

Concurrent Systems

Nebenläufige Systeme

XI. Non-Blocking Synchronisation

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Subject Matter

- discussion on abstract concepts of synchronisation without lockout of critical action sequences of interacting processes (cf. [7])
 - 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!
- 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?
- following 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
- 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.*

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Definition

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

- 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 latter²
- originally, this property was typical for an **interrupt handler**, merely, that allows for nested execution—recursion not unressembling
 - each interrupt-driven invocation goes along with a new process
 - whereby the simultaneous processes develop **vertically** (i.e., stacked)
- 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

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



- 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;
```

- 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 [3, p. 124], irrespective of the number of simultaneous processes
- 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 [3, p. 142], depending on the waitlist interpretation
- 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
- forgo dynamic data structures for any type of waitlist or synchronise them using **optimistic concurrency control** (p. 16ff.)



```
1 void prolaag(semaphore_t *sema) {
2     catch(&sema->wait);      /* expect notification */
3     while (!claim(sema))    /* acquire semaphore */
4         coast();            /* accept wakeup signal */
5     clean(&sema->wait);     /* forget notification */
6 }
7
8 void verhoog(semaphore_t *sema) {
9     if (unban(sema))        /* release semaphore */
10        cause(&sema->wait); /* notify wakeup signal */
11 }
```

■ implementation in the shape of a **non-sequential program**:

- 2 ■ show interest in the receive of a notification to continue processing
- 3 ■ as long as regulated by the semaphore value, watch for notification
- 4 ■ either suspend or continue execution, depending on notification state
- 5 ■ drop interest in receiving notifications, occupy resource
- 9 ■ deregulate “wait-and-see” position above (l. 3), allow for overtaking
- 10 ■ send notification to interested and, maybe, suspended processes



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

```
1 inline bool claim(semaphore_t *sema) {
2     return CAS(&sema->gate, 1, 0);
3 }
4
5 inline bool unban(semaphore_t *sema) {
6     return (sema->gate = 1);
7 }
```

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

```
1 inline bool claim(semaphore_t *sema) {
2     return FAA(&sema->gate, -1) > 0;
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



- 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. 10)
- 8 ■ excludes the process from potential receive of “go ahead” notifications
- treatment of “multiple personality” processes is based on **division of labour** as to the different types of waitlist (cf. p. 41)
 - “ready” waitlist, the respective idle process of a processor (p. 40)
 - “blocked” waitlist, the semaphore increasing or decreasing process



- 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
- 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**
- 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, [5])
 - but the semaphore example shows that even AOP is not the loophole here
- 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



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Definition (acc. [6])

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).
```

- during the **read phase**, all writes take place only on *local copies* of the shared data subject to modification
- a subsequent **validation phase** checks that the changes as to those local copies will not cause loss of integrity of the shared data
- 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 }
```

- 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 }
```

CAS recreated using LL/SC (cf. [12, p.16])

Is prone to a **race condition**: e.g., act out simple counting...



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;
```

- 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



- 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

```
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 }
```

- 8 ■ memorise the item located at the stack top, if any
- 9 ■ update the stack pointer with the address of the next item



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 }
```

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

```
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));
10
11     return node;
12 }
```

- 8 ■ memorise the item located at the stack top, if any
- 9 ■ attempt to update the stack pointer with the address of the next item



- 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 *)((long)item + 1) & mask);
7 }
```

- 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**: $2^N \geq \text{sizeof}(\text{datastructure})$
- zeros the N low-order bits of the pointer—and discloses the **tag field**
- rather a **kludge** (Ger. *Behelfslösung*) than a clearcut solution³
 - makes ambiguities merely unlikely, but cannot prevent them
 - “operation frequency” must be in line with the **finite values margin**
- if applicable, attempt striving for problem-specific **frequency control**

³This also holds for DCAS when using a “whole word” change-number tag.



```

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 }

```

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

Hint (CAS vs. LL/SC)

The ABA problem does not exist with LL/SC!



