Concurrent Systems

Nebenläufige Systeme

IX. Deadly Embrace

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Agenda

Preface

Resource Management
  Classification
  Illustrative Example I
  General

Deadlocks
  Fundamentals
  Illustrative Example II
  Counteractive Measures

Summary
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Resource Management
  Classification
  Illustrative Example I
  General

Deadlocks
  Fundamentals
  Illustrative Example II
  Counteractive Measures

Summary
discussion on **abstract concepts** as to the stalemate of interacting processes due to misconstructed or misguided resource allocation

- crosswise request or signalling of a reusable or consumable resource, resp.
- lost release of a produced or beforehand acquired resource
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deadly embrace (Ger. tödliche Umarmung, gegenseitiges Sperren) of interacting processes by reason of programming errors

- caused by design faults and to be corrected by design changes
- focal point is to foreground constructive and eclipse analytical measures
Subject Matter

- discussion on **abstract concepts** as to the stalemate of interacting processes due to misconstructed or misguided resource allocation
  - crosswise request or signalling of a reusable or consumable resource, resp.
  - lost release of a produced or beforehand acquired resource
- **deadly embrace** (Ger. *tödliche Umarmung, gegenseitiges Sperren*) of interacting processes by reason of programming errors
  - caused by **design faults** and to be corrected by design changes
  - focal point is to foreground constructive and eclipse analytical measures
- exemplification of the **classic** [1] by means of sample programs
  - realising that use cases of functions can uncover critical interdependencies
    - problems that are not obvious when looking at single program statements
  - race conditions that are disclosed only with having the big picture in mind
discussion on abstract concepts as to the stalemate of interacting processes due to misconstrued or misguided resource allocation
- crosswise request or signalling of a reusable or consumable resource, resp.
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exemplification of the classic [1] by means of sample programs
- realising that use cases of functions can uncover critical interdependencies
  - problems that are not obvious when looking at single program statements
- race conditions that are disclosed only with having the big picture in mind

not least, giving an idea of the typical counteractive measures
- prevention, avoidance, or detection and breakup of process deadlocks
- resource allocation graph and, as specialisation of it, wait-for graph
Deadlock

(Ger.) Verklemmung, Blockierung, Stillstand

source: National Geographic
Outline

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  Counteractive Measures

Summary
for whatever reason, use of operations on any type of resources can cause process or even system deadlocks

- **reusable**
  - crosswise request by different simultaneous processes
  - lost release of a beforehand acquired resource

- **consumable**
  - crosswise signalling by interacting processes followed by await, whereby the signal is not buffered
  - lost release of a produced resource
for whatever reason, use of operations on any type of resources can cause process or even system deadlocks

- **reusable**
  - **crosswise request** by different simultaneous processes
  - **lost release** of a beforehand acquired resource

- **consumable**
  - **crosswise signalling** by interacting processes followed by `await`, whereby the signal is not buffered
  - **lost release** of a produced resource

abstracting away from hardware, deadlocks are due to software faults
- only simultaneous processes may disclose these faults as error or failure
```
int send(pid_t pid, char *data, long size) {
    process_t *self = being(OONESELF), *peer = being(pid);

    P(&self->lock); /* protect oneself: me */
    memcpy(self->outbox.d, data, sizeof(self->outbox.d));

    P(&peer->lock); /* protect counterpart */
    serve(peer, self); /* message handover */
    V(&peer->lock); /* unprotect counterpart */
    V(&self->lock); /* unprotect oneself */

    V(&peer->inbox.gate); /* signal send done */
    P(&self->signal); /* block on receive */

    return self->merit; /* receiver pid or error code */
}
```

- fictive semaphore-based implementation of a message send operation
int send(pid_t pid, char *data, long size) {
    process_t *self = being(ONESELF), *peer = being(pid);

