

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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 - lost release of a produced or beforehand acquired resource



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 - caused by **design faults** and to be corrected by design changes
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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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 - 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





source: National Geographic



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Illustrative Example I

General

Deadlocks

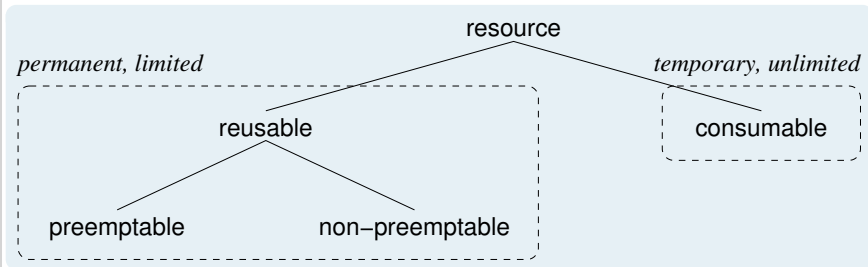
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Illustrative Example II

Counteractive Measures

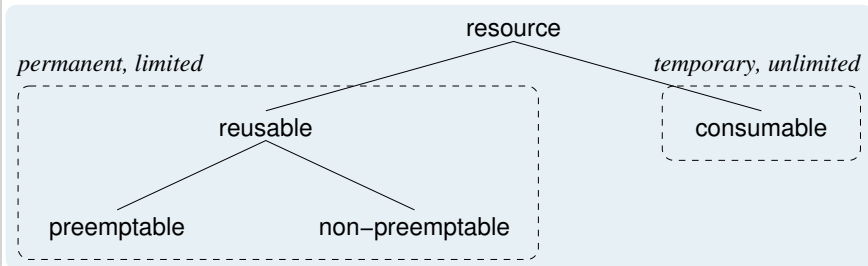
Summary





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



```
1  int send(pid_t pid, char *data, long size) {
2      process_t *self = being(ONESELF), *peer = being(pid);
3
4      P(&self->lock);      /* protect oneself: me */
5      memcpy(self->outbox.d, data, sizeof(self->outbox.d));
6
7      P(&peer->lock);      /* protect counterpart */
8      serve(peer, self);  /* message handover */
9      V(&peer->lock);      /* unprotect counterpart */
10     V(&self->lock);      /* unprotect oneself */
11
12     V(&peer->inbox.gate); /* signal send done */
13     P(&self->signal);     /* block on receive */
14
15     return self->merit; /* receiver pid or error code */
16 }
```

- 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.



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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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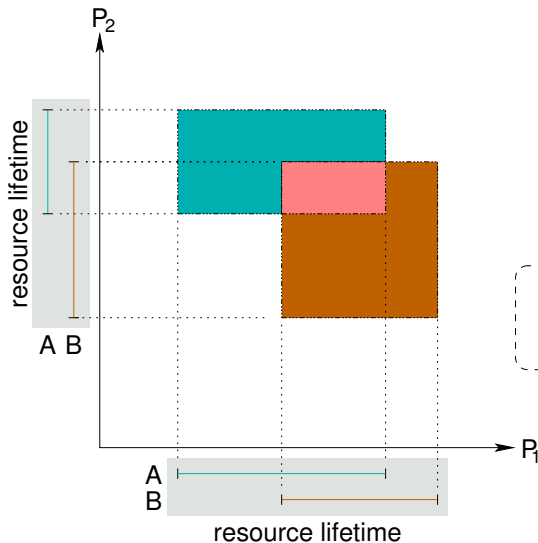
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- let A be the process descriptor of P_1 and let B be the one of P_2 :
 - P_1 : L3 ■ succeeded in completing $P(A)$, locked A and gets preempted
 - P_2 : L3 ■ succeeds in completing $P(B)$, locked B and continues
 - P_2 : L4 ■ gets blocked in $P(A)$, relinquishes control
 - P_1 : L4 ■ resumes and gets blocked in $P(B)$, relinquishes control



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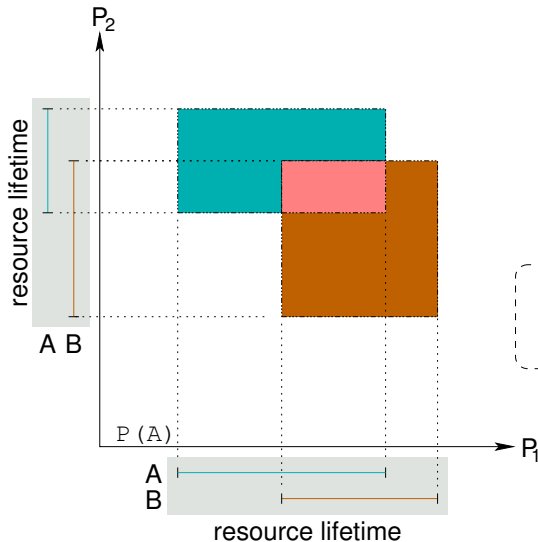
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- P_1 and P_2 are subject to **deadlock** because of crosswise requests. . .

