Concurrent Systems

Nebenläufige Systeme

X. Basics of Non-Blocking Synchronisation

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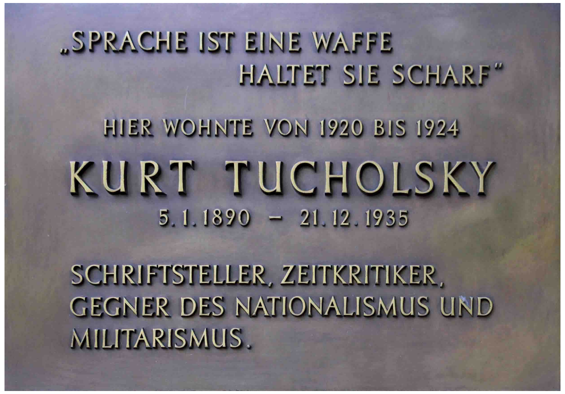
Agenda

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!
- 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]



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.

- 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]
- 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)
- 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]For example, if lockout becomes necessary to protect a critical section.

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:

```
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

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" <u>before</u> trying to acquire the semaphore
  - cancel that "state of uncertainty" <u>after</u> 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 <u>some</u> process is in its individual idle state
  - have also <u>other</u> 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.*)

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 }
```

- 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

differences to [10, p. 24/25]

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

```
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**:

```
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

```
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
- 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
  - 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

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.

```
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:

```
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:

```
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:

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

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

```
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

Unsynchronised Operations

devoid of synchronisation

- 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 }
```

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"

```
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

Shallowness: ABA Problem

cf. [8, p. 14 & 36–37]

- given a LIFO list (i.e., stack) of following structure: *head* ⇨ *A* ⇨ *B* ⇨ *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

```
1 inline chain_t *pull_lfs(stack_t *this) {
2     chain_t *node;
3     do if ((node = this->head.link) == 0) break;
4     while (!CAS(&this->head.link, node, node->link));
5     return node;
6 }
```

- 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* ⇨ *A* ⇨ *B* ⇨ *C*

P_2
- pulls head item *A* from the list: *head* ⇨ *B* ⇨ *C*
- pulls head item *B* from the list: *head* ⇨ *C*
- pushes item *A* back to the list, now followed by *C*: *head* ⇨ *A* ⇨ *C*

P_1
- resumes, CAS realises *head* = *A* (followed by *B*): *head* ⇨ *B* ⇨ ☹
- list state *head* ⇨ *A* ⇨ *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**: $2^N \geq sizeof(datastructure)$
- zeros the N low-order bits of the pointer—and discloses the **tag field**
- rather a **kludge** (Ger. *Behelfslösung*) than a clearcut solution[3]
  - 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.

ABA Problem Tackled I

... as ugly as sin

```
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 $\rightsquigarrow$ *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!

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 }
```

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

```
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

Outline

Résumé

- non-blocking synchronisation ↦ **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****.*

Reference List I

[1] Dijkstra, E. W.: Cooperating Sequential Processes / Technische Universiteit Eindhoven. Eindhoven, The Netherlands, 1965 (EWD-123). – Forschungsbericht. – (Reprinted in *Great Papers in Computer Science*, P. Laplante, ed., IEEE Press, New York, NY, 1996)

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[3] Kiczales, G. ; Lamping, J. ; Mendhekar, A. ; Maeda, C. ; Lopes, C. V. ; Loingtier, J.-M. ; Irwin, J. : Aspect-Oriented Programming. In: Aksit, M. (Hrsg.) ; Matsuoka, S. (Hrsg.): *Proceedings of the 11th European Conference on Object-Oriented Programming (ECOOP'97)* Bd. 1241, Springer-Verlag, 1997 (Lecture Notes in Computer Science). – ISBN 3–540–63089–9, S. 220–242

[4] Kung, H.-T. ; Robinson, J. T.: On Optimistic Methods for Concurrency Control. In: *ACM Transactions on Database Systems* 6 (1981), Jun., Nr. 2, S. 213–226

Reference List II

[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)

[7] Schröder-Preikschat, W. : Critical Sections. In: [6], Kapitel 4

[8] Schröder-Preikschat, W. : Elementary Operations. In: [6], Kapitel 5

[9] Schröder-Preikschat, W. : Monitor. In: [6], Kapitel 8

Reference List III

[10] SCHRÖDER-PREIKSCHAT, W. :
Semaphore.
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