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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- **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

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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

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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

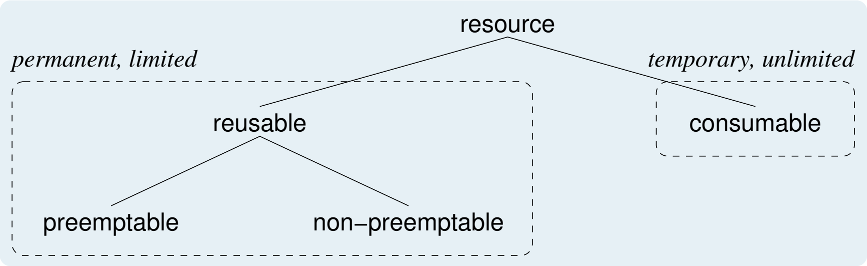
(Ger.) *Verklemmung*, *Blockierung*, *Stillstand*

source: National Geographic

Outline

Resources Revisited

cf. [6, p. 13–14]



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reusable
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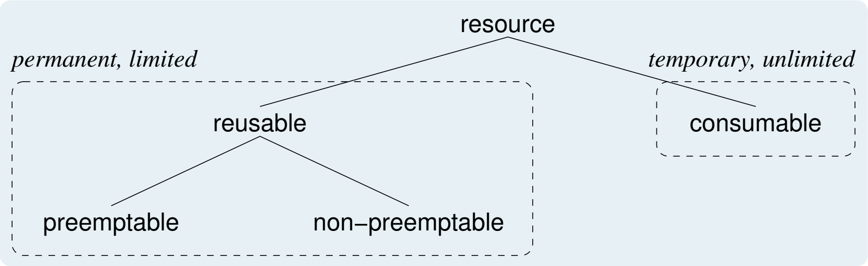

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  consumable
  - **crosswise signalling** by interacting processes followed by *await*, whereby the signal is not buffered
  - **lost release** of a produced resource
- abstracting away from hardware, deadlocks are due to software faults
  - only simultaneous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

