Concurrent Systems

Nebenläufige Systeme

IX. Deadly Embrace

Wolfgang Schröder-Preikschat

December 20, 2016

Agenda

Outline

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

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  - focal point is to foreground constructive and eclipse analytical measures

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- exemplification of the **classic** [1] by means of sample programs
  - realising that use cases of functions can uncover critical interdependencies
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  - race conditions that are disclosed only with having the big picture in mind

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  - 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

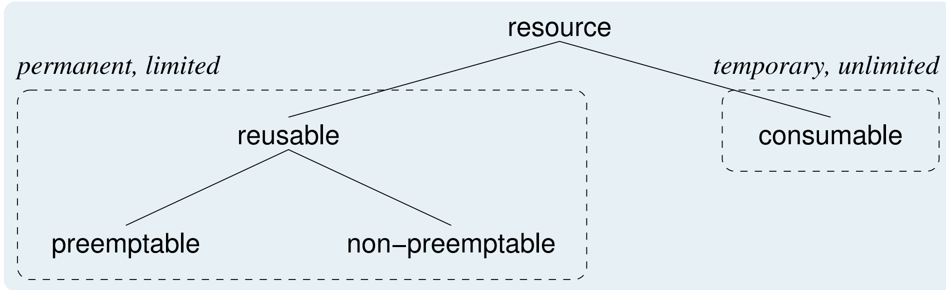
(Ger.) *Verklemmung*, *Blockierung*, *Stillstand*

source: National Geographic

Outline

Resources Revisited

cf. [6, p. 13–14]



- 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
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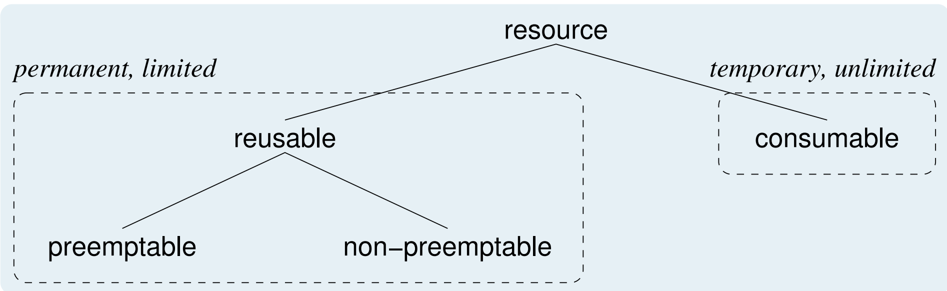

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    - **crosswise signalling** by interacting processes followed by *await*, whereby the signal is not buffered
    - **lost release** of a produced resource
- abstracting away from hardware, deadlocks are due to software faults
  - only simultaneous processes may disclose these faults as error or failure

Conflict Situation I

Inter-Process Communication (IPC)

```
int send(pid_t pid, char *data, long size) {
    process_t *self = being(ONESELF), *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

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- fictive semaphore-based implementation of a message send operation
  - **susceptible to deadlock** in case of preemptive or SMP scheduling, resp.

Conflict Situation II


```
int send(pid_t pid, char *data, long size) {
    /* ... */
    P(&self->lock);      /* protect oneself: me */
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- assuming that a process P_1 does *send*(P_2) and another process P_2 does *send*(P_1), **simultaneously**

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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

Conflict Situation II

Cooked Down

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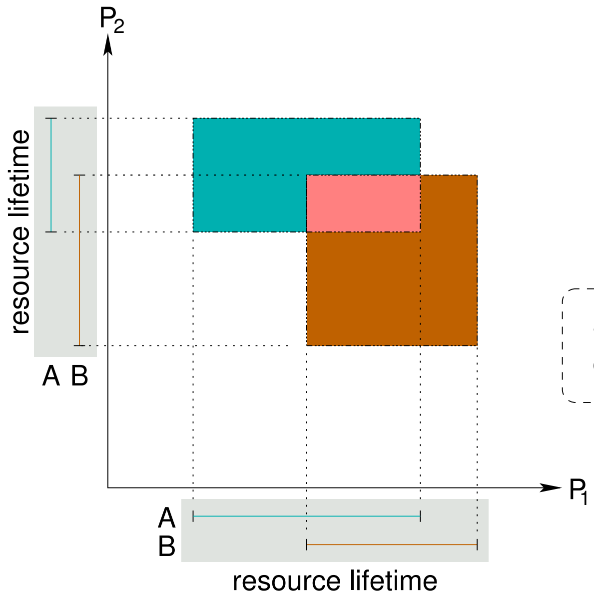
- P_1 and P_2 are subject to **deadlock** because of crosswise requests...