    P(&self->lock);  /* protect oneself: me */
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    P(&self->signal);   /* block on receive */

    return self->merit; /* receiver pid or error code */
}

- fictive semaphore-based implementation of a message send operation
- susceptible to deadlock in case of preemptive or SMP scheduling, resp.
```c
int send(pid_t pid, char *data, long size) {
    /* ... */
    P(&self->lock); /* protect oneself: me */
    P(&peer->lock); /* protect counterpart */
    /* ... */
    V(&peer->lock); /* unprotect counterpart */
    V(&self->lock); /* unprotect oneself */
    /* ... */
}
```
int send(pid_t pid, char *data, long size) {
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    V(&self->lock); /* unprotect oneself */
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}

assuming that a process $P_1$ does $send(P_2)$ and another process $P_2$
does $send(P_1)$, simultaneously
int send(pid_t pid, char *data, long size) {
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assuming that a process $P_1$ does $send(P_2)$ and another process $P_2$
does $send(P_1)$, simultaneously

let $A$ be the process descriptor of $P_1$ and let $B$ be the one of $P_2$:
$P_1$: 3  succeeded in completing $P(A)$, locked $A$ and gets preempted
$P_2$: 3  succeeds in completing $P(B)$, locked $B$ and continues
$P_2$: 4  gets blocked in $P(A)$, relinquishes control
$P_1$: 4  resumes and gets blocked in $P(B)$, relinquishes control
\begin{verbatim}
int send(pid_t pid, char *data, long size) {
    /* ... */
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/* ... */
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/* ... */
}
\end{verbatim}

assuming that a process \( P_1 \) does \textit{send}(P_2) and another process \( P_2 \) does \textit{send}(P_1), \textit{simultaneously}.

let \( A \) be the process descriptor of \( P_1 \) and let \( B \) be the one of \( P_2 \):

\( P_1: 3 \)  ■ succeeded in completing \( P(A) \), locked \( A \) and gets preempted
\( P_2: 3 \)  ■ succeeds in completing \( P(B) \), locked \( B \) and continues
\( P_2: 4 \)  ■ gets blocked in \( P(A) \), relinquishes control
\( P_1: 4 \)  ■ resumes and gets blocked in \( P(B) \), relinquishes control

\( P_1 \) and \( P_2 \) are subject to \textbf{deadlock} because of crosswise requests...
assuming that progress of $P_1$ and $P_2$ is irreversible
assuming that progress of P₁ and P₂ is irreversible
assuming that progress of $P_1$ and $P_2$ is irreversible
Progress Space

deadlock is inevitable

assuming that progress
of P₁ and P₂ is irreversible

resource lifetime

P (A)
P (B)
P₁

A
B

P₂

resource lifetime

A
B

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Resource Management – Illustrative Example I
Progress Space

A resource lifetime of P and P₂ is irreversible assuming that progress of P₁ and P₂ is irreversible.

deadlock is inevitable

acc. [1, p. 70/71]
deadlock has happened

deadlock is inevitable

assuming that progress of $P_1$ and $P_2$ is irreversible
assuming that the general semaphore used to signal availability of a consumable resource is replaced by an **event variable** mechanism:

```
int send(pid_t pid, char *data, long size) {
    /* ... */
    cause(&peer->event);    /* signal send done */
    await(&self->event);    /* block on receive */
    /* ... */
}
```
assuming that the general semaphore used to signal availability of a consumable resource is replaced by an **event variable** mechanism:

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furthermore assuming that signalling is non-effective if no process is waiting on it, i.e., is of classical **monitor semantics**
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again, assuming that $P_1$ called $send(P_2)$ and $P_2$ called $send(P_1)$ and that they both overlap in time and space within $send$:

3. $P_1$ and $P_2$ simultaneously signal each other message handover
   - both are unable waiting on it at the same moment, so the signal is lost
4. as a consequence, they will block on a signal that is over$^1$

---

$^1$Of course, an **outsider process** is able to free $P_1$ or $P_2$ by calling $send$. 

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   both are unable waiting on it at the same moment, so the signal is lost
4. as a consequence, they will block on a signal that is over\(^1\)
   things go right if one process waits in the wings to receive the signal
   i.e., one process already did $await$ before the other one will do $cause$

\(^1\)Of course, an outsider process is able to free $P_1$ or $P_2$ by calling $send$. 

resource management generally pursues the following objectives:
- processing of orders (Ger. Auftragsabwicklung) free of conflict
- correct order management (Ger. Auftragsbearbeitung) in finite time
- balancing and maximise utilisation of resources
- high throughput, short cycle (i.e., throughput) time, high reliability
- satisfying resource requests free from starvation or deadlock, resp.
Goals and Tasks

