Concurrent Systems

Nebenläufige Systeme

X. Basics of Non-Blocking Synchronisation

Wolfgang Schröder-Preikschat

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Agenda

Preface

Constructional Axis
- General
- Exemplification
- Transition

Transactional Axis
- General
- Case Study

Summary

Outline

Subject Matter

- discussion on abstract concepts of synchronisation without lockout of critical action sequences of interacting processes (cf. [5])
  - attribute "non-blocking" here means **abdication of mutual exclusion** as the conventional approach to protect critical sections
  - note that even a "lock-free" solution may "block" a process from making progress, very well!

Subject Matter

- discussion on abstract concepts of synchronisation without lockout of critical action sequences of interacting processes (cf. [5])

- develop an intuition for the dependency on **process interleaving** and **contention rate** when arguing on performance issues
  - what in case of high and what else in case of low contention?
  - what is the exception that proves the rule?

Subject Matter

- discussion on abstract concepts of synchronisation without lockout of critical action sequences of interacting processes (cf. [5])
- develop an intuition for the dependency on **process interleaving** and **contention rate** when arguing on performance issues
- follow suit, an explanation of the **two-dimensional** characteristic of non-blocking synchronisation is given
  - on the one hand, constructional, on the other hand, transactional
  - with different weighting, depending on the use case and problem size

Subject Matter

- discussion on abstract concepts of synchronisation without lockout of critical action sequences of interacting processes (cf. [5])
- develop an intuition for the dependency on **process interleaving** and **contention rate** when arguing on performance issues
- follow suit, an explanation of the **two-dimensional** characteristic of non-blocking synchronisation is given
- not least, engage in sort of *tolerance to races* of interacting processes while preventing faults caused by race conditions...

Tolerance is the suspicion
that the other person just might be right.[1]

Source: Commemorative plaque, Berlin, Bundesallee 79

[1] (Ger.) *Toleranz ist der Verdacht, dass der andere Recht hat.*

Outline

Reentrancy

(Ger.) *Eintrittsinvarianz*

Definition

A program is **re-entrant** (Ger. *ablaufinvariant*) if, at execution time, its sequence of actions tolerates self-overlapping operation.

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- those programs can be re-entered at any time by a new process, and they can also be executed by simultaneous processes
  - the latter is a logical consequence of the former: ***full re-entrant***
  - but the former does not automatically imply the latter[2]

[2] For example, if lockout becomes necessary to protect a critical section.

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- originally, this property was typical for an **interrupt handler**, merely, that allows for nested execution—recursion not unresembling
  - each interrupt-driven invocation goes along with a new process
  - whereby the simultaneous processes develop **vertically** (i.e., stacked)

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- those programs can be re-entered at any time by a new process, and they can also be executed by simultaneous processes
- originally, this property was typical for an **interrupt handler**, merely, that allows for nested execution—recursion not unresembling
- generally, this property is typical for a large class of **non-sequential programs** whose executions may overlap each other
  - each invocation goes along with a new process, it must be "thread-safe"
  - whereby the simultaneous processes develop **horizontally**, in addition

Semaphore Revisited

cf. [10, p. 22]

- devoid of an explicit protective shield all-embracing the semaphore implementation, i.e., the elementary operations P and V:

```
1 typedef struct semaphore {
2     int gate;              /* value: binary or general */
3     event_t wait;          /* list of sleeping processes */
4 } semaphore_t;
```

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```

- other than the original definition [1, p. 29], semaphore primitives are considered **divisible operations** in the following
  - merely single steps that are to be performed inside of these primitives are considered indivisible
  - these are operations changing the semaphore value (*gate*) and, as the case may be, the waitlist (*wait*)
  - but not any of these operations are secured by means of mutual exclusion at operating-system machine level
  - rather, they are safeguarded by falling back on ISA-level mutual exclusion in terms of atomic load/store or read-modify-write instructions

Building Blocks for Barrier-Free Operation

- use of **atomic** (ISA-level) **machine instructions** for changing the semaphore value consistently (p. 11)
  - a TAS or CAS, resp., for a binary and a FAA for a general semaphore
  - instruction cycle time is bounded above, solely hardware-defined
  - wait-free [2, p. 124], irrespective of the number of simultaneous processes

