Concurrent Systems

Nebenläufige Systeme

IV. Critical Sections

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November 22, 2016

Agenda

Outline

Subject Matter

- discussion on **abstract concepts** as to critical sections:
  - race condition
    - caused by a fault in a non-sequential program
    - possibly effects an error of a non-sequential process
    - if so, eventually effects failure of a computing system

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    - ↪ blocking synchronisation, lock-based
    - optimistic, concurrent control on a "multi-lane road"
    - ↪ non-blocking synchronisation, obstruction-free

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  - excursion to database systems: transactions, isolation (ACID properties)
  - basic forms of inconsistency due to actions of simultaneous processes

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Synchronisation v. Level of Abstraction of a Critical Section

i providing functionality as integral part of a critical section *or*

ii providing the same functionality on the basis of a critical section

Outline

Critical Sequence or Timing of Processes

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- in software, the program flow discloses a *fault* that possibly results in:
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    - an ***error*** that, in turn, may cause *failure* of a system
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    - unanticipated behaviour
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- **prevention** of especially critical races is a must, implicitly or explicitly
  - but before, the race condition behind must be even localised...

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  - necessary condition (i.e., mandatory) is a non-sequential program
  - sufficient condition are simultaneous processes of that very program
  - ↪ the sequence of <u>all</u> actions is defined by a **partial order** (cf. [9, p. 17])

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  - ↪ occasionally, fault diagnostics ends—and one is okay with that defect...

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- a sequential program that describes **mutual exclusive actions**
  - that is to say, activities that relate to each other as if they are indivisible because no activity interrupts or overlaps, resp., the other [6, p. 137]
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  - **separation of concerns**: non-functional v. functional properties

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A Matter of Reference

Separation of Concerns

Provide the wanted **functionality** in a first step and consider different implementation variants of that very functionality in a second step.

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Level 2 or 3 ELOP? (cf. [9, p. 34])

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- by way of example, LIFO[1] storing (*push*) with a singly-linked list
  - abstraction used to represent both the list head and a list element:

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

  - prepend specified *item* to *this* list (stack policy):

```
void push(chain_t *this, chain_t *item) {
  item->link = this->link;  /* make head follow item */
  this->link = item;        /* make item new head */
}
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[1] *last in, first out*

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- beware of simultaneous processes: race condition in *push* (cf. p.30)

[1] *last in, first out*

Operating-System Machine Level

- "take a sledgehammer to crack a nut"[2]: **blocking synchronisation**
  - extended (new) abstraction used to represent the list head:

```
typedef struct mutex_chain {
  chain_t head;
  pthread_mutex_t lock;
} mutex_chain_t;
```

  - extended and adapted (new) *push* resulting in a sequential process:

```
void mutex_push(mutex_chain_t *this, chain_t *item) {
  pthread_mutex_lock(&this->lock);
  item->link = this->head.link;
  this->head.link = item;
  pthread_mutex_unlock(&this->lock);
}
```

[2] (Ger.) *mit Kanonen auf Spatzen schießen.*

Operating-System Machine Level

Level 3 Mutual Exclusion

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- *lock* blocks simultaneous processes out from *push*, till after *unlock*

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Instruction Set Architecture Level

- avant-garde: **non-blocking synchronisation** of the *push* function
  - reused abstraction, for both list head and list element:

```
typedef struct chain {
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  - extended and adapted (new) *push* resulting in a non-sequential process:

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void cas_push(chain_t *this, chain_t *item) {
    do item->link = this->link;
    while (!CAS(&this->link, item->link, item));
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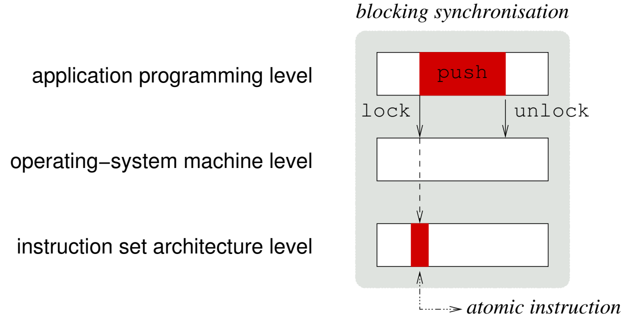
- CAS (*compare and swap*) blocks simultaneous processes out, shortly
  - built-in function: **#define** CAS __sync_bool_compare_and_swap:

```
atomic bool cas(type *ref, type old, type new) {
  return (*ref == old) ? (*ref = new, true) : false;
}
```

