Concurrent Systems

Nebenläufige Systeme

II. Concurrency

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Preface

Causality
  Interdependencies
  Dimensions

Resource Sharing
  Principles
  Competition
  Synchronisation

Summary
Subject Matter

- discussion on two fundamental abstract concepts:
  concurrency (Ger. Nebenläufigkeit),
    - designates the relation of causal independent events
    - is related to events that have no mutual influence
  causality (Ger. Kausalität, Ursächlichkeit)
    - designates the relation between cause and effect
    - is the causal chain or connection of two events

Definition (concurrent)
Events occur or are concurrent if none is the cause of the other.

- explanation of the relation of these concepts to resource sharing
  differentiated with respect to various types of resources and sharing
  classified as to appropriate or necessary synchronisation paradigms
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Summary
Principle of Causality

causal chain of events related to some other event $e_i$:

- $A$, $B$ and $C$ denote some computation on a private or shared processor
- an event is concurrent to another event ($e_i$) if it lies in the elsewhere of the other event ($e_i$)
- the event is neither cause nor effect of the other event ($e_i$)
- as the case may be, it is cause/effect of other events (different from $e_i$) that are lying in the elsewhere (cf. dash-and-dot line)
Order of Precedence

computations can be carried out concurrently provided that:

general

- none requires a result of the other (cf. p. 10)
- non-existent **data dependencies**

special

- none depends on delays brought forth by the other
  - deadlines may be missed rarely or under no circumstances
  - periods may be stretched up to a certain limit or not at any time
- non-existent **timing restrictions** \(\sim real-time\) **processing**

interrelation of computations/events constrains concurrency

Event correlations v. Processing modes

- “is cause of” \(\mapsto\) “is effect of” \(\mapsto\) **sequential** (realised before/at run-time)
- “is concurrent to” \(\mapsto\) **parallel** (realised in logical/real terms)

decrease of the portion of **sequential code** is an important aspect
Amdahl’s Law [1]: speed-up \((su)\) achievable by parallel processors

- work load remains constant with the varying number of processors
- aim at reducing overall computation time for a given fixed-size problem

\[
su = \frac{r_s + r_p}{r_s + \frac{r_p}{n}} = \frac{1}{r_s + \frac{r_p}{n}}
\]

- \(r_s\) ratio of sequential code
- \(r_p\) ratio of parallel code, independent of \(n\)
- \(n\) number of processors

- speed-up will be constrained by **data management housekeeping**
  - the nature of this overhead appears to be sequential
Adapting the Work Load

- Gustafson’s Law [4]: scaled speed-up (ssu), “hands-on experience”
  - work load varies linearly with the number of processors
  - aim at getting better results for a given fixed computation time

\[
ssu = \frac{r_s + r_p \times n}{r_s + r_p} = r_s + r_p \times n = n + (1 - n) \times r_s
\]

- \( r_p \) ratio of parallel code, scales with \( n \)
- \( r_s, n \) as with Amdahl’s Law

- data management housekeeping (serial part) becomes less important
  - in practise, the problem size scales with the number of processors: \( \text{HPC}^1 \)

^1High Performance Computing
Concurrent Operations of a Computation

operations can be concurrent if none needs the result of the other:

```c
int foo, bar;

int sample(int tupel[2]) {
    int subtotal, product;
    foo = tupel[0];
    bar = tupel[1];
    subtotal = foo + bar;
    product = bar * foo;
    return subtotal + product;
}
```

in computation:

- which statements can be concurrent?
  - 6 and 7
  - 9 and 10

- which statements are not concurrent?
  - (6, 7) and (9, 10)
  - (9, 10) and 12

defined by the causal order (Ger. Kausalordnung) of the statements

- as far as the logical dimension of a program is concerned
- but there is also a physical dimension, namely when it comes to the execution of that program by a real processor \( \sim \) level of abstraction
Level of Abstraction

- A concurrent operation (in logical terms) at a higher level can be sequential (in real terms) at a lower level.
  - The operation handles a resource that can be used only consecutively
    - A single memory area that is shared by multiple computations
    - A single communication bus that is shared by multiple processing units
  - Simultaneous executions are constrained by the resource characteristic
  - May result in a performance penalty, non-critical situation but for...