Building Blocks for Barrier-Free Operation

- use of **atomic** (ISA-level) **machine instructions** for changing the semaphore value consistently (p. 11)

- abolish abstraction in places, i.e., perform **wait-action unfolding** to prevent the lost-wakeup problem (p. 10)
  - make a process "pending blocked" before trying to acquire the semaphore
  - cancel that "state of uncertainty" after semaphore acquirement succeeded
  - wait- or lock-free [2, p. 142], depending on the waitlist interpretation

Building Blocks for Barrier-Free Operation

- use of **atomic** (ISA-level) **machine instructions** for changing the semaphore value consistently (p. 11)
- abolish abstraction in places, i.e., perform **wait-action unfolding** to prevent the lost-wakeup problem (p. 10)
- accept **dualism** as to the incidence of processing states, i.e., tolerate a "running" process being seemingly "ready to run" (p. 12)
  - delay resolving until some process is in its individual idle state
  - have also other processes in charge of clearing up multiple personality
  - wait-free, resolution produces background noise but is bounded above

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- abolish abstraction in places, i.e., perform **wait-action unfolding** to prevent the lost-wakeup problem (p. 10)
- accept **dualism** as to the incidence of processing states, i.e., tolerate a "running" process being seemingly "ready to run" (p. 12)
- forgo dynamic data structures for any type of waitlist *or* synchronise them using **optimistic concurrency control** (p. 16*ff.*)

Wait-Action Unfolding

cf. [10, p. 23]

```
1  void prolaag(semaphore_t *sema) {
2      catch(&sema->wait);       /* expect notification */
3      lodge(sema);              /* raise claim to proceed */
4      when (!avail(sema))       /* check for process delay */
5          coast();              /* accept wakeup signal */
6      clean(&sema->wait);       /* forget notification */
7  }
8
9  void verhoog(semaphore_t *sema) {
10     if (unban(sema))          /* release semaphore */
11         cause(&sema->wait); /* notify wakeup signal */
12 }
```

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```

- implementation in the shape of a **non-sequential program**:
  - 2 show interest in the receive of a notification to continue processing
  - 3/4 draw on walkover, bethink and, if applicable, watch for notification
  - 5 either suspend or continue execution, depending on notification state
  - 6 drop interest in receiving notifications, occupy resource
  - 10 deregulate "wait-and-see" position above (l. 4), check for a sleeper
  - 11 send notification to interested and, maybe, suspended processes

Atomic Machine Instructions

- load/store-based implementation for a **binary semaphore**:

```
1 inline bool avail(semaphore_t *sema) {
2     return CAS(&sema->gate, 1, 0);
3 }
```

  - both *lodge* and *unban* remain unchanged

Atomic Machine Instructions

differences to [10, p. 24/25]

- enumerator-based implementation for a **general semaphore**:

```
1  inline int lodge(semaphore_t *sema) {
2      return FAA(&sema->gate, -1);
3  }
4
5  inline bool unban(semaphore_t *sema) {
6      return FAA(&sema->gate, +1) < 0;
7  }
```

  - *avail* remains unchanged

Atomic Machine Instructions

differences to [10, p. 24/25]

- load/store-based implementation for a **binary semaphore**:

```
1 inline bool avail(semaphore_t *sema) {
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- enumerator-based implementation for a **general semaphore**:

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1 inline int lodge(semaphore_t *sema) {
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3 }
4
5 inline bool unban(semaphore_t *sema) {
6     return FAA(&sema->gate, +1) < 0;
7 }
```

- note that both variants are insensitive to simultaneous processes
  - due to **indivisible operations** for manipulation of the semaphore value

Dualism

- a process being in “running” state and, as the case may be, at the same time recorded on the waitlist of “ready to run” peers

```
1  inline void catch(event_t *this) {
2      process_t *self = being(ONESELF);
3      self->state |= PENDING;              /* watch for event */
4      apply(self, this);                   /* enter waitlist */
5  }
6
7  inline void clean(event_t *this) {
8      elide(being(ONESELF), this);         /* leave waitlist */
9  }
```