  - compiled by GCC into (x86) "lock cmpxchgl" instruction/ELOP

A Matter of Reference: Reconsidered



- *push* (left-hand) employs *lock* to "stonewall" simultaneous processes
  - it also needs to rely on an atomic instruction[3] to implement the lock
    - the sequential process lasts from that very instruction till after *unlock*

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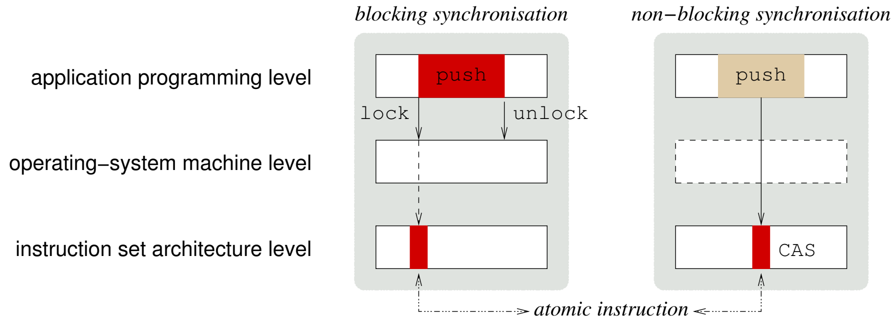

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  - nevertheless, to this end, it needs to rely on an atomic instruction as well
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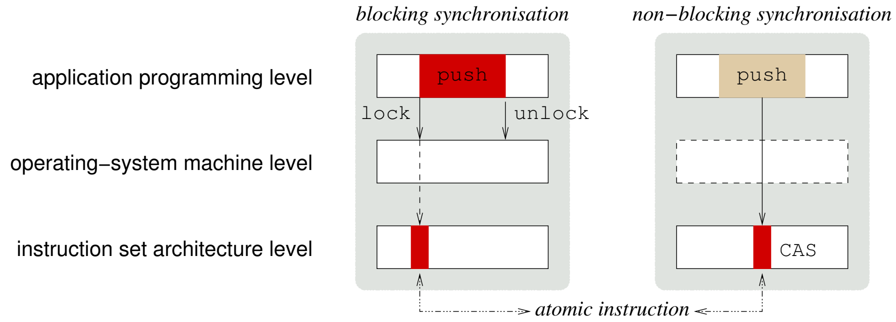

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- *push* is a **physical** (left-hand) or **logical** (right-hand) critical section

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The Problem of Locks[4]

cf. [7, p. 58–59]

- locks are not composable
- locks are prone to livelocks or deadlocks, resp.
- locks rely on programmers to strictly follow conventions
- locks are a synchronisation measure of global program property

beyond that:

- locks increase sequentiality or decrease concurrency, resp.
- locks are prone to priority violation or inversion, resp.
- locks rather waste computing time
- locks are rather coarse-grained
- ⋮
- locks require alternatives

[4] This includes all variants of locks as well as other concepts of blocking synchronisation, particularly binary semaphore, mutex, or bolt variable resp.

Transaction

Definition (cf. "logical critical section" on p. 12)

Entity of one ore more independent units of work and by means of which data integrity is ensured on the basis of well-defined rules.

- transactional processing of **shared data**

Transaction

Make-or-Break, Rollback

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  - read and execute, validate, and write or rollback (retry)
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- transactions may be concurrent, but not necessarily the work units

Devoid of Obstruction

Definition (Optimistic Concurrency Control [8])

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

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Concurrency Control Without Locks

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- simplified, a transaction is an "all or nothing" approach of computing
  - each action on shared data must either complete in its entirety or have no effect—except the time elapsed or energy consumed
  - in doing so, these actions must also adhere to a defined **isolation level**

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  - in doing so, these actions must also adhere to a defined **isolation level**
- the method establishes the basis for **non-blocking synchronisation**

```
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).
```

  - validation and, possibly, write are an "indivisible action" (cf. p. 11)

ACID Properties

Fundamental rules for an atomic transaction to establish well-defined system behaviour in the presence of faults and simultaneous actions.

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Database Systems

Fundamental rules for an atomic transaction to establish well-defined system behaviour in the presence of faults and simultaneous actions.

- **reliability attributes** according to [4] or [5, p. 289–290], resp.
  - atomicity: a transaction either happens or it does not
    - either all are bound by the contract or none are
  - consistency: each successful transaction commits only legal results
    - a transaction must obey legal protocols
  - isolation: events within a transaction must be hidden from other transactions running concurrently
    - and the key for it is **synchronisation** [2]
  - durability: once a transaction is committed, it cannot be abrogated
    - even in the event of power loss, crashes, or errors

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  - durability: once a transaction is committed, it cannot be abrogated
    - even in the event of power loss, crashes, or errors
- the isolation property is particularly important for concurrent systems
  - it has a large impact on the **degree of concurrency** that can be achieved
  - synchronisation paradigms decide upon the loss of concurrency, even too
    - along with the trade-off between synchronisation **granularity** and **frequency**

Transaction Isolation

Separation of **simultaneous transactions** in a manner that none of them falls in an undefined state or causes permanent inconsistencies.

