

Concurrent Systems

Nebenläufige Systeme

X. Guarded Sections

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Agenda

Preface

Hardware Events

Fundamentals

Sequencing

Implementation

Process Events

Fundamentals

Sequencing

Implementation

Summary



Preface

Hardware Events

- Fundamentals

- Sequencing

- Implementation

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Subject Matter

- discussion on abstract concepts as to **structural measures** suited in paving the way for non-blocking synchronisation
 - **guarded sections** ■ synchronise process-originated events¹
 - **pre-/postlude sections** ■ synchronise hardware-originated events

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 - using concepts such as the **promise** [7] or promise pipelining [12]
 - functional programming meets distributed computing for synchronisation

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- 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

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- 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
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 - 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
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 - 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



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.*

^aInterrupt requests of the same and lower priority are disabled.

^bAll interrupt requests are enabled.



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 - starts immediately if enabled by the CPU priority
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- as the case may be, interacts with a process instance



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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.



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- 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) and
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- 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 and system-stack overflow ☹
 - postlude** ■ risk of race conditions \rightsquigarrow **synchronisation** or **reentrancy** ☹



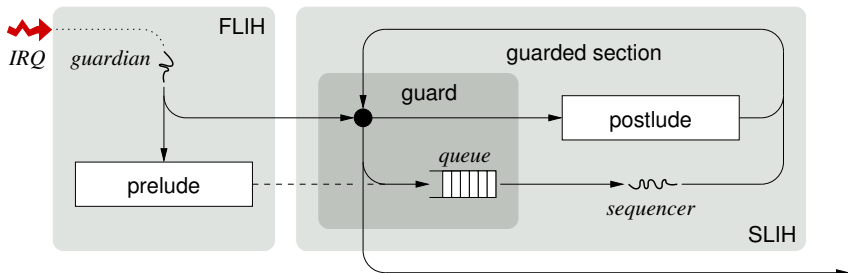
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- purpose of the postlude is to safely allow such control-flow expansions
 - its activation is controlled similar to the control of guarded sections



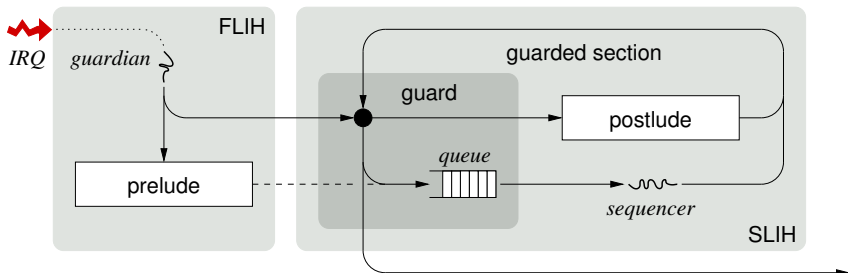
Execution Sequencing of Postludes



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 - a prelude is a **function**, its return value indicates the postlude to be run
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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**
 - postludes are still carried out **asynchronously** to the interrupted process



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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



```
1  __attribute__((fastcall)) void guardian(long irq) {
2      static usher_t tube = { 0, {0, &tube.load.head} };
3      extern remit_t *(*flih[])(usher_t *);
4      remit_t *task;
5
6      #ifdef __FAME_INTERRUPT_EDGE_TRIGGERED__
7          pivot(&tube.busy, +1); admit(IRQ); /* take OS priority */
8      #endif
9
10     task = (*flih[irq])(&tube); /* activate prelude & satisfy IRQ source */
11
12     #ifdef __FAME_INTERRUPT_LEVEL_TRIGGERED__
13         pivot(&tube.busy, +1); admit(IRQ); /* take OS priority */
14     #endif
15
16     if (tube.busy > 1) { /* sequencer is already on duty */
17         if (task != 0) deter(&tube, task); /* enqueue postlude & */
18         avert(IRQ); /* leave with CPU priority */
19     } else { /* bring sequencer into service */
20         if ((task != 0) && (tube.load.head.link == 0)) remit(task);
21
22         avert(IRQ); /* prevent lost unload */
23         while (tube.load.head.link != 0) {
24             admit(IRQ); /* take OS priority, again */
25             flush(&tube); /* forward pending postludes */
26             avert(IRQ); /* leave with CPU priority */
27         }
28     }
29     pivot(&tube.busy, -1); /* leave critical section */
30 }
```