Conflict Situation I

```
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

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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

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Cooked Down

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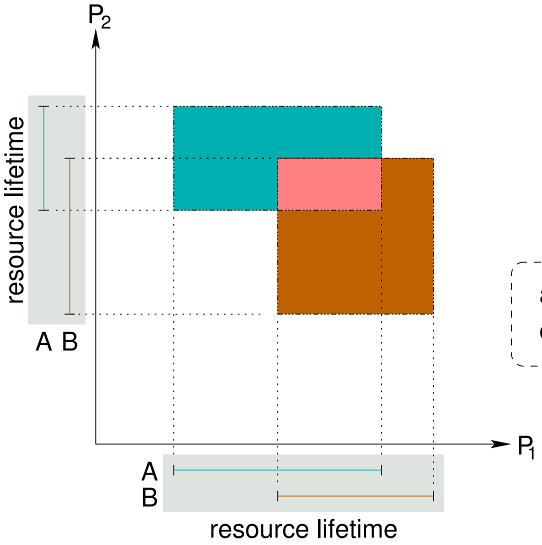
- P_1 and P_2 are subject to **deadlock** because of crosswise requests...

Progress Space



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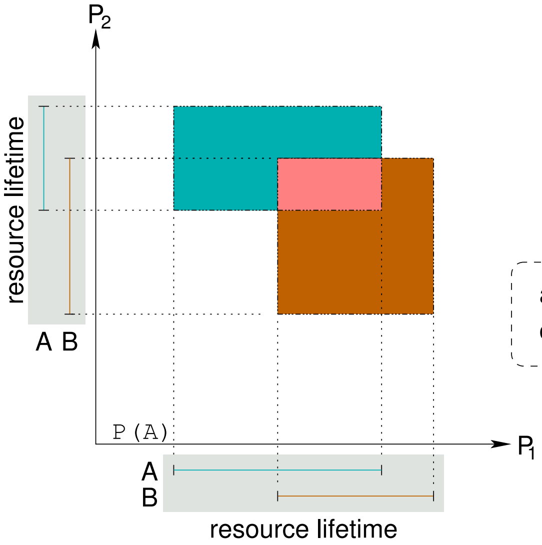

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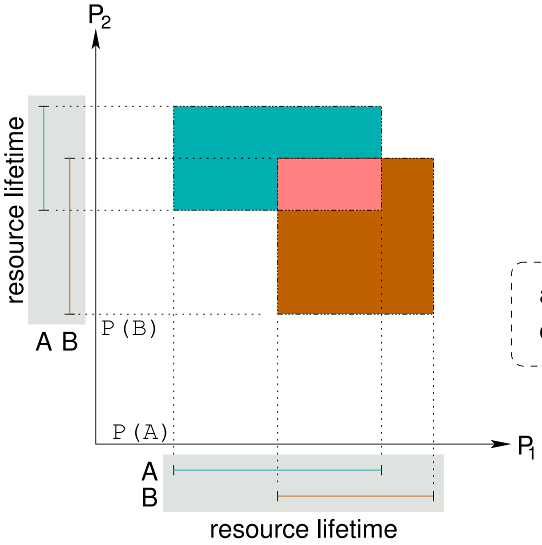

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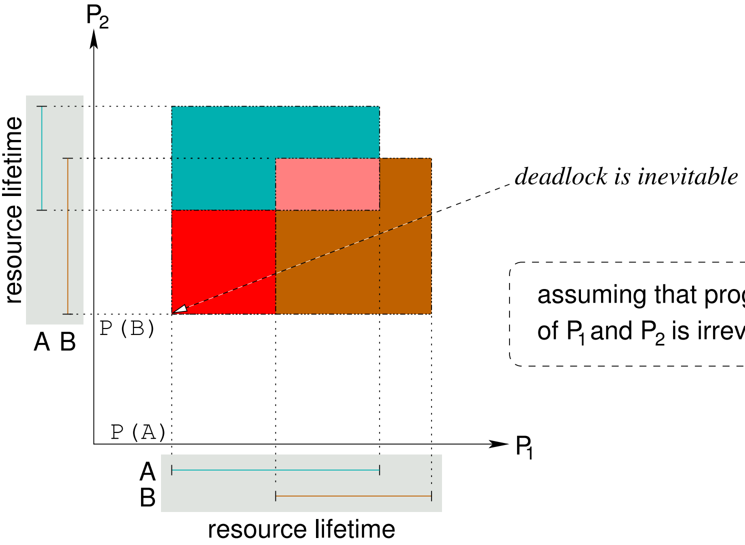

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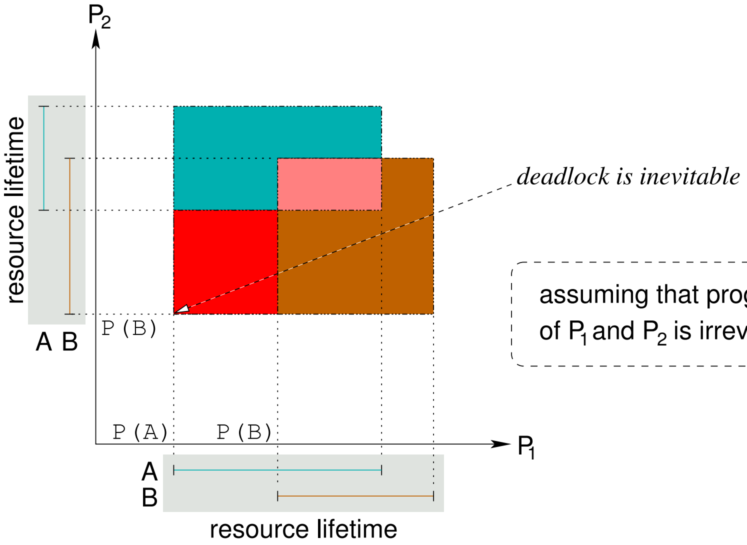

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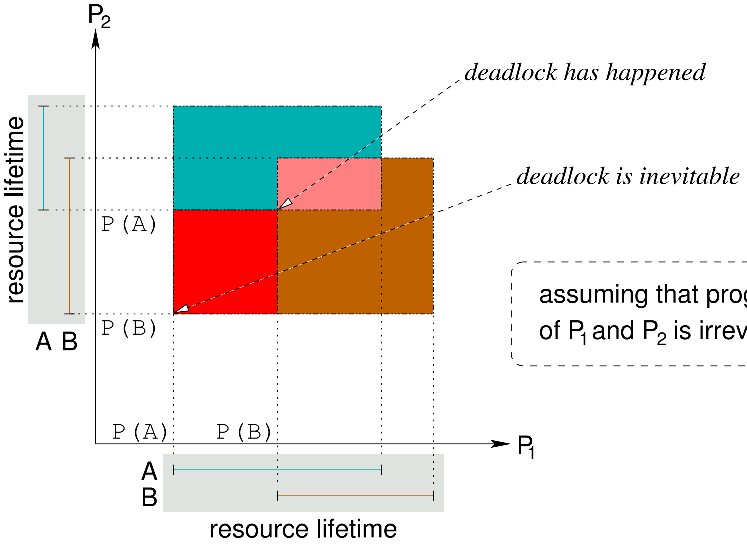

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Conflict Situation III

- 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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    /* ... */
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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

- 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
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accounting
- of all resources available within the computing system
- type, class, and number, but also
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- 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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  - 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
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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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  - 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
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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 */
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  - **locking sequence**: $P_1 : P(A)$

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typedef struct account {
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} account_t;

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    V(&from->lock);      /* release source account */
}
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- assuming that two processes, P_1 and P_2, perform $\mathit{transfer}(A, B)$ and $\mathit{transfer}(B, A)$ 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**

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}
```