- A sequential operation (in logical terms) at a higher level can be “concurrent” (i.e., non-sequential in real terms) at a lower level.
  - The operation appears to be complex, consists of multiple sub-steps
    - The $n$-bit assignment on a $\frac{n}{2}$-bit machine, with $n = 16, 32, 64$
    - The addition of a number to a shared variable located in main memory
  - Simultaneous execution of the sub-steps must be considered (cf. p. 18)
  - Reveals a race condition, substantial critical situation: error

2real-time processing, especially in case of hard deadlines.
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Summary
permanent resources are **reusable**, but always only of limited supply
- they are acquired, occupied, used, and released (when no longer required)
  - in-use resources are preemtatable or non-preemtatable, depending on whether allocation to another occupant is possible
  - when non-preemtatable, they are exclusively owned by an occupant

temporary resources are of unlimited supply, they are **consumable**
- i.e. produced, received, used, and destroyed (when no longer required)

\(^3\)Also referred to as “persistent”.
Resource Peculiarities

- **hardware resources** as to be managed, e.g., by an operating system

<table>
<thead>
<tr>
<th>reusable</th>
<th>consumable</th>
</tr>
</thead>
<tbody>
<tr>
<td>processor</td>
<td>signal</td>
</tr>
<tr>
<td>CPU, FPU, GPU; MMU</td>
<td>IRQ, NMI, trap</td>
</tr>
<tr>
<td>memory</td>
<td></td>
</tr>
<tr>
<td>RAM, scratch pad, flash</td>
<td></td>
</tr>
<tr>
<td>peripheral</td>
<td></td>
</tr>
<tr>
<td>input, output, storage</td>
<td></td>
</tr>
</tbody>
</table>

- **software resources** as to be managed by any other program

<table>
<thead>
<tr>
<th>reusable</th>
<th>consumable</th>
</tr>
</thead>
<tbody>
<tr>
<td>code</td>
<td>signal</td>
</tr>
<tr>
<td>critical section/region</td>
<td>notice</td>
</tr>
<tr>
<td>data</td>
<td>message</td>
</tr>
<tr>
<td>variable, placeholder</td>
<td>packet, stream</td>
</tr>
</tbody>
</table>

- reusable data resources are notably **container** for consumable resources
  - the latter must be contained in variables/placeholders to be processible
- availability of the former constrains production/consumption of the latter

reusable and consumable resources imply different **use patterns**
Resource Use Patterns

- if so, **reusable resources** are subject to **multilateral** synchronisation provided that the following two basic conditions (i.e., constraints) apply:
  - i. resource accesses by computations may happen (quasi-) simultaneously
  - ii. simultaneous accesses may cause a **conflicting state change** of the resource

- simultaneous use of a **shared resource** this way must be coordinated
  - coordination may affect computations in a blocking or non-blocking manner

- **consumable resources** are subject to **unilateral** synchronisation
  - generally also referred to as logical or conditional synchronisation:
    - **logical** – as indicated by the “role playing” of the involved computations
    - **conditional** – as indicated by a condition for making computational progress

- use of a **temporary resource** follows a causal course of events or actions
  - by affecting producers in a non-blocking and consumers in a blocking way

- simultaneous computations **overlap** in time, interfere with each other
  - they become critical in any case if they also overlap in (identical) place

---

4 At the same level of abstraction, use of a shareable resource is exclusive in the blocking case or never refused in the non-blocking case.
Consolidating Example

assuming that the following subroutines (put and get) are executed in any order and that they may also run simultaneously:

```c
1 char buffer[80];
2 unsigned in = 0, out = 0;
3 
4 void put(char item) {
5     buffer[in++ % 80] = item;
6 }
7 
8 char get() {
9     return buffer[out++ % 80];
10 }
```

which logical problems exist?
- buffered items may be overwritten: overflow
- values my be read from an empty buffer: underflow

which other problems exist?
- overlapping writes may go to the same memory location
- similar to overlapping reads, but reverse
- overlapping auto-increments may manifest wrong values

in which buffer is a reusable and item is a consumable resource

put and get must be subject to uni- and multilateral synchronisation
- they are not concurrent under the assumption that was made above
Serialisation of Simultaneous Computations

