Concurrent Systems

*Nebenläufige Systeme*

X. Guarded Sections

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Outline

Preface

Hardware Events
  - Fundamentals
  - Sequencing
  - Implementation

Process Events
  - Fundamentals
  - Sequencing
  - Implementation

Summary

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
  - 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].
Interrupt Handling

Definition (Interrupt)
Mechanism of a (soft- or hardware) processor to prompt software to draw attention to an external process asynchronously, unpredictably, and unrepudiable.

- 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

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
    - in case of an edge-triggered IRQ, takes OS priority before it identifies and activates the prelude for the given IRQ
    - 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) and
    - 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 and system-stack overflow
    - postlude risk of race conditions synsynchronisation 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
Guardian and Sequencer
From FLIH to SLIH (cf. p. 36ff.)

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
    - higher priority preludes may overlap lower priority preludes
    - preludes may overlap postludes, but never reverse
    - 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
From FLIH to SLIH

- 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! */
        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

```c
chain_t * fetch_ms_lfs ( 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 & */
                chart_ms_lfs ( 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 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 ;
}
```

**Special Instructions**

- 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.

- 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
- 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
  ```c
  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, **neither** depends on the computation result

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

- promise traced back to [7], a writeable, single-assignment container2
  - 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 — **signalling semaphore**

```
2Refined for promise pipelining [12] to overcome latency in distributed systems.
```
Synchronisation of Direct-Result Critical Sections

- A passage request may refer to a multi-elementary future object:
  - A promise indicator (kept, broken, pending)
  - A placeholder of problem-specific type as to the critical section
  - 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

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
- 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

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.

- Processes waiting on events caused by an external process (e.g., I/O)
- 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

Overlap Pattern

- Notably is the implication in terms of the constructive restriction of overlappings as to simultaneous requester and sequencer processes
  - Requesters of any guarded section may overlap each other
  - Self-overlapping of a sequencer is impossible
  - 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**

Critical-Section Guard

```c
typedef struct guard {
    int book; /* # of concurrent requests */
    queue_t load; /* pending passage requests */
} 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
    - the actual number of passage requests pending for processing
    - 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
  - ...

**Data Type II**

Passage Request

```c
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:
  ```c
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

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**Claiming and Clearing**

first-come, any serve (FCAS)

vouch for sequential execution of a guarded critical section:

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

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

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

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

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**Piece the Puzzle Together**

fore editing of passage-request parameters, optional:

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

- midsection (i.e., actual critical section), solo attempt:
  ```c
  /* Several Species of Small Furry Animals
  * Gathered Together in a Cave and
  * Grooving with a Pict */
  ```

- exit protocol, processing of pending passage requests:
  ```c
  while ((task = clear(&gate)));
  ```

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

Reference List I


Reference List II


**Reference List III**

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The Design and Implementation of the 4.3 BSD UNIX Operating System.
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**Reference List IV**

[12] **Liskov, B. J. H.; Shrira, L.**
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[13] **Pu, C.; Massalin, H.**

[14] **Schön, F.; Schröder-Preikschat, W.; Spinczyk, O.; Spinczyk, U.**
On Interrupt-Transparent Synchronization in an Embedded Object-Oriented Operating System.

**Reference List V**

[15] **Schröder-Preikschat, W.**
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[16] **Schröder-Preikschat, W.**
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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`

```
Joint Invoking

1 _joint42:
  2 pushl %ecx # save volatile register
  3 movl $42, %ecx # pass IRQ number
  4 jmp _jointN # switch to common joint section...
```
Simple Interrupt Handler

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

remit_t * prelude(/*optional*/ usher_t * tube) {
  static remit_t task = { {}, postlude };
  /* Come here for device pre-processing & * device-related IRQ acknowledgement. */
  deter(tube, &task); /* force postlude to queue */
  return 0; /* don’t request shortcut */
}

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)

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]

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);
}

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

Art of Waiting Inside a Guarded Section

straightforward is the use of a signalling semaphore:

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); }

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 order 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

Simple 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); }