Operating Systems

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V. Deadlocks
May 10, 2023 (Summer Term 2023)

RUB Faculty of Computer Science

RUHR UNIVERSITÄT BOCHUM RUB

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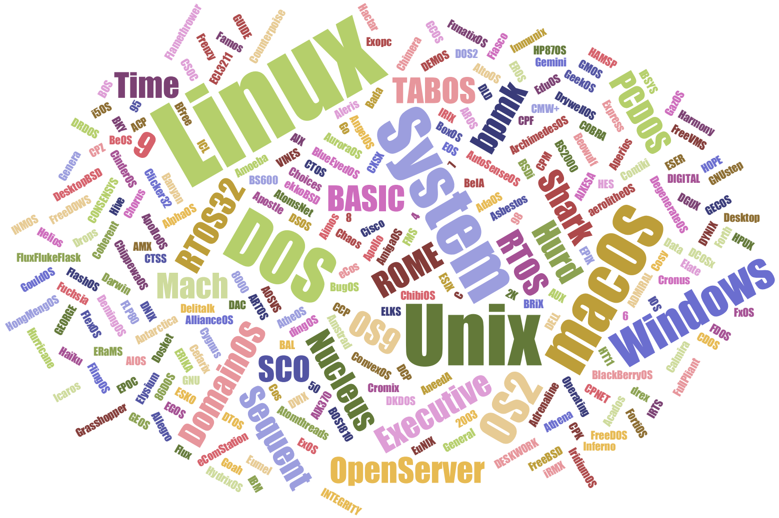
Chair of Operating Systems and System Software

Agenda



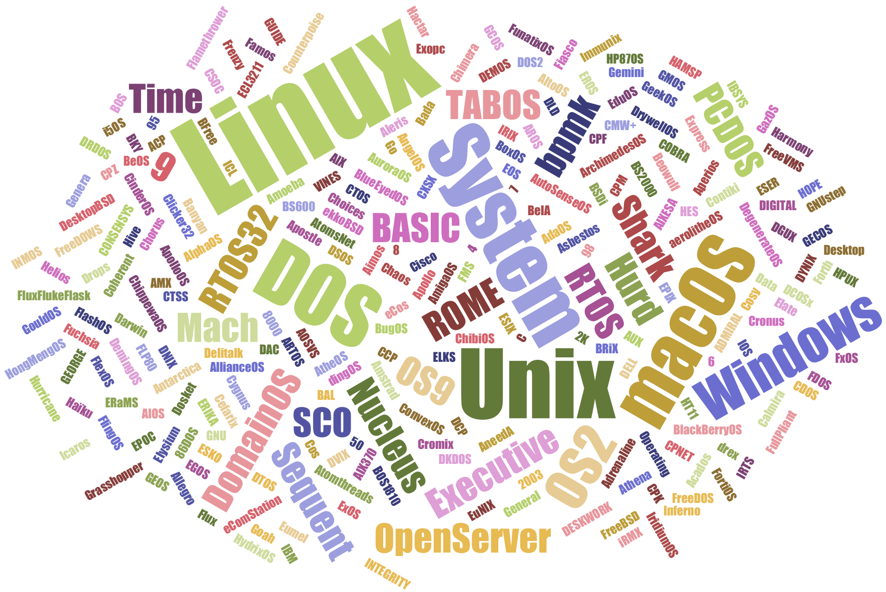
- Recap
- Organizational Matters
- Problem Scenario and Cause Study
- Process Deadlocks
  - Definition, Variants, and Conditions
  - Consumable and Non-consumable Resources
  - Resource Allocation Graphs
- Classic Deadlock Situation
  - The Dining Philosophers Problem
- Deadlock Counter Measures
  - Prevention, Avoidance, Detection and Recovery
- Summary and Outlook

Literature References

Silberschatz, Chapter 8

Tanenbaum, Chapter 6

⏮ Recap



- **process synchronisation**
  - **critical sections, race conditions**
  - coordination methods to **avoid errors** due to uncontrolled, **concurrent data access**
- ad-hoc methods using **busy waiting**
  - **inefficient** solutions, dangerous illusion of correctness
  - **waste of resource** (i.e., CPU cycles)
- advanced methods to ensure mutual exclusion: **passive waiting**
  - exploit hardware support: **atomic operations**
  - operating system support: **semaphores** to implement **passive waiting**

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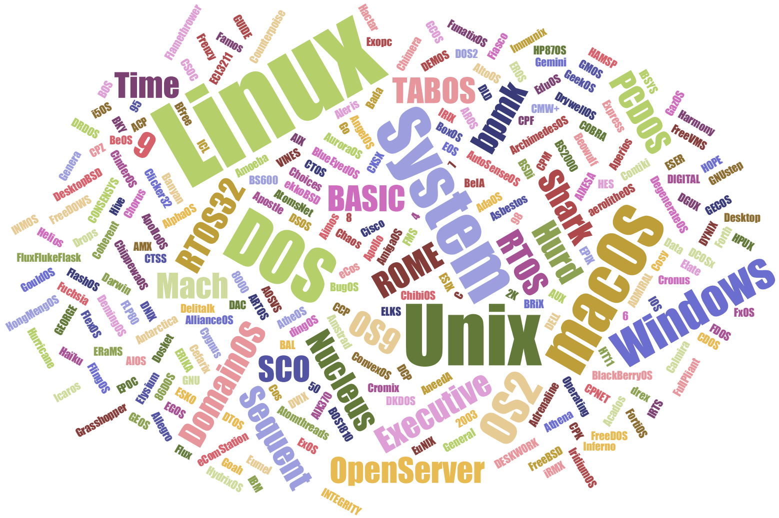

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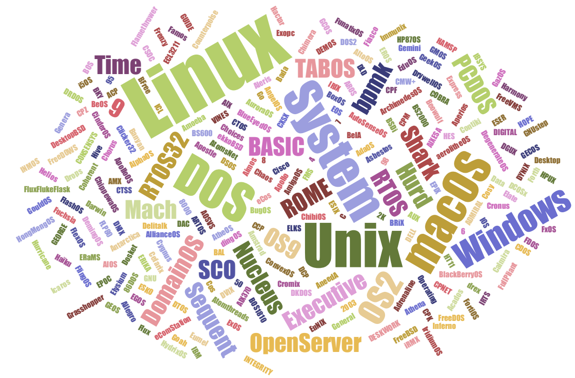
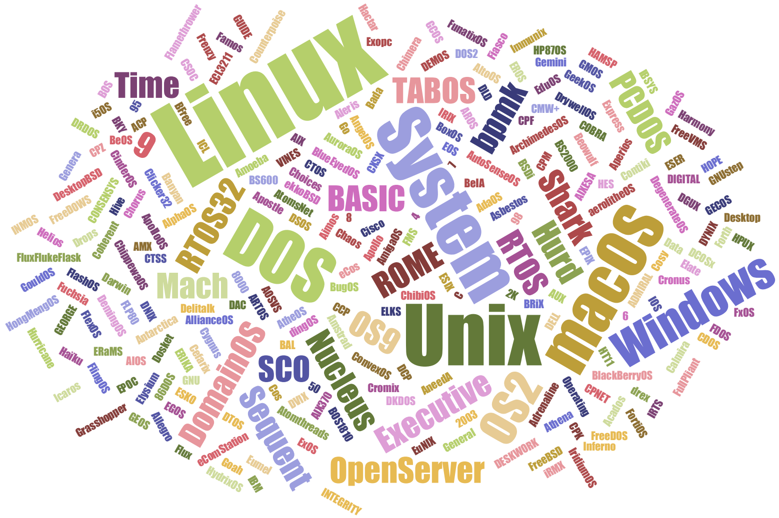
Organizational Matters



