Concurrent Systems

Nebenläufige Systeme

IX. Deadly Embrace

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Preface

Resource Management
  Classification
  Illustrative Example I
  General

Deadlocks
  Fundamentals
  Illustrative Example II
  Counteractive Measures

Summary
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  Illustrative Example I
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  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
Subject Matter

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

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

**deadly embrace** (*Ger. tödliche Umarmung, gegenseitiges Sperren*) of interacting processes by reason of programming errors

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
Subject Matter

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

- **deadly embrace** (Ger. *tödliche Umarmung, gegenseitiges Sperren*) of interacting processes by reason of programming errors

- exemplification of the **classic** [1] by means of sample programs

- 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

 source: National Geographic
Outline

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Summary
for whatever reason, use of operations on any type of resources can cause process or even system deadlocks
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- **reusable**
  - crosswise request by different simultaneous processes
  - lost release of a beforehand acquired resource
for whatever reason, use of operations on any type of resources can cause process or even system deadlocks

- **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

abstracting away from hardware, deadlocks are due to software faults

- only simultaneous processes may disclose these faults as error or failure
```c
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
Conflict Situation I

Inter-Process Communication (IPC)

```c
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
- **susceptible to deadlock** in case of preemptive or SMP scheduling, resp.
Conflict Situation II

/* a deadlock-prone basic block */ {
    /* ... */
    P(&self->lock); /* protect oneself: me */
    P(&peer->lock); /* protect counterpart */
    /* ... */
    V(&peer->lock); /* unprotect counterpart */
    V(&self->lock); /* unprotect oneself */
    /* ... */
}

assuming that a process \( P_1 \) does \texttt{adpbb}(P_2) and another process \( P_2 \) does \texttt{adpbb}(P_1), simultaneously let \( A \mapsto self \) be the process descriptor of some process \( P_1 \) and let \( B \mapsto peer \) be the one of another process \( P_2 \), \( P_1 \neq P_2 \): 

\( P_1 \): \texttt{L3} succeeded in completing \( P(A) \), locked \( A \) and gets preempted

\( P_2 \): \texttt{L3} succeeds in completing \( P(B) \), locked \( B \) and continues

\( P_2 \): \texttt{L4} gets blocked in \( P(A) \), relinquishes control

\( P_2 \): \texttt{L4} resumes and gets blocked in \( P(B) \), relinquishes control

\( P_1 \) and \( P_2 \) are subject to deadlock because of crosswise requests...
Conflict Situation II

```c
/* a deadlock-prone basic block */ {
    /* ... */
P(&self -> lock);  /* protect oneself: me */
P(&peer -> lock);   /* protect counterpart */
    /* ... */
V(&peer -> lock);   /* unprotect counterpart */
V(&self -> lock);   /* unprotect oneself */
    /* ... */
}
```

assuming that a process $P_1$ does $adpbb(P_2)$ and another process $P_2$ does $adpbb(P_1)$, **simultaneously**
Conflict Situation II

Cooked Down

/* a deadlock-prone basic block */ {
    /* ... */
    P(&self->lock);    /* protect oneself: me */
    P(&peer->lock);    /* protect counterpart */
    /* ... */
    V(&peer->lock);    /* unprotect counterpart */
    V(&self->lock);    /* unprotect oneself */
    /* ... */
}

let $A \mapsto \text{self}$ be the process descriptor of some process $P_1$ and let $B \mapsto \text{peer}$ be the one of another process $P_2$, $P_1 \neq P_2$:

$P_1$: L3  ■ succeeded in completing $P(A)$, locked $A$ and gets preempted
$P_2$: L3  ■ succeeds in completing $P(B)$, locked $B$ and continues
$P_2$: L4  ■ gets blocked in $P(A)$, relinquishes control
$P_1$: L4  ■ resumes and gets blocked in $P(B)$, relinquishes control
/* a deadlock-prone basic block */ {
    /* ... */
    P(&self->lock);    /* protect oneself: me */
    P(&peer->lock);    /* protect counterpart */
    /* ... */
    V(&peer->lock);    /* unprotect counterpart */
    V(&self->lock);    /* unprotect oneself */
    /* ... */
}

