Concurrent Systems

Nebenläufige Systeme

X. Basics of 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. [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!
- 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?
- 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
- 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

¹(Ger.) Toleranz ist der Verdacht, dass der andere Recht hat.
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Summary
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 latter

- originally, this property was typical for an interrupt handler, merely, that allows for nested execution—recursion not unresizing
  - 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

\[^{2}\text{For example, if lockout becomes necessary to protect a critical section.}\]
Semaphore Revisited

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

```c
typedef struct semaphore {
    int gate;   /* value: binary or general */
    event_t wait;  /* list of sleeping processes */
} 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

cf. [10, p. 22]
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
- 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
- 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. 16 ff.)
void prolaag(semaphore_t *sema) {
    catch(&sema->wait);          /* expect notification */
    lodge(sema);                 /* raise claim to proceed */
    when (!avail(sema))          /* check for process delay */
        coast();                  /* accept wakeup signal */
    clean(&sema->wait);          /* forget notification */
}

void verhoog(semaphore_t *sema) {
    if (unban(sema))             /* release semaphore */
        cause(&sema->wait);      /* notify wakeup signal */
}

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

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

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

- Both `lodge` and `unban` remain unchanged.

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

```c
inline int lodge(semaphore_t *sema) {
    return FAA(&sema->gate, -1);
}

inline bool unban(semaphore_t *sema) {
    return FAA(&sema->gate, +1) < 0;
}
```

- `avail` remains unchanged.

- 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

```c
inline void catch(event_t *this) {
    process_t *self = being(ONESELF);
    self->state |= PENDING; /* watch for event */
    apply(self, this);       /* enter waitlist */
}

inline void clean(event_t *this) {
    elide(being(ONESELF), this); /* leave waitlist */
}
```

- prepares the “multiple personality” process to be treated in time
- makes the process amenable to “go ahead” notification (p. 10, l. 11)
- 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. 34)
  - “ready” waitlist, the respective idle process of a processor (p. 33)
  - “blocked” waitlist, the semaphore increasing or decreasing process
Propagate “go ahead” Notifications

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)**

```c
inline int coast() {
    stand();                    /* latch event */
    return being(OONESELF)->merit;  /* signaller pid */
}

int cause(event_t *this) {
    process_t *next;
    int done = 0;

    for (next = being(0); next < being(NPROC); next++)
        if (CAS(&next->event, this, 0))
            done += hoist(next, being(OONESELF)->name);

    return done;
}
```

11  ■ recognise willingness to catch a signal and continue execution
12  ■ notify “go ahead”, pass own identification, and ready signallee
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, [3])
- 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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Optimistic Concurrency Control

Definition (acc. [4])
Method of coordination for the purpose of updating shared data by mainly relying on transaction backup as control mechanisms.

```
do
  read phase:
  save a private copy of the shared data to be updated;
  compute a new private data value based on that copy;
  validation and, possibly, write phase:
  try to commit the computed value as new shared data;
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:

```c
word_t any; /* shared data */
{
    word_t old, new; /* own data */
    do new = compute(old = any); /* read */
    while (!CAS(&any, old, new)); /* validate/write */
}
```

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

```c
word_t any; /* shared data */
{
    word_t new; /* own data */
    do new = compute(LL(&any)); /* read */
    while (!SC(&any, new)); /* validate/write */
}
```

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:

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

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

  ```c
  typedef struct chain {
    struct chain *link;   /* next list element */
  } 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

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

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

```c
inline chain_t *pull_dos(stack_t *this) {
    chain_t *node;
    if ((node = this->head.link))
        this->head.link = node->link;
    return node;
}
```

7. memorise the item located at the stack top, if any
8. 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”

```c
inline void push_lfs(stack_t *this, chain_t *item) {
    do item->link = this->head.link;
    while (!CAS(&this->head.link, item->link, item));
}
```

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

```c
inline chain_t *pull_lfs(stack_t *this) {
    chain_t *node;

    do if ((node = this->head.link) == 0) break;
    while (!CAS(&this->head.link, node, node->link));

    return node;
}
```

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
Shallowness: ABA Problem

cf. [8, p.14 & 36–37]

given a LIFO list (i.e., stack) of following structure: \( \text{head} \triangleq A \triangleq B \triangleq C \)

- with \( \text{head} \) stored at location \( L_i \) shared by processes \( P_1 \) and \( P_2 \)
- furthermore assume actual parameter \text{this} is pointing to \( L_i \)

```c
inline chain_t *pull_lfs(stack_t *this) {
    chain_t *node;
    do if (((node = this->head.link) == 0) break;
    while (!CAS(&this->head.link, node, node->link));
    return node;
}
```

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: \( \text{head} \triangleq A \triangleq B \triangleq C \)

- \( P_2 \):
  - pulls head item \( A \) from the list:
  - pulls head item \( B \) from the list:
  - pushes item \( A \) back to the list, now followed by \( C \): \( \text{head} \triangleq B \triangleq C \)

- \( P_1 \):
  - resumes, CAS realises \( \text{head} = A \) (followed by \( B \)): \( \text{head} \triangleq B \triangleq \odot \)
  - list state \( \text{head} \triangleq A \triangleq C \) as left behind by \( P_2 \) is lost...
Approach to Solving the ABA Problem

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

