Concurrent Systems

Nebenläufige Systeme

II. Concurrency

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Agenda

Preface

Causality
  Interdependencies
  Dimensions

Resource Sharing
  Principles
  Competition
  Synchronisation

Summary
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
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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)
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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
  Principles
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Summary
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

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- $A$, $B$ 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 $e_i$:

- $A$, $B$ 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**
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**
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interrelation of computations/events constrains concurrency

Event correlations v. Processing modes

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

- “is concurrent to”
  $\implies$ parallel (realised in logical/real terms)
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interrelation of computations/events constrains concurrency

**Event correlations v. Processing modes**

- "is cause of" "is effect of"
  $\quad \mapsto \quad$ **sequential** (realised before/at run-time)

- "is concurrent to"
  $\quad \mapsto \quad$ **parallel** (realised in logical/real terms)

$\mapsto$ 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
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

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

- $r_s$ ratio of sequential code
- $r_p$ ratio of parallel code, independent of $n$
- $n$ number of processors
Limits in the Degree of Concurrency

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- \(r_s\): 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
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\text{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
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
  - in practise, the problem size scales with the number of processors: HPC\(^1\)

\(^1\)High Performance Computing
Concurrent Operations of a Computation

- operations can be concurrent if none needs the result of the other
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;
}
```
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in computation:
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- which statements are not concurrent?
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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

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

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1 int foo, bar;

2 int sample(int tupel[2]) {
3     int subtotal, product;

4     foo = tupel[0];
5     bar = tupel[1];

6     subtotal = foo + bar;
7     product = bar * foo;

8     return subtotal + product;
9 }
```

- defined by the causal order (Ger. Kausalordnung) of the statements
  - as far as the logical dimension of a program is concerned

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Concurrent Operations of a Computation

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

```java
int foo, bar;

int sample(int[] tupel) {
    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?
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    - (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

- a sequential operation (in logical terms) at a higher level can be “concurrent” (i.e., non-sequential in real terms) at a lower level

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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

Simultaneous execution of the sub-steps must be considered (cf. p.18) reveals a race condition, substantial critical situation: error
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may result in a *performance penalty*, non-critical situation
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- 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
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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.
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    - 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

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- 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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Resource Sharing
  Principles
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Summary
Resource Classification

permanent, limited

resource

reusable

preemptable non-preemptable

temporary, unlimited

consumable

Also referred to as “persistent.”
permanent\textsuperscript{3} resources are \textbf{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

\textsuperscript{3}Also referred to as “persistent”. 
permanent resources are **reusable**, but always only of limited supply
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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”. 

\(^3\)
## Resource Peculiarities

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

<table>
<thead>
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Reusable data resources are notably
the former constrains production/consumption of the latter

Reusable and consumable resources imply different use patterns

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## Resource Peculiarities

### hardware resources

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### software resources

As to be managed by any other program:

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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

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

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- 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

- **consumable resources** are subject to **unilateral** synchronisation
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 manner⁴

---

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.
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
Resource Use Patterns

- if so, **reusable resources** are subject to **multilateral** synchronisation
  - provided that the following two basic conditions (i.e., constraints) apply:
    1. resource accesses by computations may happen (quasi-) simultaneously
    2. 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:
    1. **logical** – as indicated by the “role playing” of the involved computations
    2. **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

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
Consolidating Example

Character Buffer of Limited Size

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```

- which logical problems exist?

  - buffered items may be overwritten: overflow
  - values may be read from an empty buffer: underflow
  - 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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Which other problems exist?

- Overlapping writes may go to the same memory location.

In which buffer is a reusable and item is a consumable resource.
Consolidating Example

assumes that the following subroutines \((\text{put and get})\) are executed in any order and that they may also run simultaneously:

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2. \texttt{unsigned in = 0, out = 0;}
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   \hspace{1em} buffer[in++ \% 80] = item;
}}
4. \texttt{}}
5. \texttt{char get() {
   \hspace{1em} return buffer[out++ \% 80];
}}
6. \texttt{}}

\(\rightarrow\) in which buffer is a \textit{reusable} and item is a \textit{consumable} resource

\(\rightarrow\) which other problems exist?

- overlapping writes may go to the same memory location
- similar to overlapping reads, but reverse
Consolidating Example

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- 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:
  - they compete for the **sharing** of the same reusable resource(s)
  - they compete for the **handover** of the same consumable resource(s)
Serialisation of Simultaneous Computations

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  - they compete for the **sharing** of the same reusable resource(s)
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    - 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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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*)
Divisibility in Temporal Respect

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

```plaintext
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
```

- the critical case may result in wrong reading (Ger. *Zählerwert*) of in++ or out++ are not concurrent to oneself, resp.: they are not re-entrant

Assuming that processor registers are private to each computation.
Divisibility in Temporal Respect

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**non-critical**
- overlapping execution of in++ and out++
- simultaneous operations work on different variables\(^5\)

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Divisibility in Temporal Respect

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

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5 Assuming that processor registers are private to each computation.
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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.
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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.
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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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

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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
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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

- Sequential code
  - Inhibiting
    - Interruption
    - Continuation
    - Preemption
  - Blocking
    - Semaphore (counting)
  - Non-blocking
    - CAS
    - LL/SC
    - Atomic R/W
    - TM

- Non-sequential code
  - Atomic R/W
  - LL/SC

The methods are more or less disruptive of the problematic operation. 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 synchronization.
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Varieties of Synchronisation

Relevant to Operating Systems

- Sequential code
- Inhibiting: interruption, continuation, preemption

- Multilateral
- Blocking
- Semaphore (counting)
- Lock
- Condition variable
- Mutex

- Non-sequential code
- Non-blocking
- CAS
- LL/SC
- Atomic R/W
- TM

- 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
the methods are more or less disruptive of the problematic operation:

non-sequential  ■ reprogram sequential code as a transaction
■ for the most part, the original code cannot be reused
  ➔ optimistic, overlapping is a rare event
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
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- 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, only
    - running computations are not delayed
Synchronisation Behaviour

- effect of synchronisation procedures on the computations involved:
  
  **blocking**
  - delays computations subject to resource availability
    - 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
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
understanding (Ger.) *Gleichzeitigkeit* in its various meanings:

- concurrency = simultaneity – synchronism

**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
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- concurrency implies unconstrained overlapping in time and place
- but simultaneity my also cause overlapping that must be constrained
Abstract Concepts Revisited

concurrency = simultaneity − synchronism

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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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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

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  - 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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Résumé

- 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 virtualization (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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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*);
sSemaphore_t free = 80;
sSemaphore_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;
}

char buffer[80];
unsigned in = 0, out = 0;
void put(char item) {
    P(&free);
    buffer[fai(&in) % 80] = item;
    V(&empty);
}
char get() {
    char item;
    P(&empty);
    item = buffer[fai(&out) % 80];
    V(&free);
    return item;
}
```

- **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