Let A ↦ self be the process descriptor of some process P₁ and let
B ↦ peer be the one of another process P₂, P₁ ≠ P₂:
P₁: L₃  ■ succeeded in completing P(A), locked A and gets preempted
P₂: L₃  ■ succeeds in completing P(B), locked B and continues
P₂: L₄  ■ gets blocked in P(A), relinquishes control
P₁: L₄  ■ resumes and gets blocked in P(B), relinquishes control

P₁ and P₂ are subject to deadlock because of crosswise requests...
assuming that progress of $P_1$ and $P_2$ is irreversible
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assuming that progress of $P_1$ and $P_2$ is irreversible
deadlock is inevitable

assuming that progress
of $P_1$ and $P_2$ is irreversible
Progress Space

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resource lifetime

A B

P(B) P(A)

P(B) of P and P is irreversible assuming that progress

A B

resource lifetime

P1

P2

deadlock is inevitable

assuming that progress of P1 and P2 is irreversible
deadlock has happened

deadlock is inevitable

assuming that progress
of P₁ and P₂ is irreversible
assuming that the general semaphore used to signal availability of a consumable resource is replaced by an \textbf{event variable} mechanism:

```c
/* another deadlock-prone basic block */ {
    /* ... */
    cause(&peer->event);       /* signal handover */
    await(&self->event);      /* block on receive */
    /* ... */
}
```

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

L3 $P_1$ and $P_2$ simultaneously signal each other message handover both cannot wait for it at the same time, so the signal is lost

L4 as a consequence, they will block on a signal that is over

things go right if one process waits in the wings to receive the signal i.e., one process already did \texttt{await} before the other one will do \texttt{cause}