- lecture
  - Wednesday, 10:15 – 11:45
  - format: synchronous, **hybrid**
    - → in presence (Room HID, Building ID)
    - → online lecture (Zoom)
  - **exam:** August 7, 2023 (first appointment)
    September 25, 2023 (retest appointment)
- exercises: **group allocation ~~almost~~ complete**

  - make use of group work - for your own benefit!
  - remarks on Wednesday for Übung T03
- manage course material, asynchronous communication: Moodle
- `https://moodle.ruhr-uni-bochum.de/course/view.php?id=50698`

Agenda



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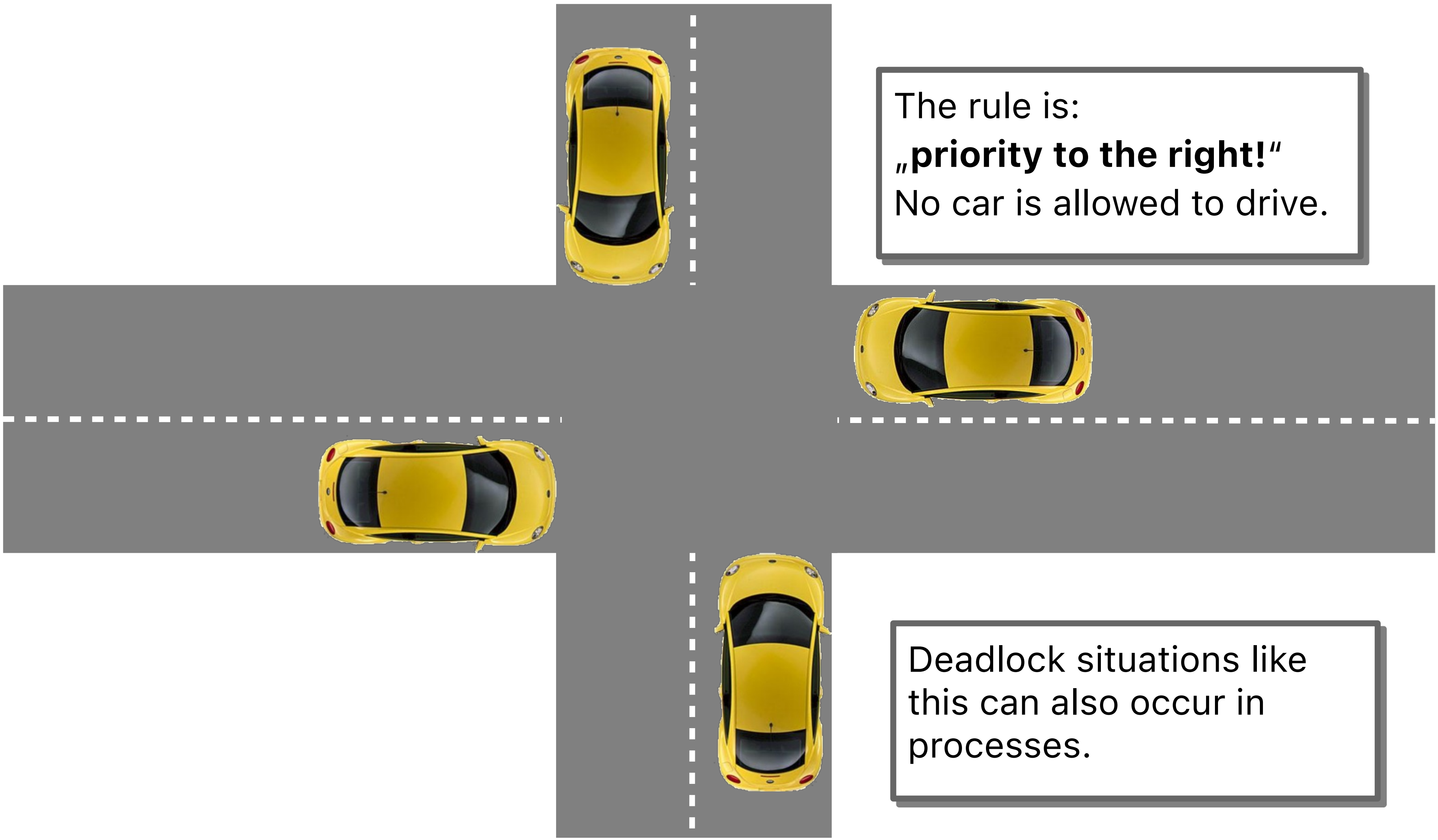
Problem Scenario and Cause Study

- **processes operate concurrently** (cooperation and competition)
  - increased utilization of shared resources (e.g., CPU)
- mandatory: **synchronisation** primitives are used to coordinate processes
  - data races induce the need of synchronisation methods
- concept: **passive waiting** by blocking and waking processes
  - resource usage and availability decides on process states
  - eliminates **busy waiting**, which is considered an anti-pattern (too expensive, error prone)

- solution with OS support: **semaphores** → implement **passive waiting** and enable:
  - unilateral synchronisation (→ e.g., producer/consumer)
  - multilateral synchronisation
    - interlaced producer/consumer, "prosumer"
    - mutual exclusion (e.g., exclusive access to a critical section)

- **waiting mechanisms** can lead to **deadlock** situations...

Deadlocks (dt. Verklemmungen)