3 - prepares the “multiple personality” process to be treated in time
4 - makes the process amenable to “go ahead” notification (p. 10, l. 11)
8 - excludes the process from potential receive of “go ahead” notifications

Dualism

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```

- treatment of “multiple personality” processes is based on **division of labour** as to the different types of waitlist (cf. p. 34)
  - “ready” waitlist, the respective idle process of a processor (p. 33)
  - “blocked” waitlist, the semaphore increasing or decreasing process

Propagate “go ahead” Notifications

cf. p. 30

- catch of a “go ahead” event is by means of a **per-process latch**
  - i.e., a “sticky bit” holding member of the *process control block* (PCB)

```
1  inline int coast() {
2      stand();                                /* latch event */
3      return being(ONESELF)->merit;           /* signaller pid */
4  }
5
6  int cause(event_t *this) {
7      process_t *next;
8      int done = 0;
9
10     for (next = being(0); next < being(NPROC); next++)
11         if (CAS(&next->event, this, 0))
12             done += hoist(next, being(ONESELF)->name);
13
14     return done;
15 }
```

11 - recognise willingness to catch a signal and continue execution

12 - notify “go ahead”, pass own identification, and ready signallee

A Means to an End...

- non-blocking synchronisation spans **two dimensions** of measures in the organisation of a non-sequential program
  - i a constructional axis, as was shown with the semaphore example, and
  - ii a transactional axis, which is coming up in the next section

A Means to an End...

- non-blocking synchronisation spans **two dimensions** of measures in the organisation of a non-sequential program
  - i a constructional axis, as was shown with the semaphore example, and
  - ii a transactional axis, which is coming up in the next section
- in many cases, particularly given complex software structures such as operating systems, the former facilitates the latter
  - the building blocks addressed and drafted so far are not just dedicated to operating systems, but are suited for any kind of "threads package"
  - although quite simple, they still disclose handicaps as to **legacy software**

A Means to an End...

- non-blocking synchronisation spans **two dimensions** of measures in the organisation of a non-sequential program
  - i a constructional axis, as was shown with the semaphore example, and
  - ii a transactional axis, which is coming up in the next section

- reservation towards the exploitation of non-blocking synchronisation originates much more from the **constructional axis**
  - synchronisation is a typical **cross-cutting concern** of software and, thus, use case of *aspect-oriented programming* (AOP, [3])
  - but the semaphore example shows that even AOP is not the loophole here

A Means to an End...

- non-blocking synchronisation spans **two dimensions** of measures in the organisation of a non-sequential program
  - i a constructional axis, as was shown with the semaphore example, and
  - ii a transactional axis, which is coming up in the next section
- reservation towards the exploitation of non-blocking synchronisation originates much more from the **constructional axis**
- but note that the **transactional axis** does not suggest effortlessness and deliver a quick fix to the synchronisation problem
  - appropriate solutions, however, benefit from a much more localised view

Outline

Optimistic Concurrency Control

cf. [7, p. 15]

Definition (acc. [4])

Method of coordination for the purpose of updating shared data by mainly relying on **transaction backup** as control mechanisms.

```
1  do
2       read phase:
3            save a private copy of the shared data to be updated;
4            compute a new private data value based on that copy;
5       validation and, possibly, write phase:
6            try to commit the computed value as new shared data;
7  while commit failed (i.e., transaction has not completed).
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- during the **read phase**, all writes take place only on *local copies* of the shared data subject to modification

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- a subsequent **validation phase** checks that the changes as to those local copies will not cause loss of integrity of the shared data

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- if approved, the final **write phase** makes the local copies global, i.e., commits their values to the shared data

Transactional Computation

- CAS-oriented approach, value-based, typical for CISC:

```
1  word_t any;                                  /* shared data */
2  {
3      word_t old, new;                         /* own data */
4      do new = compute(old = any);             /* read */
5      while (!CAS(&any, old, new));            /* validate/write */
6  }
```

Transactional Computation

- LL/SC-oriented approach, reservation-based, typical for RISC:

```
1  word_t any;                                  /* shared data */
2  {
3      word_t new;                              /* own data */
4      do new = compute(LL(&any));              /* read */
5      while (!SC(&any, new));                  /* validate/write */
6  }
```

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```

CAS recreated using LL/SC (cf. [8, p. 16])

Reading phase carried out simultaneously remains undetected...

Data Type I

- let a very simple **dynamic data structure** be object of investigation
  - modelling a **stack** in terms of a single-linked list:

```
1 typedef struct stack {
2     chain_t head;         /* top of stack: list head */
3 } stack_t;
```

  - whereby a single **list element** is of the following structure:

```
1 typedef struct chain {
2     struct chain *link; /* next list element */
3 } chain_t;
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```

- stack manipulation by pushing or pulling an item involves the update of a single variable, only: the "stack pointer"
- when simultaneous processes are allowed to interact by sharing that stack structure, the update must be an indivisible operation

Unsynchronised Operations

- basic **precondition**: an item to be stacked is not yet stacked/queued

```
1 inline void push_dos(stack_t *this, chain_t *item) {
2     item->link = this->head.link;
3     this->head.link = item;
4 }
```

2 - copy the contents of the stack pointer to the item to be stacked
3 - update the stack pointer with the address of that item

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5  inline chain_t *pull_dos(stack_t *this) {
6      chain_t *node;
7      if ((node = this->head.link))
8          this->head.link = node->link;
9      return node;
10 }
```

7 - memorise the item located at the stack top, if any

8 - update the stack pointer with the address of the next item

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Lock-Free Synchronised Operations

- benefit from the precondition: an item to be stacked is "own data"

```
1 inline void push_lfs(stack_t *this, chain_t *item) {
2     do item->link = this->head.link;
3     while (!CAS(&this->head.link, item->link, item));
4 }
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2 - copy the contents of the stack pointer to the item to be stacked
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5  inline chain_t *pull_lfs(stack_t *this) {
6      chain_t *node;
7
8      do if ((node = this->head.link) == 0) break;
9      while (!CAS(&this->head.link, node, node->link));
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11     return node;
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```

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```

Shallowness: ABA Problem

- given a LIFO list (i.e., stack) of following structure: $head \Rightarrow A \Rightarrow B \Rightarrow C$
  - with *head* stored at location L_i shared by processes P_1 and P_2
  - furthermore assume actual parameter `this` is pointing to L_i

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- assuming that the following sequence of actions will take place:

P_1
- reads head item A followed by B on the list, gets delayed at line 4
- remembers $node = A$, but has not yet done CAS: $head \Rightarrow A \Rightarrow B \Rightarrow C$

Shallowness: ABA Problem

cf. [8, p. 14 & 36–37]

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5       return node;
6  }
```

- assuming that the following sequence of actions will take place:

P_2	▪ pulls head item A from the list:	$head \Rightarrow B \Rightarrow C$
	▪ pulls head item B from the list:	$head \Rightarrow C$
	▪ pushes item A back to the list, now followed by C:	$head \Rightarrow A \Rightarrow C$

Shallowness: ABA Problem

cf. [8, p. 14 & 36–37]

- given a LIFO list (i.e., stack) of following structure: $head \Rightarrow A \Rightarrow B \Rightarrow C$
  - with *head* stored at location L_i shared by processes P_1 and P_2
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- assuming that the following sequence of actions will take place:

P_1
- reads head item A followed by B on the list, gets delayed at line 4
- remembers $node = A$, but has not yet done CAS: $head \Rightarrow A \Rightarrow B \Rightarrow C$

P_1
- resumes, CAS realises $head = A$ (followed by B): $head \Rightarrow B \Rightarrow \text{☹}$
- list state $head \Rightarrow A \Rightarrow C$ as left behind by P_2 is lost...

Approach to Solving the ABA Problem

- workaround using a **change-number tag** as pointer label:

```
1  inline void *raw(void *item, long mask) {
2      return (void *)((long)item & ~mask);
3  }
4
5  inline void *tag(void *item, long mask) {
6      return (void *)
7          ((long)raw(item, mask) | ((long)item + 1) & mask);
8  }
```

  - **alignment** of the data structure referenced by the pointer is assumed
    - an **integer factor** in accord with the data-structure size (in bytes)
    - rounded up to the next **power of two**: $2^N \geq sizeof(datastructure)$
  - zeros the N low-order bits of the pointer—and discloses the **tag field**

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```

- rather a **kludge** (Ger. *Behelfslösung*) than a clearcut solution[3]
  - makes ambiguities merely unlikely, but cannot prevent them
  - "operation frequency" must be in line with the **finite values margin**

[3] This also holds for DCAS when using a "whole word" change-number tag.

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- rather a **kludge** (Ger. *Behelfslösung*) than a clearcut solution[3]

- if applicable, attempt striving for problem-specific **frequency control**

[3] This also holds for DCAS when using a "whole word" change-number tag.

ABA Problem Tackled I

. . . as ugly as sin

```
1  typedef chain_t* chain_l;            /* labelled pointer! */
2
3  #define BOX (sizeof(chain_t) - 1)    /* tag-field mask */
4
5  inline void push_lfs(stack_t *this, chain_l item) {
6     do ((chain_t *)raw(item, BOX))->link = this->head.link;
7     while (!CAS(&this->head.link, ((chain_t *)raw(item, BOX))->link, tag(item, BOX)));
8  }
9
10 chain_l pull_lfs(stack_t *this) {
11    chain_l node;
12
13    do if (raw((node = this->head.link), BOX) == 0) break;
14    while (!CAS(&this->head.link, node, ((chain_t *)raw(node, BOX))->link));
15
16    return node;
17 }
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15
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```

- aggravating side-effect of the solution is the **loss of transparency**
  - the pointer in question originates from the environment of the critical operation (i.e., *push* and *pull* in the example here)
  - tampered pointers must not be used as normal $\rightsquigarrow$ *derived type*

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- language embedding and compiler support would be of great help. . .

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Hint (CAS vs. LL/SC)

The ABA problem does not exist with LL/SC!

ABA Problem Tackled II

- same precondition (cf. p. 20): an item to be stacked is "own data"

```
1 inline void push_lfs(stack_t *this, chain_t *item) {
2     do item->link = LL(&this->head.link);
3     while (!SC(&this->head.link, item));
4 }
```

2 - copy the head pointer and make a reservation to his address
3 - update the head pointer if the reservation still exists

ABA Problem Tackled II

- same precondition (cf. p. 20): an item to be stacked is "own data"

```
1  inline void push_lfs(stack_t *this, chain_t *item) {
2      do item->link = LL(&this->head.link);
3      while (!SC(&this->head.link, item));
4  }



5  inline chain_t *pull_lfs(stack_t *this) {
6      chain_t *node;
7
8      do if ((node = LL(&this->head.link)) == 0) break;
9      while (!SC(&this->head.link, node->link));
10
11     return node;
12 }
```

8 - memorise the head pointer and make a reservation to his address

9 - update the head pointer if the reservation still exists

ABA Problem Tackled II

. . . provided the processor plays along

- same precondition (cf. p. 20): an item to be stacked is "own data"

```
1  inline void push_lfs(stack_t *this, chain_t *item) {
2      do item->link = LL(&this->head.link);
3      while (!SC(&this->head.link, item));
4  }



5  inline chain_t *pull_lfs(stack_t *this) {
6      chain_t *node;
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8      do if ((node = LL(&this->head.link)) == 0) break;
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Outline

Résumé

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The latter copes with *non-blocking synchronisation* "in the small", while the former is a *state-machine outgrowth* using atomic instructions, sporadically, and enables barrier-free operation "in the large".

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  - but it constrains sequential operation to the absolute minimum and,
  - thus, paves the way for parallel operation to the maximum possible

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  - thus, paves the way for parallel operation to the maximum possible

Hint (Manyfold Update)

Solutions for twofold updates already are no "no-brainer", without or with special instructions such as CDS or DCAS. Major updates are even harder and motivate techniques such as ***transactional memory****.*

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In: [6], Kapitel 7

Propagate Notifications

