Concurrent Systems

Nebenläufige Systeme

X. Guarded Sections

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Agenda

Outline

Subject Matter

- discussion on abstract concepts as to **structural measures** suited in paving the way for non-blocking synchronisation

guarded sections	▪ synchronise process-originated events[1]
pre-/postlude sections	▪ synchronise hardware-originated events

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  - using concepts such as the **promise** [6] or promise pipelining [11]
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  - using concepts such as the **promise** [6] or promise pipelining [11]
  - functional programming meets distributed computing for synchronisation
- one learns that guarded sections largely resemble conventional critical sections, but with a much more relaxed execution model

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Definition (Interrupt)

Mechanism of a (soft- or hardware) processor to prompt software to draw attention to an external process asynchronously, unpredictable, and unreproducible.

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- as to operating systems, usually a **trinity** of problem-specific routines is to be considered—and assumed in the following:

guardian ▪ *interrupt-handler dispatcher* running at CPU priority
prelude ▪ *first-level interrupt handler* (FLIH) running at CPU/OS priority
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- what all have in common is the **asynchronism** to the current process that was interrupted and will be delayed by their particular actions

Responsibility Assignment (Ger.) *Aufgabenverteilung*

Hint (Interrupt Latency)

*In order to make **loss of interrupts** improbable, CPU priority[a] must be cancelled and OS priority[b] must be taken in minimum time.*

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Hint (Asynchronous System Trap, AST [10, p. 414])

On the VAX, a software-initiated interrupt to a service routine. ASTs enable a process to be notified of the occurrence of a specific event asynchronously with respect to its execution. In 4.3 BSD, ASTs are used to initiate process rescheduling.

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prelude	risk of race conditions <u>and</u> system-stack overflow	☹
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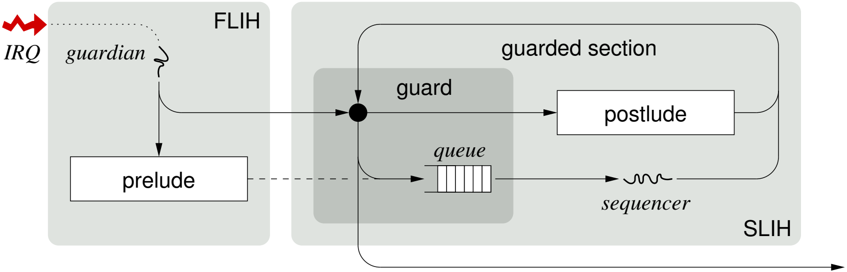
- purpose of the postlude is to safely allow such control-flow expansions
  - its activation is controlled similar to the control of guarded sections

Execution Sequencing of Postludes



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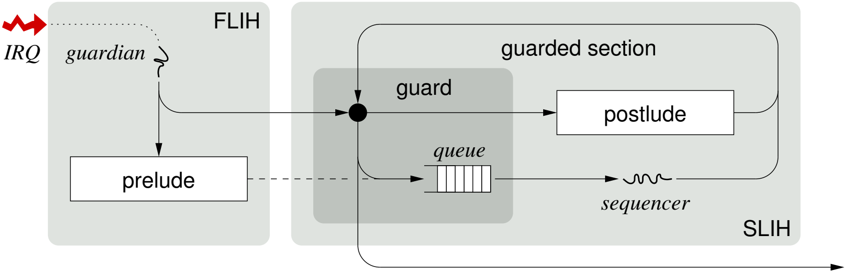

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- according to the model, an interrupt indeed causes a new process but not a new process instance
  - the guardian is such a process, it operates in the name of the interrupted process instance and commands no own context
  - same applies for the sequencer, it is an optional **guardian continuation** and takes care for safe postlude processing