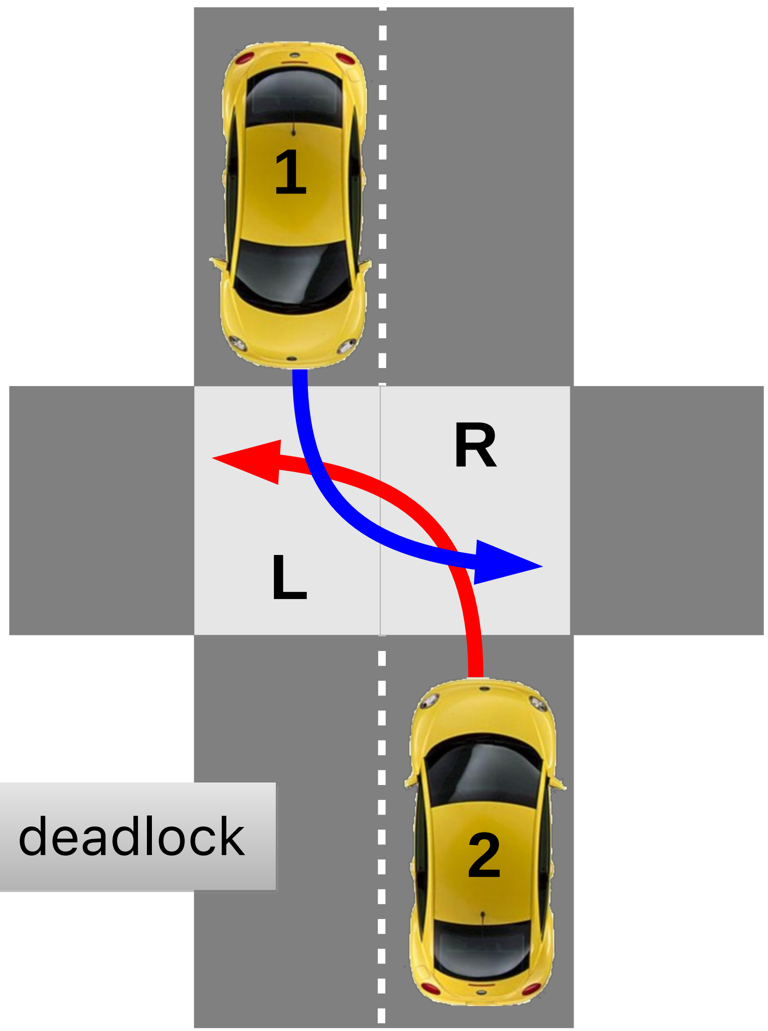


The rule is:
„priority to the right!"
No car is allowed to drive.

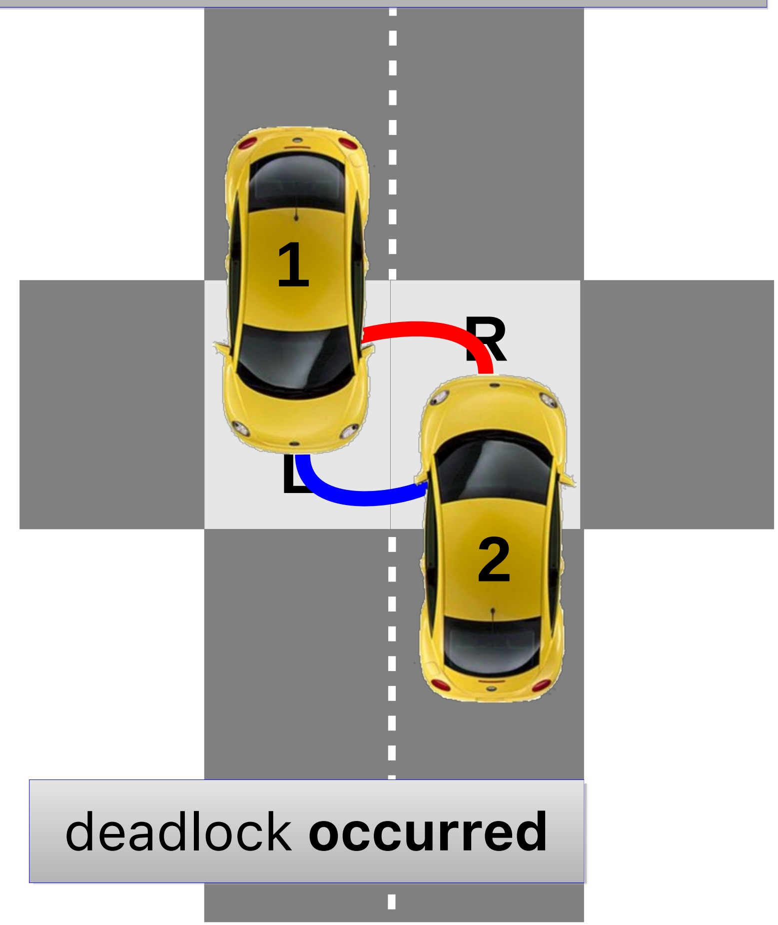
Deadlock situations like this can also occur in processes.

Deadlocks Cause Study - Example

car **1** occupies **L** and requires **R**
car **2** occupies **R** and requires **L**