Race Condition

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

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  - **locking sequence**: $P_1 : P(A) \leadsto P_2 : P(B) \leadsto P_1 : P(B) \leadsto P_2 : P(A)$
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Approach to the Problem

```
transfer(account_t *from, account_t *to, double amount) {
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  - 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

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transfer(account_t *from, account_t *to, double amount) {
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10     to->balance += amount;             /* and deposit it */
11
12     V(&to->lock);            /* release target account */
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

Indivisble 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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- particularly non-sequential programs must be of a "good" structure

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Solution III


```
transfer(account_t *from, account_t *to, double amount) {
    change(from, -amount);        /* withdraw money */
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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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```

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```

- 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


```
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 */
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}
```

- 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

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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  - 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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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.*

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Hint (*a priori* Knowledge)

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

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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

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- 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
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- not only the need for *a priori* data is a big problem, but also scalability

Deadlock Detection and Breakup

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- deadlocks are under the **tacit** (Ger. *stillschweigend*) **assumption**
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- as the case may be, the sequence repeats until closed loops vanished

Deadlock Detection and Breakup

- 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]

[a] Swedish proverb.

Resource Allocation Graph

abbr. RAG

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

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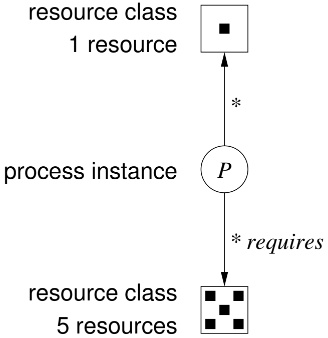
- optional (static) preliminary information as to the *requires* relation
  - resource classes and number of requires resources each



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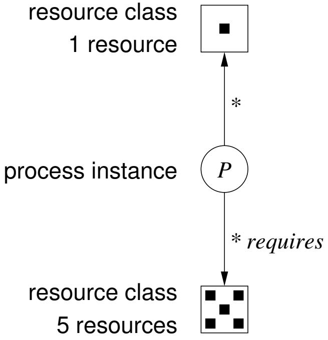

- mandatory ongoing information as to all process/resource relations
  - each process instance includes a resource allocation list (*requires*)

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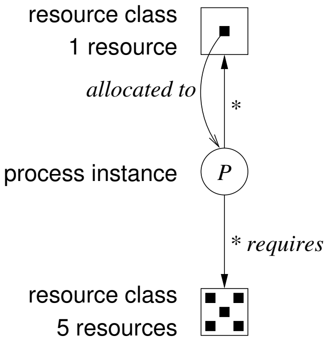

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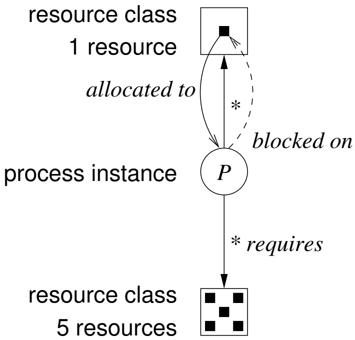

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- likewise, when a process expects (re-) allocation of a resource[6]
  - each process instance records to which resource it is *blocked on*

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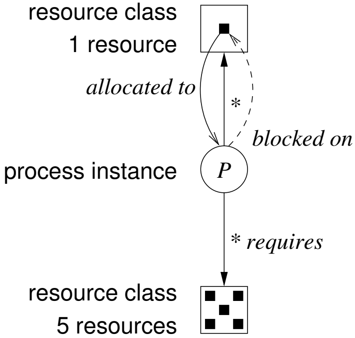

