Operating Systems

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IV. Synchronisation
May 3, 2023 (Summer Term 2023)

www.informatik.rub.de
Chair of Operating Systems and System Software

Agenda

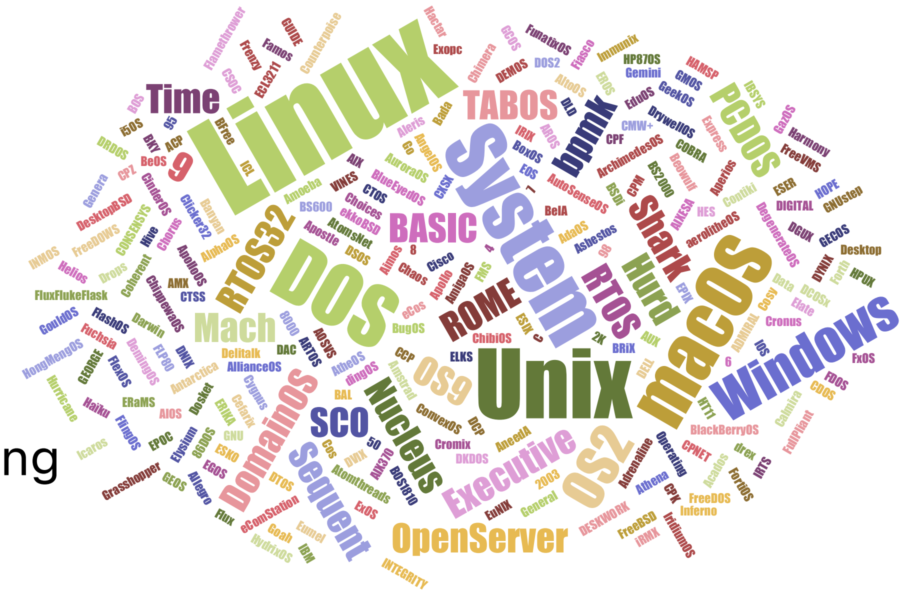
- Recap
- Organizational Matters
- Problem Scenario and Concepts
  - Critical Sections, Race Conditions
- Synchronisation
  - Ad-hoc Solutions, Busy Waiting
  - Hardware Support, Atomic Operations
  - Operating System Support, Passive Waiting
- Summary and Outlook

Literature References

Silberschatz, Chapter 6

Tanenbaum, Chapters 2.3, 2.5

⏮ Recap



- processes: **key abstraction** for **activities** in operating systems
  - conceptually independent **sequential control flows** (alternating CPU and I/O bursts)
  - **multiplexing** of the CPU
- **process models**
  - discussion: the **weight** of processes
  - processes vs. threads vs. user-level threads
- processes in practice: **Unix process model**
  - UNIX systems provide **system calls** to create, manage, and link processes