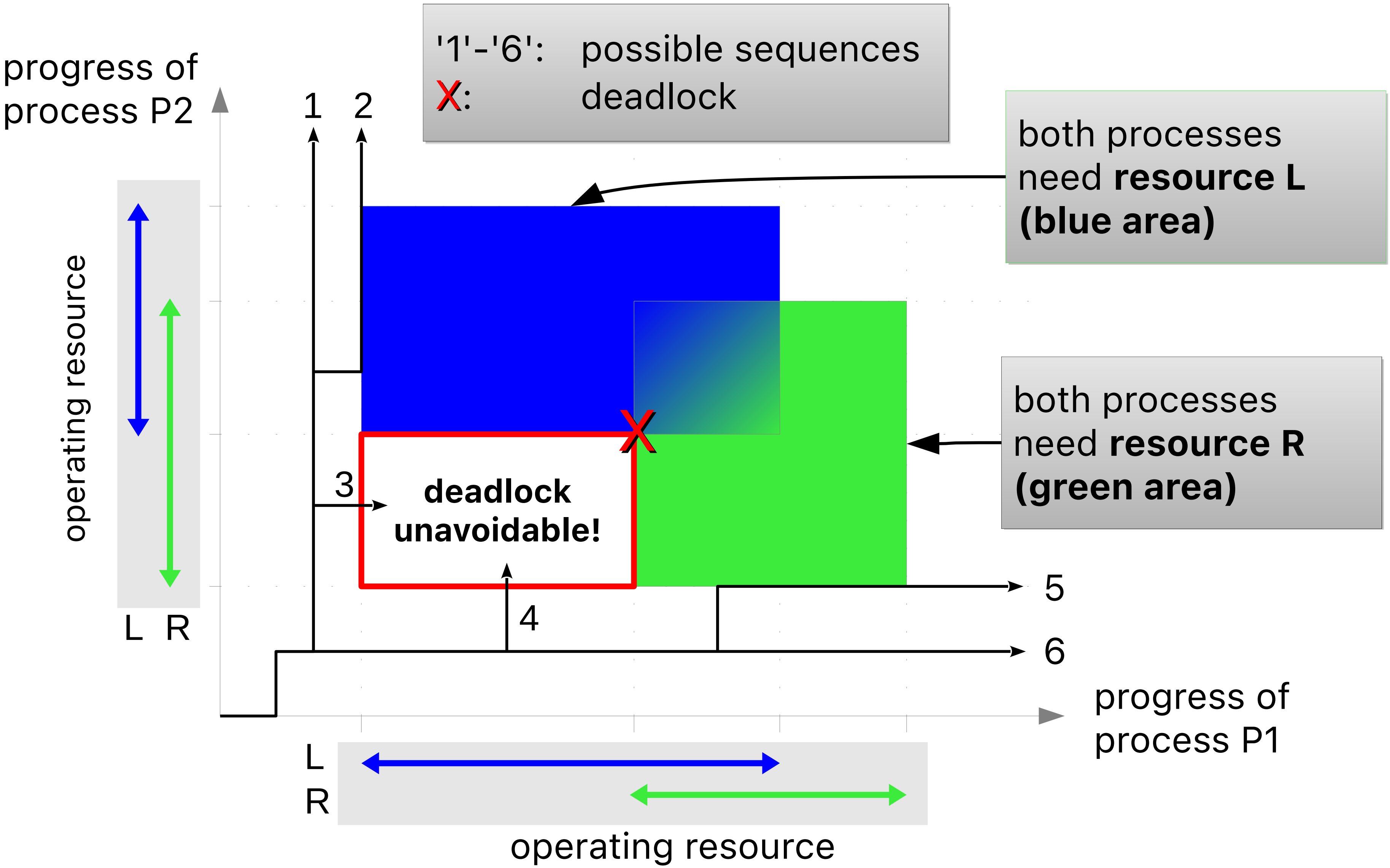


potential deadlock

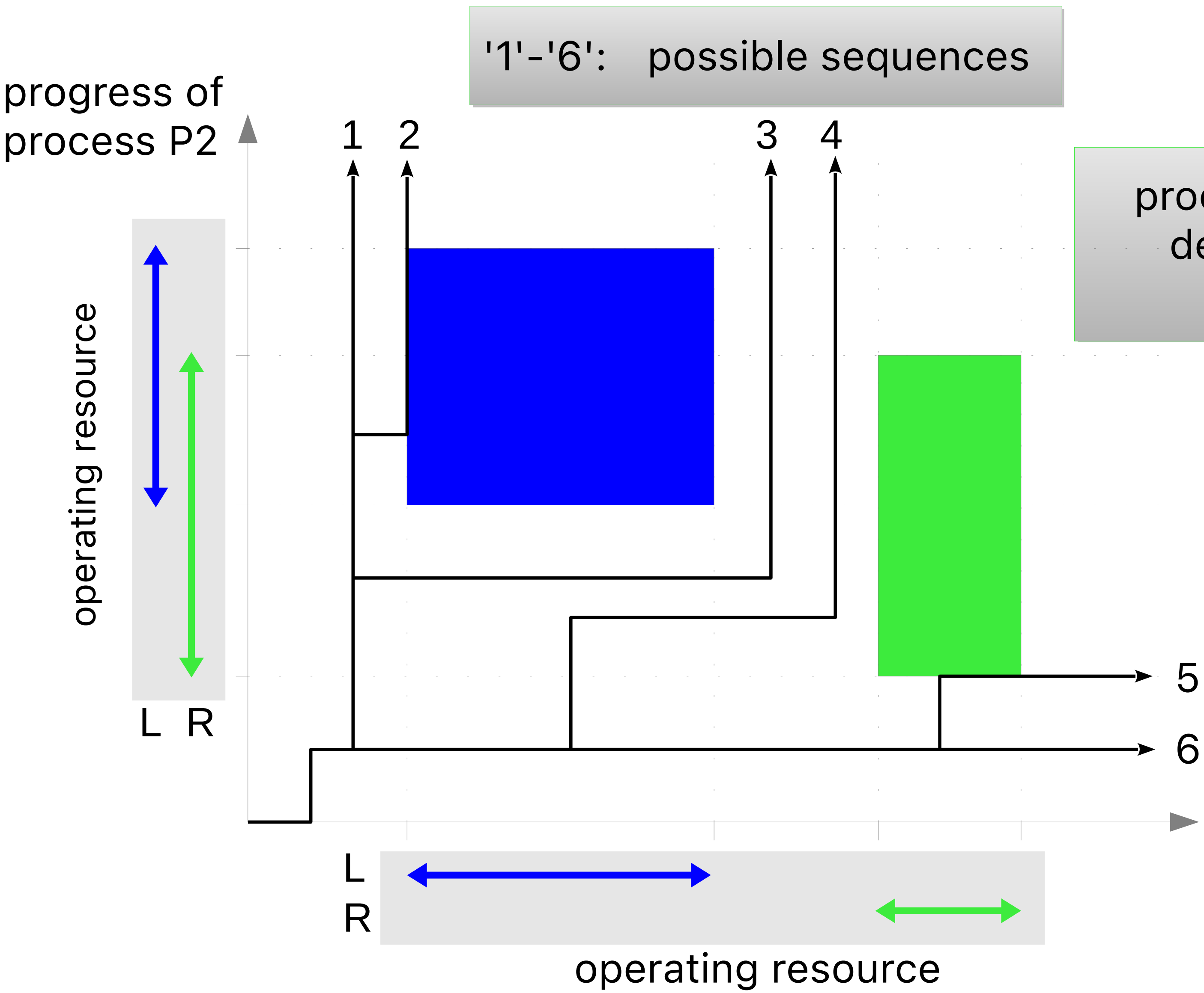


deadlock **occurred**

Deadlocks Cause Study - Abstract

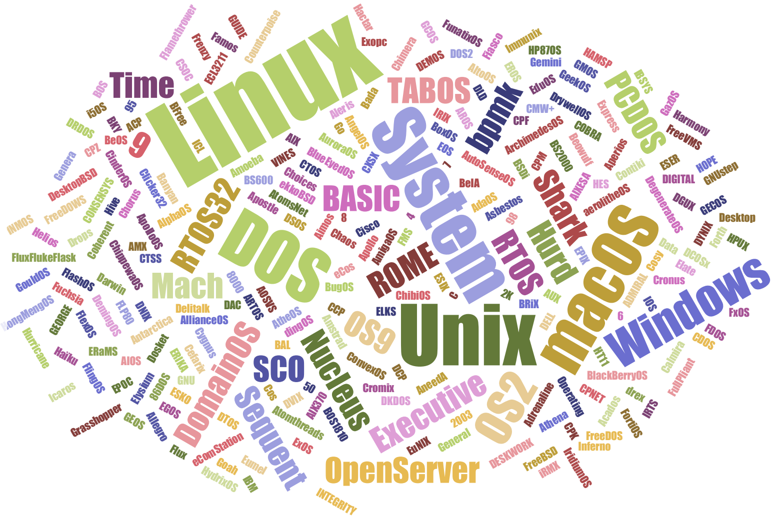


Deadlocks Cause Study - Abstract



processes **can not** deadlock in this scenario

Agenda



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Deadlocks of Processes: Definition

- Deadly Embrace

Photo: David Maitland, National Geographic

- Definition (Tanenbaum and Woodhull):

„*A* ***set*** *of* ***processes*** *is* ***deadlocked***
if ***each process*** *in the set*
is waiting *for an event*
that only ***another process*** *in the set* ***can cause***.“

Deadlocks of Processes: Variants

- **deadlock** (first variant)
  - passive waiting
  - process state: **BLOCKED**
- **livelock** (second variant)
  - busy waiting (or *„lazy“ busy waiting*)
  - arbitrary process state (including **RUNNING**), but: no progress!
- by comparison, deadlocks are the lesser evil
  - condition can be identified → prerequisite for „resolution“
  - extremely high system load due to busy waiting

Deadlocks of Processes: Conditions

For deadlocks to occur, **all** of the following conditions must be met ("necessary conditions"):

1. **mutual exclusion condition:** exclusive allocation of resources
   - only one process may use a resource at a time
2. **hold-and-wait condition:** follow-up request for resources
   - processes currently holding resources can request new resources
3. **no preemption condition:** no withdrawal of resources
   - granted resources must be explicitly released by the process holding them
4. **circular wait condition:** processes wait for each other circularly
   - several processes, each of which is waiting for a resource held by the next member of the chain