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

```
1 void chart_ms_lfs(queue_t *this, chain_t *item) {
2     chain_t *last;
3
4     item->link = 0;           /* terminate chain: FIFO */
5
6     last = this->tail;       /* settle insertion point */
7     this->tail = item;      /* create new partial list */
8
9     while (last->link != 0) /* overlapping enqueue! */
10         last = last->link; /* find end of orig. list */
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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**



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1 chain_t *fetch_ms_lfs(queue_t *this) {
2     chain_t *item;
3
4     if ((item = this->head.link) /* next item fetched */
5         && !(this->head.link = item->link)) {
6         this->tail = &this->head; /* is last one, reset */
7         if (item->link != 0) { /* overlapping enq.! */
8             chain_t *help, *lost = item->link;
9             do { /* recover latecomers */
10                help = lost->link; /* remember next & */
11                chart_ms_lfs(this, lost); /* rearrange */
12            } while ((lost = help) != 0);
13        }
14    }
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- one moment the fetched item was last, now latecomers must be recovered



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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. [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

```
1 void chart_ms_wfs(queue_t *this, chain_t *item) {
2     chain_t *last;
3     item->link = 0;      /* terminate chain: FIFO */
4     last = FAS(&this->tail, item);
5     last->link = item;  /* eventually append item */
6 }
7
8 chain_t *fetch_ms_wfs(queue_t *this) {
9     chain_t *item = this->head.link;
10    if (item) {          /* check for last item */
11        if (item->link) /* is not, non-critical */
12            this->head.link = item->link;
13        else if (CAS(&this->tail, item, &this->head))
14            CAS(&this->head.link, item, 0);
15    }
16    return item;
17 }
```

- with the following mapping to GCC atomic intrinsic functions:

```
1 #define FAS(ref, val) __sync_lock_test_and_set(ref, val)
2 #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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*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** [13, p. 10], a technique to serialize execution of conflicting threads
 - differences are due to the constrained pre-/postlude overlapping pattern
 - unless stack-based scheduling [1], any process overlapping is assumed



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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