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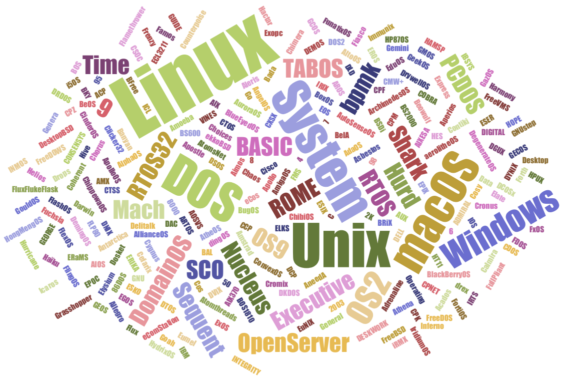
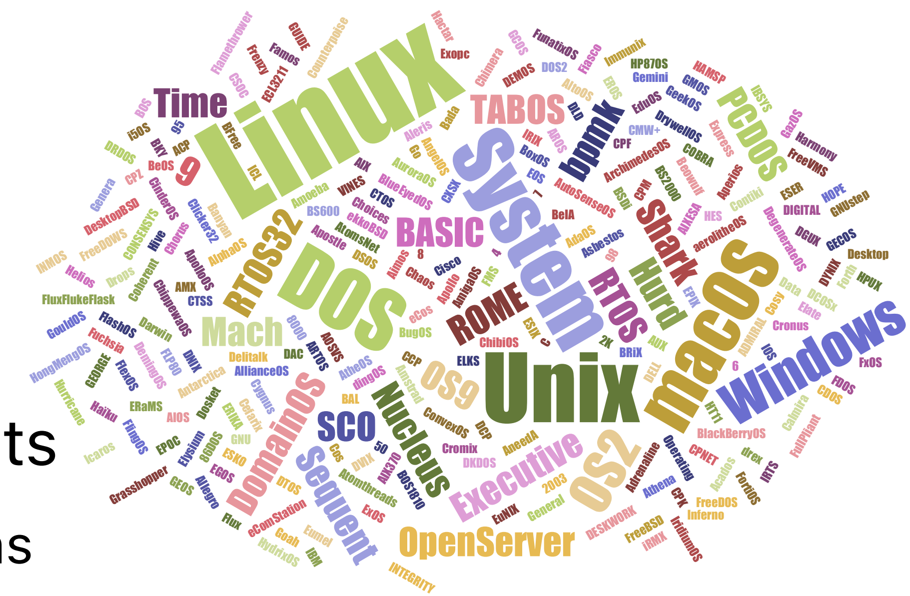
Organizational Matters



- lecture
  - Wednesday, 10:15 – 11:45
  - format: synchronous, **hybrid**
    - → in presence (Room HID, Building ID)
    - → online lecture (Zoom)
  - language: English/German
  - exercises: **group allocation ~~almost~~ complete**
    - if you are not yet signed up → Moodle
    - make use of group work - for your own benefit!
- manage course material, asynchronous communication: Moodle
- `https://moodle.ruhr-uni-bochum.de/course/view.php?id=50698`

Agenda



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Scenario: Processes and Shared Resources

- process := **program in execution** (under OS control)
  - the core abstraction for control flows in computer systems
  - conceptually independent
  - technically a multiplexing of the CPU takes place
  - the operating system determines the time of **preemption** and the dispatching order of the processes in the ready list

- sharing of resources: **code** and **data**
  - **threads** (and user-level threads) operate in the **same address space**
  - the operating system can use the MMU to map a **single memory area** into **multiple address spaces (i.e., different processes)**
  - operating system data is also shared (in a **controlled** manner)

Definition: Critical Section

- in the case of race conditions, n processes fight over access to shared data
- the code fragments in which this critical data is accessed are called **critical sections**

Problem

- it must be ensured that only one process can be in a critical section at any time