Progress Space

acc. [1, p. 70/71]



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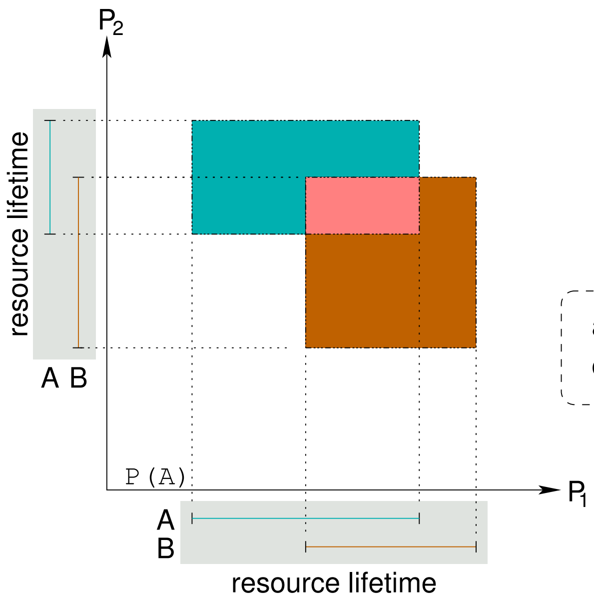

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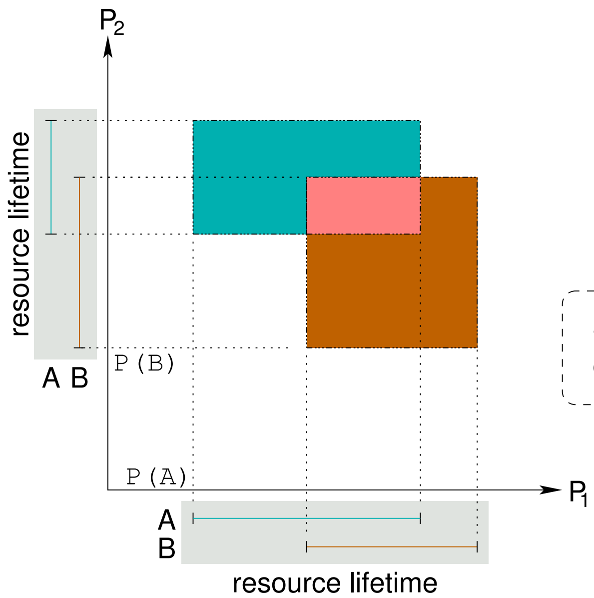

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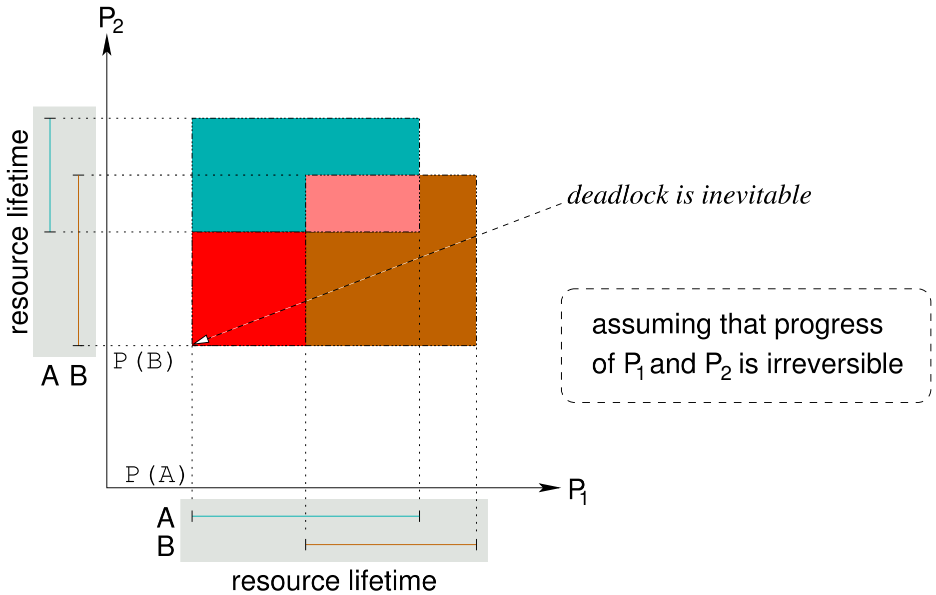