```
1  int cause(event_t *this) {
2      chain_t *item;
3      int done = 0;
4
5      if ((item = detach(&this->wait)))
6          do done += hoist((process_t *)
7                coerce(item, (int)&((process_t *)0)->event),
8                    being(ONESELF)->name);
9          while ((item = item->link));
10
11     return done;
12 }
```

- variant relying on a **dynamic data structure** for the waitlist
  - 5 adopt the waitlist on the whole, indivisible, and wait-free
  - 6–8 notify "go ahead", pass own identification, and ready signallee
  - 7 pattern a dynamic type-cast from the `chain_t*` member `event` to the `process_t*` of the enclosing process structure (i.e., PCB)
  - 9 notify one process at a time, bounded above, $N - 1$ times at worst

Receive-Side "Sticky Bit" Operations

cf. p. 13

- a simple mechanism that allows a process to "latch onto" an event:

```
1  inline void shade(process_t *this) {
2      this->latch.flag = false;          /* clear latch */
3  }
4
5  inline void stand() {
6      process_t *self = being(ONESELF);
7      if (!self->latch.flag)             /* inactive latch */
8          block();                       /* relinquish... */
9      shade(self);                       /* reset latch */
10 }
11
12 inline void latch() {
13     being(ONESELF)->state |= PENDING;   /* watch for */
14     stand();                           /* & latch */
15 }
```

8
- either suspend or continue the current process (cf. p. 33)
- was marked "pending" to catch a "go ahead" notification (cf. p.12)

Send-Side "Sticky Bit" Operations

cf. p. 13

- non-blocking measure to signal a single process, one-time, and keep signalling effective, i.e., "sticky" (Ger. *klebrig*) until perceived[4]

```
1  inline void punch(process_t *this) {
2      if (!this->latch.flag) {          /* inactive latch */
3          this->latch.flag = true;      /* activate it */
4          if (this->state & PENDING)    /* is latching */
5              yield(this);              /* set ready */
6      }
7  }
8
9  inline int hoist(process_t *next, int code) {
10     next->merit = code;               /* pass result */
11     punch(next);                      /* send signal */
12     return 1;
13 }
```

2–3
- assuming that the PCB is not shared by simultaneous processes
- otherwise, replace by `TAS(&this->latch.flag)` or similar

5
- makes the process become a "multiple personality", possibly queued

[4] In contrast to the signalling semantics of monitors (cf. [9, p. 8]).

Resolving Multiple Personality

cf. [10, p. 37]

```
1  void block() {
2      process_t *next, *self = being(ONESELF);
3
4      do {                        /* ...become the idle process */
5          while (!(next = elect(hoard(READY))))
6              relax();            /* enter processor sleep mode */
7      } while ((next->state & PENDING)        /* clean-up? */
8            &&  (next->scope != self->scope));
9
10     if (next != self) {  /* it's me who was set ready? */
11         self->state = (BLOCKED | (self->state & PENDING));
12         seize(next);          /* keep pending until switch */
13     }
14     self->state = RUNNING;          /* continue cleaned... */
15 }
```

- a "pending blocked" process is still "running" but may also be "ready to run" as to its queueing state regarding the ready list
  - such a process must never be received by another processor (l. 7–8)

Waitlist Association

- depending on the **waitlist interpretation**, operations to a greater or lesser extent in terms of non-functional properties:

```
1  inline void apply(process_t *this, event_t *list) {
2  #ifdef __FAME_EVENT_WAITLIST__
3      insert(&list->wait, &this->event);
4  #else
5      this->event = list;
6  #endif
7  }
8
9  inline void elide(process_t *this, event_t *list) {
10 #ifdef __FAME_EVENT_WAITLIST__
11     winnow(&list->wait, &this->event);
12 #else
13     this->event = 0;
14 #endif
15 }
```

3/11 - dynamic data structure, bounded above, lock-free, lesser list walk

5/13 - elementary data type, constant overhead, atomic, larger table walk