Overlapping Pattern

- not unlike the guarded section as to process events described below (cf. p. 20), but with the following fundamental differences:
  - simultaneous requests to run through a guarded section occur **stack-wise**
  - processing start as to delayed (i.e., pending) passage requests is **AST-like**
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  - the guardian (incl. prelude) enqueues postludes possibly simultaneously, but never dequeues them
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- this **multiple-enqueue/single-dequeue** mode of operation eases the design of a non-blocking synchronised postlude queue

```
__attribute__ ((fastcall)) void guardian(long irq) {
    static usher_t tube = { 0, {0, &tube.load.head} };
    extern remit_t *(*flih[])(usher_t *);
    remit_t *task;

#ifdef __FAME_INTERRUPT_EDGE_TRIGGERED__
    pivot(&tube.busy, +1); admit(IRQ);  /* take OS priority */
#endif

    task = (*flih[irq])(&tube);         /* activate prelude & satisfy IRQ source */

#ifdef __FAME_INTERRUPT_LEVEL_TRIGGERED__
    pivot(&tube.busy, +1); admit(IRQ);  /* take OS priority */
#endif

    if (tube.busy > 1) {                /* sequencer is already on duty */
        if (task != 0) deter(&tube, task);  /* enqueue postlude & */
        avert(IRQ);                         /* leave with CPU priority */
    } else {                            /* bring sequencer into service */
        if ((task != 0) && (tube.load.head.link == 0)) remit(task);

        avert(IRQ);                         /* prevent lost unload */
        while (tube.load.head.link != 0) {
            admit(IRQ);                     /* take OS priority, again */
            flush(&tube);                   /* forward pending postludes */
            avert(IRQ);                     /* leave with CPU priority */
        }
    }
    pivot(&tube.busy, -1);              /* leave critical section */
}
```

Lock-Free Synchronised Enqueue cf. [13]

- assuming that simultaneous enqueues can happen only in a **stacking arrangement**, then the following is “thread safe”:

```
void chart_ms_lfs(queue_t *this, chain_t *item) {
    chain_t *last;

    item->link = 0;          /* terminate chain: FIFO */

    last = this->tail;       /* settle insertion point */
    this->tail = item;       /* create new partial list */

    while (last->link != 0) /* overlapping enqueue! */
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- idea is to create a new partial list using an **atomic store** and, thus, isolate the original list for later safe manipulation
  - but simultaneous enqueues then may shift the **actual insertion point**

Lock-Free Synchronised Dequeue cf. [13]

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chain_t *fetch_ms_lfs(queue_t *this) {
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    if ((item = this->head.link)  /* next item fetched */
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        this->tail = &this->head;  /* is last one, reset */
        if (item->link != 0) {     /* overlapping enq.! */
            chain_t *help, *lost = item->link;
            do {                   /* recover latecomers */
                help = lost->link;   /* remember next & */
                chart_ms_lfs(this, lost);  /* rearrange */
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- critical is dequeuing as to the **last element** and overlapped by one or more enqueues, thus, filling up the queue again
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Hint (Lock Freedom)

Some process will complete an operation in a finite number of steps, regardless of the relative execution speeds of the processes. [7, p. 142]

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Wait-Free Solution


```
void chart_ms_wfs(queue_t *this, chain_t *item) {
    chain_t *last;
    item->link = 0;      /* terminate chain: FIFO */
    last = FAS(&this->tail, item);
    last->link = item;   /* eventually append item */
}

chain_t *fetch_ms_wfs(queue_t *this) {
    chain_t *item = this->head.link;
    if (item) {          /* check for last item */
        if (item->link) /* is not, non-critical */
            this->head.link = item->link;
        else if (CAS(&this->tail, item, &this->head))
                CAS(&this->head.link, item, 0);
    }
    return item;
}
```

- with the following mapping to GCC atomic intrinsic functions:

```
#define FAS(ref,val) __sync_lock_test_and_set(ref, val)
#define CAS          __sync_bool_compare_and_swap
```

Recapitulation

- in the **pre-/postlude model**, sequencer becomes that process in the context of which interrupt handling is carried out
  - more precisely, the process at the bottom of an interrupt-handler stack
  - put differently, the interrupted process that "activated" the guard (p. 9)

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Hint (Pro-/Epilogue [14, 13])

At first glance, interrupt handler pre-/postludes seemingly resemble the pro-/epilogue model. While this is quite true for preludes, it does not hold for postludes. Epilogue execution is a ***synchronous event*** *as to the interrupted kernel-level process, in contrast to postludes.*

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- postlude guide through is not unlike **procedure chaining** [12, p. 10], a technique to serialize execution of conflicting threads
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  - differences are due to the constrained pre-/postlude overlapping pattern
  - unless stack-based scheduling [1], any process overlapping is assumed
- this similarity gives reason to think about a **generalisation** of the pre-/postlude model to synchronise **process-*instance*** events

Outline

Principle of Operation

- in structural respect not unlike conventional critical sections, but as to its flow model very different and non-blocking

```
{
    future tobe;                /* value container & promise */

    guarded(tobe) *task = {     /* future as parameter */
        /* compute promised value 'item', part 1 */