Of course, an outsider process is able to free $P_1$ or $P_2$ by calling \texttt{adpbb}.
assuming that the general semaphore used to signal availability of a consumable resource is replaced by an **event variable** mechanism:

```c
/* another deadlock-prone basic block */ {
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assuming that the general semaphore used to signal availability of a consumable resource is replaced by an event variable mechanism:

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/* another deadlock-prone basic block */ {
    /* ... */
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```

again, assuming that $P_1$ called $adpbb(P_2)$ and $P_2$ called $adpbb(P_1)$ and that they both overlap in time and space within $adpbb$:

L3  $P_1$ and $P_2$ simultaneously signal each other message handover
    both cannot wait for it at the same time, so the signal is lost
L4  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 $adpbb$. 

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assuming that the general semaphore used to signal availability of a consumable resource is replaced by an event variable mechanism:

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- $P_1$ and $P_2$ simultaneously signal each other message handover
- both cannot wait for it at the same time, so the signal is lost
- as a consequence, they will block on a signal that is over

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`
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

In a Nutshell

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- 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. 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

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)
Goals and Tasks

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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
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

- **static, off-line**
  - at load time or at the outset of a particular run-time phase
  - *anticipatory* request for all resources required

- **dynamic, on-line**
  - at run-time, particularly at arbitrary moments
  - *on-demand* request for each required resource at a time
Methods

- **static, off-line**
  - at load time or at the outset of a particular run-time phase
  - *anticipatory* request for all resources required
  - allocation of resources takes place apart to their use

- **dynamic, on-line**
  - at run-time, particularly at arbitrary moments
  - *on-demand* request for each required resource at a time
  - allocation of resources takes place promptly to their use
Methods

- **static, off-line**
  - at load time or at the outset of a particular run-time phase
  - *anticipatory* request for all resources required
  - allocation of resources takes place apart to their use
  - release of all resources occurs upon (phase) exit

- **dynamic, on-line**
  - at run-time, particularly at arbitrary moments
  - *on-demand* request for each required resource at a time
  - allocation of resources takes place promptly to their use
  - release of each resource occurs when need expires
Methods

- **static, off-line**
  - supports **deterministic** and causes unthrifty processes
    - utilisation and behaviour of the system is **predictable**
    - elongates response time

- **dynamic, on-line**
  - supports **reactive** and causes non-deterministic processes
    - utilisation and behaviour of the system is **hardly predictable**
    - shortens response time
Methods

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

- risk of under-utilisation due to idle resources
- risk of system deadlock due to awkward resource demands

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Summary
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.
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.

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
### 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.

- concretely, these conditions reveal the state of **resource availability**

- according to [1], such deadly embrace of waiting processes can arise:
  1. even though no single process requires more than the total resources that are available in the system and
  2. whether the allocation of resources is the responsibility of the operating system or of the application programs themselves
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.

- concretely, these conditions reveal the state of resource availability

waiting can happen in inactive (deadlock) or active (livelock) mode
# Waiting Mode “Inactive”

**Definition (dead-lock [5])**

1. a standstill resulting from the action of equal and opposed forces; standoff

2. a tie between opponents in the course of a contest

3. **DEADBOLT**—to bring or come to a 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
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
    - except for the respective—but nevertheless “blocked”—idle process
    - the processor runs in standby mode until a process becomes “ready”
Waiting Mode “Inactive”

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
- 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 (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.
Waiting Mode “Active”

Livelock

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.

denotes the deadly embrace of interacting processes in awake state
- the program counter of a livelocked process keeps changing
### 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

---

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Livelock

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.

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:

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

Livelock

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.

denotes the deadly embrace of interacting processes in awake state

- the program counter of a livelocked process keeps changing

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 {
    semaphore_t lock;
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void
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    to->balance += amount; /* and deposit it */
    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

locking sequence: $P_1 : P(A)$
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 */
}

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

- **locking sequence**: $P_1 : P(A) \leadsto P_2 : P(B)$
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 */
}

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

- locking sequence: $P_1 : P(A) \rightsquigarrow P_2 : P(B) \rightsquigarrow P_1 : P(B)$
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 */
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    from->balance -= amount; /* withdraw money */
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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: $P_1 : P(A) \rightsquigarrow P_2 : P(B) \rightsquigarrow P_1 : P(B) \rightsquigarrow P_2 : P(A)$
Problem Revisited

Crosswise Use of Reusable Resources

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 */
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    from->balance -= amount;   /* withdraw money */
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    V(&from->lock);    /* release source account */
}

assuming that two processes, $P_1$ and $P_2$, perform $transfer(A, B)$ and $transfer(B, A)$ simultaneously

- locking sequence: $P_1 : P(A) \rightsquigarrow P_2 : P(B) \rightsquigarrow P_1 : P(B) \rightsquigarrow P_2 : P(A)$
- $P_2$ waits on $A$ occupied by $P_1$ waiting on $B$ occupied by $P_2$: deadlock
typedef struct account {
    semaphore_t lock;
    double balance;
} account_t;

void
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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: $P_1 : P(A) \leadsto P_2 : P(B) \leadsto P_1 : P(B) \leadsto P_2 : P(A)$
- $P_2$ waits on $A$ occupied by $P_1$ waiting on $B$ occupied by $P_2$: deadlock
- both processes hold and wait for a non-preemptable reusable resource
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 */
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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

- **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
- both processes **hold and wait** for a non-preemptable reusable resource

**Race Condition**
Due to divisible operation of \( \text{transfer} \). The code shows a critical section. A **design change** is appropriate.
Approach to the Problem

Indivisible Overall Function

```
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 */
}
```
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

- all transfers are locked out, particularly also those transfers that apply to unrelated pairs of accounts (i.e., reusable resources)
Approach to the Problem