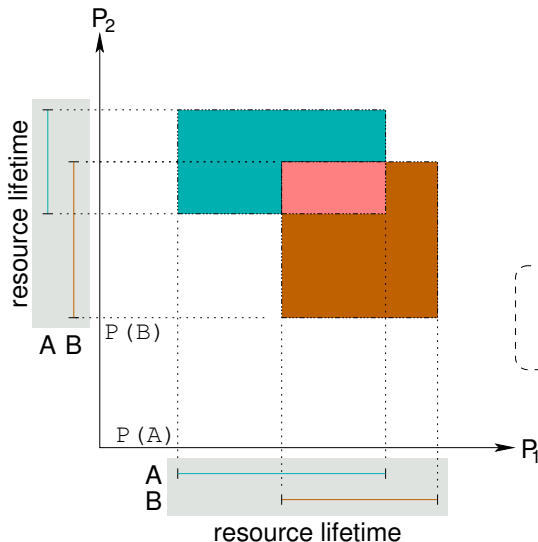


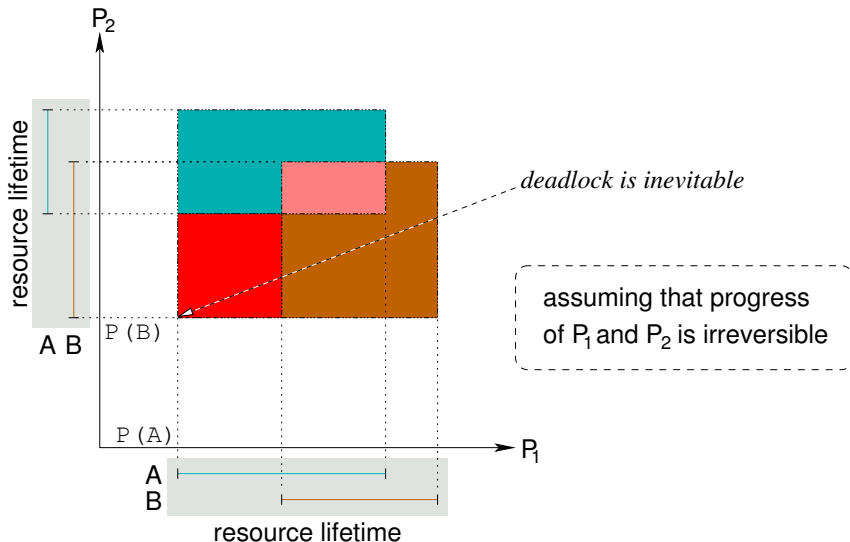


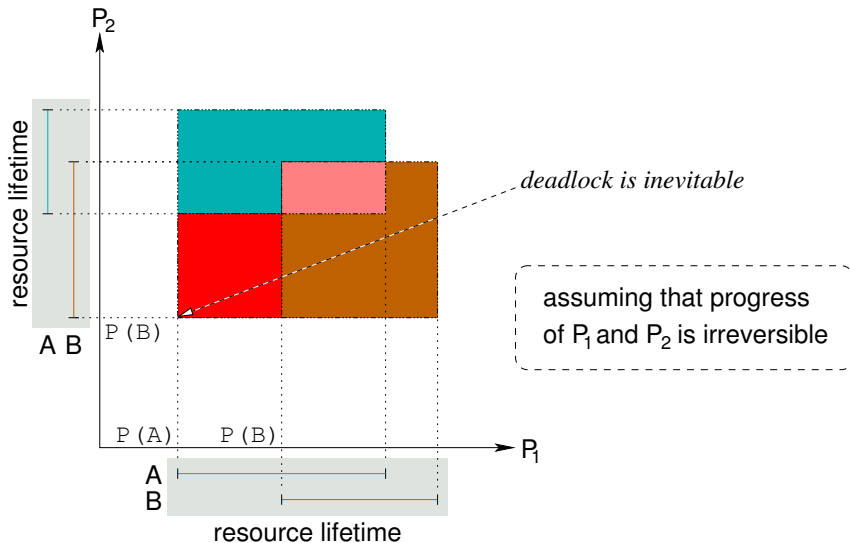
assuming that progress of P_1 and P_2 is irreversible

