Concurrent Systems

Nebenläufige Systeme

II. Concurrency

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Outline

Preface

Causality
  Interdependencies
  Dimensions

Resource Sharing
  Principles
  Competition
  Synchronisation

Summary
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
discussion on two fundamental **abstract concepts**: concurrency (Ger. *Nebenläufigkeit*),
- designates the relation of causal independent events
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- designates the relation between cause and effect
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**Definition (concurrent)**

Events occur or are concurrent if none is the cause of the other.
discussion on two fundamental abstract concepts: concurrency (Ger. *Nebenläufigkeit*),
- designates the relation of causal independent events
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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

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Causality
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Resource Sharing
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Summary
**Principle of Causality**

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

  ![Diagram showing causality relationships](image)

  - A, B and C denote some computation on a private or shared processor.
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
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 ($e_i$)
Principle of Causality

- causal chain of events related to some other event \( e_i \):

  - is cause of \( e_i \)
  - is effect of \( e_i \)
  - 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)
computations can be carried out concurrently provided that:

general
- none requires a result of the other (cf. p. 10)
- non-existent **data dependencies**
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**general**
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**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**
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interrelation of computations/events constrains concurrency

---

**Event correlations v. Processing modes**

\[
\begin{align*}
\text{“is cause of”} & \quad \leftrightarrow \quad \text{sequential} \quad (\text{realised before/at run-time}) \\
\text{“is effect of”} & \quad \leftrightarrow \quad \text{parallel} \quad (\text{realised in logical/real terms})
\end{align*}
\]
Order of Precedence

computations can be carried out concurrently provided that:

- **general**
  - none requires a result of the other (cf. p. 10)
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- **special**
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interrelation of computations/events constrains concurrency

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**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)
```

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

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

- speed-up will be constrained by data management housekeeping
  - the nature of this overhead appears to be sequential
Limits in the Degree of Concurrency

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- work load remains constant with the varying number of processors
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\[
su = \frac{(r_s + r_p)}{(r_s + \frac{r_p}{n})} = \frac{1}{r_s + \frac{r_p}{n}}
\]

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

Number of Processors

<table>
<thead>
<tr>
<th>Number of Processors</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
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</tr>
<tr>
<td>4</td>
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<tr>
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<td>32768</td>
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</tr>
<tr>
<td>65536</td>
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The speed-up will be constrained by data management housekeeping, the nature of this overhead appears to be sequential.
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
  \[ su = \frac{(r_s + r_p)}{(r_s + \frac{r_p}{n})} = \frac{1}{r_s + \frac{r_p}{n}} \]
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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
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ssu = \frac{r_s + r_p \times n}{r_s + r_p} = r_s + r_p \times n = n + (1 - n) \times r_s
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- \( r_p \) ratio of parallel code, scales with \( n \)
- \( r_s, n \) as with Amdahl’s Law
Adapting the Work Load

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

- data management housekeeping (serial part) becomes less important

\[\text{in practise, the problem size scales with the number of processors: HPC}^1\]
Concurrent Operations of a Computation

- Operations can be concurrent if none needs the result of the other.
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- 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];
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    subtotal = foo + bar;
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In computation:
- Which statements can be concurrent?
- Which statements are not concurrent?

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; level of abstraction.
Concurrent Operations of a Computation

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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
Concurrent Operations of a Computation

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- 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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CS (WS 2018/19, LEC 2) Causality – Dimensions
Level of Abstraction

- a concurrent operation (in logical terms) at a higher level can be sequential (in real terms) at a lower level

- a sequential operation (in logical terms) at a higher level can be “concurrent” (i.e., non-sequential in real terms) at a lower level
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
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may result in a performance penalty, non-critical situation
Level of Abstraction

- 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)
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- Reveals a race condition, substantial critical situation.
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  - simultaneous executions are constrained by the resource characteristic
  - may result in a performance penalty, non-critical situation but for... ²

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    - 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.
Outline

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Causality
  Interdependencies
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Resource Sharing
  Principles
  Competition
  Synchronisation

Summary
Resource Classification

Resource classification can be analogously with [5, 6].

- **Permanent, limited**
  - Reusable
    - Preemptable
    - Non-preemptable
  - Consumable
- **Temporary, unlimited**

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).

Also referred to as “persistent.”
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 preemptable or non-preemptable, depending on whether allocation to another occupant is possible.
- When non-preemptable, they are exclusively owned by an occupant.

---

3 Also referred to as “persistent”.

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permanent³ resources are **reusable**, but always only of limited supply
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temporary resources are of unlimited supply, they are **consumable**
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Resource Peculiarities

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

| reusable        | consumable
<table>
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<tbody>
<tr>
<td>processor</td>
<td>signal</td>
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<tr>
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**reusable** and **consumable** resources imply different use patterns. The availability of the former constrains the production/consumption of the latter.
### Resource Peculiarities

#### Hardware Resources

- **Reuseable**
  - Processor: CPU, FPU, GPU; MMU
  - Memory: RAM, scratch pad, flash
  - Peripheral: Input, output, storage

- **Consumable**
  - Signal: IRQ, NMI, trap

#### Software Resources

- **Reuseable**
  - Code: Critical section/region
  - Data: Variable, placeholder

- **Consumable**
  - Signal: Notice
  - Message: Packet, stream
Resource Peculiarities

- **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
Resource Peculiarities

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- reusable and consumable resources imply different **use patterns**
if so, **reusable resources** are subject to **multilateral** synchronisation.

**consumable resources** are subject to **unilateral** synchronisation.
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

---

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.
Resource Use Patterns

- 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
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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

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 in = 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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  - buffered items may be overwritten: overflow
  - values may be read from an empty buffer: underflow

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  - 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
Consolidating Example

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 in = 0, out = 0;

void put(char item) {
    buffer[in++ % 80] = item;
}

char get() {
    return buffer[out++ % 80];
}
```

