Concurrent Systems

*Nebenläufige Systeme*

XII. Guarded Sections

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  Fundamentals
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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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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:
  - when no interrupt handler prelude is pending (i.e., stacked) and
  - 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:

- not applicable, controls prelude and postlude (i.e., an AST)
- risk of race conditions and system-stack overflow
- risk of race conditions \(\leadsto\) 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
  - 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 (cf. p. 36ff.)

```c
__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);
        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 */
}```
assuming that simultaneous enqueues can happen only in a **stacking arrangement**, then the following is “thread safe”:

```c
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]

```c
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;
}
```

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]
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:

#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
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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
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.
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

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a passage request may refer to a multi-elementary future object:

i. a promise indicator (kept, broken, pending)

ii. a placeholder of problem-specific type as to the critical section

iii. a binary semaphore that is used in producer/consumer mode

   - 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
  - 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

```c
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
    - the actual number of passage requests pending for processing
    - 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
  - ...
Claiming and Clearing

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;
}
```

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:

```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
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;`

**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 * Gathered Together in a Cave and * Grooving with a Pict */`

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

7. `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
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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*
- 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

```assembly
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...
```
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.

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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

```c
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**\(^5\):

```c
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

```c
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.
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.
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
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); }