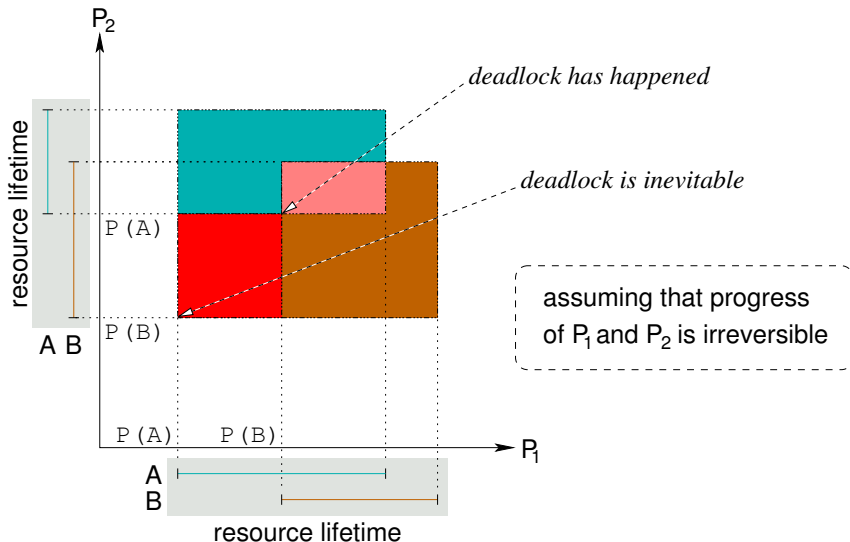












- assuming that the general semaphore used to signal availability of a consumable resource is replaced by an **event variable** mechanism:

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1 int send(pid_t pid, char *data, long size) {  
2     /* ... */  
3     cause(&peer->event);      /* signal send done */  
4     await(&self->event);      /* block on receive */  
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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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 - 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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- 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
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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 or
 - to partially or fully virtualise the hardware (e.g. processor or memory)



Methods

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



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- at load time or at the outset of a particular run-time phase

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 - i even though no single process requires more than the total resources that are available in the system and
 - ii whether the allocation of resources is the responsibility of the operating system or of the application programs themselves
- waiting can happen in **inactive** (deadlock) or **active** (livelock) mode



Definition (dead-lock [5])

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



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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** ■ the process state alternates between “running” and “ready”
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 - 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 feasible²

²Checking whether or not the values of the program counters of apparently stalemate processes stay within a certain values margin—but for how long?



```
1  typedef struct account {
2      semaphore_t lock;
3      double balance;
4  } account_t;
5
6  void
7  transfer(account_t *from, account_t *to, double amount) {
8      P(&from->lock);      /* acquire source account */
9      P(&to->lock);         /* acquire target account */
10     from->balance -= amount; /* withdraw money */
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 - locking sequence: $P_1 : P(A)$



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 - P_2 waits on A occupied by P_1 waiting on B occupied by P_2 : **deadlock**



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10     from->balance -= amount; /* withdraw money */
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12     V(&to->lock);          /* release target account */
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14 }

```

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



```

1  typedef struct account {
2      semaphore_t lock;
3      double balance;
4  } account_t;
5
6  void
7  transfer(account_t *from, account_t *to, double amount) {
8      P(&from->lock);          /* acquire source account */
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14 }

```

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
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1 transfer(account_t *from, account_t *to, double amount) {
2     static semaphore_t bolt = {1};
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4     P(&bolt);           /* block transfer operation */
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- restricts parallelism unnecessarily

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



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- restricts parallelism unnecessarily and is flawed by a **race condition**
 - 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 incurred³

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



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 - ii interest paid on overdraft (Ger. *Überziehungszinsen*) is incurred³
- synchronisation must be **all-embracing**: per transfer and account

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- 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



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 - as to software structure, one failed to apply Occam's razor⁴
 - 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

⁴A 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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```
1 transfer(account_t *from, account_t *to, double amount) {  
2     change(from, -amount);          /* withdraw money */  
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- mutual exclusion using operating system machine level functions:
 - take a sledgehammer to crack the nut...