        if (!phase(ewd)) break; /* conditional synchr. */

        /* compute promised value 'item', part 2 */

        task->tobe.prove(item);       /* fulfil promise */
    }

    tobe.exact();         /* await fulfilment of promise */
}
```

- key aspect is that a process never blocks incoming a guarded section, but its request to pass through that section may be delayed

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  - thereto, computation results need to be returned and accepted **by proxy**
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- in the final analysis, critical sections are **twofold**, namely one that is *procedure*- and another one that is *function*-like
  - with the former delivering no direct result, in contrast to the latter

Handling of a Cirtical-Section Function

- fall back on known **linguistic concepts** in order to pattern a solution for the above-mentioned problem:

  future
  - the *promise* to deliver a value at some later point in time [2]
  - read-only placeholder object created for a not yet existing result
  - the result is computed concurrently and can be later collected

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- each future instance has a dedicated **resolver** taking care of (a) value assignment and (b) **promise states**:
  - kept
    - value computed, assignment took place
  - broken
    - computation aborted, assignment ceases to take place
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    - process in progress, assignment did not just yet take place
- based on these states, a process is able to synchronise on the **event** that the promise to deliver a value was either kept or broken
  - the resolver (process inside the critical section) acts as producer
  - the future using process acts as consumer ⇝ ***signalling semaphore***

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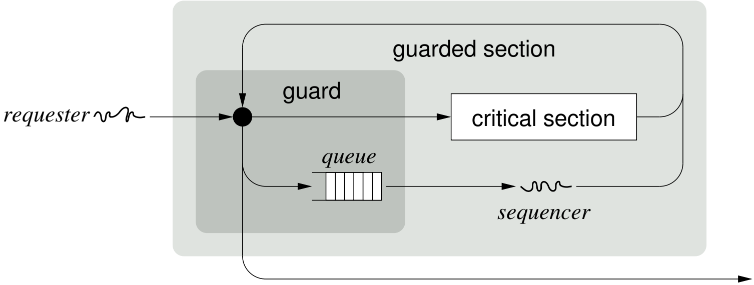
Execution Sequencing of Critical Sections



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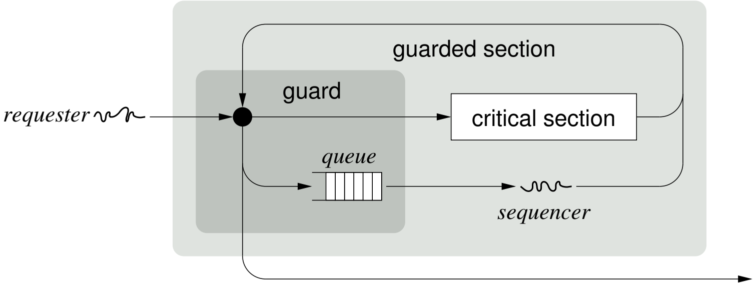

- heading for a critical section depending on the **state of occupancy**:

unoccupied	■ guard grants requester access to the critical section ■ the critical section becomes occupied by the requester
occupied	■ guard denies requester access to the critical section ■ the request gets queued and the requester bypasses

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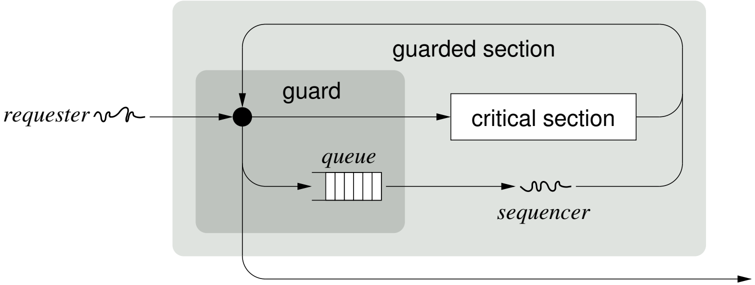

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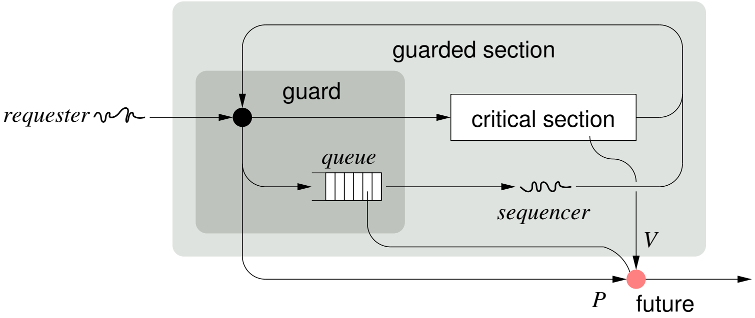
  - the request gets queued and the requester bypasses

- leaving a critical section depending on the **request-queue state**:

  empty
  - critical section becomes unoccupied, the process continues

  full
  - the actual leaving process becomes sequencer and re-enters the critical section for each queued request

Synchronisation of Direct-Result Critical Sections



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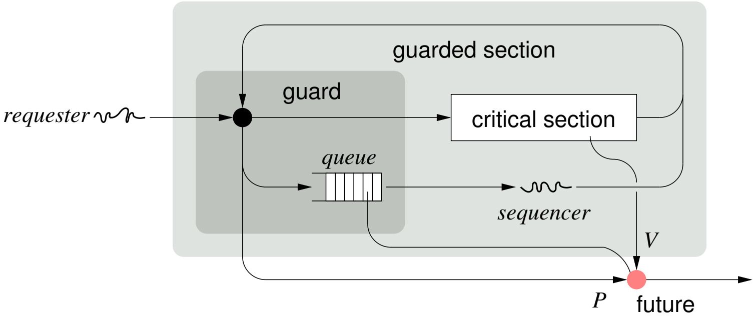

- a passage request may refer to a multi-elementary **future object**:
  i a promise indicator (kept, broken, pending)
  ii a placeholder of problem-specific type as to the critical section
  iii a binary semaphore that is used in producer/consumer mode
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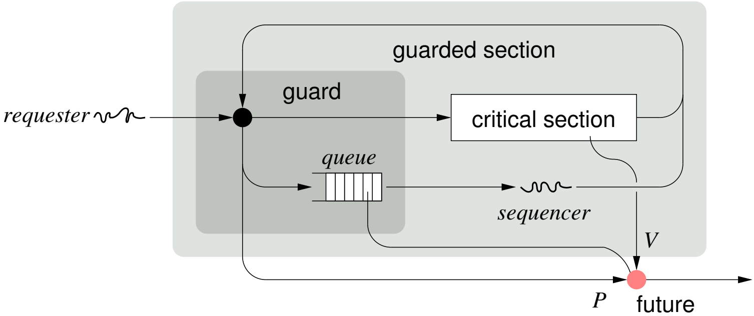

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    - i.e., a **signalling semaphore** applicable by different processes
- in case of a direct-result critical section, the sequencer takes the part of a **resolver** that also have to signal the "kept" or "broken" state
  - V does the signalling and by means of P the signal can be consumed

Execution Characteristics of the Critical Section

- critical sections controlled by processes in a **run-to-completion style** can be handled straightforwardly

Definition (Run to Completion (Process))

A potentially preemptive process free from self-induced wait states as to the possible non-availability of reusable or consumable resources.

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- both styles of execution concern the period of a critical section, only
  - but at large, a process may be classified run to completion <u>and</u> stopover

Run-to-Stopover for Peer Processes

- critical sections controlled by processes waiting on events caused by **external processes** can be handled straightforwardly
  - as the external process, in order to making progress, does not depend on any internal process or state of any critical section
  - thus, interaction between external and internal processes is **non-critical**[3]

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  - other "critical interaction" is implicit subject matter of any critical section
- as a consequence, **precautions** must be taken for interacting internal processes—similar to signalling inside monitors [15, p. 9]
  - without clearing the guarded section, a **stopover process** may deadlock

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Hint (Wait Freedom)

Any process can complete any operation in a finite number of steps, regardless of the execution speeds of the other processes. [7, p. 124]

Data Type I