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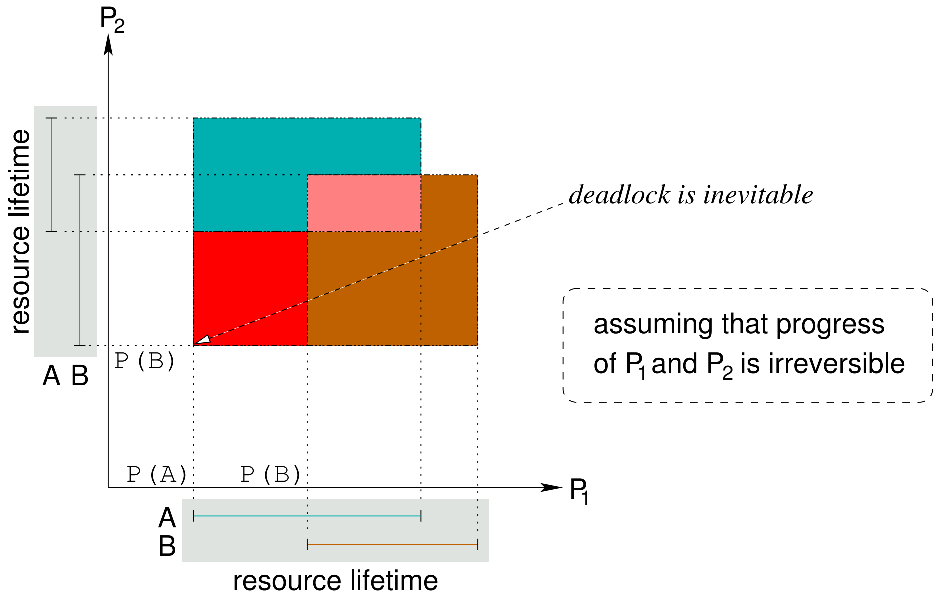

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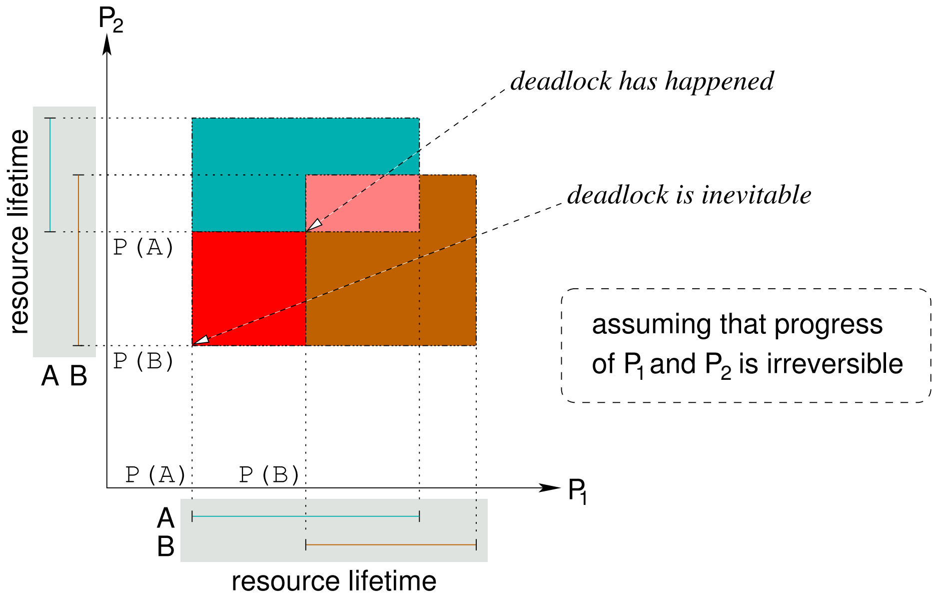