Deadlocks of Processes: Conditions

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   - processes currently holding resources can request new resources
3. **no preemption condition:** no withdrawal of resources
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A deadlock **only occurs** when a **fourth condition** holds true at runtime:

4. **circular wait condition:** processes wait for each other circularly
   - several processes, each of which is waiting for a resource held by the next member of the chain

Operating Resources (dt. Betriebsmittel)

- operating resources are managed by the operating system and are made accessible to the processes
- types of operating resources:
  - **consumable operating resources**
    - → are generated (produced) and destroyed (consumed) at runtime
    - → examples: interrupt requests, signals, messages, data from input devices
    - → typical access synchronisation: **unilateral synchronisation**
  - **reusable operating resources**
    - → are allocated by processes for a certain time and then released
    - → examples: CPU, main and background memory, I/O devices, system data structures such as files, process table entries
    - → typical access synchronisation: **multilateral synchronisation, mutual exclusion**
- both resource types are prone to deadlocks

Operating Resources - Reusable

- a deadlock occurs when two processes use a **reusable operating resource** that is requested by the other process
- example: a computer system has 200 GiB of main memory, two processes allocate the memory step by step (memory allocation is done block by block)

Process 1	Process 2
`...`	`...`
`allocate 80 GiB;`	`allocate 70 GiB;`
`...`	`...`
`allocate 60 GiB;`	`allocate 80 GiB;`

If both processes issue their first request before memory is requested, a deadlock is unavoidable.

Operating Resources - Consumable

- a deadlock occurs when two processes are waiting for a **consumable operating resource** to be produced by the other
- example: synchronisation signals are "sent" between two processes using the **wait** and **signal** semaphore operations

Process P1

```
semaphore s1 = {0, NULL};
wait (&s1);
… // consume (from P2)
… // produce (for P2)
signal (&s2);
```

Process P2

```
semaphore s2 = {0, NULL};
wait (&s2);
… // consume (from P1)
… // produce (for P1)
signal (&s1);
```

Each process waits for a synchronisation signal from the other, but this cannot be sent because it is blocked itself.

Resource Allocation Graphs (RAGs)

(dt. **Betriebsmittelbelegungsgraphen**)

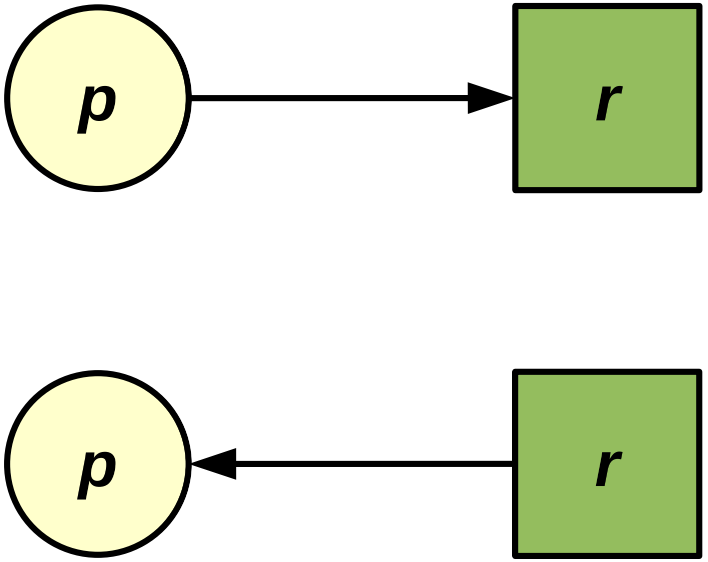
- to visualise and automatically detect deadlock situations Resource Allocation Graphs (RAGs) are used
- RAGs describe a current system state
  - **nodes:** processes and resources
  - **edges:** indicate an occupation or a request

operating resource R_1 is **requested** by process P_1

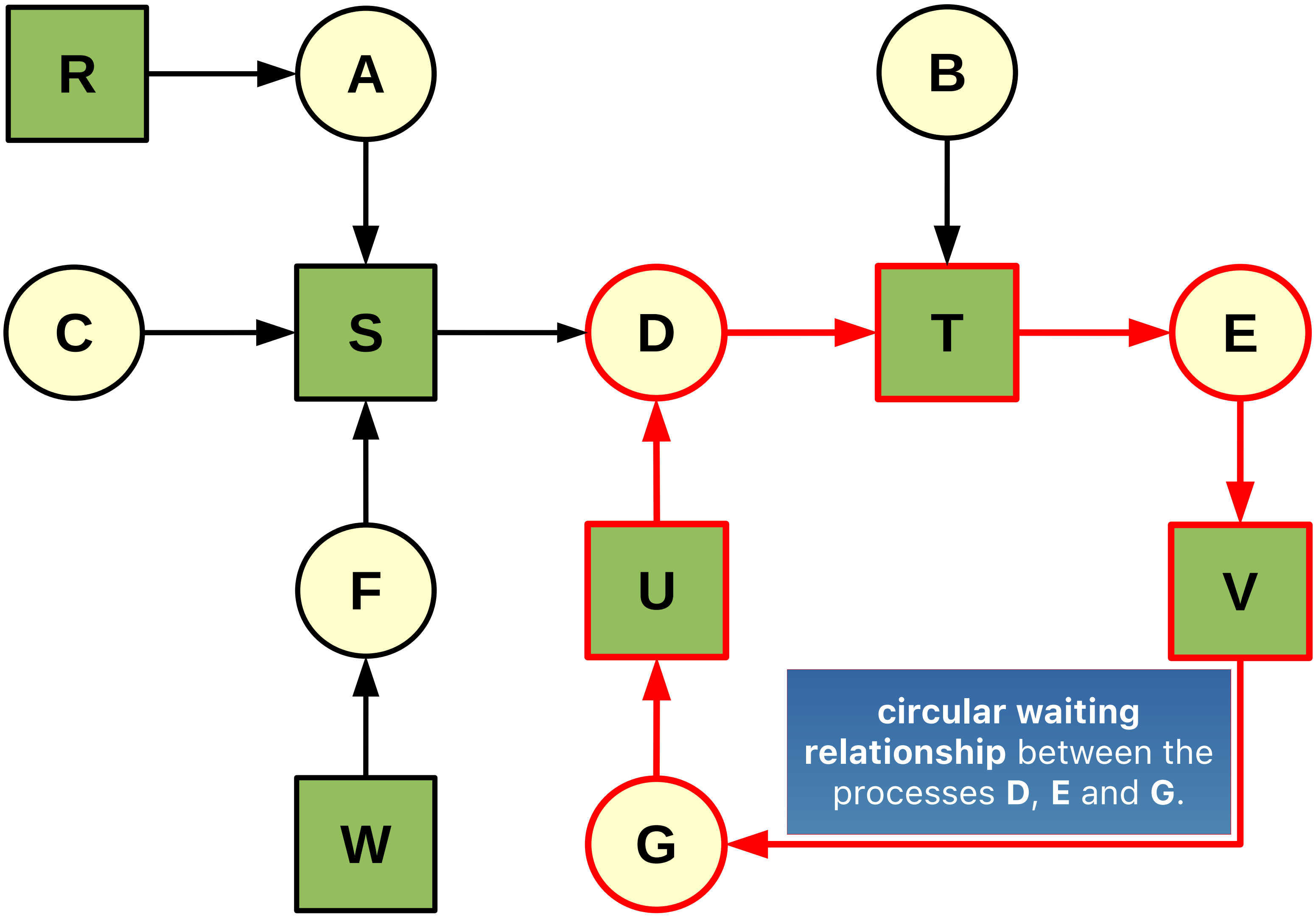
process P_2 **has occupied** the operating resource R_2

