Concurrent Systems

Nebenläufige Systeme

XI. Guarded Sections

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Agenda

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   Fundamentals
   Sequencing
   Implementation

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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\(^1\)
  - **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**
  - 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 ↼ 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
Guardian and Sequencer

From FLIH to SLIH (cf. p. 36 ff.)

```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); /* prevent lost unload */
        while (tube.load.head.link != 0) { /* take OS priority, again */
            admit(IRQ);
            flush(&tube); /* forward pending postludes */
            avert(IRQ); /* leave with CPU priority */
        }
    }

    pivot(&tube.busy, -1); /* leave critical section */
}
```

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CS (WS 2018/19, LEC 11) Hardware Events – Implementation
assuming that simultaneous enqueues can happen only in a **stacking arrangement**, then the following is “thread safe”:

```c
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 */
}
```

The idea is to create a new partial list using an **atomic store** and, thus, isolate the original list for later safe manipulation.

However, simultaneous enqueues then may shift the **actual insertion point**.
Lock-Free Synchronised Dequeue

cf. [14]

```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;
}
```

**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 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;
}

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
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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
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 at 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:
    - 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
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
    - 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 ː **signalling semaphore**

---

2Refined 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
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
  - 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]
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

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:

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

exit protocol, processing of pending passage requests:
9  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)
  - 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

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4 Operating-system machine or instruction set architecture level, respectively.
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Guardian Insulating and Invoking

 joint:
    pushl %ecx               # save volatile register
    movl $0, %ecx            # pass IRQ number

 jointN:                      # come here for IRQ number N > 0
    pushl %edx               # save another volatile register
    pushl %eax               # ditto
    call _guardian           # fastcall to guardian
    popl %eax                # restore volatile register
    popl %edx                # ditto
    popl %ecx                # ditto
    iret                      # resume interrupted process

Each IRQ entry in the CPU exception vector is associated with a joint

 joint42:
    pushl %ecx               # save volatile register
    movl $42, %ecx           # pass IRQ number
    jmp _jointN              # switch to common joint section...
**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) {
    chart(&tube->load, &task->data.next);
}

inline remit_t *untie(usher_t *tube) {
    return (remit_t *)fetch(&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 “{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

```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 oder to decrease latency and lower overhead, specialisation towards
the use of an order pool is recommended
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;

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); }