```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:
  - either the transfer operation fails due to overdraft or, as supposed here,
  - interest paid on overdraft (Ger. Überziehungszinsen) is incurred\(^3\)

\(^3\)The bank feels happy about this, but not the account holder.
Approach to the Problem

Indivisible Overall Function

```
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

synchronisation must be all-embracing: per transfer and account
Solution I  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 */

    from->balance -= amount; /* withdraw money */
    to->balance += amount; /* and deposit it */

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

    from->balance -= amount; /* withdraw money */
    to->balance += amount; /* and deposit it */

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

- a doable solution, however risk is not to see the forest for the trees
  - in terms of **deadlock prevention**, one is on the right track

---

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Solution II

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

A doable solution, however risk is not to see the forest 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.
transfer(account_t *from, account_t *to, double amount) {
    P(&from->lock);  /* acquire source account */
    from->balance -= amount;  /* withdraw money */
    V(&from->lock);  /* release source account */
    P(&to->lock);  /* acquire target account */
    to->balance += amount;  /* deposit money */
    V(&to->lock);  /* release target account */
}

a doable solution, however risk is not to see the forest for the trees

particularly non-sequential programs must be of a “good” structure
Solution III

Procedural Abstraction

```c
1 transfer(account_t *from, account_t *to, double amount) {
   2 change(from, -amount);    /* withdraw money */
   3 change(to, amount);       /* and deposit it */
}
```

mutual exclusion using operating system machine level functions:

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

mutual exclusion using instruction set architecture level functions:

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

#define FAA __sync_fetch_and_add
Solution III

Procedural Abstraction

```c
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...

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

```c
#define FAA __sync_fetch_and_add
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Solution III

Procedural Abstraction

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transfer(account_t *from, account_t *to, double amount) {
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mutual exclusion using operating system machine level functions:
- take a sledgehammer to crack the nut...