Resource Allocation Graphs (RAGs)

- situation: there are 7 processes (**A** to **G**) and 6 resources (**R** to **W**)
  - **is there circular waiting?**
  - **which processes are involved?**
- **current state**:
  - **A** occupies **R** and requests **S**
  - **B** does not occupy anything, but requests **T**
  - **C** does not occupy anything, but requests **S**
  - **D** occupies **U** and **S** and requests **T**
  - **E** occupies **T** and requests **V**
  - **F** occupies **W** and requests **S**
  - **G** occupies **V** and requests **U**



Resource Allocation Graphs (RAGs)



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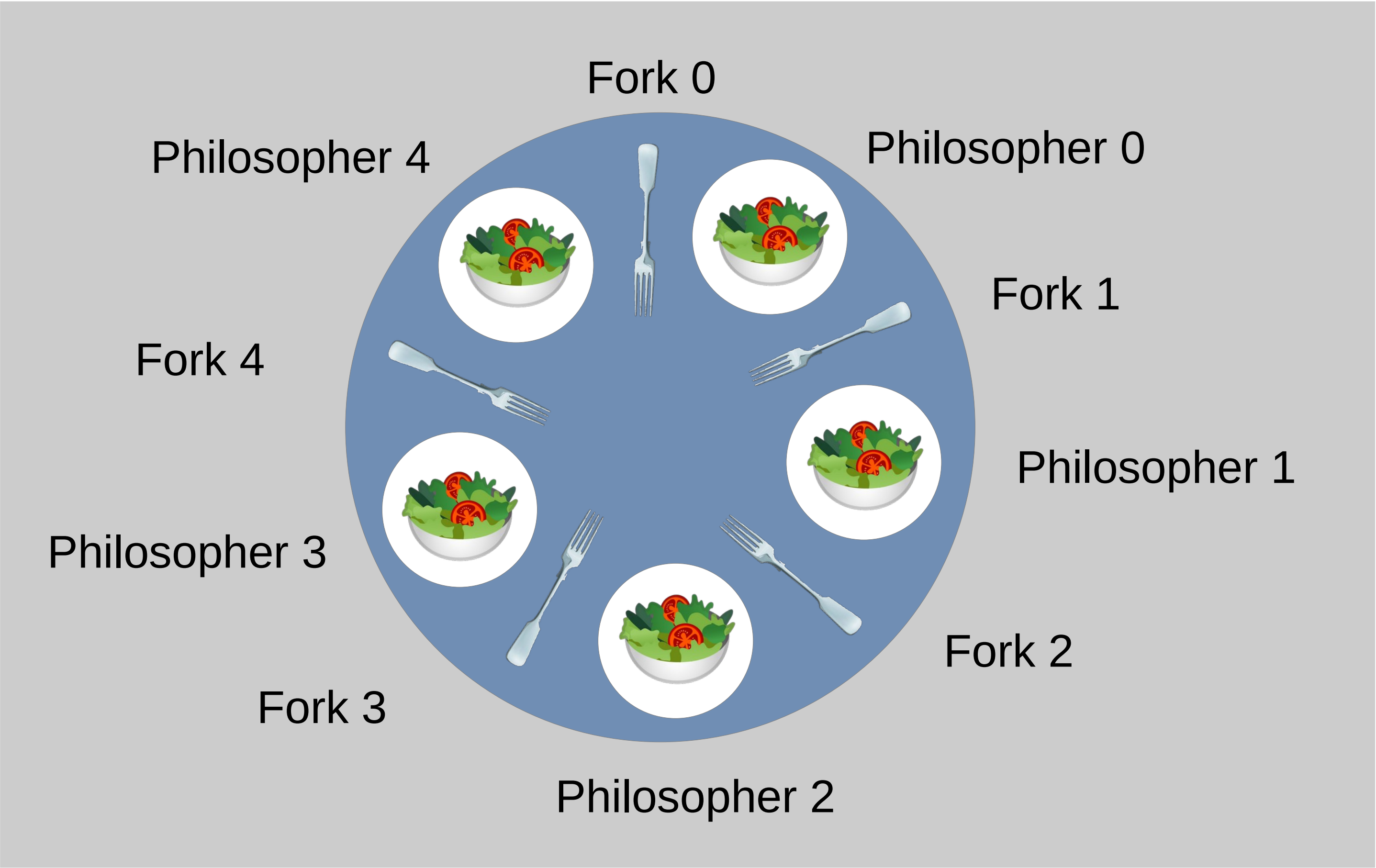
The Dining Philosophers Problem



The Dining Philosophers Problem (by E. W. Dijkstra)

Five philosophers, who have nothing else to do but think and eat, sit at a round table.

Thinking makes you hungry - so every philosopher will also eat. For this, however, a philosopher always needs **both** forks lying next to his plate.

Philosopher → Process
Fork → Operating Resource

Deadlocked Philosophers?

The first three necessary conditions are met:

✓ ■ **mutual exclusion**

- for reasons, the philosophers are not allowed to share forks

✓ ■ **hold and wait**

- the philosophers are so preoccupied with their thoughts before eating that they can neither really grasp their forks at the same time, nor do they think of putting a fork down again

✓ ■ **no preemption**

- snatching the fork from another philosopher is out of the question

? **But:** does a deadlock really happen?

Dining Philosophers - Attempt 1

```
void phil (int who) {
    while (1) {
        think();
        grab(who);
        eat();
        drop(who);
    }
}

void think () { ... }
void eat   () { ... }
```

```
semaphore fork[NPHIL] = {
  {1, NULL}, ...
};

void grab (int who) {
    wait(&fork[who]);
    wait(&fork[(who+1)%NPHIL]);
}

void drop (int who) {
    signal(&fork[who]);
    signal(&fork[(who+1)%NPHIL]);
}
```

With the help of a semaphore, **mutual exclusion** is guaranteed when accessing the forks. Each philosopher first takes his right fork and then his left fork.