Example: Singly Linked List in C

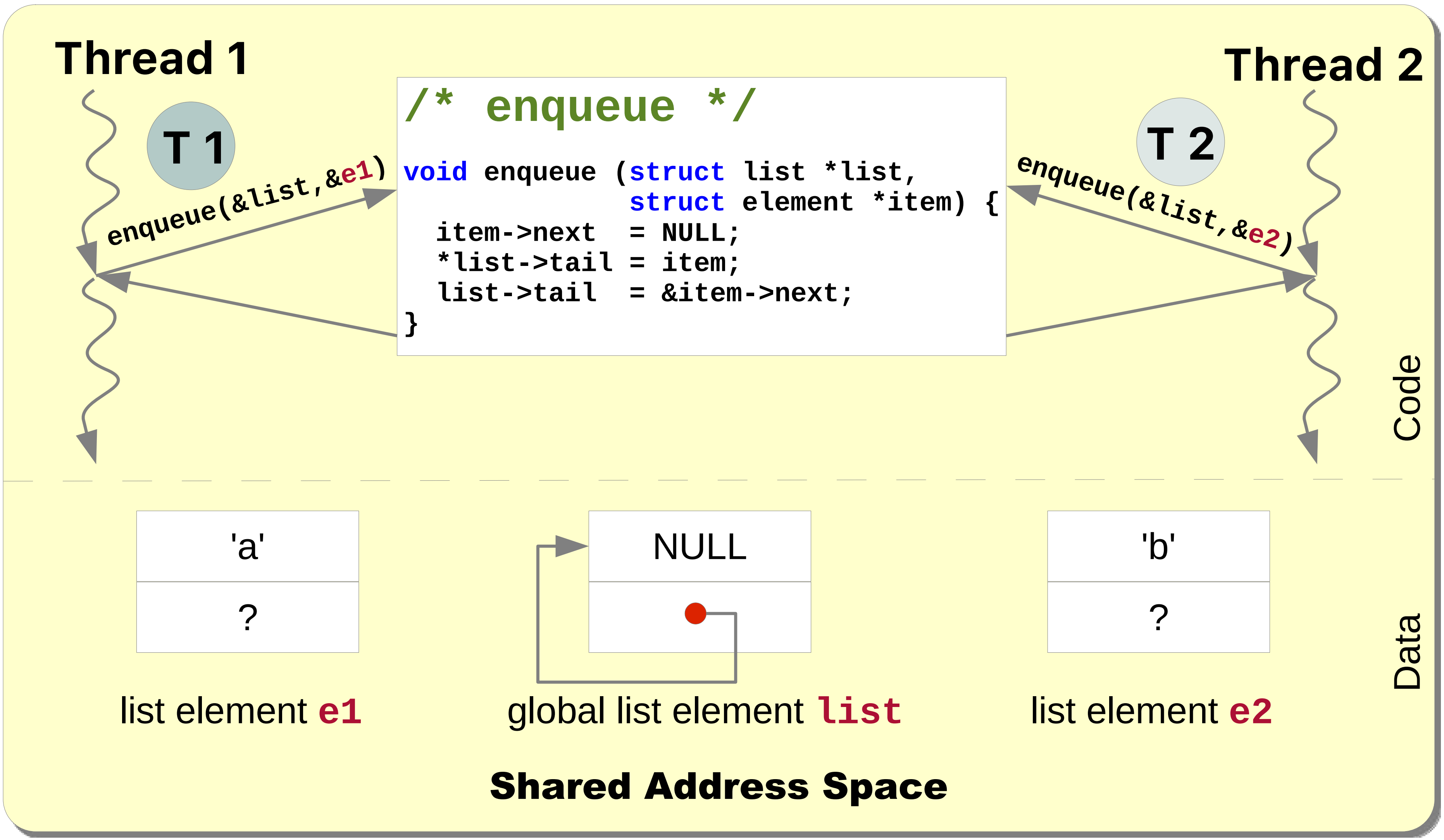
```
/* data type for list elements */
struct element {
  char payload;             /* actual “payload” */
  struct element *next;     /* next pointer */
};

/* data type for managing lists */
struct list {
  struct element *head;     /* first element */
  struct element **tail;    /* 'next' of the last element */
};

/* function to insert a new list element */
void enqueue (struct list *list, struct element *item) {
  item->next  = NULL;
  *list->tail = item;
  list->tail  = &item->next;
}
```

Note: The list implementation is clever because tail does *not* refer to the last element but to the next pointer, there is *no* special treatment for insertion into an empty list.

Example: Singly Linked List in C



Example: Singly Linked List in C

First Scenario:
Thread 2 *after* Thread 1

T 1

```
enqueue(&list,&e1)
```

```
e1->next = NULL;
```

```
*list->tail = e1;
```