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



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```

- mutual exclusion using instruction set architecture level functions:⁵

```
1 inline void change(account_t *this, double amount) {
2     FAA(&this->balance, amount);    /* do operation */
3 }
```

⁵ #define FAA __sync_fetch_and_add



```
1  monitor Account {
2      double balance;
3  public:
4      inline void change(double amount) {
5          balance += amount;  /* do operation */
6      }
7  };
8
9  void
10 transfer(Account& from, account& to, double amount) {
11     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 $V(\text{mutex})$ even for Hoare-style [4, p. 551, 1.]
 - as *change*, by default, is defined to be indivisible, additional semantics is available to apply the FAA to the otherwise trivial computation



*Once the critical section has been identified, to **factor out** is maxim. Although corresponding measures sometimes appear to be superfluous, they increase awareness for the options of improvement. This insight not only holds for the initial design or redevelopment, respectively, but also legacy software.*



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- a **constructive approach** has been exercised, which finally opened a path for cross-layer optimisation
 - analytical approaches, if applicable, are without doubt important but they are nevertheless second quality in cases similar to those as were shown
 - here, the problem could be put down to a plain type of critical operation



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:
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Hint (Prevention/Avoidance)

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



Hint (Primary Prevention)

Protect interacting processes from developing a standstill.



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Hint (Prophylaxis)

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



Hint (*a priori* Knowledge)

Preliminary information as to processes and their resource demands.



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- 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



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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



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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
 - 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



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





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Tightrope Walk between Damage and Cost

What breaks in a moment may take years to mend.^a

^aSwedish proverb.



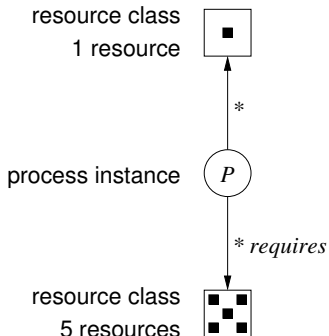
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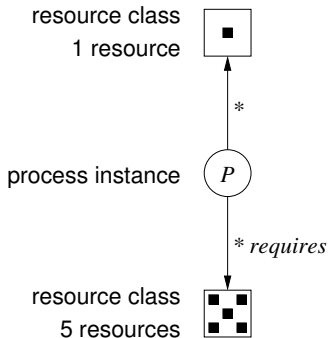
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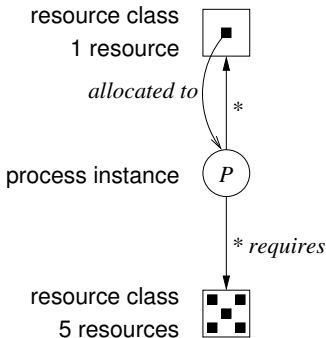
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 - resource classes and number of requires resources each



