Concurrent Systems

Nebenläufige Systeme

XII. Guarded Sections

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February 4, 2021

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

- both approaches common is the fact that processes of whichever kind will never be blocked at entrance to a critical section
  - however their requests to enter and pass through may be delayed
  - an **alternating sequencer** takes care of retroactive request processing
  - this constrains overlapping and, thus, eases non-blocking request queues
    - per sample of *interrupt-transparent synchronisation* [14], for instance
- similar to an explicit ("eventual values" [9, 10]) or implicit **future** [2], it is shown how to deal with "direct-result critical sections"
  - using concepts such as the **promise** [7] or promise pipelining [12]
  - 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

[1] Not to be confused with "guarded commands" [4].

Outline

Interrupt Handling

Definition (Interrupt)

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

- a **sudden upcall** (acc. [3]) performed by a processor in the middle of or between actions, depending on the processor model
  - start of a simultaneous process on this very processor in **stacking** mode
  - most notably, this process is characteristic of a **run-to-completion** flow
- 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
postlude	*second-level interrupt handler* (SLIH) running at OS priority

- 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.*

[a] Interrupt requests of the same and lower priority are disabled.
[b] All interrupt requests are enabled.

- conceptually, prelude and postlude together constitute the interrupt handler to be dispatched due to an **interrupt request** (IRQ):

guardian
- identifies and activates the prelude for the given IRQ
  - ↪ in case of an **edge-triggered** IRQ, takes OS priority before it
  - ↪ in case of a **level-triggered** IRQ, takes OS priority afterwards

prelude
- operates and "unloads" the device to satisfy the IRQ source
- starts immediately if enabled by the CPU priority
- as the case may be, releases its postlude for post-processing

postlude
- operates the device, if still required, and particularly the system
- starts when no more preludes are stacked and, thus, pending
- as the case may be, interacts with a process instance

Relevance of Postlude

Hint (Asynchronous System Trap, AST [11, p. 414])

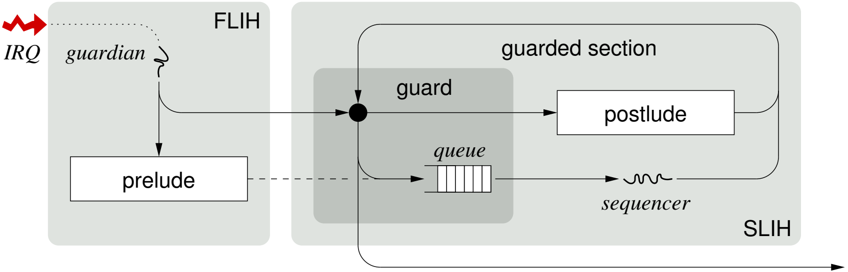
On the VAX, a software-initiated interrupt to a service routine. ASTs enable a process to be notified of the occurrence of a specific event asynchronously with respect to its execution. In 4.3 BSD, ASTs are used to initiate process rescheduling.

- essentially, the interrupt handler postlude equates to such an AST
  - a mechanism that forces an interrupted process back into system mode:
    - i when no interrupt handler prelude is pending (i.e., stacked) <u>and</u>
    - ii in the moment when the interrupt handler guardian terminates (i.e., returns)
  - as if this very process performs a system call to the interrupt postlude
- caution is advised when an **interrupt-handler control flow** expands

guardian	not applicable, controls prelude and postlude (i.e., an AST)	☹
prelude	risk of race conditions <u>and</u> system-stack overflow	☹
postlude	risk of race conditions ⇝ **synchronisation** or **reentrancy**	☺

- 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



- heading for postlude execution depends on the particular prelude
  - a prelude is a **function**, its return value indicates the postlude to be run
  - a return value of *NULL* indicates that this prelude asks for no postlude
- 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**
  - postludes are still carried out **asynchronously** to the interrupted process
- notably is the implication in terms of the **constructive restriction** of overlappings as to simultaneous pre- and postludes
  - i higher priority preludes may overlap lower priority preludes
  - ii preludes may overlap postludes, but never reverse
  - iii postludes may overlap other postludes and process instances
- regarding the whole processing chain and the involvement of guardian and sequencer process one may realise:
  - the guardian (incl. prelude) enqueues postludes possibly simultaneously, but never dequeues them
  - the sequencer dequeues postludes possibly overlapped by enqueues, but these dequeues will never overlap enqueues performed by the guardian
- this **multiple-enqueue/single-dequeue** mode of operation eases the design of a non-blocking synchronised postlude queue

Guardian and Sequencer


```
__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. [14]

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

```
void enqueue_lfs_ms(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! */
        last = last->link;      /* find end of orig. list */

    last->link = item;          /* insert & combine lists */
}
```

- 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. [14]