Attempt 1: Prone to Deadlock Situations

context switch

every philosopher grabs his **right fork** first

```
void grab(0) {
  wait(&fork[0]);
```

```
void grab(1) {
  wait(&fork[1]);
```

```
void grab(2) {
  wait(&fork[2]);
```

```
void grab(3) {
  wait(&fork[3]);
```

```
void grab(4) {
  wait(&fork[4]);
  wait(&fork[0]);
}
```

Attempt 1: Prone to Deadlock Situations

context switch

```
void grab(0) {
  wait(&fork[0]);
```

```
void grab(1) {
  wait(&fork[1]);
```

```
void grab(2) {
  wait(&fork[2]);
```

```
void grab(3) {
  wait(&fork[3]);
```

```
void grab(4) {
  wait(&fork[4]);
  wait(&fork[0]);
}
```

```
  wait(&fork[4]);
}
```

```
  wait(&fork[3]);
}
```

```
  wait(&fork[2]);
}
```

```
  wait(&fork[1]);
}
```

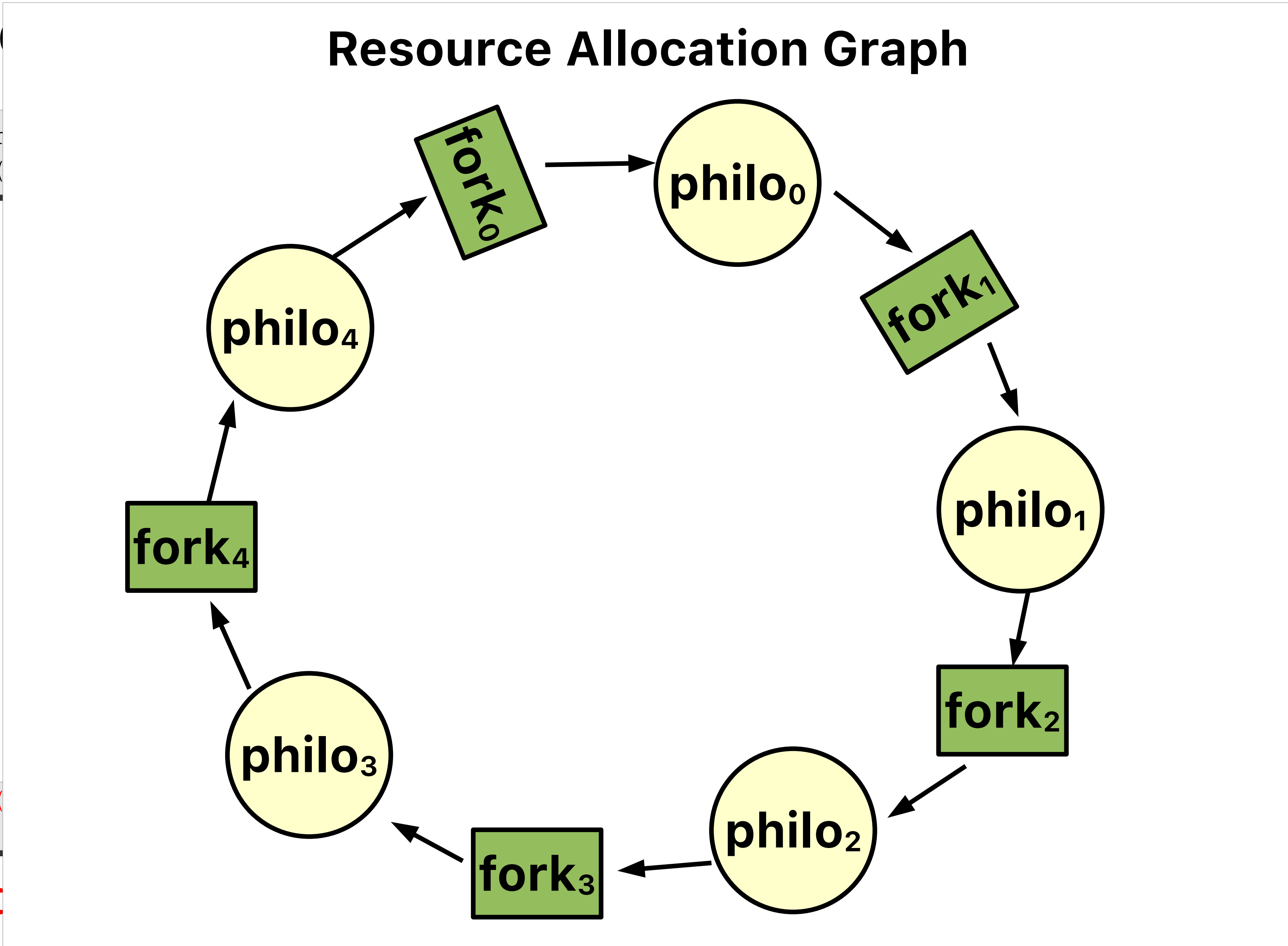
every philosopher grabs his **right fork** first

all philosophers block at the second wait

Deadlock Situation

Att

```
void gr
  wait(
```




```
);
);
```

he

```
  wait(
}
```

Dead

Dining Philosophers - Attempt 2

```
semaphore mutex = {1, NULL};

void grab (int who) {
  wait(&mutex);
  wait(&fork[who]);
  wait(&fork[(who+1) % NPHIL]);
  signal(&mutex);
}
```

The problem of the first implementation were context switches between the 1st and 2nd wait, in fact, a **critical section**.

The second implementation protects this critical section by mutual exclusion.

- Is it deadlock free?

- Is the second attempt a solid solution?

Dining Philosophers - Attempt 2

```
semaphore mutex = {1, NULL};

void grab (int who) {
  wait(&mutex);
  wait(&fork[who]);
  wait(&fork[(who+1) % NPHIL]);
  signal(&mutex);
}
```

The problem of the first implementation were context switches between the 1st and 2nd wait, in fact, a **critical section**.

The second implementation protects this critical section by mutual exclusion.

✓ - Is it deadlock free? **Yes**
  - max. 1 process can wait for a fork (cycle needs 2!)
  - a process waiting for **mutex** has no fork

! - Is the second attempt a solid solution? - No!
  - when $\mathbf{philo}_{who}$ eats, $\mathbf{philo}_{who+1}$ blocks a the entry of the critical section and **all other** philosophers **block**, too.
  - **result: low degree of concurrency** and **inefficient use of available resources**

Dining Philosophers - Attempt 3

```
const int N = 5;                        /* number of dining philosophers     */
semaphore mutex = {1, NULL};            /* mutual exclusion                  */
semaphore s[N] = {{0, NULL},...};       /* one semaphor for each philosopher */
enum {THINKING, EATING, HUNGRY } state[N]; /* philosopher states             */

int left(i) { return (i+N-1)%N; } /* index left neighbor  */
int right(i) { return (i+1)%N; }  /* index right neighbor */
```

```
void test (int i) {
  if (state[i] == HUNGRY && state[left(i)]  != EATING &&
                            state[right(i)] != EATING) {
    state[i] = EATING;
    signal(&s[i]);
  }
}
```

```
void grab(int i) {
  wait(&mutex);
  state[i] = HUNGRY;
  test(i);
  signal(&mutex);
  wait(&s[i]);
}
```

```
void drop(int i) {
  wait(&mutex);
  state[i] = THINKING;
  test(left(i));
  test(right(i));
  signal(&mutex);
}
```

This solution is deadlock-free and has a maximum degree of concurrency

Dining Philosophers - Discussion

- **for specific problems:** there are usually many different ways to ensure deadlock freedom
  - solutions differ in the degree of possible concurrency
  - if a solution is too restrictive, operating resources will temporarily lie idle unnecessarily
- **in general:** representative example of deadlock problems in the management of indivisible resources
  - based on E.W. Dijkstra (1965)
  - established standard scenario for evaluating and illustrating operating system and language mechanisms for concurrent programming