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- basic forms of **inconsistency due to concurrency** [3, p. 431]:[5]

  - non-repeatable read
    - repeated read actions deliver different values
    - *read* → *write* dependency
  - dirty read
    - not yet committed data is already (early) read
    - *write* → *read* dependency
  - lost update
    - already committed data is overwritten
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[5] Concurrency is not affected by the order of read actions, which in particular commute: *read* → *read* dependency is thus excluded.

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  - inconsistent read
    - same search criteria apply to different data sets

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↪ **data race patterns** that remain valid beyond data base systems

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Preface

Fundamentals
- Race Condition
- Sequential Control
- Concurrent Control

Patterns
- Data Race
- Control-Flow Race

Summary

Non-Repeatable Read

When the same read operation consecutively executed by a process on a shared data set may deliver different results.

- assuming that *i* may be manipulated by a simultaneous process:

```
1 int twofold() {
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4     return i + i;
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Solution Statement (rank-order priority, ROP)

1. reduction to hardware ELOP, 2. non-blocking, or 3. blocking synchronisation.

Inconsistent Read

Phantom Read

When the value computed on the basis of the results of several read operations consecutively executed by a process would be different at the time the value is actually used by that process.

- assuming that *string* is reduced/enlarged by a simultaneous process:

```
1  char string[80];
2
3  int fill(char c) {
4      int i;
5      for (i = 0; i < 80; i++) {
6          if (!string[i]) {
7              string[i] = c;
8              return i;
9          }
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```

- apparently correct

Inconsistent Read

Phantom Read

When the value computed on the basis of the results of several read operations consecutively executed by a process would be different at the time the value is actually used by that process.

- assuming that *string* is reduced/enlarged by a simultaneous process:

```
1  char string[80];
2
3  int fill(char c) {
4      int i;
5      for (i = 0; i < 80; i++) {
6          if (!string[i]) {
7              string[i] = c;
8              return i;
9          }
10     }
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```

- apparently correct, but...
- that *i* identified the first free entry in line 6
- must no longer hold in line 7

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Solution Statement (ROP)

1. non-blocking or
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Dirty Read

When the same uncommitted shared variable is read by a process and written by another one, simultaneously.

- assuming that the ASM part is run by two simultaneous processes:
  - reading of uncommitted data: counting revisited [9, p. 14–15]

C/C++

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1  i++;
```

ASM

```
2  movl i, %eax
3  addl $1, %eax
4  movl %eax, i
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- apparently correct

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Solution Statement (ROP)

1. reduction to hardware ELOP, 2. non-blocking, or 3. blocking synchronisation.

Lost Update

When the same uncommitted shared variable is written by processes simultaneously without having noticed prior writes of each other.

- assuming that *vary* and *init* are run by own simultaneous processes:

```
int total = 0;

int vary(int i) {
    return total += i;
}

void init(int i) {
    total = i;
}
```

- apparently correct

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```
1 int total = 0;
2
3 int vary(int i) {
4     return total += i;
5 }
6
7 void init(int i) {
8     total = i;
9 }
```

```
10 vary:
11     movl total, %eax
12     addl 4(%esp), %eax
13     movl %eax, total
14     ret
15
16 init:
17     movl 4(%esp), %eax
18     movl %eax, total
19     ret
```

- apparently correct, but...
- the write in line 13 is unaware of the write in line 18

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↪ risk of blind writes

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Lost Update — Write-Write Conflict

When the same uncommitted shared variable is written by processes simultaneously without having noticed prior writes of each other.

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```
1  int total = 0;
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- apparently correct, but. . .

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- the write in line 13 is unaware of the write in line 18

Solution Statement: same as "dirty read", but this problem is <u>not serializable</u>

Non-sequential and sequential execution results in different states (cf. p. 32).

Lost Wakeup — Check-Block Conflict

When a process identified a waiting condition and will seek blocking simultaneously to the invalidation of the condition by another process.

- assuming that both sections are run by <u>two</u> interacting processes:

check condition and block

```
1  while (this->load == 0)
2      await(this);
```

invalidate condition and proceed

```
3  if (this->load++ == 0)
4      cause(this);
```

- apparently correct

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Solution Statement (ROP)

1. non-blocking or 2. blocking synchronisation.