- simultaneous computations or operations, resp., are in competition:
  - **sharing** of the same **reusable** resource(s)
  - **handover** of the same **consumable** resource(s)
  - in either case hardware and, if applicable, software resources, too

- both aspects, in turn, apply against the background of the following:
  1. the moment of an **simultaneous operation** is not predetermined
  2. the operation in question is complex (i.e., consists of multiple steps)
  3. the characteristic of this operation is its **divisibility** in temporal respect

- **conflict-prone operations** must go on **seriatim** (Ger. *nacheinander*)

  - **off-line**
    - static scheduling based on control-flow and data dependencies
    - **analytical approach** that takes *a priori* knowledge as given (v.s. i)
    - at run-time, dependable operations are implicitly synchronised

  - **on-line**
    - suitable explicit synchronisation of all dependable operations
    - **constructive approach** in shape of a **non-sequential program**
    - based on either pessimistic or optimistic run-time assumptions

- the chosen synchronisation method should be **minimally invasive**
Divisibility in Temporal Respect

when the steps of a complex operation may overlap at run-time

to simultaneous operation (Ger. Simultanbetrieb)

by way of example an auto-increment operator (cf. p. 16):

as compiled from C to ASM (x86): gcc -O3 -m32 -static -S

in++

1 movl _in, %ecx
2 leal 1(%ecx), %eax
3 movl %eax, _in

out++

4 movl _out, %ecx
5 leal 1(%ecx), %eax
6 movl %eax, _out

non-critical

- overlapping execution of in++ and out++
- simultaneous operations work on different variables

critical

- self-overlapping execution of in++ or out++, resp.
- simultaneous operations work on the same variable

the critical case may result in wrong reading (Ger. Zählerwert) of in/out

- in++ or out++ are not concurrent to oneself, resp.: they are not re-entrant

Assuming that processor registers are private to each computation.
assure a conflict-prone complex operation of (logical) **indivisibility**
- interpret the equivalent computation as **elementary operation** (ELOP)
  - an operation of indivisible cycle (Ger. *zeitlicher Ablauf*), apparently **atomic**

indivisibility of a *cycle* is achieved through **synchronisation**,\(^6\) i.e.:

- **i** coordination of the cooperation and competition between processes
- **ii** calibration of real-time clocks or data in distributed systems
- **iii** sequencing of events along the causal order

two fundamental approaches to synchronisation are distinguished:

**blocking**
- ensure synchronism at **operation start**
- lock potential overlapping out in the first place
- synchronised operation is made of sequential code

**non-blocking**
- ensure synchronism at **operation end**
- allow potential overlapping, achieve consistency afterwards
- synchronised operation is made of non-sequential code

both approaches come in a variety of solutions to the same problem

\(^6\)(Gr. *sýn*: synced, *chrónos*: time)
the methods are more or less disruptive of the problematic operation:

**sequential**
- bracket sequential code by a **locking protocol**
- for the most part, the original code can be reused
  - pessimistic, overlapping is not a rare event

**non-sequential**
- reprogram sequential code as a **transaction**
- for the most part, the original code cannot be reused
  - optimistic, overlapping is a rare event

wherever applicable, **downsizing sequential code** is basic
- i.a. Amdahl’s Law (cf. p. 8) argues for non-blocking synchronisation
Synchronisation Behaviour

- effect of synchronisation procedures on the computations involved:
  - inhibiting
    - prevents other computations from launching
    - irrespective of the eventuality of co-occurrence
    - applies to consumable resources (i.e., signals), only
  - running computations are not delayed
  - blocking
    - delays computations subject to resource availability
    - takes effect only in case of co-occurrence (overlapping)
    - applies to reusable and consumable resources
  - running computations are possibly delayed
  - non-blocking
    - may force non-dominantly running computations to repeat
    - takes effect only in case of co-occurrence (overlapping)
    - applies to reusable resources, only
  - dominantly running computations are not delayed
  - it bears repeating: **downsizing sequential code** is basic
  - where possible, non-blocking synchronisation should be the first choice
  - but even then: there is no all-in-one approach for every purpose...
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Summary