Conflict Situation III
Crosswise Signalling

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

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int send(pid_t pid, char *data, long size) {
    /* ... */
    cause(&peer->event);     /* signal send done */
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  - both are unable waiting on it at the same moment, so the signal is lost
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- 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*

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Goals and Tasks

In a Nutshell

- 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
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  accounting
  - of all resources available within the computing system
  - type, class, and number, but also
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  - 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 <u>or</u>
  - to partially or fully virtualise the hardware (e.g processor or memory)

Methods

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

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- risk of **system deadlock** due to awkward resource demands

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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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  - ii 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

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

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- 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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- **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

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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.

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- 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"
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- **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?

Problem Revisited

```
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 */
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  - **locking sequence**: $P_1 : P(A)$

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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 *transfer*(A, B) and *transfer*(B, A) simultaneously
  - **locking sequence**: $P_1 : P(A) \rightsquigarrow P_2 : P(B) \rightsquigarrow P_1 : P(B) \rightsquigarrow P_2 : P(A)$

Problem Revisited

Crosswise Use of Reusable Resources

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    double balance;
} account_t;

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```

> **Race Condition**
>
> Due to divisible operation of *transfer*. The code shows a critical section. A **design change** is appropriate.

- assuming that two processes, P_1 and P_2, perform *transfer*(A, B) and *transfer*(B, A) simultaneously
  - **locking sequence**: $P_1 : P(A) \rightsquigarrow P_2 : P(B) \rightsquigarrow P_1 : P(B) \rightsquigarrow P_2 : P(A)$
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Approach to the Problem

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

    P(&bolt);            /* block transfer operation */
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}
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  - all transfers are locked out, particularly also those transfers that apply to unrelated pairs of accounts (i.e., reusable resources)
  - 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. *Überziehungszinsen*) is incurred[3]

[3] The bank feels happy about this, but not the account holder.

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    - ii interest paid on overdraft (Ger. *Überziehungszinsen*) is incurred[3]
- synchronisation must be **all-embracing**: per transfer and account

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Solution I


```
1  transfer(account_t *from, account_t *to, double amount) {
2      static semaphore_t bolt = {1};
3
4      P(&bolt);              /* block transfer operation */
5      P(&from->lock);          /* acquire source account */
6      P(&to->lock);            /* acquire target account */
7      V(&bolt);              /* clear transfer operation */
8
9      from->balance -= amount;        /* withdraw money */
10     to->balance += amount;          /* and deposit it */
11
12     V(&to->lock);            /* release target account */
13     V(&from->lock);          /* release source account */
14 }
```


Solution I

Indivisble Allocation and Overall Function

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13     V(&from->lock);          /* release source account */
14 }
```


- 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


```
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 */
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}
```


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Indivisible Sub-Function

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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

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  - in terms of **deadlock prevention**, one is on the right track—*but*
  - as to software structure, one failed to apply Occam's razor[4]
    - hyphotesis that the level of abstraction of the solution is adequate
    - hyphotesis that the program is readable and easily adaptable
    - hyphotesis 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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    - hyphotesis that the level of abstraction of the solution is adequate
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- particularly non-sequential programs must be of a "good" structure

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Solution III

Procedural Abstraction

```
transfer(account_t *from, account_t *to, double amount) {
    change(from, -amount);        /* withdraw money */
    change(to, amount);           /* and deposit it */
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Solution III

Procedural Abstraction

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- 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 */
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```

Solution III — Procedural Abstraction

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    V(&this->lock);               /* release account */
}
```

- mutual exclusion using instruction set architecture level functions:[5]