```
chain_t *dequeue_lfs_ms(queue_t *this) {
    chain_t *item;

    if ((item = this->head.link)  /* next item fetched */
    &&  !(this->head.link = item->link)) {
        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 & */
                enqueue_lfs_ms(this, lost);   /* rearrange */
            } while ((lost = help) != 0);
        }
    }

    return item;
}
```

Hint (Lock Freedom)

Some process will complete an operation in a finite number of steps, regardless of the relative execution speeds of the processes. [8, p. 142]

- critical is dequeuing as to the **last element** and overlapped by one or more enqueues, thus, filling up the queue again
  - one moment the fetched item was last, now latecomers must be recovered

Wait-Free Solution

```c
void enqueue_wfs_ms(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 *dequeue_wfs_ms(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:

```c
#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)

Hint (Pro-/Epilogue [15, 14])

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 — which are more comparable to AST handlers.*

- postlude guide through is not unlike **procedure chaining** [13, p. 10], a technique to serialise execution of conflicting threads
  - 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

Critical Sections Revisited

. . . what makes the difference?

- assuming a **stack** represented as LIFO (*last in, first out*) single-linked list, whose *push*- and *pop*-operations need to be critical sections

```
void push(lifo_t *list, chain_t *item) {
    acquire(&list->lock);         /* enter critical section */
    item->link = list->link;
    list->link = item;
    release(&list->lock);         /* leave critical section */
}
```

  - processes proceed successively, <u>neither</u> depends on the computation result

```
chain_t *pull(lifo_t *list) {
    chain_t *item;

    acquire(&list->lock);         /* enter critical section */
    if ((item = list->link) != 0)
        list->link = item->link;
    release(&list->lock);         /* leave critical section */

    return item;
}
```

  - processes proceed successively, <u>each</u> depends on the computation result

Conditional Fire-and-Forget Pattern

- processes heading for passing through a critical section will proceed unstopped, though simultaneous **passage requests** are serialised
  - at the end of a critical section, these requests will be processed one a time
- accordingly, the **exit protocol** does not have to take care of blocked processes but rather intermediately incurred passage requests
  - the particular leaving process attends to handle accumulated entry calls
  - thus, critical-section execution is **asynchronous** to its requesting process
- in case of data dependencies as to the computation within a critical section, synchronisation on **result delivery** becomes necessary
  - thereto, computation results need to be returned and accepted **by proxy**
  - to this end, the following measures have to be provided:
    - i as additional element of the corresponding passage request, a placeholder for the computation result (*consumable resource*) and
    - ii a signalling mechanism to indicate result delivery (*logical synchronisation*)
- 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 Critical-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

  promise
  - traced back to [7], a writeable, single-assignment container[2]
  - can be used to successfully complete a future with a value
- each future instance has a dedicated **resolver** taking care of (a) value assignment and (b) **promise states**:

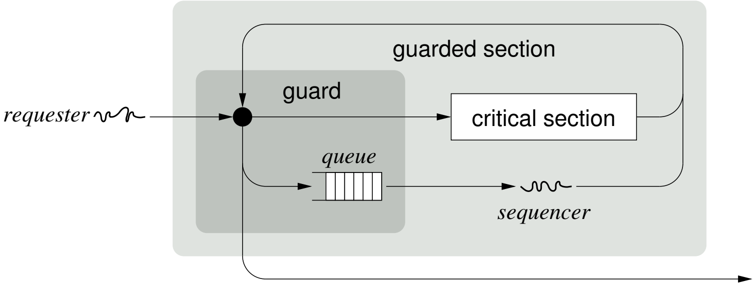
  kept
  - value computed, assignment took place

  broken
  - computation aborted, assignment ceases to take place

  pending
  - 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 $\rightsquigarrow$ ***signalling semaphore***

[2]Refined for *promise pipelining* [12] to overcome latency in distributed systems.

Execution Sequencing of Critical Sections



- 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

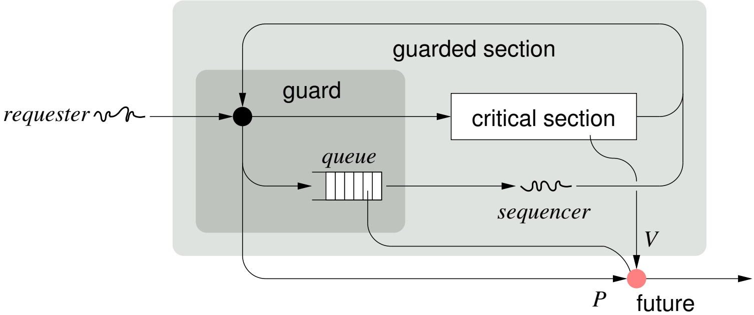
  occupied
  - guard denies requester access to the critical section
  - the request gets queued and the requester bypasses

- 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



- 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
    - 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.

  - processes will not await external events from inside the critical section

- control of a **run-to-stopover style** of execution of a critical section depends on the locality of peer processes

Definition (Run to Stopover (Process))

A potentially preemptive process possibly being subject to wait states.

  i processes waiting on events caused by an **external process** (e.g., I/O)
  ii processes interacting with an **internal process** due to *resource sharing*

- both styles of execution concern the period of a critical section, only
  - but at large, a process may be classified run to completion and 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]
- unlike **internal processes**, provided that they have to interact with their peers using ***shared resources*** inside a critical section
  - relevant at this point is the producer/consumer style of interaction, only
    - if the consumer needs to wait on the producer inside a critical section
    - then the critical section must be unoccupied by the consumer while waiting
  - 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 [16, p. 9]
  - without clearing the guarded section, a **stopover process** may deadlock

[3] Have peripherals (i.e., I/O devices) in mind to understand external processes. Production of input data using a keyboard, mouse, network card, disk, or sensor, for example, is not caused by an OS-controlled **producer-process instance**.

Overlapping Pattern

- notably is the implication in terms of the **constructive restriction** of overlappings as to simultaneous requester and sequencer processes
  - i requesters of any guarded section may overlap each other
  - ii self-overlapping of a sequencer is impossible
  - iii only sequencers of different guarded sections may overlap each other
- regarding the whole request processing chain and the involvement of requester and sequencer process one may realise:
  - multiple requester may enqueue passage requests possibly simultaneously, but they will never dequeue these
  - a single sequencer only dequeues passage requests, but this may happen simultaneously to enqueues of one or more requesters
- this **multiple-enqueue/single-dequeue** mode of operation eases the design of a non-blocking synchronised passage-request queue
  - furthermore, synchronisation then happens to be even **wait-free** [6, 5]

Hint (Wait Freedom)

Any process can complete any operation in a finite number of steps, regardless of the execution speeds of the other processes. [8, p. 124]

Data Type I

