

Concurrent Systems

Nebenläufige Systeme

II. Concurrency

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Outline

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Causality

Interdependencies

Dimensions

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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



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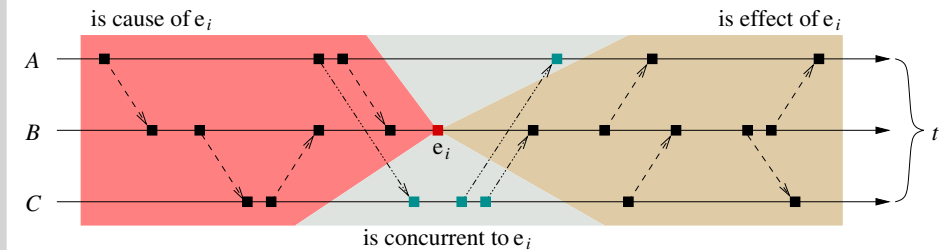
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Principle of Causality

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

Event correlations v. Processing modes

“is cause of”
“is effect of”
} $\mapsto$ **sequential** (realised before/at run-time)

“is concurrent to” $\mapsto$ **parallel** (realised in logical/real terms)

$\hookrightarrow$ decrease of the portion of **sequential code** is an important aspect



Limits in the Degree of Concurrency

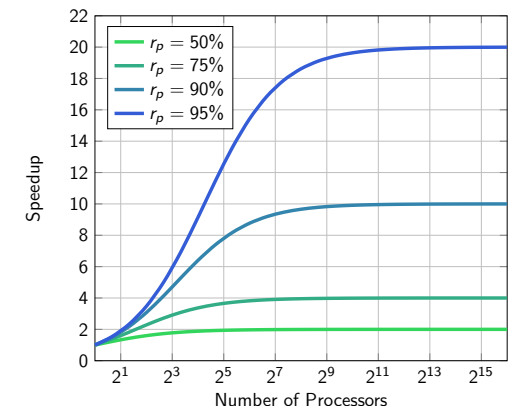
- Amdahl's Law [1]: speed-up (su) achievable by parallel processors
 - work load remains constant with the varying number of processors
 - aim at reducing overall computation time for a given fixed-size problem

$$su = (r_s + r_p) / (r_s + \frac{r_p}{n})$$
$$= \frac{1}{r_s + \frac{r_p}{n}}$$

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



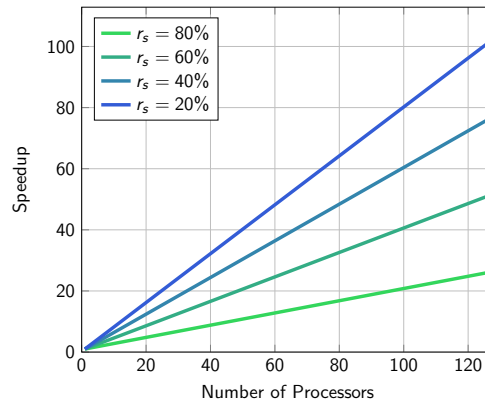
Adapting the Work Load

- 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

$$\begin{aligned}ssu &= \frac{r_s + r_p \times n}{r_s + r_p} \\&= r_s + r_p \times n \\&= n + (1 - n) \times r_s\end{aligned}$$

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: **HPC**¹

¹High Performance Computing



Concurrent Operations of a Computation

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

```
1 int foo, bar;
2
3 int sample(int tuple[2]) {
4     int subtotal, product;
5
6     foo = tuple[0];
7     bar = tuple[1];
8
9     subtotal = foo + bar;
10    product = bar * foo;
11
12    return subtotal + product;
13 }
```

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 $\leadsto$ *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...**²
- 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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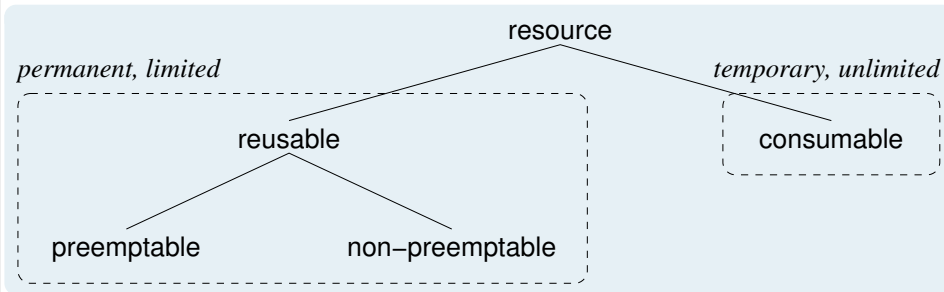
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- permanent³ resources are **reusable**, but always only of limited supply
 - they are acquired, occupied, used, and released (when no longer required)
 - in-use resources are preemptable or non-preemptable, depending on whether allocation to another 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)

³Also referred to as “persistent”.