```c
typedef struct guard {
    bool busy;              /* state: initial false */
    queue_t load;           /* pending passage requests */
    indicator_t *hint;      /* sequencer blocked-on event */
} guard_t;
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- locking (*clasp*) and unlocking (*loose*) of a guarded section:

```
inline bool clasp(guard_t *this) {
    return this->busy || TAS(&this->busy);
}

inline void loose(guard_t *this) {
    this->busy = false;
}
```

- *clasp* is a **test-and-test-and-set** (TATAS) to mitigate **bus lock bursts**
- note that the TAS-part should be mapped to CAS or LL/SC, resp.
  - the former or a CISC- and the latter for a RISC-type of processor

Claiming and Clearing


```
inline bool vouch(guard_t *this, order_t *work) {
    bool busy = clasp(this);
    if (busy)
        chart(&this->load, &work->next);
    return busy == false;
}

inline order_t *clear(guard_t *this) {
    order_t *next;
    if ((next = (order_t *)fetch(&this->load)) == 0)
        loose(this);
    return next;
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first-come, any serve (FCAS)

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- clearing, as shown here, is prone to the **lost update** problem:
  - 10 ▪ the process just leaving the critical section finds no pending passage request and will loose the guarded section next
  - 11 ▪ but before the guarded sections is loosened, a simultaneous process comes in and attempts claiming it
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Waiting

- using an **indicator** for the “art of waiting” (p. 42) of the sequencer

```
inline bool phase(guard_t *this, indicator_t *hint) {
    enroll(hint);        /* expect external event */
    loose(this);         /* leave guarded section */
    repose(hint);        /* receive external event */
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2 ▪ the sequencer indicates interest in receiving an external signal,
3 ▪ leaves the guarded section—but pending requests still may exist,
4 ▪ will block (if signal is pending) or continue (if signal occurred),
5 ▪ and, finally, reapplies for passing through the guarded section
  ▪ further action is context-dependent and better up to the *phase* caller

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- if **reapplication** fails, the current process is no longer sequencer
  - during the waiting period, another process entered the guarded section
  - thus, the current process must leave the guarded section or synchronise
- as requests may be and remain still pending, waiting on respective internal processes is problematic $\leadsto$ **trailing conditional wait**

```
inline void trail(guard_t *this, indicator_t *hint) {
    enroll(this->hint = hint);
}

inline order_t *clear(guard_t *this) {
    order_t *next;
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- **deadlock hazard** due to potential of a **lost update** (cf. p. 26):
  - 7–10 **hazard zone** of missing meanwhile arriving passage requests
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Trailing Conditional Wait

Watch for Ex-/Internal Processes

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- layout of an **argument vector** for passage-request parameters:

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typedef union item {
    long (*lump)[];      /* argument vector (N > 1) */
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  - depending on the number of parameters, the structure describes a multi- or uni-element argument vector
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- in addition, this vector also serves as placeholder for a *future value*

Piece the Puzzle Together

cf. p. 44

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- fore **editing** of passage-request parameters, optional:

```
order_t *task = order(2);              /* two parameters */
(*task->post.lump)[0] = (long)index;
(*task->post.lump)[1] = value;
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Piece the Puzzle Together

cf. p. 44

- **entry protocol**, agreement on the sequencer process:

```
extern guard_t gate;
if (vouch(&gate, task)) do                /* enter section */
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- midsection (i.e., actual critical section) **flow control**, optional:

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extern indicator_t hint = { 0 };      /* initial: block */
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  - besides logical synchronisation in the **midsection**, any other programming statements are doable as well—like in conventional critical sections

Outline

Résumé

- guarding of critical sections at operating-system as well as instruction set architecture level and in a non-blocking manner
  - processes are never delayed at entrance of an already occupied critical section, however their requests to pass through
  - not unlike **procedure chaining**, but also supporting in-line functions
- at both levels, overlappings as to simultaneous processes result in a **multiple-enqueue/single-dequeue** model of request handling
  - the **sequencer** will be the only process being in charge of dequeuing
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  - whereby this continuation is **commander-in-chief** of a critical section
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[4] Operating-sytem machine or instruction set architecture level, respectively.

Résumé

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Guardian Insulating and Invoking

```
_joint:
    pushl %ecx         # save volatile register
    movl  $0, %ecx     # pass IRQ number
_jointN:               # come here for IRQ number N > 0
    pushl %edx         # save another volatile register
    pushl %eax         # ditto
    call _guardian     # fastcall to guardian
    popl  %eax         # restore volatile register
    popl  %edx         # ditto
    popl  %ecx         # ditto
    iret               # resume interrupted process
```

- each IRQ entry in the CPU exception vector is associated with a *joint*

```
_joint42:
    pushl %ecx         # save volatile register
    movl  $42, %ecx    # pass IRQ number
    jmp   _jointN      # switch to common joint section...
```

S{a,i}mple Interrupt Handler

- first-level interrupt handler (FLIH), at CPU/OS priority (p. 11, l. 7)

```
1 remit_t *prelude(/*optional*/usher_t *tube) {
2     static remit_t task = { {}, postlude};
3     /* Come here for device pre-processing &
4      * device-related IRQ acknowledgement. */
5     deter(tube, &task); /* force postlude to queue */
6     return 0;           /* don't request shortcut */
7 }
```

  - without l. 5, **postlude shortcut** (p. 11, l. 20) goes with `return &task`

- second-level interrupt handler (SLIH), at OS priority (p. 11, l. 7/13)

```
void postlude(/*optional*/order_t *todo) {
    /* Come here for device post-processing &
     * any asynchronous system interaction. */
    V((semaphore_t *)todo->post.sole);
}
```

  - system interaction means: to *vouch* for guarded sections (cf. p. 30)

Interrupt-Handler Guard

- a **doorman** (Ger. *Pförtner*) for guarded sections at the low level of handling asynchronous program interrupts, a **specialised guard**:

```
typedef guard_t usher_t;

inline void deter(usher_t *tube, remit_t *task) {
    chart(&tube->load, &task->data.next);
}

inline remit_t *untie(usher_t *tube) {
    return (remit_t *)fetch(&tube->load);
}

inline void flush(usher_t * tube) {
    remit_t *next;
    do if ((next = untie(tube))) remit(next);
    while (next != 0);
}
```

- with queue synchronisation style: `#define __FAME_SYNC_ITS__`
  - resulting in "`{chart,fetch}_ms_lfs`" or -"`_wfs`", resp.

Job Definition and Start

- a SLIH or an interrupt-handler postlude, resp., is a **passage request** (cf. p. 29) attended by a procedure address
  - that is to say, a request object with implicit processing method