- 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

- put and get must be subject to uni- and multilateral synchronisation

- they are **not** concurrent under the assumption that was made above

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Resource Sharing – Principles  
16
Serialisation of Simultaneous Computations

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  - **sharing** of the same **reusable** resource(s)
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→ in either case hardware and, if applicable, software resources, too
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ii. the operation in question is complex (i.e., consists of multiple steps)
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- **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
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- 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
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- 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*)

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Assuming that processor registers are private to each computation.
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- 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
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- **non-critical**: overlapping execution of `in++` and `out++`
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**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

---

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Establishing of Synchronism

- assure a conflict-prone complex operation of (logical) **indivisibility**
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  - an operation of indivisible cycle (Ger. *zeitlicher Ablauf*), apparently **atomic**
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  i. **coordination** of the cooperation and competition between processes
  ii. **calibration** of real-time clocks or data in distributed systems
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- 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

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

\(^6\)(Gr. *sýn*: synced, *chrónos*: time)
Varieties of Synchronisation

Relevant to Operating Systems

- **Synchronisation**
  - **Unilateral**
    - Inhibiting
      - Interruption
      - Continuation
      - Preemption
  - Blocking
    - Semaphore
      - Counting
    - Lock
    - Condition Variable
    - Mutex
  - Non-blocking
    - CAS
    - LL/SC
    - Atomic R/W
    - TM

- **Sequential Code**
- **Non-sequential Code**

The methods are more or less disruptive of the problematic operation:
- Sequential parallel/bracket sequential code by a locking protocol. For the most part, the original code can be reused.
- Non-sequential reprogram sequential code as a transaction, for the most part, the original code cannot be reused.

Wherever applicable, downsizing sequential code is basic.

i.a. Amdahl's Law (cf. p.8) argues for non-blocking synchronisation.

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- bracket sequential code by a **locking protocol**
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the methods are more or less disruptive of the problematic operation:

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Synchronisation Behaviour

- effect of synchronisation procedures on the computations involved
Synchronisation Behaviour

- effect of synchronisation procedures on the computations involved:
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    - prevents other computations from launching
      - irrespective of the eventuality of co-occurrence
      - applies to consumable resources, only
    - running computations are not delayed
Synchronisation Behaviour

- effect of synchronisation procedures on the computations involved:

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    - takes effect only in case of co-occurrence (overlapping)
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- effect of synchronisation procedures on the computations involved:
  
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- 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...
Outline

Preface

Causality
  Interdependencies
  Dimensions

Resource Sharing
  Principles
  Competition
  Synchronisation

Summary
Abstract Concepts Revisited

concurrency = simultaneity − synchronism

- understanding (Ger.) *Gleichzeitigkeit* in its various meanings
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**concurrency**
- happening together in time and place [7]
- designates the relation of causal independent events
- when none computation depends on results of the other
understanding (Ger.) *Gleichzeitigkeit* in its various meanings:

- **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
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- fact of being synchronous; simultaneous occurrence [7]
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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
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.
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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

\(^7\)Due to the fact that each one refers to an ELOP (cf. p. 19), logically.
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- 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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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 😊
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[7] **Neufeldt, V. (Hrsg.) ; Guralnik, D. A. (Hrsg.):**
*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

```c
typedef int semaphore_t;
extern void P(semaphore_t*);
extern void V(semaphore_t*);
semaphore_t free = 80;
semaphore_t empty = 0;

static inline int fai(int *ref) {
    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