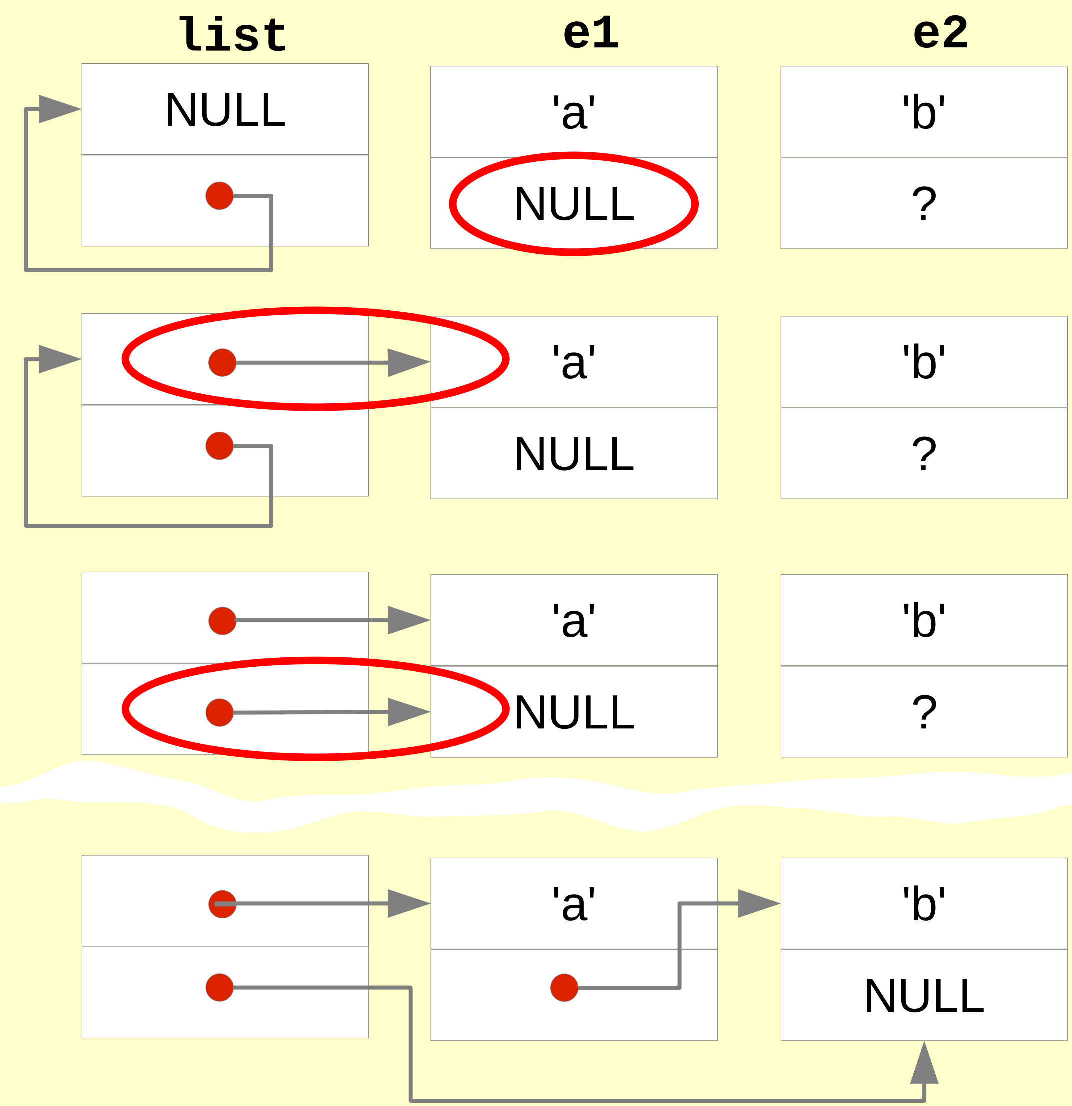
```
list->tail = &e1->next;
```

⋮

T 2

```
enqueue(&list,&e2)
```

```
e2->next  = NULL;
*list->tail = e2;
list->tail  = &e2->next;
```