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- likewise, when a process expects (re-) allocation of a resource[6]
  - each process instance records to which resource it is *blocked on*
- a **dynamic data structure** to be maintained by the operating system

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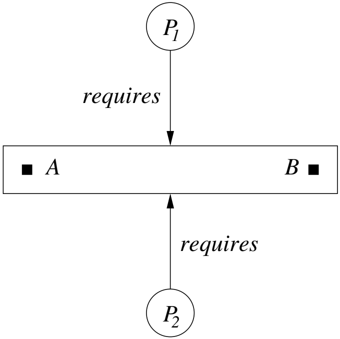
Wait-for Graph

(Ger.) *Wartegraph*



- let *A* and *B* be resources of the same resource class (cf. p. 8 and 18):

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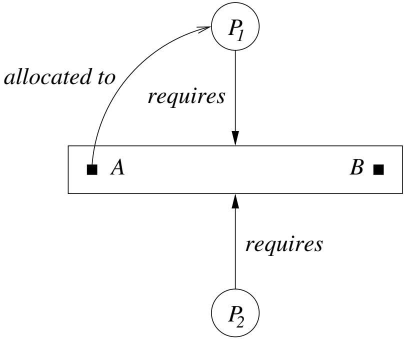

- let A and B be resources of the same resource class (cf. p. 8 and 18):

1. P_1 performs $P(A)$, A is unoccupied and gets allocated to P_1

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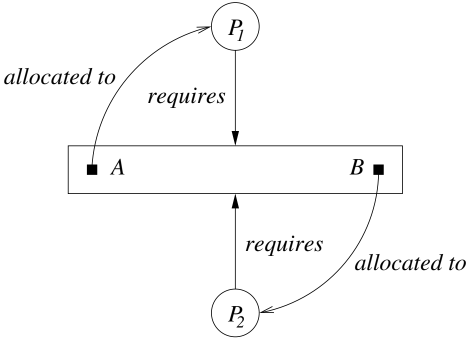

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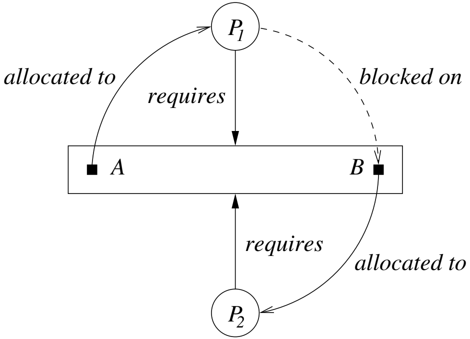

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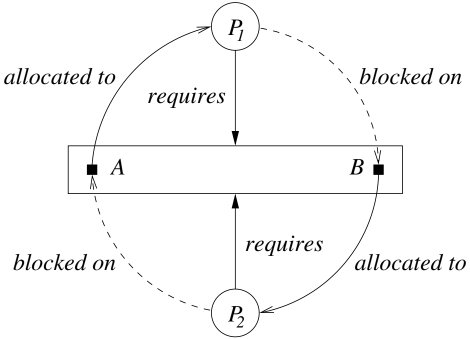

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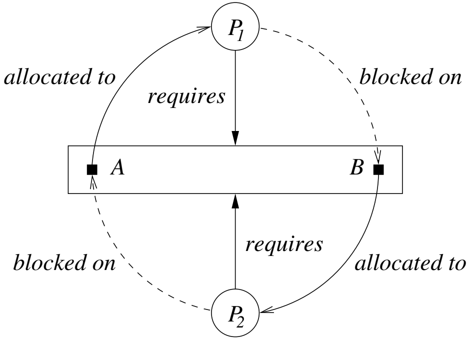

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- a **closed loop** from P_1 to P_2 via A and B, back and forth: **deadlock**

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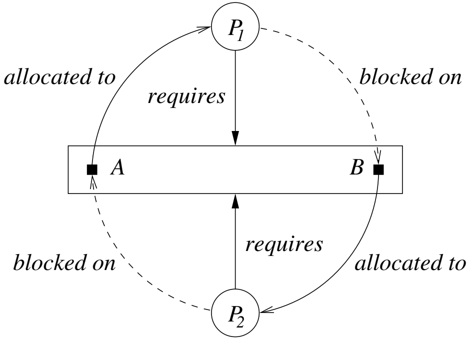

Hint

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

- 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:

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

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]