Data Type II

- a much more complex object of investigation, at a second glance:

```
1 typedef struct queue {
2     chain_t head;           /* first item */
3     chain_t *tail;         /* insertion point */
4 } queue_t;
```

- the tail pointer addresses the linkage element of a next item to be queued
- it does not directly address the last element in the queue, but indirectly

- consequence is that even an empty queue shows a valid tail pointer:

```
1 inline chain_t *drain(queue_t *this) {
2     chain_t *head = this->head.link;
3
4     this->head.link = 0;      /* null item */
5     this->tail = &this->head; /* linkage item */
6
7     return head;
8 }
```

- used to reset a queue and at the same time return all its list members



- same **precondition** as before: an item to be queued is not yet queued
 - a simple **first-in, first-out method** (FIFO) is implemented

```
1 inline void chart_dos(queue_t *this, chain_t *item) {
2     item->link = 0;           /* finalise chain */
3     this->tail->link = item;  /* append item */
4     this->tail = item;       /* set insertion point */
5 }
```

- note that the queue head pointer gets set to the first item implicitly

```
6 inline chain_t* fetch_dos(queue_t *this) {
7     chain_t *node;
8     if ((node = this->head.link)           /* filled? */
9         && !(this->head.link = node->link)) /* last item? */
10        this->tail = &this->head;         /* reset */
11     return node;
12 }
```

- 11 ■ the tail pointer must always be valid, even in case of an empty queue



- inspired by the lock-free solution using atomic load/store [13, p. 28]:

```
1 void chart_lfs(queue_t *this, chain_t *item) {
2     chain_t *last;
3
4     item->link = 0;
5
6     do last = this->tail;
7     while (!CAS(&this->tail, last, item));
8
9     last->link = item;
10 }
```

Hint (Onefold Update)

Only a single shared variable needs to be updated in this scenario.

- a **plausibility check** shows correctness as to this overlap pattern:
 - 6 ■ critical shared data is the tail pointer, a local copy is read
 - each overlapping enqueue holds its own copy of the tail pointer
 - 7 ■ validate and, if applicable, write to update the tail pointer
 - the item becomes new fastener for subsequent enqueue operations
 - 9 ■ eventually, the item gets inserted and becomes queue member
 - the assignment operator works on local operands, only



- inspired by the lock-free solution for a stack pull operation (p. 20):

```
1 chain_t* fetch_lfs(queue_t *this) {
2     chain_t *node;
3
4     do if ((node = this->head.link) == 0) return 0;
5     while (!CAS(&this->head.link, node, node->link));
6
7     if (node->link == 0)
8         this->tail = &this->head;
9
10    return node;
11 }
```

Hint (Onefold Update)

Only a single shared variable needs to be updated in this scenario.

- a **plausibility check** shows correctness as to this overlap pattern:
 - 4 ■ critical shared data is the head pointer, a local copy is read
 - each overlapping dequeue holds its own copy of the head element
 - 5 ■ validate and, if applicable, write to update the head pointer
 - 7 ■ each dequeued item is unique, only of them was last in the queue
 - 8 ■ the tail pointer must always be valid, even in case of an empty queue



- critical is when head *and* tail pointer refer to the same “hot spot” and enqueue and dequeue happen simultaneously
- assuming that the **shared queue** consists of only a single element:
 - chart* || *fetch* ■ enqueue memorised the chain link of that element
 - dequeue removed that element including the chain link
 - enqueue links the new element using an invalid chain link
 - ↪ **lost enqueue**: linking depends on dequeue progression
 - fetch* || *chart* ■ dequeue removed that element and notices “vacancy”
 - enqueue appends an element to the one just removed
 - dequeue assumes “vacancy” and resets the tail pointer
 - ↪ **lost enqueue**: resetting depends on enqueue progression
- enqueue and dequeue must assist each other to solve the problem:
 - i identify the conditions under which lost-enqueue may happen
 - ii identify a way of interaction between enqueue and dequeue
- assist without special auxiliary nodes but preferably with simultaneous consideration of **conservative data-structure handling**