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

reusable

- processor ■ CPU, FPU, GPU; MMU
- memory ■ RAM, scratch pad, flash
- peripheral ■ input, output, storage

consumable

- signal ■ IRQ, NMI, trap

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

reusable

- code ■ critical section/region
- data ■ variable, placeholder

consumable

- signal ■ notice
- message ■ packet, stream

- 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:
 - 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 manner⁴
- **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

⁴At 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

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:


```

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 may 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:
 - i the moment of an **simultaneous operation** is not predetermined
 - ii the operation in question is complex (i.e., consists of multiple steps)
 - iii 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
 - 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`
- | in++ | out++ |
|-----------------------------------|-----------------------------------|
| 1 <code>movl _in, %ecx</code> | 4 <code>movl _out, %ecx</code> |
| 2 <code>leal 1(%ecx), %eax</code> | 5 <code>leal 1(%ecx), %eax</code> |
| 3 <code>movl %eax, _in</code> | 6 <code>movl %eax, _out</code> |
- non-critical**
 - overlapping execution of `in++` and `out++`
 - simultaneous operations work on different variables⁵
 - critical**
 - self-overlapping execution of `in++` or `out++`, resp.
 - simultaneous operations work on the same variable⁵
 - 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**

⁵Assuming that processor registers are private to each computation.



Establishing of Synchronism

cf. p. 28

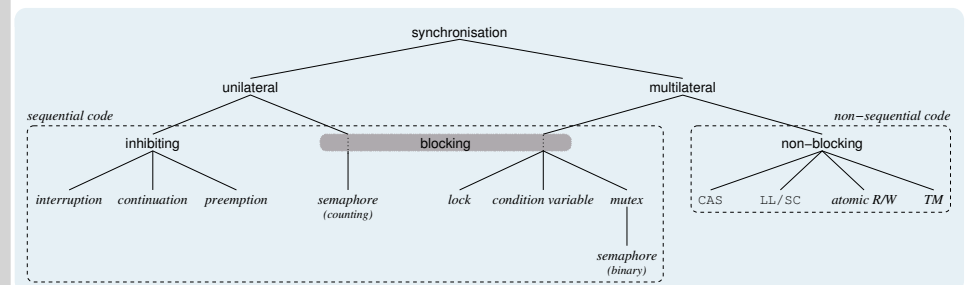
- assure a conflict-prone complex operation of (logical) **indivisibility**
 - interpret the equivalent computation as **elementary operation** (ELOP)
 - an operation of indivisible cycle (Ger. *zeitlicher Ablauf*), apparently **atomic**
- indivisibility of a *cycle* is achieved through **synchronisation**,⁶ 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. *syn*: synced, *chrónos*: time)



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. . .



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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,⁷ 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

⁷Due 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 😊



- [1] AMDAHL, G. M.:
Validity of the Single-Processor Approach to Achieving Large Scale Computing Capabilities.
In: *Proceedings of the AFIPS Spring Joint Computer Conference (AFIPS 1967 (Spring))*, AFIPS Press, 1967, S. 483–485
- [2] COMSTOCK, D. F.:
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In: *Science* 31 (1910), Mai 20, Nr. 803, S. 767–772.
<http://dx.doi.org/10.1126/science.31.803.767>. – DOI 10.1126/science.31.803.767
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Cooperating Sequential Processes / Technische Universiteit Eindhoven.
Eindhoven, The Netherlands, 1965 (EWD-123). – Forschungsbericht. – (Reprinted in *Great Papers in Computer Science*, P. Laplante, ed., IEEE Press, New York, NY, 1996)
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- [5] HOLT, R. C.:
On Deadlock in Computer Systems.
Ithaca, NY, USA, Cornell University, Diss., 1971
- [6] HOLT, R. C.:
Some Deadlock Properties of Computer Systems.
In: *ACM Computing Surveys* 4 (1972), Sept., Nr. 3, S. 179–196
- [7] NEUFELDT, V. (Hrsg.) ; GURALNIK, D. A. (Hrsg.):
Webster's New World Dictionary.
Simon & Schuster, Inc., 1988



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

```

1  typedef int semaphore_t;           18  char buffer[80];
2                                     19  unsigned in = 0, out = 0;
3  extern void P(semaphore_t*);       20
4  extern void V(semaphore_t*);       21  void put(char item) {
5                                     22      P(&free);
6  semaphore_t free = 80;             23      buffer[fai(&in) % 80] = item;
7  semaphore_t empty = 0;             24      V(&empty);
8                                     25  }
9  static inline int fai(int *ref) {   26
10     int aux = 1;                    27  char get() {
11                                     28      char item;
12     asm volatile("lock; xaddl %0,%1" 29
13         : "=r" (aux), "=m" (*ref)    30      P(&empty);
14         : "0" (aux), "m" (*ref));    31      item = buffer[fai(&out) % 80];
15                                     32      V(&free);
16     return aux;                      33
17 }                                     34     return item;
                                       35 }
    
```

- 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