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To this end, the function is twofold in the following respect:

Accounting
- of all resources available within the computing system
  - type, class, and number, but also
  - access rights, process allocation, and service life

Control
- of the processing of the resource requests
- acceptance and checking (e.g., of the access rights)
- scheduling of the use of requested resources by processes
- dispatching of resources to processes

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Thereby, revocation and reallocation of resources is means to an end

- to recapture resources from processes being out of hand or
- to partially or fully virtualise the hardware (e.g., processor or memory)
Methods

- static, off-line
- dynamic, on-line

- allocation of resources takes place apart to their use
- release of all resources occurs upon (phase) exit
- supports deterministic and causes unthrifty processes utilisation and behaviour of the system is predictable which elongates response time
- risk of under-utilisation due to idle resources

- allocation of resources takes place promptly to their use
- release of each resource occurs when need expires
- supports reactive and causes non-deterministic processes utilisation and behaviour of the system is hardly predictable which shortens response time
- risk of system deadlock due to awkward resource demands
Methods

- **static, off-line**
  - at load time or at the outset of a particular run-time phase

- **dynamic, on-line**
  - at run-time, particularly at arbitrary moments
Methods

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  - *on-demand* request for each required resource at a time
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  - allocation of resources takes place apart to their use
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  risk of **under-utilisation** due to idle resources

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  risk of **system deadlock** due to awkward resource demands
Stalemate of Processes

Definition (deadly embrace)

A situation in which the **interacting processes** mutually wait on the occurrence of conditions that can be induced and established only by other processes of this very group.
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Concretely, these conditions reveal the state of **resource availability**
- independently of the kind (reusable, consumable) of resource, interacting processes expect supply by means of corresponding actions of the peers
- as all these processes wait on each other, no resource becomes available
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- according to [1], such deadly embrace of waiting processes can arise:
  i even though no single process requires more than the total resources that are available in the system and
  ii whether the allocation of resources is the responsibility of the operating system or of the application programs themselves
Stalemate of Processes

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  2. whether the allocation of resources is the responsibility of the operating system or of the application programs themselves

- waiting can happen in **inactive** (deadlock) or **active** (livelock) mode
Definition (dead-lock [5])

1. a standstill resulting from the action of equal and opposed forces; stalemate
2. a tie between opponents in the course of a contest
3. DEADBOLT—to bring or come to a deadlock
# Waiting Mode “Inactive”

## Deadlock

### Definition (dead·lock [5])

1. a standstill resulting from the action of equal and opposed forces; stalemate
2. a tie between opponents in the course of a contest
3. deadbolt—to bring or come to a deadlock

strictly speaking, **sleep state** deadly embrace of interacting processes
- the program counter of a deadlocked process remains constant, for the most part, and waiting means to be:

- **deep**
  - the process state stays “blocked”, the blocked-on event is defined
  - the process releases its processor in favour of other processes
    - except for the respective—but nevertheless “blocked”—idle process
    - the processor runs in standby mode until a process becomes “ready”
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      - except for the respective—but nevertheless “blocked”—idle process
      - the processor runs in standby mode until a process becomes “ready”
  - **benign**, the lesser of two evils (inactive or active stalemate, resp.)
    - in case it cannot be prevented or avoided, it can be detected
    - waiting conditions of stalemate processes can be identified externally
    - differentiation from non-stalemate processes is doubtlessly feasible
Definition (live-lock)

A deadlock-like situation in which the interacting processes indeed do not block (i.e., relinquish processor control), but they are also unable in making any actual progress in program execution.
Waiting Mode “Active”

Definition (livelock)

A deadlock-like situation in which the interacting processes indeed do not block (i.e., relinquish processor control), but they are also unable in making any actual progress in program execution.

denotes the deadly embrace of interacting processes in awake state

- the program counter of a livelocked process keeps changing and waiting

means to be either of:

- **busy**
  - the process state stays “running”, the process keeps its processor

- **lazy**
  - the process state alternates between “running” and “ready”
  - the process releases its processor in favour of other processes
## Waiting Mode “Active”

### Livelock

#### Definition (livelock)

A deadlock-like situation in which the interacting processes indeed do not block (i.e., relinquish processor control), but they are also unable in making any actual progress in program execution.