- idea is to use the chain-link of a queue element as **auxiliary means** for the interaction between enqueue and dequeue [9]
 - let $last$ be the pointer to the chain link of the queue end tail and
 - let $link_{last}$ be the chain link pointed to by $last$, then:

$$link_{last} = \begin{cases} last, & \text{chain link is valid, was not deleted} \\ 0, & \text{chain link is invalid, was deleted} \\ \text{else,} & \text{chain link points to successor element} \end{cases}$$

- $link_{last}$ set to 0 models the per-element “deleted bit” as proposed in [2]
- for a FIFO queue, only the end-tail element needs to carry that “bit”
- in contrast to [2], advanced idea is to do without a garbage-collection mechanism to dispose of the “deleted” queue end-tail element
 - purpose is to signal unavailability of the end-tail chain link to enqueue
 - thus, when dequeue is going to remove $last$ it attempts to zero $link_{last}$
 - contrariwise, enqueue appends to $last$ only if $link_{last}$ still equals $last$
- signalling as well as validation can be easily achieved using CAS
 - algorithmic construction versus CDS [4, p. 124] or DCAS [8, p. 4-66]...



```
1 void chart_lfs(queue_t *this, chain_t *item) {
2     chain_t *last, *hook;
3
4     item->link = item;           /* self-reference: hook */
5
6     do hook = (last = this->tail)->link; /* tail end */
7     while (!CAS(&this->tail, last, item));
8
9     if (!CAS(&last->link, hook, item)) /* endpiece? */
10        this->head.link = item;      /* no longer! */
11 }
```

- validate availability of the ending and potential **volatile chain link**:
 - 9 ■ CAS succeeds only if the last chain link is still a self-reference
 - in that case, the embracing last element was not dequeued
 - 10 ■ CAS fails if the last chain link is no more a self-reference
 - in that case, the embracing last element was dequeued
 - ↪ the item to be queued must be head element of the queue, because further enqueues use this very item as leading chain link (l.7)



```
1 chain_t* fetch_lfs(queue_t *this) {
2     chain_t *node, *next;
3
4     do if ((node = this->head.link) == 0) return 0;
5     while (!CAS(&this->head.link, node,
6         ((next = node->link) == node ? 0 : next)));
7
8     if (next == node) {          /* self-reference, is last */
9         if (!CAS(&node->link, next, 0)) /* try to help */
10            this->head.link = node->link; /* filled */
11        else CAS(&this->tail, node, &this->head);
12    }
13
14    return node;
15 }
```

- validate **tail-end invariance** of a one-element queue ($head = tail$):
 - 9 ■ CAS fails if the node dequeued no more contains a self-reference
 - 10 ■ thus, enqueue happened and left at least one more element queued
 - 11 ■ enqueue was assisted and the dequeued node could be last, really



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- non-blocking synchronisation \mapsto **abdication of mutual exclusion**
- systems engineering makes a **two-dimensional approach** advisable
 - the *constructional track* brings manageable “complications” into being
 - these “complications” are then subject to a *transactional track*

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”.

- no bed of roses, no picnic, no walk in the park—so is non-blocking synchronisation of reasonably complex simultaneous processes
 - but it constrains sequential operation to the absolute minimum and,
 - 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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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 waitist
 - 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



- 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.40)
- was marked “pending” to catch a “go ahead” notification (cf. p.12)



- non-blocking measure to signal a single process, one-time, and keep signalling effective, i.e., “sticky” (Ger. *klebrig*) until perceived⁴

```
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

⁴In contrast to the signalling semantics of monitors (cf. [14, p.8]).



```
1 void block() {
2     process_t *next, *self = being(ONESELF);
3
4     do {
5         /* ...become the idle process */
6         while (!(next = elect(hoard(READY))))
7             relax(); /* enter processor sleep mode */
8     } while ((next->state & PENDING) /* clean-up? */
9             && (next->scope != self->scope));
10
11     if (next != self) { /* it's me who was set ready? */
12         self->state = (BLOCKED | (self->state & PENDING));
13         seize(next); /* keep pending until switch */
14     }
15     self->state = RUNNING; /* continue cleaned... */
16 }
```

- 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

