Concurrent Systems

Nebenläufige Systeme

X. Non-Blocking Synchronisation

Wolfgang Schröder-Preikschat

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Agenda

Outline

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.*

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. [15, 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 [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. 16*ff.*)

Wait-Action Unfolding

cf. [15, 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

- 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. 41)
  - "ready" waitlist, the respective idle process of a processor (p. 40)
  - "blocked" waitlist, the semaphore increasing or decreasing process

Propagate “go ahead” Notifications

cf. p. 37

- 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

Outline

Optimistic Concurrency Control

cf. [11, p. 15]

Definition (acc. [6])

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 */
}
```

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

- 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

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

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 ⇝ *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:

```
typedef struct queue {
    chain_t  head;                  /* first item */
    chain_t *tail;                  /* insertion point */
} 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:

```
inline chain_t *drain(queue_t *this) {
    chain_t *head = this->head.link;

    this->head.link = 0;          /* null item */
    this->tail = &this->head;     /* linkage item */

    return head;
}
```

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

Unsynchronised Operations

- 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

Synchronisation, Take One: *chart*||*chart*

- 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

Synchronisation, Take Two: *fetch*||*fetch*

- 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

Synchronisation, Take Three

- 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

$\hookrightarrow$ **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

$\hookrightarrow$ **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]...

Lock-Free Synchronised Operations I

```
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)

Lock-Free Synchronised Operations II

Dequeue acc. [9]

```
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 <u>no more</u> 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

Outline

Résumé

- 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 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. 40)
- 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. [14, p. 8]).

Resolving Multiple Personality

cf. [15, 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