```
typedef struct guard {
    int book;           /* # of concurrent requests */
    queue_t load;       /* pending passage requests */
#ifdef __FAME_GUARD_ADVANCED__
    ...
#endif
} guard_t;
```

- invariably, a **chain-like queue** of registered "passage requests"
  - mandatory, sufficient for elementary guarded sections
  - with a twofold meaning of the *book* attribute depending on its value
    - i the actual number of passage requests pending for processing
    - ii the state of occupancy (cf. p. 20): occupied if *book* > 0, unoccupied else
- variably, additional stuff for advanced control of guarded sections:
  - some **timeout** that ensures progress for the actual **major sequencer**
  - a **minor sequencer** to replace the major sequencer at timeout
  - any management data to prevent **priority inversion**, if applicable
  - ...

Claiming and Clearing

first-come, any serve (FCAS)

- vouch for sequential execution of a guarded critical section:

```
1  inline order_t *vouch(guard_t *this, order_t *work) {
2      enqueue(&this->load, work);
3      if (FAA(&this->book, 1) == 0)
4          return dequeue(&this->load);
5      return 0;
6  }
```

  - 2 remember this passage request
  - 3 check state of occupancy and book passage request
  - 4 was unoccupied, became sequencer, accept first passage request
    - could be a request different from the one that was just remembered

- clear the next passage request, if any, pending for processing:

```
7  inline order_t *clear(guard_t *this) {
8      if (FAA(&this->book, -1) > 1)
9          return dequeue(&this->load);
10     return 0;
11 }
```

  - 8 count completion and check for further pending requests
  - 9 remove next passage request, if any available

Data Type II

```
typedef struct order {
    chain_t next;        /* passage-request chaining */
    item_t post;         /* argument placeholder */
} order_t;
```

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

```
typedef union item {
    long (*lump)[];      /* argument vector (N > 1) */
    long sole;           /* single argument (N = 1) */
} item_t;
```

  - depending on the number of parameters, the structure describes a multi- or uni-element argument vector
  - in the multi-element case, the argument vector is placed adjacent to its item or order, resp., instance (cf. p. 41)
- in addition, this vector also serves as placeholder for a *future value*

Piece the Puzzle Together

- 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;
```

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

```
extern guard_t gate;
if (vouch(&gate, task)) do                    /* enter section */
```

- midsection (i.e., actual critical section), **solo attempt**:

```
/* Several Species of Small Furry Animals
 * Gathered Together in a Cave and
 * Grooving with a Pict */
```

- **exit protocol**, processing of pending passage requests:

```
while ((task = clear(&gate)));                /* leave section */
```

  - 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
  - that is, the continuation of a **requester** (lev. 3) or the **guardian** (lev. 2)[4]
  - whereby this continuation is **commander-in-chief** of a critical section
- when a requester process requires a direct result from the sequencer process, interaction in a **consumer/producer-style** takes place
  - in such a case, the respective request is associated with a **future object**
  - it carries the promise of the sequencer to deliver a result to the requester
  - a future-specific **signalling semaphore** then indicates result availability
- besides supporting conventional critical sections, this approach eases design of non-blocking synchronised non-sequential programs

[4] Operating-system machine or instruction set architecture level, respectively.

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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. 28)

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) {
    enqueue(&tube->load, &task->data.next);
}

inline remit_t *untie(usher_t *tube) {
    return (remit_t *)dequeue(&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 "`{en,de}queue_ms_lfs`" or -"`_wfs`", resp.

Job Definition and Start

- a SLIH or an interrupt-handler postlude, resp., is a **passage request** (cf. p. 27) 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 [13, p. 10]

- 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** [16, 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

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); }
```