Concurrent Systems

Nebenläufige Systeme

XI. Guarded Sections

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Agenda

Preface

Hardware Events
  Fundamentals
  Sequencing
  Implementation

Process Events
  Fundamentals
  Sequencing
  Implementation

Summary
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].
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Summary
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
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) 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 \( \sim \) 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
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
__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

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

```c
void enqueue_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 *dequeue_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 {
                help = lost->link; /* remember next & */
                enqueue_ms_lfs(this, lost); /* rearrange */
            } while ((lost = help) != 0);
        }
    }
    
    return item;
}
```

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.

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]

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Hardware Events – Implementation
void enqueue_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 *dequeue_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)

**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 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
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

```c
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, **each** depends on the computation result
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 atttends 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:
  - as additional element of the corresponding passage request, a placeholder for the computation result (consumable resource) and
  - 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

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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**

\(^2\)Revised 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.

- 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.
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

\[3\] 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
  1. requesters of any guarded section may overlap each other
  2. self-overlapping of a sequencer is impossible
  3. 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]
```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
  - i. the actual number of passage requests pending for processing
  - ii. the state of occupancy (cf. p. 20): occupied if `book > 0`, unoccupied else

Invariably, 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:

```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;
}
```

1. remember this passage request
2. check state of occupancy and book passage request
3. 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:

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

8. count completion and check for further pending requests
9. remove next passage request, if any available
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:
  
  ```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))); /* leave section */
  ```

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

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Summary
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)
- 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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On Interrupt-Transparent Synchronization in an Embedded Object-Oriented Operating System.
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_The Logical Design of Parallel Operating Systems._

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_In: Lehrstuhl Informatik 4 (Hrsg.): Concurrent Systems._
FAU Erlangen-Nürnberg, 2014 (Lecture Slides), Kapitel 8
each IRQ entry in the CPU exception vector is associated with a `joint`
Simple Interrupt Handler

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

```c
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)

```c
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**:

```c
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]
Art of Waiting

Inside a Guarded Section

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); }`

\(^5\)A **binary semaphore** used in a producer/consumer style of interaction.
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

Future Object

```c
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:

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

```c
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.
```c
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); }
```