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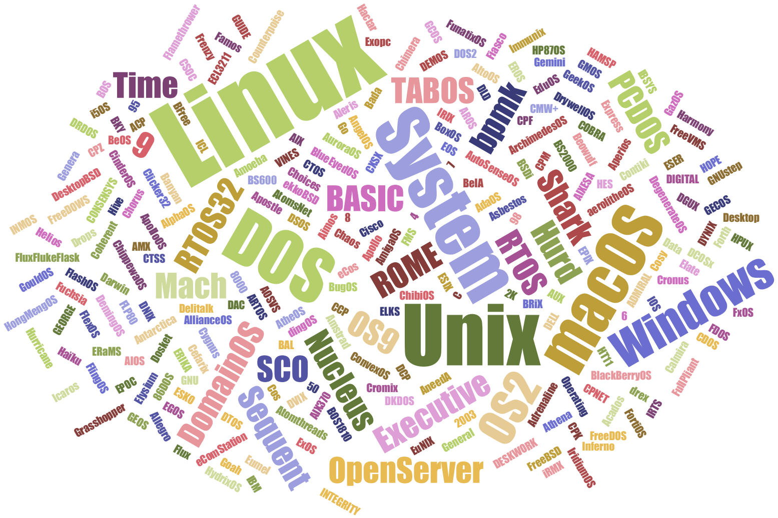

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Deadlock Prevention

(dt. **Verklemmungsvorbeugung**)

- **indirect methods** invalidate (at least) one of the conditions 1-3
  1. use of non-blocking process synchronisation methods
  2. design resource requests in an indivisible (atomic) way
  3. withdrawal of operating resources through **virtualisation**
     - ➔ virtual memory, virtual devices, virtual processor cores
- **direct methods** invalidate condition 4
  4. linear/total order of operating resources:
     - ➔ operating resource R_i can only be allocated before resource R_j, if i is in a linear order directly before j (i.e., $i < j$).

➔ indirect/direct methods: rules, that prevent the occurrence of deadlocks

- methods that take effect at **design/implementation time**

Deadlock Avoidance

(dt. **Verklemmungsvermeidung**)

- preventing circular waiting (**at run-time**) through strategic measures:
  - none of the first three necessary conditions is invalidated
  - ongoing **resource requirement analysis** eliminates circular waiting
- requests for operating resources of the processes are to be controlled:
  - **„safe state“** must always be maintained:
    - → there is a process sequence in which each process can cover its maximum resource requirement
  - **„unsafe states“** must be **avoided**:
    - → allocation rejection in the event of uncovered operating resource requirements
    - → do not serve requesting processes or suspend them at an early stage
- problem: a priori knowledge of maximum operating resource requirements of processes is necessary

Deadlock Avoidance: Safe and Unsafe States

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- c
  F ... ch,
  2

„Banker's Algorithm“

- management of process/operating resource matrices for **current occupancy** and **maximum occupancy**
- function for **finding a process sequence** in which the which the resources do not run out even if the "credit limit" is exhausted completely
- anticipatory application of this function in the event of fulfilling resource allocation requests

(c.f., Tanenbaum)

Deadlock Avoidance: Safe and Unsafe States

(using the example of multiple existing resources)

- **initial state**: a UNIX system with **12 shared memory segments**
  - process P1 requires max. 10 segments, P2: 4 segments, P3: 9 segments
- **current state**:
  P1 occupies 6 segments, P2 and P3 occupy 2 segments each,
  2 segments are still available (free)
  - P3 requests 1 segment, 1 would remain free → **unsafe state**
    - ➔ P3's request is rejected, P3 has to wait
  - P1 requests 2 segments, no free segment remains → **unsafe state**
    - ➔ the request of P1 is rejected, P1 has to wait
  - **safe** process **sequence**: P2 → P1 → P3

Deadlock Detection

(dt. **Deadlockerkennung**)

- deadlocks are (silently) accepted (**„ostrich algorithm“**) . . .
  - nothing in the system prevents the occurrence of circular wait conditions
  - *none* of the four conditions is invalidated
- approach: create **waiting graph** and search cycles → **O(n)**
  - too frequent verification wastes resources/computational power
  - too infrequent verification leaves operating resources lying idle
- **search for cycles** occurs mostly at large time intervals when:
  - serving operating resource requests takes too long
  - the utilisation of the CPU decreases despite process increase
  - the CPU has already been idle for a very long period of time

Deadlock Recovery

recovery phase *after* the detection phase

- **terminate processes** and thus free up operating resources
  - stopping deadlocked processes step by step (huge efforts)
    - ➔ start with the "most effective victim" – who is it?
  - terminate **all** deadlocked processes (huge damage)
- **revoke operating resources** and begin with the „most effective victim“ – again, who is it?
  - reverse or restart the identified process
    - ➔ transactions, checkpointing/recovery (huge effort)
  - starvation of the processes that have been reversed must be avoided
  - also, beware of livelocks!
- walking a tightrope between harm and expense:
  - damage is unavoidable, potential for (severe) follow-up damage

Discussion on Countermeasures

- deadlock *prevention*, *avoidance*, *detection*, *recovery*
- methods for avoidance/detection are less relevant in practice in the context of operating systems
  - methods are hard to implement, too costly and therefore not applicable
  - moreover, the prevalence of sequential programming makes these methods little necessary
- risk of deadlocks can be solved by virtualisation of operating equipment
  - processes use/occupy **logical operating resources** only
  - goal: withdraw **physical operating resources** from the processes (without their knowledge) at critical moments
  - with this, condition of preemption is defused
- deadlock prevention methods are more relevant

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⏭ Summary and Outlook

- **summary**
  - **process deadlocks:** mutual blocking of concurrent but independent processes
    - → deadly embrace: deadlocks and livelocks
    - → four deadlock conditions must hold true – invalidate (at least) a single condition to avoid deadlocks
    - → occurs with reusable and consumable resources
  - **deadlock handling**
    - → dining philosophers and discussion of (potential) solutions
    - → countermeasures: deadlock prevention, avoidance, detection and resolution
- **outlook: memory management**
  - main memory is a fundamental operating resource to processes
  - memory allocation and memory management for multi-program operation, address mapping

References and Acknowledgments

Lecture

- Systemnahe Programmierung in C (SPiC), Betriebssysteme (Jürgen Kleinöder, Wolfgang Schröder-Preikschat)
- Betriebssysteme und Rechnernetze (Olaf Spinczyk, Embedded Software Systems Group, Universität Osnabrück)

Teaching Books and Reference Book

[1] Avi Silberschatz, Peter Baer Galvin, Greg Gagne: *Operating System Concepts*, John Wiley & Sons*, 2018*.

[2] Andrew Tanenbaum, Herbert Bos: *Modern Operating Systems*, Pearson, 2015.

[3] Wolfgang Schröder-Preikschat: *Grundlage von Betriebssystemen – Sachwortverzeichnis*, 2023.
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