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

[5] `#define FAA __sync_fetch_and_add`

Solution IV — Abstract Data Type

```
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* (☺)

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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

Interlude — Lessons Learned

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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- 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
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  - but reducing the problem such that downscaling the solution was feasible
- 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.

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- **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.

Deadlock Prevention (Ger.) *Vorbeugung*

Hint (Primary Prevention)

Protect interacting processes from developing a standstill.

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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.*

Deadlock Avoidance (Ger.) *Vermeidung*

Hint (*a priori* Knowledge)

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

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- basic approach is to control processes and all their resource requests
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  - in case of unsecured resource demand, a **denial of allocation** takes place
  - effect is to either suspend or refuse serving of requesting processes

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  - 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

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
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    - (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

Deadlock Detection and Breakup

Diagnosis and Recovery

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- deadlocks are under the **tacit** (Ger. *stillschweigend*) **assumption**
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  - 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

Deadlock Detection and Breakup — Diagnosis and Recovery

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Tightrope Walk between Damage and Cost

What breaks in a moment may take years to mend.[a]

[a] Swedish proverb.

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Resource Allocation Graph

- a **directed graph** that interrelates process instances and resources or resource classes, resp.

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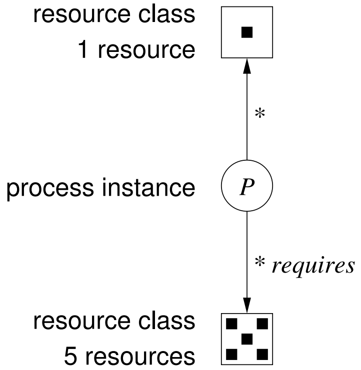
- optional (static) preliminary information as to the *requires* relation
  - resource classes and number of requires resources each



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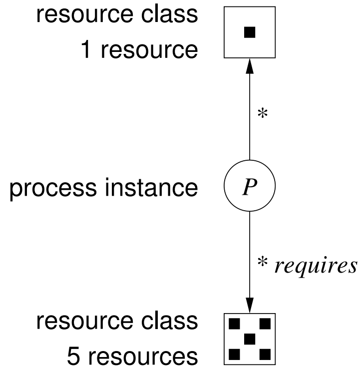

- mandatory ongoing information as to all process/resource relations
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abbr. RAG

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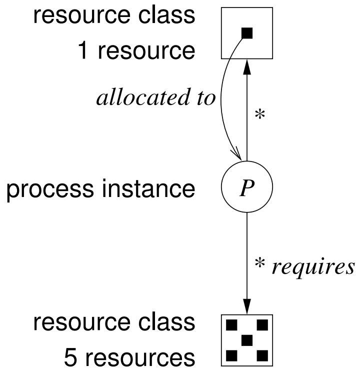

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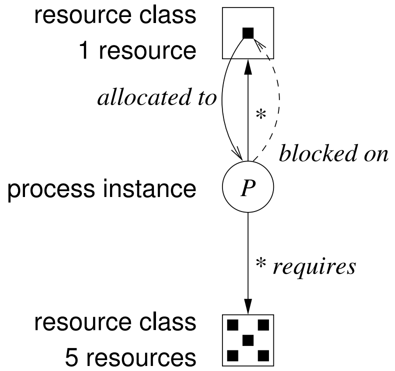

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[6] Mandatory ongoing information to derive a wait-for graph from a RAG.

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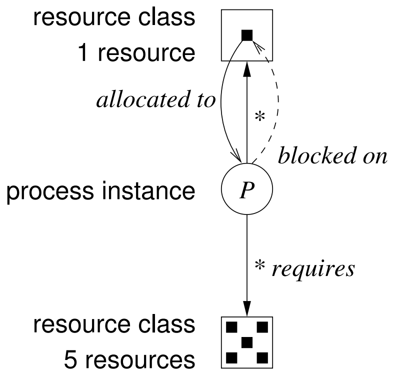

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  - each process instance records to which resource it is *blocked on*
- a **dynamic data structure** to be maintained by the operating system

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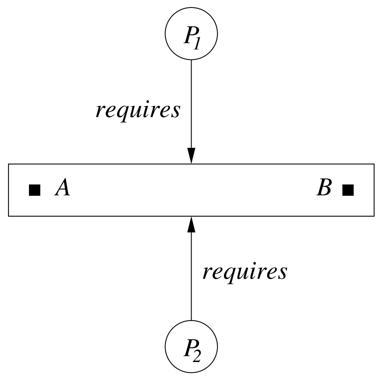
Wait-for Graph

(Ger.) *Wartegraph*



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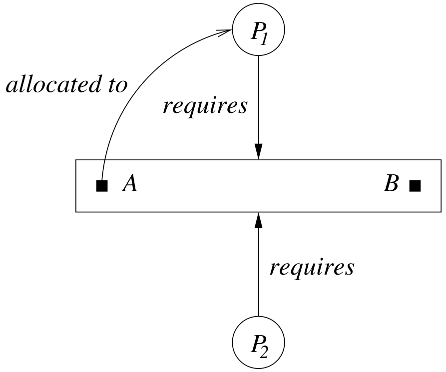

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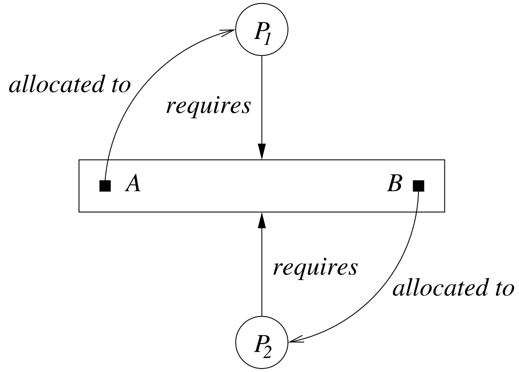

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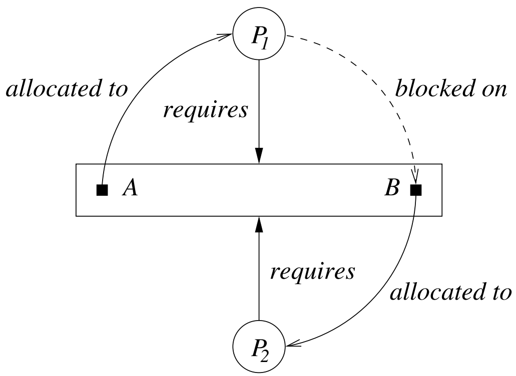

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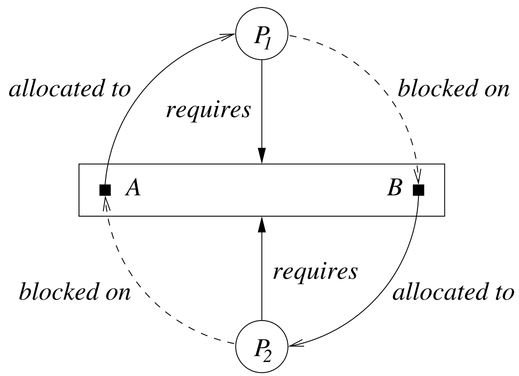

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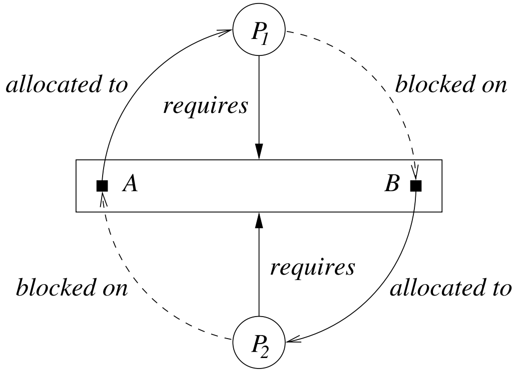

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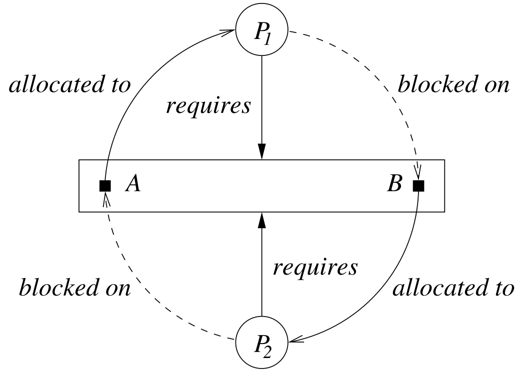

Hint

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

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)

*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 $\rightsquigarrow$ **ignorance**.*

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Safe State

acc. [3]

- 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:

$$\forall_{P_k \in S} b_k \leq r(t) + \sum_{s(l) \leq s(k)} c_l(t) \qquad (1)$$

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]