Example: Singly Linked List in C

Second Scenario:
Thread 2 *overlaps* Thread 1

T 1

```
enqueue(&list,&e1)
```

```
e1->next = NULL;
*list->tail = e1;
```

context switch

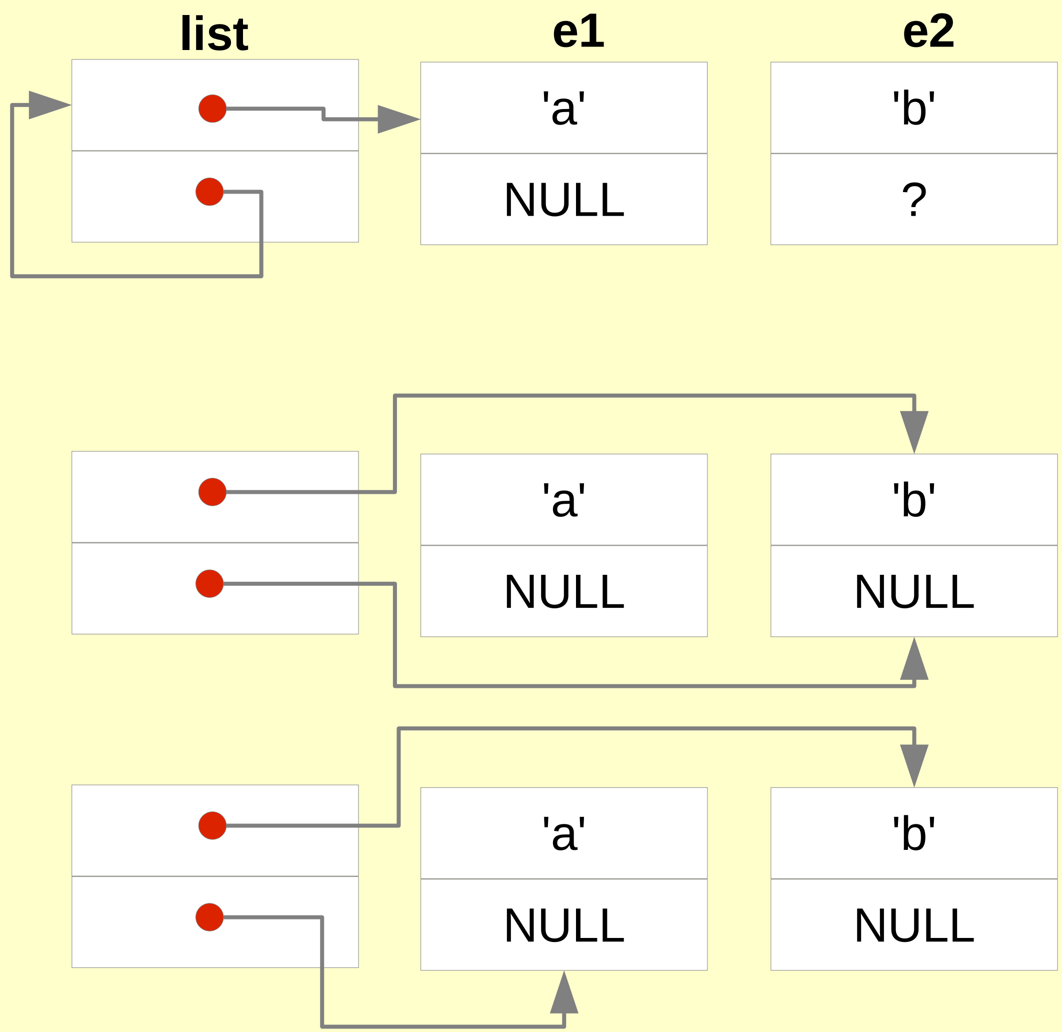
T 2

```
enqueue(&list,&e2)
```

```
e2->next  = NULL;
*list->tail = e2;
list->tail  = &e2->next;
```