```c
inline void change(account_t *this, double amount) {
    P(&this->lock); /* acquire account */
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}
```

mutual exclusion using instruction set architecture level functions:

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

#define FAA __sync_fetch_and_add

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```cpp
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;
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 procedure \textit{change} contains neither \textit{wait} nor \textit{signal}, thus monitor \textit{exit} may degenerate to \( V(\textit{mutex}) \) even for Hoare-style [4, p.551, 1.]
- as \textit{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.
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.

In the example shown, the conflict could be eliminated by replacing a sequence of actions by an atomic instruction:

- neither blocking nor non-blocking synchronisation is used in the end
- but reducing the problem such that downscaling the solution was feasible
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.

- in the example shown, the conflict could be eliminated by replacing a sequence of actions by an atomic instruction

- a **constructive approach** has been exercised, which finally opened a path for cross-layer optimisation
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.

- in the example shown, the conflict could be eliminated by replacing a sequence of actions by an atomic instruction

- 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.
Conditions to Deadlock

**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**
Conditions to Deadlock

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- **necessary and sufficient condition** that eventually must be true:
  4. a situation of a **circular wait** has been occurred
     - each process holds one or more resources that are being requested by the next process in the chain
Conditions to Deadlock

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  4. a situation of a **circular wait** has been occurred
     - each process holds one or more resources that are being requested by the next process in the chain

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.
Deadlock Prevention

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Protect interacting processes from developing a standstill.

- **indirect methods** that invalidate a necessary condition, only
Deadlock Prevention

Hint (Primary Prevention)

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- **indirect methods** that invalidate a necessary condition, only

  1. consider either non-blocking synchronisation or downscaling (p. 22)
**Hint (Primary Prevention)**

*Protect interacting processes from developing a standstill.*

- **indirect methods** that invalidate a necessary condition, only
  1. consider either non-blocking synchronisation or downscaling (p. 22)
  2. acquire all resources at one blow indivisibly (p. 20) or restructure (p. 21)
Hint (Primary Prevention)

*Protect interacting processes from developing a standstill.*

- **indirect methods** that invalidate a necessary condition, only
  1. consider either non-blocking synchronisation or downscaling (p. 22)
  2. acquire all resources at one blow indivisibly (p. 20) or restructure (p. 21)
  3. virtualise selectively so that preemption of real resources becomes eligible, but their virtual analogues still remain ineligible for preemption
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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 $i < j$
Deadlock Prevention

Hint (Primary Prevention)

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  1. consider either non-blocking synchronisation or downscaling (p. 22)
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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 $i < j$

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 (\textit{a priori} Knowledge)

\textbf{Preliminary information as to processes and their resource demands.}
Deadlock Avoidance

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*

- 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
Hint (*a priori* Knowledge)

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

- circumvention of deadly embrace by means of *strategical methods*
- basic approach is to control processes and all their resource requests
- 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)
Deadlock Avoidance

Hint (a priori Knowledge)

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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)

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) 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 ongoing analysis as to the development of potential cycles in the graph.

Another approach is by application of the banker's algorithm [2] provided that the system knows the quantity of each resource: i) each process instance could possibly request (maximum claim: credit), ii) each process instance is currently holding (allocated: debit), and iii) is currently unallocated for all these process instances (available: balance) then a safe state (cf. p.36) is given if the request does not exceed: (a) the maximum claim of the requesting process and (b) the currently available stock of resources of the requested class 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...
one approach is using a resource allocation graph (RAG, cf. p.30)
- 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
- ongoing analysis as to the development of potential cycles in the graph
Determination of the Unsafe State

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If (a) fails the request is rejected, if (b) fails the process gets suspended.
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    - i. each process instance could possibly request (**maximum claim**: credit),
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Determination of the Unsafe State

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then a safe state (cf. p. 36) is given if the request does not exceed:
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Determination of the Unsafe State

- one approach is using a resource allocation graph (RAG, cf. p.30)

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- not only the need for \textit{a priori} data is a big problem, but also scalability
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.30) 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. – Swedish proverb.
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
deadlocks are under the **tacit** (Ger. *stillschweigend*) assumption

- a **wait-for graph** (cf. p. 31) is created and searched for closed loops