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Critical Sections Revisited

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

```
1 void push(lifo_t *list, chain_t *item) {
2     acquire(&list->lock);           /* enter critical section */
3     item->link = list->link;
4     list->link = item;
5     release(&list->lock);           /* leave critical section */
6 }

7 chain_t *pull(lifo_t *list) {
8     chain_t *item;
9
10    acquire(&list->lock);           /* enter critical section */
11    if ((item = list->link) != 0)
12        list->link = item->link;
13    release(&list->lock);           /* leave critical section */
14
15    return item;
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- processes proceed successively, neither depends on the computation result

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Conditional Fire-and-Forget Pattern

- 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



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



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
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 - 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*)



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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



- 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
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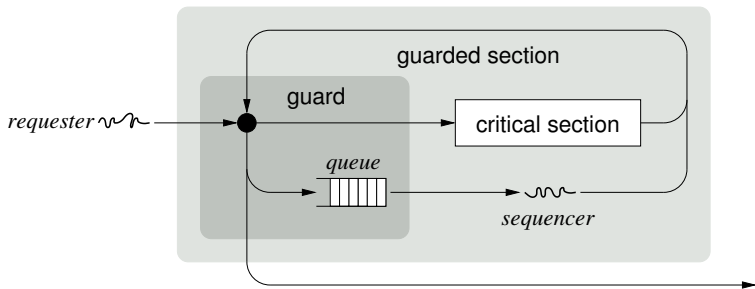
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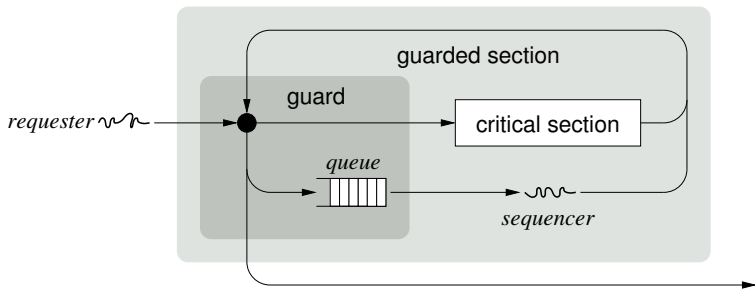
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- based on these states, a process is able to synchronise on the **event** that the promise to deliver a value was either kept or broken
 - the resolver (process inside the critical section) acts as producer
 - the future using process acts as consumer \rightsquigarrow **signalling semaphore**

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Execution Sequencing of Critical Sections



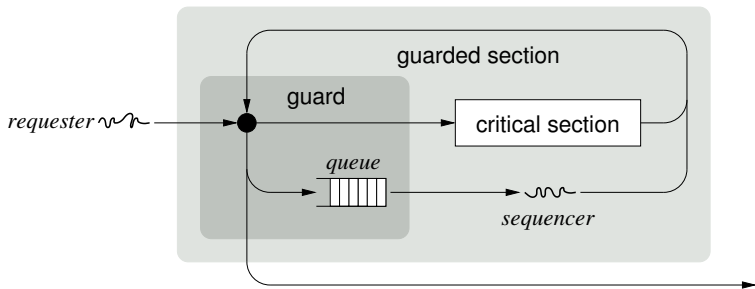
Execution Sequencing of Critical Sections



- 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



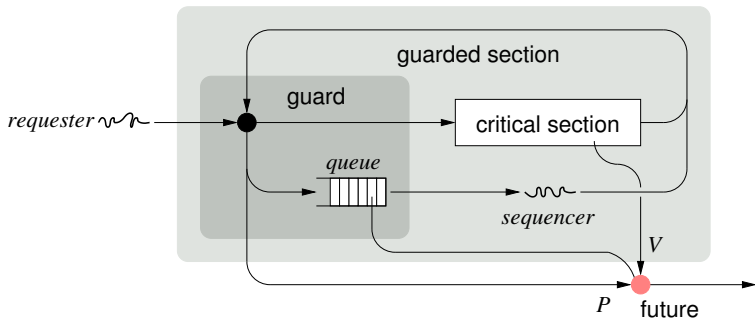
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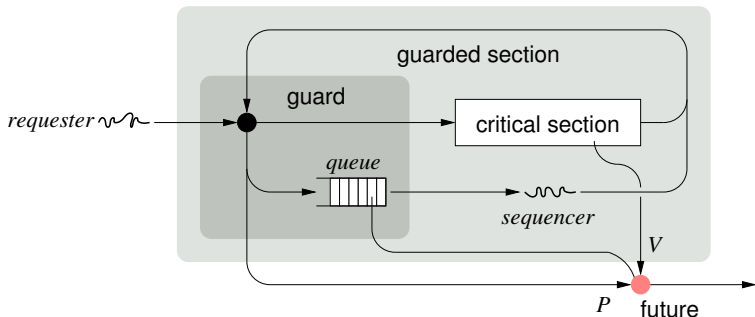
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 - the request gets queued and the requester bypasses
- leaving a critical section depending on the **request-queue state**:
 - empty** ■ critical section becomes unoccupied, the process continues
 - full** ■ the actual leaving process becomes sequencer and re-enters the critical section for each queued request



Synchronisation of Direct-Result Critical Sections



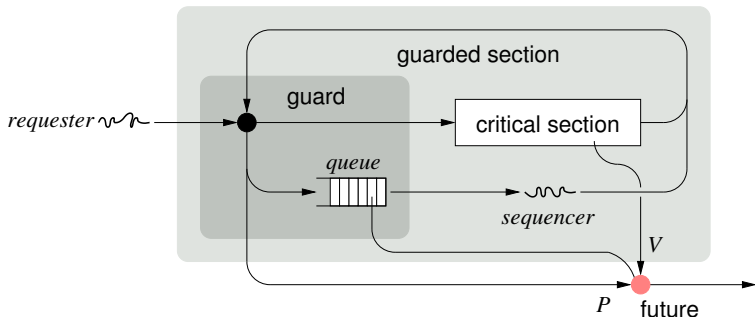
Synchronisation of Direct-Result Critical Sections



- 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
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- 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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- 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

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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 [16, p. 9]
 - without clearing the guarded section, a **stopover process** may deadlock

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- regarding the whole request processing chain and the involvement of requester and sequencer process one may realise:
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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. [8, p. 124]



```
1 typedef struct guard {
2     int book;           /* # of concurrent requests */
3     queue_t load;      /* pending passage requests */
4 #ifdef __FAME_GUARD_ADVANCED__
5     ...
6 #endif
7 } guard_t;
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- 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



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 - 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
 - ...