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



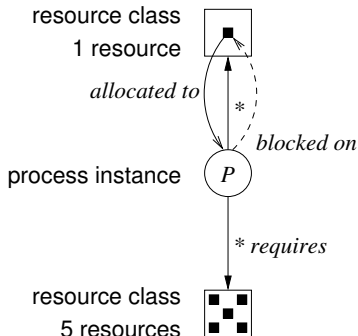
- a **directed graph** that interrelates process instances and resources or resource classes, resp.: serves also as basis for a **wait-for graph** (p. 31)
- optional (static) preliminary information as to the *requires* relation
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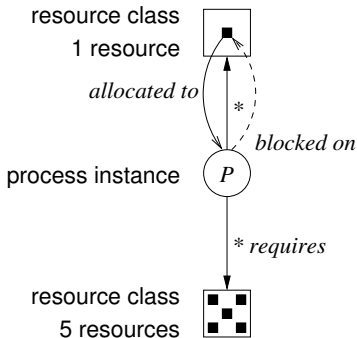
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- likewise, when a process expects (re-) allocation of a resource⁶
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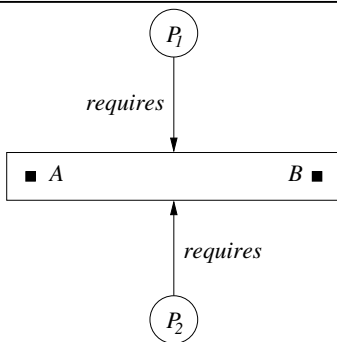
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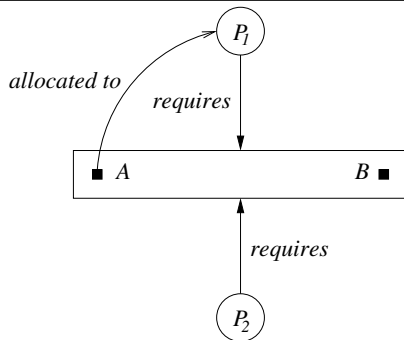
- a **dynamic data structure** to be maintained by the operating system

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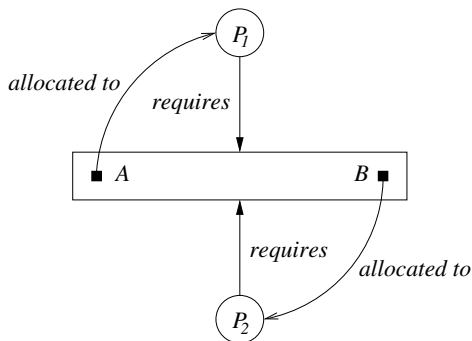
- let A and B be resources of the same resource class (cf. p. 8 and 18):





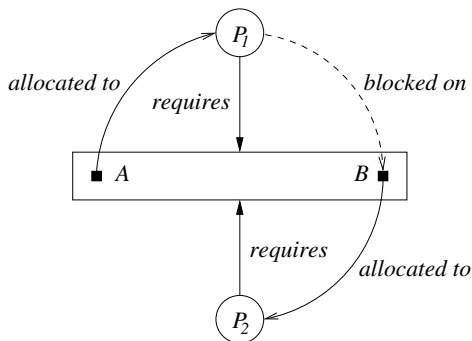
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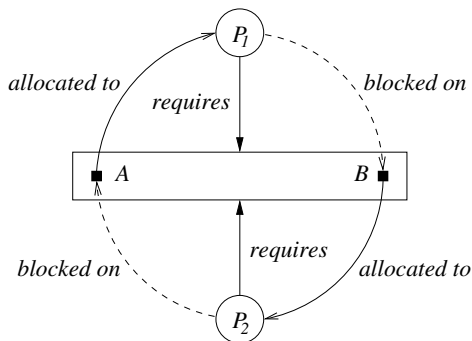
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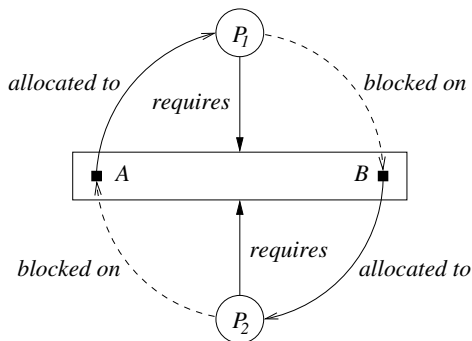
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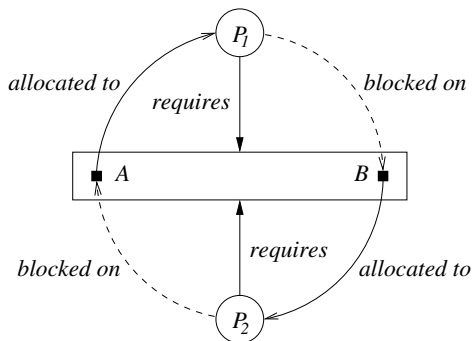
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 a **closed loop** from P_1 to P_2 via A and B , back and forth: **deadlock**





Hint

Created in situations where the operating system may assume a deadlock case:

- response time increase
- throughput decrease
- idle time overexpansion

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Outline

Preface

Resource Management

- Classification

- Illustrative Example I

- General

Deadlocks

- Fundamentals

- Illustrative Example II

- Counteractive Measures

Summary



- state of **stalemate** of interacting processes because of misguided or misconstructured 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 $\leadsto$ **ignorance**.*



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Reference List I

- [1] COFFMAN, JR., E. G. ; ELPHICK, M. J. ; SHOSHANI, A. :
System Deadlocks.
In: *Computing Surveys* 3 (1971), Jun., Nr. 2, S. 67–78

- [2] DIJKSTRA, E. W.:
Cooperating Sequential Processes / Technische Universiteit Eindhoven.
Eindhoven, The Netherlands, 1965 (EWD-123). –
Forschungsbericht. –
(Reprinted in *Great Papers in Computer Science*, P. Laplante, ed., IEEE Press, New York, NY, 1996)

- [3] HABERMANN, A. N.:
Prevention of System Deadlocks.
In: *Communications of the ACM* 12 (1969), Jul., Nr. 7, S. 373–377/385

- [4] HOARE, C. A. R.:
Monitors: An Operating System Structuring Concept.
In: *Communications of the ACM* 17 (1974), Okt., Nr. 10, S. 549–557

- [5] NEUFELDT, V. (Hrsg.) ; GURALNIK, D. A. (Hrsg.):
Webster's New World Dictionary.
Simon & Schuster, Inc., 1988



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



- 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]