- denotes the deadly embrace of interacting processes in **awake state**
  - the program counter of a livelocked process keeps changing and waiting means to be either of:
    - **busy** the process state stays “running”, the process keeps its processor
    - **lazy** the process state alternates between “running” and “ready”
    - the process releases its processor in favour of other processes

- **malign**, the larger of two evils (inactive or active stalemate, resp.)
  - in case it cannot be prevented or avoided, it also cannot be detected
  - waiting conditions of stalemate process cannot be identified externally
  - differentiation from non-stalemate processes is hardly or not feasible\(^2\)

\(^2\)Checking whether or not the values of the program counters of apparently stalemate processes stay within a certain values margin—but for how long?
typedef struct account {
    semaphore_t lock;
    double balance;
} account_t;

void transfer(account_t *from, account_t *to, double amount) {
    P(& from -> lock); /* acquire source account */
    P(& to -> lock); /* acquire target account */
    from -> balance -= amount; /* withdraw money */
    to -> balance += amount; /* and deposit it */
    V(& to -> lock); /* release target account */
    V(& from -> lock); /* release source account */
}
typedef struct account {
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    V(&from->lock);  /* release source account */
}

assuming that two processes, \( P_1 \) and \( P_2 \), perform \( \text{transfer}(A, B) \) and \( \text{transfer}(B, A) \) simultaneously

- **locking sequence**: \( P_1 : P(A) \)
typedef struct account {
    semaphore_t lock;
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void
transfer(account_t *from, account_t *to, double amount) {
    P(&from->lock);  /* acquire source account */
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    V(&from->lock); /* release source account */
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assuming that two processes, \(P_1\) and \(P_2\), perform \(\text{transfer}(A, B)\) and \(\text{transfer}(B, A)\) simultaneously

- locking sequence: \(P_1 : P(A) \leadsto P_2 : P(B)\)
Problem Revisited

Crosswise Use of Reusable Resources

typedef struct account {
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transfer(account_t *from, account_t *to, double amount) {
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assuming that two processes, $P_1$ and $P_2$, perform transfer($A, B$) and transfer($B, A$) simultaneously

- **locking sequence:** $P_1 : P(A) \leadsto P_2 : P(B) \leadsto P_1 : P(B) \leadsto P_2 : P(A)$
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- **locking sequence**: \( P_1 : P(A) \leadsto P_2 : P(B) \leadsto P_1 : P(B) \leadsto P_2 : P(A) \)
- \( P_2 \) waits on \( A \) occupied by \( P_1 \) waiting on \( B \) occupied by \( P_2 \): **deadlock**
Problem Revisited

Crosswise Use of Reusable Resources

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- locking sequence: \( P_1 : P(A) \sim P_2 : P(B) \sim P_1 : P(B) \sim P_2 : P(A) \)
- \( P_2 \) waits on \( A \) occupied by \( P_1 \) waiting on \( B \) occupied by \( P_2 \): deadlock
- both processes hold and wait for a non-preemptable reusable resource
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    V(&to->lock); /* release target account */
    V(&from->lock); /* release source account */
}

assuming that two processes, \( P_1 \) and \( P_2 \), perform \( \text{transfer}(A, B) \) and \( \text{transfer}(B, A) \) simultaneously

- \textbf{locking sequence}: \( P_1 : P(A) \leadsto P_2 : P(B) \leadsto P_1 : P(B) \leadsto P_2 : P(A) \)
- \( P_2 \) waits on \( A \) occupied by \( P_1 \) waiting on \( B \) occupied by \( P_2 \): \textbf{deadlock}
- both processes \textbf{hold and wait} for a non-preemptable reusable resource
Approach to the Problem

Indivisible Overall Function

```c
transfer(account_t *from, account_t *to, double amount) {
    static semaphore_t bolt = {1};

    P(&bolt);        /* block transfer operation */
    from->balance -= amount;   /* withdraw money */
    to->balance += amount;     /* and deposit it */
    V(&bolt);            /* clear transfer operation */
}
```

restricts parallelism unnecessarily and is flawed by a race condition assuming that, in the background, the source account (from) is subject to a simultaneous process of withdrawal a negative balance may be the result, with the following consequence:

i either the transfer operation fails due to overdraft or, as supposed here,
ii interest paid on overdraft (Ger. Überschuldungszinsen) is incurred

synchronisation must be all-embracing: per transfer and account

The bank feels happy about this, but not the account holder.
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3The bank feels happy about this, but not the account holder.
Solution 1