```
typedef struct remit {
    order_t data;                 /* parameter set */
    void (*code)(order_t *);      /* procedure address */
} remit_t;

inline void remit(remit_t *this) {
    (*this->code)(&this->data); /* run that job */
}
```

- at process-event level, this structure specifies different **parameterised critical sections** associated with the same guarded section
  - it allows for **procedure chaining** similar to that of Synthesis [12, p. 10]

Art of Waiting

- straightforward is the use of a **signalling semaphore**[5]:

```
typedef semaphore_t indicator_t;
inline void enroll(indicator_t *hint) { }
inline void repose(indicator_t *hint) { P(hint); }
inline void arouse(indicator_t *hint) { V(hint); }
```

  - note that a semaphore has **memory semantics** with regard to signals
  - thus, awaiting a signal by means of *P* once a sequencer process released the guarded section is free of the lost-wakeup problem
  - a *V* saves the signalling event in the semaphore, causing *P* to continue
- another option is falling back on the **event queue** [15, p. 17]:
  - just if one wants to implement *P* and *V* as a guarded section, for example

```
typedef event_t indicator_t;
inline void enroll(indicator_t *hint) { catch(hint); }
inline void repose(indicator_t *hint) { coast(); }
inline void arouse(indicator_t *hint) { cause(hint); }
```

[5] A **binary semaphore** used in a producer/consumer style of interaction.

Order Allocation/Deallocation

```
inline order_t *order(unsigned long n) {
    order_t *item;
    if (n < 2)
        item = (order_t *)malloc(sizeof(order_t));
    else {
        item = (order_t *)
            malloc(sizeof(order_t) + n * sizeof(long));
        if (item)
            item->post.lump = (void *)
                ((long)item + sizeof(*item));
    }
    return item;
}

inline void ditch(order_t *item) {
    free(item);
}
```

- in oder to decrease latency and lower overhead, specialisation towards the use of an **order pool** is recommended

Guarded-Section Sample


```
1  void alert(void *index, long value) {
2    extern guard_t gate;                  /* guard instance */
3    order_t *task = order(2); /* order of 2 parameters */
4
5    (*task->post.lump)[0] = (long)index;
6    (*task->post.lump)[1] = value;    /* request filled */
7
8    if (vouch(&gate, task)) do {          /* try to pass */
9      extern semaphore_t sign;    /* to await clearance */
10
11     backup(&task->post);  /* buffer and display data */
12     printf("order %p with [%p, %lu]\n", task,
13       (*task->post.lump)[0], (*task->post.lump)[1]);
14
15     ditch(task);               /* delete current request */
16     if (!phase(&gate, &sign)) break;    /* clearance? */
17
18   } while ((task = clear(&gate)));   /* next request? */
19 }
```

- for **trailing conditional wait**, line 16 reads: `trail(&gate, &sign);`

Data Type III

```
typedef struct future {
    promise_t data;      /* prospective value */
    indicator_t gate;    /* signalling element */
} future_t;
```

- a future object is the promise—of a guarded section, here—to deliver a result at some later point in time:

```
typedef enum status {
    PENDING, KEPT, BROKEN
} status_t;

typedef struct promise {
    status_t bond;       /* processing state */
    item_t item;         /* future-value placeholder */
} promise_t;
```

  - whereby the promise is a result placeholder, on the one hand, and keeps track of the status of result delivery, on the other hand

S{a,i}mple Future Implementation

```
inline status_t probe(future_t *this) {
    return this->data.bond;
}

inline void trust(future_t *this) { enroll(&this->gate); }

inline item_t *exact(future_t *this) {
    repose(&this->gate);
    return probe(this) == KEPT ? &this->data.item : 0;
}

inline void bring(future_t *this, status_t bond) {
    this->data.bond = bond;
    arouse(&this->gate);
}

inline void prove(future_t *this, item_t *item) {
    this->data.item = *item;
    bring(this, KEPT);
}

inline void abort(future_t *this) { bring(this, BROKEN); }
```