- 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



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- 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



```
1 typedef struct order {
2     chain_t next;      /* passage-request chaining */
3     item_t post;      /* argument placeholder */
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- layout of an **argument vector** for passage-request parameters:

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

- 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)



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- in addition, this vector also serves as placeholder for a *future value*



Piece the Puzzle Together



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

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



Piece the Puzzle Together

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

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



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

```
6 /* Several Species of Small Furry Animals
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- **exit protocol**, processing of pending passage requests:

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- besides logical synchronisation in the **midsection**, any other programming statements are doable as well—like in conventional critical sections



Outline

Preface

Hardware Events

- Fundamentals

- Sequencing

- Implementation

Process Events

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Summary



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**
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 - 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**

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

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- [1] BAKER, T. P.:
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Guardian Insulating and Invoking

```
1  _joint:
2      pushl %ecx      # save volatile register
3      movl  $0, %ecx  # pass IRQ number
4  _jointN:           # come here for IRQ number N > 0
5      pushl %edx      # save another volatile register
6      pushl %eax      # ditto
7      call  _guardian # fastcall to guardian
8      popl  %eax      # restore volatile register
9      popl  %edx      # ditto
10     popl  %ecx      # ditto
11     iret           # resume interrupted process
```

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

```
1  _joint42:
2      pushl %ecx      # save volatile register
3      movl  $42, %ecx # pass IRQ number
4      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)

```
1 void postlude(/*optional*/order_t *todo) {
2     /* Come here for device post-processing &
3      * any asynchronous system interaction. */
4     V((semaphore_t *)todo->post.sole);
5 }
```

- 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**:

```
1 typedef guard_t usher_t;
2
3 inline void deter(usher_t *tube, remit_t *task) {
4     chart(&tube->load, &task->data.next);
5 }
6
7 inline remit_t *untie(usher_t *tube) {
8     return (remit_t *)fetch(&tube->load);
9 }
10
11 inline void flush(usher_t * tube) {
12     remit_t *next;
13     do if ((next = untie(tube))) remit(next);
14     while (next != 0);
15 }
```

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



- 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

```
1 typedef struct remit {
2     order_t data;           /* parameter set */
3     void (*code)(order_t *); /* procedure address */
4 } remit_t;
5
6 inline void remit(remit_t *this) {
7     (*this->code>(&this->data); /* run that job */
8 }
```

- 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:

```
1 typedef semaphore_t indicator_t;
2 inline void enroll(indicator_t *hint) { }
3 inline void repose(indicator_t *hint) { P(hint); }
4 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

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

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



Order Allocation/Deallocation

```
1  inline order_t *order(unsigned long n) {
2      order_t *item;
3      if (n < 2)
4          item = (order_t *)malloc(sizeof(order_t));
5      else {
6          item = (order_t *)
7              malloc(sizeof(order_t) + n * sizeof(long));
8          if (item)
9              item->post.lump = (void *)
10                 ((long)item + sizeof(*item));
11     }
12     return item;
13 }
14
15 inline void ditch(order_t *item) {
16     free(item);
17 }
```

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



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

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

```
1 typedef enum status {
2     PENDING, KEPT, BROKEN
3 } status_t;
4
5 typedef struct promise {
6     status_t bond;      /* processing state */
7     item_t item;       /* future-value placeholder */
8 } 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

```
1  inline status_t probe(future_t *this) {
2      return this->data.bond;
3  }
4
5  inline void trust(future_t *this) { enroll(&this->gate); }
6
7  inline item_t *exact(future_t *this) {
8      repose(&this->gate);
9      return probe(this) == KEPT ? &this->data.item : 0;
10 }
11
12 inline void bring(future_t *this, status_t bond) {
13     this->data.bond = bond;
14     arouse(&this->gate);
15 }
16
17 inline void prove(future_t *this, item_t *item) {
18     this->data.item = *item;
19     bring(this, KEPT);
20 }
21
22 inline void abort(future_t *this) { bring(this, BROKEN); }
```

