Concurrent Systems

II. Concurrency

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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
**Outline**

Preface
Causality
Interdependencies
Dimensions
Resource Sharing
Principles
Competition
Synchronisation
Summary

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**Principle of Causality**

- causal chain of events related to some other event $e_i$
- $A$ is cause of $e_i$
- $B$ is effect of $e_i$
- $C$ is concurrent to $e_i$

- $A$, $B$ 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)

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**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 $\rightarrow$ real-time processing
  - interrelation of computations/events constrains concurrency

**Event correlations v. Processing modes**

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

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**Limits in the Degree of Concurrency**

- 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
  - $su = \frac{r_s + r_p}{r_s + \frac{r_p}{n}}$
  - $r_s$ 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

\[
ssu = \frac{rs + rp \times n}{rs + rp} = n + (1 - n) \times rs
\]

- data management housekeeping (serial part) becomes less important
  - in practise, the problem size scales with the number of processors: HPC
  
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;
}
```

- 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

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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
    \[ \rightarrow \text{may result in a performance penalty, non-critical situation but for...} \]

- 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)
    \[ \rightarrow \text{reveals a race condition, substantial critical situation: error} \]

2Real-time processing, especially in case of hard deadlines.
Resource Classification analogically with [5, 6]

- permanent, limited resources are reusable, but always only of limited supply
  - they are acquired, occupied, used, and released (when no longer required)
  - in-use resources are preemptable or non-preemptable, depending on whether allocation to another occupant is possible
  - when non-preemptable, 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)

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Radio resource - also referred to as “persistent”.

Resource Peculiarities

- hardware resources as to be managed, e.g., by an operating system
  - reusable
  - consumable
  - processor: CPU, FPU, GPU; MMU
  - memory: RAM, scratch pad, flash
  - peripheral: input, output, storage
- software resources as to be managed by any other program
  - reusable
  - consumable
  - code: critical section/region
  - data: variable, placeholder
  - signal: IRQ, NMI, trap
  - message: packet, stream

Resource Use Patterns

- if so, reusable resources are subject to multilateral synchronisation
  - provided that the following two basic conditions (i.e., constraints) apply:
    - resource accesses by computations may happen (quasi-) simultaneously
    - 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

consolidating example
character buffer of limited size
assuming that the following subroutines (put and get) are executed in any order and that they may also run simultaneously:

```c
char buffer[80];
unsigned int = 0, out = 0;
void put(char item) {
  buffer[in ++ % 80] = item;
}
char get() {
  return buffer[out ++ % 80];
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in which buffer is a reusable and item is a consumable resource
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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)
  \[\rightarrow\]
  in either case hardware and, if applicable, software resources, too
- both aspects, in turn, apply against the background of the following:
  - the moment of an simultaneous operation is not predetermined
  - the operation in question is complex (i.e., consists of multiple steps)
  - 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

establishing of synchronism

- 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 synchronisation at operation start
    - lock potential overlapping out in the first place
  - non-blocking
    - ensure synchronisation at operation end
    - allow potential overlapping, achieve consistency afterwards
- both approaches come in a variety of solutions to the same problem

\(^6\)(Gr. σύν: synced, χρόνος: time)

divisibility in temporal respect

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

\[\begin{align*}
in++ & \to \quad \text{out++} \\
1 \text{ movl } & _{\text{in}}, \%\text{ecx} \\
4 \text{ movl } & _{\text{out}}, \%\text{ecx} \\
2 \text{ leal } & 1(\%\text{ecx}), \%\text{eax} \\
5 \text{ leal } & 1(\%\text{ecx}), \%\text{eax} \\
3 \text{ movl } & \%\text{eax}, _{\text{in}} \\
6 \text{ movl } & \%\text{eax}, _{\text{out}}
\end{align*}\]

- non-critical
  - overlapping execution of in++ and out++
  - simultaneous operations work on different variables\(^5\)
- critical
  - self-overlapping execution of in++ or out++, resp.
  - simultaneous operations work on the same variable\(^5\)
- 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

\(^5\)Assuming that processor registers are private to each computation.

varieties of synchronisation relevant to operating systems

- 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...

Abstract Concepts Revisited

- 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

- 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

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
  
** Résumé **

In order to be concurrent, computations must be **simultaneous** and they must be free of data and control-flow dependencies. Critical overlapping must be counteracted through **synchronisation**. Synchronisation ensures for **indivisibility** of a computation cycle.

**Consolidating Example Revisited**

Using a counting semaphore for unilateral and an ELOP (x86) for multilateral synchronisation:

```c
typedef int semaphore_t;
extern void P(semaphore_t*);
extern void V(semaphore_t*);

semaphore_t free = 80;
semaphore_t empty = 0;

in = 0, out = 0;

item = buffer[fai(&out) % 80];
buffer[fai(&in) % 80] = item;

void put(char item) {
    V(&free);
    P(&free);
}

void get() {
    char aux = 1;
    int aux = 1;
    asm volatile("lock; xaddl %0,%1" : "r" (aux), "m" (ref) : "o" (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

**Reference List I**

1. **Amdahl, G. M.:**  
   Validity of the Single-Processor Approach to Achieving Large Scale Computing Capabilities.  

2. **Comstock, D. F.:**  
   The Principle of Relativity.  
   In: *Science* 31 (1910), Mai 20, Nr. 803, S. 767–772.  
   DOI 10.1126/science.31.803.767

3. **Dijkstra, E. W.:**  
   Cooperating Sequential Processes / Technische Universiteit Eindhoven.  

4. **Gustafson, J. L.:**  
   Reevaluating Amdahl’s Law.  
   In: *Communications of the ACM* 31 (1988), Mai, Nr. 5, S. 532–533