Indivisible Allocation and Overall Function

```c
transfer(account_t *from, account_t *to, double amount) {
    static semaphore_t bolt = {1};

    P(&bolt);       /* block transfer operation */
    P(&from->lock); /* acquire source account */
    P(&to->lock);   /* acquire target account */
    V(&bolt);       /* clear transfer operation */

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    V(&from->lock); /* release source account */
}

classic textbook solution: a measure of **deadlock prevention**

- allocation of source and target account now happens indivisibly
- transfers using the same resource pair, thus, are mutually exclusive
- but the target account **lies waste** for operations not destined for it
  - here: already blocked from line 6, although used not until line 10
Solution II

Indivisible Sub-Function

```c
transfer(account_t *from, account_t *to, double amount) {
    P(&from->lock);    /* acquire source account */
    from->balance -= amount;    /* withdraw money */
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- a doable solution, however risk is not to see the wood for the trees
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A doable solution, however risk is not to see the wood for the trees
- in terms of **deadlock prevention**, one is on the right track—*but*
- as to software structure, one failed to apply Occam’s razor\(^4\)
  - hypothesis that the level of abstraction of the solution is adequate
  - hypothesis that the program is readable and easily adaptable
  - hypothesis that the implementation is efficient

\(^4\)A problem-solving principle, meaning that among competing hypotheses the one with the fewest assumptions should be selected.
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particularly non-sequential programs must be of a “good” structure

---

4 A problem-solving principle, meaning that among competing hypotheses the one with the fewest assumptions should be selected.
transferto account_t *from, account_t *to, double amount) {
    change(from, -amount); /* withdraw money */
    change(to, amount); /* and deposit it */
}

mutual exclusion using instruction set architecture level functions:

#define FAA __sync_fetch_and_add
transfer(account_t *from, account_t *to, double amount) {
    change(from, -amount);     /* withdraw money */
    change(to, amount);        /* and deposit it */
}

mutual exclusion using operating system machine level functions:
- take a sledgehammer to crack the nut...

inline void change(account_t *this, double amount) {
    P(& this->lock);           /* acquire account */
    this->balance += amount;   /* do operation */
    V(& this->lock);           /* release account */
}
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}

mutual exclusion using instruction set architecture level functions:

    inline void change(account_t *this, double amount) {
    FAA(&this->balance, amount);  /* do operation */
}

#define FAA __sync_fetch_and_add
monitor Account {
    double balance;

public:
    inline void change(double amount) {
        balance += amount; /* do operation */
    }
};

void transfer(Account & from, account & to, double amount) {
    from.change(-amount); /* withdraw money */
    to.change(amount); /* and deposit it */
}

leave it up to the compiler to do the $P/V$-pair 😞 or the FAA 😊
monitor Account {
    double balance;

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    inline void change(double amount) {
        balance += amount; // do operation */
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void transfer(Account& from, account& to, double amount) {
    from.change(-amount); // withdraw money */
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}

leave it up to the compiler to do the $P/V$-pair (⊔) or the FAA (⊓)

- monitor procedure change contains neither wait nor signal, thus monitor exit may degenerate to $V(mutex)$ even for Hoare-style [4, p. 551, 1.]
- as change, by default, is defined to be indivisible, additional semantics is available to apply the FAA to the otherwise trivial computation
Once the critical section has been identified, to **factor out** is maxim. Although corresponding measures sometimes appear to be superfluous, they increase awareness for the options of improvement. This insight not only holds for the initial design or redevelopment, respectively, but also legacy software.
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- a constructive approach has been exercised, which finally opened a path for cross-layer optimisation
  - analytical approaches, if applicable, are without doubt important but they are nevertheless second quality in cases similar to those as were shown
  - here, the problem could be put down to a plain type of critical operation
Conditions to Deadlock

acc. [1, p. 70]

Hint (Livelock)

All of the following applies also to stillstand in active waiting mode.
necessary conditions that the interacting processes are subject to:
1. demand control of the resources required by means of **mutual exclusion**
2. **hold** a shared resource **and wait** for another one required to proceed
3. resources held cannot be forcibly removed, are **ineligible for preemption**