context switch

```
list->tail = &e1->next;
```



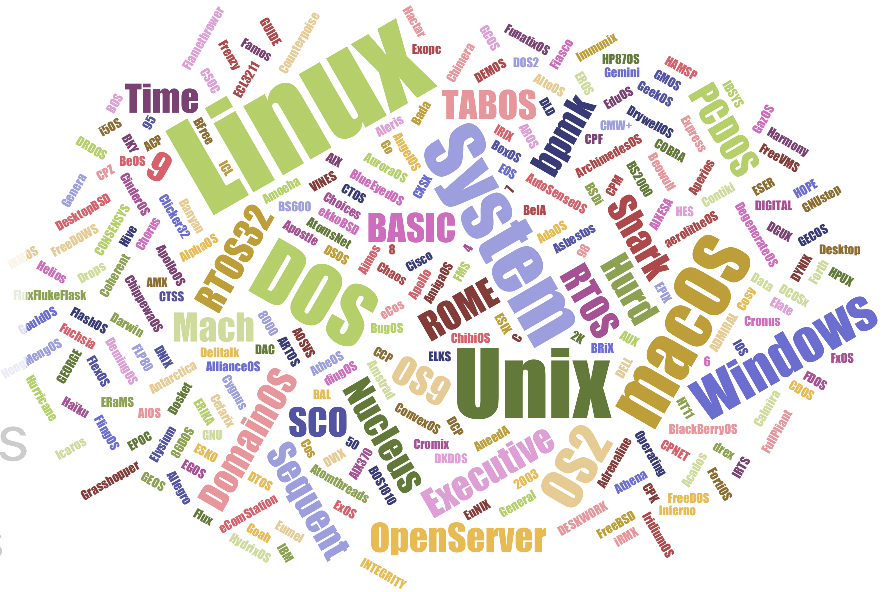
Similar Patterns

- **shared memory** used for interprocess communication
  - systems with “shared memory” service
- **threads (and user-level threads)**
  - concurrent (write) access to shared variables
- **operating system data** needed to coordinate the access of processes to indivisible resources
  - file system structures, process table, memory management
  - devices (e.g., terminals, printers, network interfaces)
- **interrupt synchronisation**
  - **caution:** synchronisation methods that are suitable for *process synchronisation* do not necessarily work for *interrupt synchronisation*!

Definition: Race Condition

- a race condition (dt. Wettlaufsituation) is a situation in which **multiple processes concurrently access shared data** and **at least one manipulates** it
- the ultimate value of the shared data in such a race condition depends on the **order** in which the processes access it
- the result is therefore **unpredictable** and may even be **incorrect** in the case of overlapping accesses!
- to **avoid** race conditions, concurrent processes that work on shared data must be **synchronised**

Agenda



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Definition: Synchronisation

- synchronisation := **coordination of cooperation and competition** between processes
- synchronisation brings the activities of different concurrent processes into a **<u>certain</u> order**
- it thus achieves across processes what the sequentiality of activities ensures within a process

Based on: Herrtwich/Hommel (1989), Cooperation and Competition

Approach: Lock Variables

a lock variable is an abstract data type with two operations: **`acquire`** and **`release`**

```
Lock lock; /* global lock variable */

/* code example: enqueue */
void enqueue (struct list *list, struct element *item) {
  item->next  = NULL;

  acquire (&lock);

  *list->tail = item;
  list->tail  = &item->next;

  release (&lock);
}
```

- block a process until the associated lock is *released*
- then *acquires* the lock "from the inside"

- *release* the associated lock - without delaying (or even blocking) the calling process

basic pattern of a **locking algorithm**

Naive Solution with Busy Waiting

```c
/* lock variable (initially zero) */
typedef unsigned char Lock;

/* enter critical section */
void acquire (Lock *lock) {
  while (*lock); /* empty loop body, block */
  *lock = 1;
}

/* leave critical section */
void release (Lock *lock) {
  *lock = 0;
}
```

Naive Solution with Busy Waiting

```
/* lock variable */
typedef unsigned char Lock;

/* enter critical section */
void acquire (Lock *lock) {
  while (*lock);
  *lock = 1;
}

/* leave critical section */
void release (Lock *lock) {
  *lock = 0;
}
```

- **`acquire`** is supposed to protect a critical section, but its execution itself is critical!
  - problematic is the moment *after* leaving the while-loop and *before* setting the lock variable
  - when the running process is preempted at this moment, another process could find the critical section free and enter it, **too**

In the further course (at least) two processes could overlap the critical section that actually is (pseudo-)protected by **`acquire`**!

