Concurrent Systems

Nebenläufige Systeme

IV. Critical Sections

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October 30, 2014

Agenda

Preface

Fundamentals
- Race Condition
- Sequential Control
- Concurrent Control

Patterns
- Data Race
- Control-Flow Race

Summary

Outline

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  - if so, eventually effects failure of a computing system

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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

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  - non-critical race
    - unanticipated behaviour
    - e.g., the hand of the "clock app" overleaps time data
- **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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  - ↪ the sequence of <u>all</u> actions is defined by a **partial order** (cf. [9, p. 17])

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  - as the case may be, a still present fault no longer manifest into an error
  - ↪ occasionally, fault diagnostics ends—and one is okay with that defect...

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

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

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

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

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

```
void cas_push(chain_t *this, chain_t *item) {
  do item->link = this->link;
  while (!CAS(&this->link, item->link, item));
}
```

Instruction Set Architecture Level

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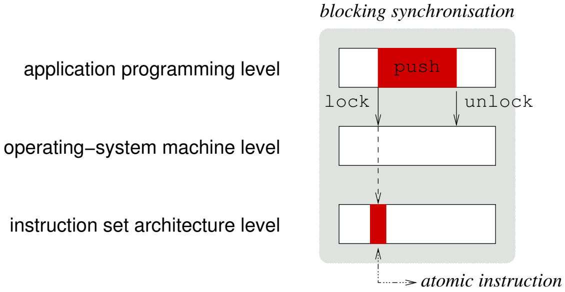
```

- 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
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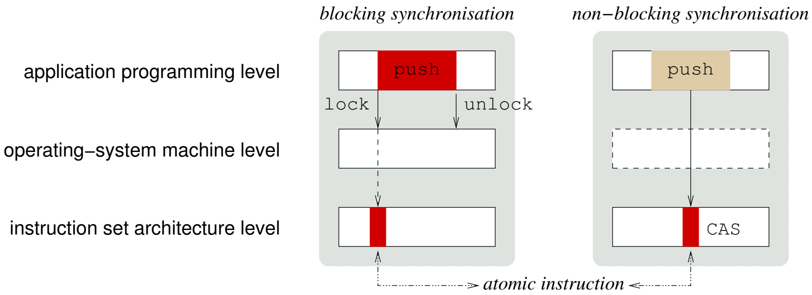

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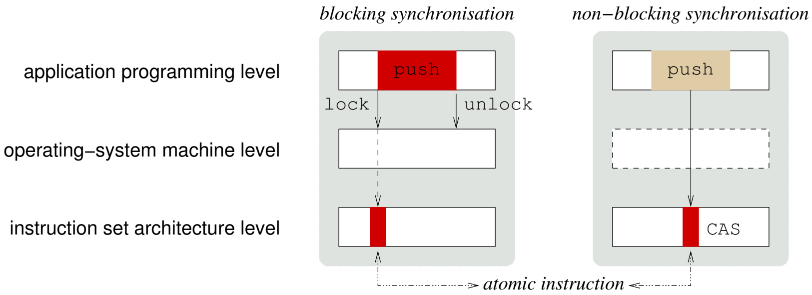

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- *push* is a **physical** (left-hand) or **logical** (right-hand) critical section

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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**

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- transactions may be concurrent, but not necessarily the work units

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- 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)

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- **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]
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  - durability
    - once a transaction is committed, it cannot be abrogated
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- 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**

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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* $\rightarrow$ *write* dependency

dirty read
- not yet committed data is already (early) read
- *write* $\rightarrow$ *read* dependency

lost update
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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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Solution Statement (rank-order priority, ROP)

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

Inconsistent 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:

```
char string[80];

int fill(char c) {
    int i;
    for (i = 0; i < 80; i++) {
        if (!string[i]) {
            string[i] = c;
            return i;
        }
    }
    return -1;
}
```

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6          if (!string[i]) {
7              string[i] = c;
8              return i;
9          }
10     }
11     return -1;
12 }
```

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

Inconsistent 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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Solution Statement (ROP)

1. non-blocking or
2. blocking synchronisation.

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++

```
i++;
```

ASM

```
movl i, %eax
addl $1, %eax
movl %eax, i
```

  - apparently correct

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- the old value of *i* can be read by both processes (line 2)
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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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- assuming that *vary* and *init* are run by own simultaneous processes:

```
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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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

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

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

invalidate condition and proceed

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

- apparently correct

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- lines 3–4 can overlap adversely with lines 1–2
- unblocking (line 4) sidesteps the process that will block (line 2)

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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:

```
#include <stdio.h>
#include <sys/stat.h>

int main(int argc, char *argv[]) {
    struct stat buf;
    if (lstat(argv[1], &buf))
        perror("lstat failed");
    else {
        printf("%s is ", argv[1]);
        if (buf.st_size != 0)
            printf("not ");
        printf("empty\n");
    }
}
```

- apparently correct

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↪ risk of false positive or negative, resp.

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Solution Statement ☹

blocking synchronisation.

Outline

Preface

Fundamentals
- Race Condition
- Sequential Control
- Concurrent Control

Patterns
- Data Race
- Control-Flow Race

Summary

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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$X \to Z$	`this->link = item`	$X \to Z$		$Y \to Z$

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$Y \to Z$		–	`this->link = item`	$Y \to Z$
$X \to Z$	`this->link = item`	$X \to Z$		$Y \to Z$

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

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  - process A resumes and completes its *push* of item X, deposits its item
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$\hookrightarrow$ 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

i++		simultaneous processes[6]			
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i	step	action	%eax	action	%eax
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42	4		–	`addl $1, %eax`	43

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42	3		–	`movl i, %eax`	42
42	4		–	`addl $1, %eax`	43
43	5		–	`movl %eax, i`	43

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Reading and Processing Uncommitted Data

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i	step	action	%eax	action	%eax
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42	2	`addl $1, %eax`	43		–
42	3		–	`movl i, %eax`	42
42	4		–	`addl $1, %eax`	43
43	5		–	`movl %eax, i`	43
43	6	`movl %eax, i`	43		–

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

Reading and Processing Uncommitted Data

`i++`		simultaneous processes[6]			
		A		*B*	
i	step	action	`%eax`	action	`%eax`
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42	2	`addl $1, %eax`	43		–
42	3		–	`movl i, %eax`	42
42	4		–	`addl $1, %eax`	43
43	5		–	`movl %eax, i`	43
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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

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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

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

Serialisability Unresolved

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

```
#include "aaf.h"

extern int total;

int vary(int i) {
    return AAF(&total, i);
}
```

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