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**Hint (Prevention/Avoidance)**

*All of these four conditions must be operative at the same point in time in order to deadlock. Invalidation of only one of these conditions makes the respective process system free of deadlock.*
Hint (Primary Prevention)

Protect interacting processes from developing a standstill.
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- **indirect methods** that invalidate a necessary condition, only
Deadlock Prevention

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2. acquire all resources at one blow indivisibly (p. 20) or restructure (p. 21)
deadlock prevention

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- **direct method** that invalidates the necessary and sufficient condition
  4. define a linear and total ordering of resource classes such that resource $R_i$ can be acquired previous to resource $R_j$ only if $i < j$
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Hint (Prophylaxis)

As a matter of principle, any rule that “prevents” the occurrence of a deadlock is a constructive measure that has to take effect at design and implementation time.
Hint (a priori Knowledge)

**Preliminary information** as to processes and their resource demands.
Hint (a priori Knowledge)

**Preliminary information** as to processes and their resource demands.

- Circumvention of deadly embrace by means of **strategical methods**
- No attempt is made to invalidate any of the necessary conditions
- But circular wait gets precluded by a **continuous demands analysis**
Hint (*a priori* Knowledge)

**Preliminary information** as to processes and their resource demands.

- circumvention of deadly embrace by means of *strategical methods*
  - no attempt is made to invalidate any of the necessary conditions
  - but circular wait gets precluded by a *continuous demands analysis*
- basic approach is to control processes and all their resource requests
  - all processes are subject to continuous checking for an *unsafe state*
  - in case of unsecured resource demand, a *denial of allocation* takes place
  - effect is to either suspend or refuse serving of requesting processes
Deadlock Avoidance

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- Resource allocation succeeds only with certainty of a safe state, i.e.:
  - If there exists a process sequence that satisfies all future resource requests
  - By respecting all present allocations and pending releases (cf. p. 36)
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Hint (Avoidance)

In principle, any rule that “avoids” the occurrence of a deadlock is an analytical measure that has to take effect at run time.
Determination of the Unsafe State

One approach is using a resource allocation graph (RAG, cf. p.30) which defines a quantity contract for process instances regarding demand and current allocation of resources belonging to particular resource classes created at process incarnation time by relying on preliminary information and updated with current data at each resource request. An ongoing analysis as to the development of potential cycles in the graph is necessary.

Another approach is by application of the banker’s algorithm [2] provided that the system knows the quantity of each resource:

1. Each process instance could possibly request (maximum claim: credit)
2. Each process instance is currently holding (allocated: debit)
3. Is currently unallocated for all these process instances (available: balance)

If the request does not exceed:

(a) the maximum claim of the requesting process
(b) the currently available stock of resources of the requested class

Then a safe state (cf. p.36) is given. If (a) fails, the request is rejected. If (b) fails, the process gets suspended.

Not only the need for a priori data is a big problem, but also scalability.
Determination of the Unsafe State

- one approach is using a **resource allocation graph** (RAG, cf. p.30)
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Deadlock Detection and Breakup

Diagnosis and Recovery

Deadlocks are under the tacit (Ger. stillschweigend) assumption no attempt is made to invalidate any of the necessary conditions but circular wait is detected by a sporadic search for blocked processes. A wait-for graph (cf. p. 31) is created and searched for closed loops for that purpose, data derived from a RAG (cf. p. 31) is taken as a basis. Detected closed loops are to be broken open in a downstream step. One option is process termination, either by selecting a single instance or by taking the whole lot on the closed loop. Another option is resource revocation, by selecting the apparently most effective victim followed by a rollback of the owning process instance as the case may be, the sequence repeats until closed loops vanished.