```
inline void *raw(void *item, long mask) {
    return (void *)((long)item & ~mask);
}

inline void *tag(void *item, long mask) {
    return (void *)
        ((long)raw(item, mask) | ((long)item + 1) & mask);
}
```

- 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**: \(2^N \geq \text{sizeof(datastructure)}\)

- zeros the \(N\) low-order bits of the pointer—and discloses the tag field

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

- 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**

---

\(^3\)This also holds for DCAS when using a “whole word” change-number tag.
typedef chain_t * chain_l;  /* labelled pointer! */

#define BOX (sizeof(chain_t) - 1)  /* tag-field mask */

inline void push_lfs(stack_t *this, chain_l item) {
    do ((chain_t *)raw(item, BOX))->link = this->head.link;
    while (!CAS(&this->head.link, ((chain_t *)raw(item, BOX))->link, tag(item, BOX)));
}

chain_l pull_lfs(stack_t *this) {
    chain_l node;
    do if (raw((node = this->head.link), BOX) == 0) break;
    while (!CAS(&this->head.link, node, ((chain_t *)raw(node, BOX))->link));
    return node;
}

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 \sim 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!
same precondition (cf. p. 20): an item to be stacked is “own data”

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

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

```c
inline chain_t *pull_lfs(stack_t *this) {
    chain_t *node;
    do if ((node = LL(&this->head.link)) == 0) break;
    while (!SC(&this->head.link, node->link));
    return node;
}
```

3. memorise the head pointer and make a reservation to his address
4. update the head pointer if the reservation still exists
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Résumé

- non-blocking synchronisation $\rightarrow$ **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*. 
[1] **Dijkstra, E. W.**:
Cooperating Sequential Processes / Technische Universiteit Eindhoven.

[2] **Herlihy, M.**:
Wait-Free Synchronization.
In: *ACM Transactions on Programming Languages and Systems* 11 (1991), Jan., Nr. 1, S. 124–149

Aspect-Oriented Programming.

On Optimistic Methods for Concurrency Control.
[5] **Moir, M.** ; **Shavit, N.** : "Concurrent Data Structures".  
In: **Mehta, D. P. (Hrsg.) ; Sahni, S. (Hrsg.)**: *Handbook of Data Structure and Applications*.  
CRC Press, Okt. 2004, Kapitel 47, S. 1–32

[6] **Schröder-Preikschat, W.** ; **Lehrstuhl Informatik 4 (Hrsg.)**: *Concurrent Systems*.  
FAU Erlangen-Nürnberg, 2014 (Lecture Slides)

In: [6], Kapitel 4

In: [6], Kapitel 5

In: [6], Kapitel 8
   In: [6], Kapitel 7
Propagate Notifications

```c
int cause(event_t *this) {
    chain_t *item;
    int done = 0;

    if ((item = detach(&this->wait)))
        do done += hoist((process_t *)
            coerce(item, (int)&((process_t *)0)->event),
            being(OONESELF)->name);
        while ((item = item->link));

    return done;
}
```

- variant relying on a **dynamic data structure** for the waitlist
  - adopt the waitlist on the whole, indivisible, and wait-free
  - notify “go ahead”, pass own identification, and ready signallee
  - pattern a dynamic type-cast from the chain_t* member event to
    the process_t* of the enclosing process structure (i.e., PCB)
  - 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:

```c
inline void shade ( process_t *this ) {
    this->latch.flag = false; /* clear latch */
}

inline void stand () {
    process_t *self = being(ONESELF);
    if (!self->latch.flag) /* inactive latch */
        block (); /* relinquish... */
    shade ( self ); /* reset latch */
}

inline void latch () {
    being(ONESELF)->state |= PENDING; /* watch for */
    stand (); /* & latch */
}
```

- 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

```c
inline void punch(process_t *this) {
    if (!this->latch.flag) { /* inactive latch */
        this->latch.flag = true; /* activate it */
        if (this->state & PENDING) /* is latching */
            yield(this); /* set ready */
    }
}
```

```c
inline int hoist(process_t *next, int code) {
    next->merit = code; /* pass result */
    punch(next); /* send signal */
    return 1;
}
```

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]).
void block() {
    process_t *next, *self = being(OONESELF);

    do {
        /* ...become the idle process */
        while (!(next = elect(hoard(READY))))
            relax(); /* enter processor sleep mode */
    } while ((next->state & PENDING) /* clean-up? */
            && (next->scope != self->scope));

    if (next != self) { /* it’s me who was set ready? */
        self->state = (BLOCKED | (self->state & PENDING));
        seize(next); /* keep pending until switch */
    }
    self->state = RUNNING; /* continue cleaned... */
}

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

```
inline void apply(process_t *this, event_t *list) {
    #ifdef __FAME_EVENT_WAITLIST__
        insert(&list->wait, &this->event);
    #else
        this->event = list;
    #endif
}
```

```
inline void elide(process_t *this, event_t *list) {
    #ifdef __FAME_EVENT_WAITLIST__
        winnow(&list->wait, &this->event);
    #else
        this->event = 0;
    #endif
}
```

- dynamic data structure, bounded above, lock-free, lesser list walk
- elementary data type, constant overhead, atomic, larger table walk