© wosch, thoenig CS (WS 2020/21, LEC 2) Summary
Abstract Concepts Revisited

concurrency = simultaneity − synchronism

understanding (Ger.) *Gleichzeitigkeit* in its various meanings:

**concurrency**
- happening together in time and place [7]
- designates the relation of causal independent events
- when none computation depends on results of the other

**simultaneity**
- occurring, done, existing together or at the same time [7]
- effect of a certain operation mode of a computing machine
- causes possibly critical overlapping of computations

**synchronism**
- fact of being synchronous; simultaneous occurrence [7]
- in respect of the multiple sub-steps of a complex operation
- achieved through “ELOP-ifying” coherent instructions

simultaneity includes concurrency, but not the other way round

- concurrency implies unconstrained overlapping in time and place
- but simultaneity may also cause overlapping that must be constrained

synchronism ensures that overlapped complex operations do right

- the individual sub-steps will be strictly executed *interim* (consecutively) or
- a *transaction* will take care for consistent (pseudo-) parallel execution
Relativity of Simultaneity

Physics figuratively

- The concept of (distant) simultaneity is not absolute, but depends on the frame of reference (Ger. Bezugssystem) an observer takes.
  - Moving- and fixed-platform thought experiment [2, p. 768]:

    The simultaneity of two distant events means a different thing to two different observers if they are moving with respect to each other.

- The reference frame when reflecting on simultaneous computations is the level of abstraction (cf. p. 11) of a particular program section.
  - A simplistic operation (++) at a higher level may translate to a complex operation (read-modify-write) at a lower level:
    - While multiple invocations of the former will take place sequentially, the corresponding ones of the latter may come about non-sequentially.
    - While multiple invocations of the latter discretely can be concurrent, their logical correlation to the former makes them possibly not concurrent.
  - Operations must be resolved cross-level (from “fixed platform” observed) in order to realise their ability for concurrency or need for synchronism.

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7 Due to the fact that each one refers to an ELOP (cf. p. 19), logically.
computations can be **concurrent** if none needs a result of the other
- they must be free of data and control-flow dependencies

in order to be concurrent, computations must be **simultaneous**
- quasi-simultaneous through partial virtualisation (hardware multiplexing)
  - or real simultaneous by multiprocessing (hardware multiplication)
- both techniques will induce computations to overlap in time and place

**overlapping** in time cause interference but is the lesser of two evils
- more critical is overlapping **in place** relating to the same resource
- particularly with regard to the same (i.e., shared) memory area

critical overlapping must be counteracted through **synchronisation**
- i.e., coordination of the cooperation and competition between processes
- here: uni- or multilateral synchronisation, depending on the resource type

synchronisation ensures for **indivisibility** of a computation cycle
- at the outset: physical, in blocking manner, by being pessimistic
- at the road’s end: logical, in non-blocking manner, by being optimistic


*On Deadlock in Computer Systems.*
Ithaca, NY, USA, Cornell University, Diss., 1971

Some Deadlock Properties of Computer Systems.
In: *ACM Computing Surveys* 4 (1972), Sept., Nr. 3, S. 179–196

*Webster’s New World Dictionary.*
Simon & Schuster, Inc., 1988
Consolidating Example Revisited

**bounded buffer** using a counting semaphore [3] for unilateral and an
ELOP (x86) for multilateral synchronisation

define int semaphore_t;
define void P(semaphore_t*);
define void V(semaphore_t*);

semaphore_t free = 80;
semaphore_t empty = 0;

static inline int fai(int *ref) {
define int aux = 1;
asm volatile("lock; xaddl %0,%1"
: "=r" (aux), "=m" (*ref)
: "0" (aux), "m" (*ref));
return aux;
}

free controls the number of unused buffer entries
- \(P\) prevents from buffer overflow, \(V\) signals reusable resource

empty controls the number of used buffer entries
- \(P\) prevents from buffer underflow, \(V\) signals consumable resource

fai indivisibly fetch and increment specified counter variable