Tightrope Walk between Damage and Cost
What breaks in a moment may take years to mend.
A Swedish proverb.
deadlocks are under the **tacit** (Ger. *stillschweigend*) **assumption**
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Resource Allocation Graph

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Resource Allocation Graph (abbr. RAG)

- A directed graph that interrelates process instances and resources or resource classes, resp.: serves also as basis for a wait-for graph (p. 31)
- Optional (static) preliminary information as to the requires relation
  - Resource classes and number of requires resources each

```
<table>
<thead>
<tr>
<th>Process Instance (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>* requires</td>
</tr>
<tr>
<td>Resource Class</td>
</tr>
<tr>
<td>1 resource</td>
</tr>
<tr>
<td>5 resources</td>
</tr>
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Mandatory ongoing information to derive a wait-for graph from a RAG.
a **directed graph** that interrelates process instances and resources or resource classes, resp.: serves also as basis for a *wait-for graph* (p. 31)

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<tr>
<td>process instance</td>
<td>*</td>
</tr>
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</tr>
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</table>

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- mandatory ongoing information as to all process/resource relations
  - each process instance includes a resource allocation list (*requires*)
Resource Allocation Graph

- A **directed graph** that interrelates process instances and resources or resource classes, resp.: serves also as basis for a *wait-for graph* (p. 31)
- Optional (static) preliminary information as to the *requires* relation
  - Resource classes and number of requires resources each

```
resource class
1 resource
allocated to

process instance
P

* requires

resource class
5 resources
```

- Mandatory ongoing information as to all process/resource relations
  - Each process instance includes a resource allocation list (*requires*)
  - Each resource records its owning process instance (*allocated to*)
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<tr>
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<th>Process Instance includes a resource allocation list (<em>requires</em>)</th>
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<tr>
<td><em>Requires</em></td>
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<td>Process Instance</td>
<td>Each resource records its owning process instance (<em>allocated to</em>)</td>
</tr>
<tr>
<td><em>Blocked on</em></td>
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\(^6\) Mandatory ongoing information to derive a wait-for graph from a RAG.
Resource Allocation Graph (abbr. RAG)

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  - Each process instance includes a resource allocation list (requires)
  - Each resource records its owning process instance (allocated to)
- Likewise, when a process expects (re-) allocation of a resource:
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- A dynamic data structure to be maintained by the operating system

---

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a closed loop from $P_1$ to $P_2$ via $A$ and $B$, back and forth: deadlock
Wait-for Graph

Hint

Created in situations were the operating system may assume a deadlock case:
- response time increase
- throughput decrease
- idle time overexpansion

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Outline

Preface

Resource Management
  Classification
  Illustrative Example I
  General

Deadlocks
  Fundamentals
  Illustrative Example II
  Counteractive Measures

Summary
Résumé

- state of **stalemate** of interacting processes because of misguided or misconstructed resource allocation
  - crosswise request or signalling of a reusable or consumable resource, resp.
  - lost release of a produced or beforehand acquired resource
- a deadly embrace in terms of a **deadlock** (waiting mode “inactive”) rather than livelock (waiting mode “active”)
  - in the face of all logic, the former is benign and the lesser of the two evils
  - in case it cannot be prevented or avoided, it can be detected though
  - differentiation from non-stalemate processes is doubtlessly feasible
- prevention, avoidance, or detection and breakup of process deadlocks as the classic **counteractive measures**

**Hint (Relevancy to Practice)**

*Memes for avoidance or detection of deadlocks are rather irrelevant as to practice. They are hardly realisable, too expensive, and, thus, not applicable. Besides, still dominance of sequential programming makes counteractive measures little necessary ~ ignorance.*
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Reference List I


[6] **SCHRÖDER-PREIKSCHAT, W.** :
Concurrency.
In: **LEHRSTUHL INFORMATIK 4** (Hrsg.): *Concurrent Systems.*
FAU Erlangen-Nürnberg, 2014 (Lecture Slides), Kapitel 2
Safe State

- let $P_k$ be a sequential process
- let $S$ be an ordered set of those processes
- let $b_k$ be the resource claim of a process, $P_k$
- let $s(k)$ represent the ordinal number of $P_k \in S$
- let $r(t)$ describe the number of resources available at time $t$
- let $c_k(t)$ denote the number of resources allocated to $P_k$ at time $t$
- then, a state is safe if there is a full sequence $S$ such that:

$$\forall P_k \in S \; b_k \leq r(t) + \sum_{s(l) \leq s(k)} c_l(t)$$

(1)

Condition (1) says that the claim by process $P_k$ must not exceed the sum of the free resources and those resources which will become free “in due time,” when the processes preceding in $S$ have released theirs. [3, p. 375]