))  /* signalleee done! */
    occupy(this->guard);  /* re-enter monitor */
}
Signal and Wait

Combined Monitor Waitlist

```c
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 (evoke(&this->queue)) /* signallelee done! */
        occupy(this->guard); /* re-enter monitor */
}
```

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

- in case of a pending signalleee, 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

accordingly, the signaller must make sure to **relock** the monitor
Signal and Urgent Wait I

Monitor Entrance/Exit

```c
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 ($\text{prime}$), but only in case of urgent processes

ii. the entrance waitlist ($\text{mutex}$), else by definition, urgent processes interrupted their own operation in favor of processes pending for event handling.

Urgent processes caused events recently, and want to be resumed, expressly.

Indicator of urgent waiting processes is a counter by means of which the number of process blockings is registered.
in contrast to the solutions discussed before, **exit** from the monitor needs to check two waitlists for pending processes:

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

2. `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:

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- The entrance waitlist (**mutex**), else

By definition, urgent processes interrupted own operation in favour of processes pending for event handling:

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- Indicator of urgent waiting processes is a counter by means of which the number of process blockings is registered
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)) /* watcher waiting? */
        defer(&this->guard->prime); /* urgent wait */
}
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)) /* watcher waiting? */
        defer(&this->guard->prime); /* urgent wait */
}

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

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- 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  

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

- running → blocked  
- blocked → ready
Process States and State Transitions

cf. [17, p. 27]

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

- ready ↔ running
  - wait ($\leftarrow$), scheduler ($\leftrightarrow$)
  - urgent wait
  - all, iff effective signalling (i.e., waiting signallees)

- running → blocked
  - urgent wait

- blocked → ready
  - all, iff effective signalling (i.e., waiting signallees)

- running ↔ pending
  - all ($\rightarrow$), signallees released monitor ($\leftarrow$)

- pending → blocked
  - all, no overlap of signaller and signallees
Process States and State Transitions

- **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 signallee)
- **Running ↔ Pending**: all (→), signallee released monitor (←)
- **Pending → Blocked**: all, no overlap of signaller and signalleel

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CS (WS 2019/20, LEC 8) Addendum – Operations