- for that purpose, data derived from a RAG (cf. p. 30) is taken as a basis
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- one option is process termination, either by selecting a single instance or by taking the whole lot on the closed loop
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deadlocks are under the **tacit** (Ger. *stillschweigend*) **assumption**

- detected closed loops are to be broken open in a **downstream step**

- 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.\(^a\)

\(^a\)Swedish proverb.
a **directed graph** that interrelates process instances and resources or resource classes, resp.
a **directed graph** that interrelates process instances and resources or resource classes, resp.: serves also as basis for a **wait-for graph** (p. 31)
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 required resources each

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)

Likewise, when a process expects (re-) allocation of a resource

- each process instance records to which resource it is blocked on

A dynamic data structure to be maintained by the operating system

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)

optional (static) preliminary information as to the requires relation
- resource classes and number of required resources each
- process instance includes a resource allocation list (requires)

mandatory ongoing information as to all process/resource relations
- each process instance records to which resource it is blocked on
- dynamic data structure to be maintained by the operating system
Resource Allocation Graph

- **Abbreviation**: RAG

- **Definition**: A directed graph that interrelates process instances and resources or resource classes, respectively. It serves as a basis for a wait-for graph (p. 31).

- **Optional Information**: Preliminary information regarding the requires relation:
  - Resource classes and number of required resources for each process instance.

- **Mandatory Information**: Ongoing information for all process/resource relations:
  - Each process instance includes a resource allocation list (requires).
  - Each resource records its owning process instance (allocated to).

![Diagram of Resource Allocation Graph]

- A process instance (P) is blocked on a resource class.
- Resource allocation and requires relations are illustrated.

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Deadlocks – Counteractive Measures  
30
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 required resources each

- 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*)
- likewise, when a process expects (re-) allocation of a resource
  - each process instance records to which resource it is *blocked on*

---

6 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)

A **dynamic data structure** to be maintained by the operating system
let $A$ and $B$ be resources of the same resource class (cf. p. 8 and 18):
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1. $P_1$ performs $P(A)$, $A$ is unoccupied and gets allocated to $P_1$
let $A$ and $B$ be resources of the same resource class (cf. p. 8 and 18):
1. $P_1$ performs $P(A)$, $A$ is unoccupied and gets allocated to $P_1$
2. $P_2$ performs $P(B)$, $B$ is unoccupied and gets allocated to $P_2$
let $A$ and $B$ be resources of the same resource class (cf. p. 8 and 18):

1. $P_1$ performs $P(A)$, $A$ is unoccupied and gets allocated to $P_1$
2. $P_2$ performs $P(B)$, $B$ is unoccupied and gets allocated to $P_2$
3. $P_1$ performs $P(B)$, $B$ is occupied $\rightarrow P_1$ has to wait for $V(B)$ by $P_2$
let $A$ and $B$ be resources of the same resource class (cf. p. 8 and 18):

1. $P_1$ performs $P(A)$, $A$ is unoccupied and gets allocated to $P_1$
2. $P_2$ performs $P(B)$, $B$ is unoccupied and gets allocated to $P_2$
3. $P_1$ performs $P(B)$, $B$ is occupied $\Rightarrow P_1$ has to wait for $V(B)$ by $P_2$
4. $P_2$ performs $P(A)$, $A$ is occupied $\Rightarrow P_2$ has to wait for $V(A)$ by $P_1$
Let $A$ and $B$ be resources of the same resource class (cf. p. 8 and 18):

- 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
Outline

Preface

Resource Management
  Classification
  Illustrative Example I
  General

Deadlocks
  Fundamentals
  Illustrative Example II
  Counteractive Measures

Summary
Résumé

État de stase ou stase de processus d'interaction à cause de mauvaise attribution ou construction de ressources, ou demande ou signalisation de ressources réutilisables ou consommables, respectivement. Pertes de libération de ressources produites ou acquises précédemment.

Un étreintage mortel en termes de morts-vives (mode d'attente "inactive") plutôt que de livelocks (mode d'attente "active") en face de toute logique, le premier est bénéfique et la moindre des deux maladies. Si elle ne peut être prévenue ou évitée, elle peut être détectée bien que la différenciation de ressources non-stalemate soit douteuse.

La prévention, éviction ou détection et le désagrégement de morts-vives de processus sont les mesures classiques contre-attaquantes.

Indication (rélevé à la pratique)

Mesures pour éviter ou détecter les morts-vives sont généralement irrélevantes en termes de pratique. Elles ne sont pas réalisables, trop coûteuses, et donc inapplicables. De plus, l'hégémonie de la programmation séquentielle rend les contre-attaques peu nécessaires; l'ignorance.

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Résumé

- state of **stalemate** of interacting processes because of misguided or misconstrued resource allocation
  - crosswise request or signalling of a reusable or consumable resource, resp.
  - lost release of a produced or beforehand acquired resource
Résumé

- state of **stalemate** of interacting processes because of misguided or misconstrued resource allocation

- 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
Résumé

- state of **stalemate** of interacting processes because of misguided or misconstructed resource allocation

- a deadly embrace in terms of a **deadlock** (waiting mode “inactive”) rather than livelock (waiting mode “active”)

- prevention, avoidance, or detection and breakup of process deadlocks as the classic **counteractive measures**
Résumé

- state of **stalemate** of interacting processes because of misguided or misconstructed resource allocation

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**Hint (Relevancy to Practice)**

*Measures 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.*


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:

\[
\forall P_k \in S \; b_k \leq r(t) + \sum_{s(l) \leq s(k)} c_l(t) \tag{1}
\]

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]