"Time-of-Check to Time-of-Use" Problem

When a process checks the state of a resource before using this very resource, but the state is modified interim by another process.

- assuming that file "argv[1]" is modified by a simultaneous process:

```
1  #include <stdio.h>
2  #include <sys/stat.h>
3
4  int main(int argc, char *argv[]) {
5      struct stat buf;
6      if (lstat(argv[1], &buf))
7          perror("lstat failed");
8      else {
9          printf("%s is ", argv[1]);
10         if (buf.st_size != 0)
11             printf("not ");
12         printf("empty\n");
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- apparently correct

TOCTOU

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↪ risk of false positive or negative, resp.

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Solution Statement ☹

blocking synchronisation.

Outline

Résumé

- a race condition is an adverse behaviour of a computing system
  - caused by a fault ("concurrency bug") in a non-sequential program
  - possibly effects an error of a non-sequential process
  - as a further consequence, possibly effects failure of the system
- the faulty area in the non-sequential program is a "critical section"
  - it must be protected by making pessimistic or optimistic assumptions
  - computer science folklore goes the pessimistic way: **mutual exclusion**
  - avant-garde takes up a position that favours an optimistic approach

In the strict sense, it is still a matter of the level of abstraction at which the folkloristic critical section appears.

- in practice, one is faced with different patterns of race conditions
  - data races: non-repeatable read, inconsistent read, dirty read, lost update
  - control flow races: lost wakeup, TOCTOU
- problem solving should respect differentiated views and techniques
  - 1. hardware ELOP, 2. non-blocking, and 3. blocking synchronisation

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Simultaneous Push Considered Harmful

push	simultaneous processes			
	A : *push*(*list*, X)		B : *push*(*list*, Y)	
list	action	*item*	action	*item*
Z	`item->link = this->link`	$X \rightarrow Z$		–
Z		–	`item->link = this->link`	$Y \rightarrow Z$
$Y \rightarrow Z$		–	`this->link = item`	$Y \rightarrow Z$
$X \rightarrow Z$	`this->link = item`	$X \rightarrow Z$		$Y \rightarrow Z$

- assuming that the stack is implemented as singly-linked list (cf. p. 9)
  - initially, Z is the only stored entry and placed on the top of stack
- **misadventure**: processes A and B simultaneously apply the stack

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    - the top of stack has been updated, the stack contains two entries: $Y \rightarrow Z$

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  - process A resumes and completes its *push* of item X, deposits its item
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↪ two *push* operations executed, but only one more item was stored...

Reading and Processing Uncommitted Data

i++		simultaneous processes[6]			
		A		*B*	
i	step	action	%eax	action	%eax
42					

[6] Each process has a *software prototype* of %eax available.

Reading and Processing Uncommitted Data

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42	3		–	`movl i, %eax`	42

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42	3		–	`movl i, %eax`	42
42	4		–	`addl $1, %eax`	43

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Reading and Processing Uncommitted Data

i++		simultaneous processes[6]			
		A		*B*	
i	step	action	%eax	action	%eax
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  - step 3 ▪ reads *i* although it was (logically) already dirtied in step 2
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- dirty read or lost update—that is the legitimate question
  - step 3 ▪ reads *i* although it was (logically) already dirtied in step 2
  - step 6 ▪ writes *i* unaware of the update already committed in step 5
- both is true, each one ends in a reading of one less than expected
  - i++ twice-executed but its value reads as only once-counted

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Serialisability Unresolved

- correct (indivisible) update of the global counter variable *total*:

```
1 #include "aaf.h"
2
3 extern int total;
4
5 int vary(int i) {
6     return AAF(&total, i);
7 }
```

- procedural abstraction
- reduction to an ELOP: AAF
  - *add and fetch*
  - atomic *read-modify-write*
- with GCC atomic built-in function:
  `#define AAF __sync_add_and_fetch`

Serialisability Unresolved

Despite Indivisibility

- correct (indivisible) update of the global counter variable *total*:

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  - *add and fetch*
  - atomic *read-modify-write*
- with GCC atomic built-in function:
  `#define AAF __sync_add_and_fetch`

- but parallel actions *vary*||*init* are not equivalent to a serial schedule:

```
8  vary:
9      movl  4(%esp), %ecx
10     movl  %ecx, %eax
11     lock
12     xaddl %eax, total
13     addl  %ecx, %eax
14     ret
```

- *init* (cf. p. 22) may be carried out either before or after lines 11–12
- consequently, the final value of *total* remains indeterminate
  - it may read *i* or $total + i$, depending on which action came first