Lamport: Bakery Algorithm

- **before** a process is allowed to enter the critical section, it is given a **wait number**
- **entrance** to the critical section in **order** of the **wait number**
- if the critical section is free, the process with the **lowest wait number** may enter the critical section
- wait number **expires** upon leaving the critical section

Caveat:

- the algorithm *cannot* guarantee that a wait number is assigned to only one process
- consideration of process priorities to resolve this limitation

Lamport: Bakery Algorithm

```
typedef struct { /* lock variable (initially everything 0) */
  bool choosing[N]; /* is x drawing a waiting number? */
  int number[N];    /* which waiting number has x?    */
} Lock;

void acquire (Lock *lock) { /* enter critical section */
  int j; int i = pid();
  lock->choosing[i] = true;
  lock->number[i]   = max(lock->number[0], …, number[N-1]) + 1;
  lock->choosing[i] = false;
  for (j = 0; j < N; j++) {
    while (lock->choosing[j]);
    while (lock->number[j] != 0 &&
           (lock->number[j] < lock->number[i] ||
            (lock->number[j] == lock->number[i] && j < i)));
} }

void release (Lock *lock) { /* leave critical section */
  int i = pid(); lock->number[i] = 0;
}
```

note: pseudo code

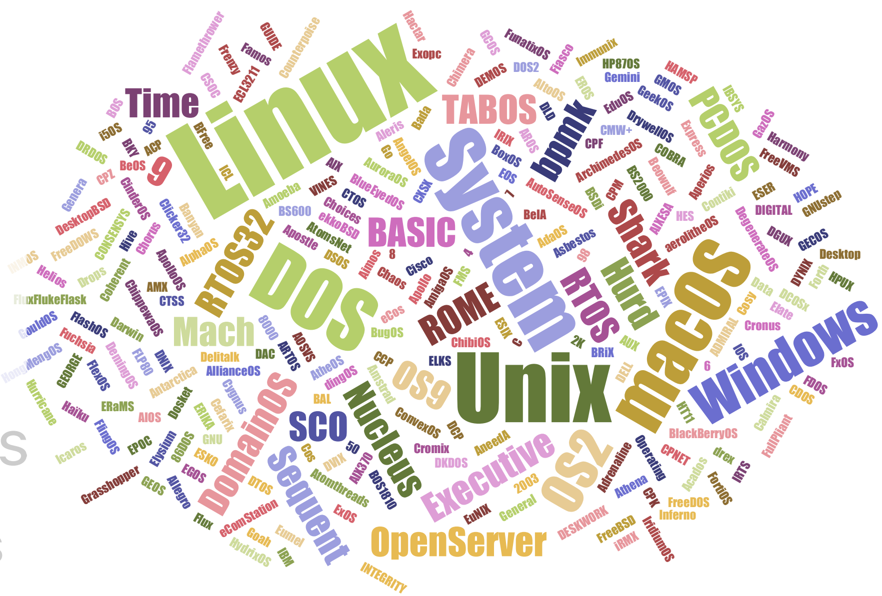
Discussion: Bakery Algorithm

the algorithm is a provably correct solution to the problem of critical sections, but:

- as a rule, it is **unknown** in advance **how many processes** will compete for entry into a critical section
- process IDs are not in the value range from 0 to N-1
- execution time of the function acquire is $O(N)$ even **if the critical section is free**

Wanted: A algorithm which is correct *and* as simple as the naive approach!

Agenda



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Locks with Atomic Operations

- at the hardware level, CPUs implement (atomic) **read/modify/write (RMW) operations** which are suitable for the implementation of lock algorithms
- Motorola 68K: TAS (***test-and-set***)
  - sets bit 7 of the destination operand and returns the previous state in condition code bits

```
acquire:    TAS    lock
            BNE    acquire
```

- Intel x86: XCHG (***exchange***)
  - atomically exchanges the contents of a register with that of a variable in memory

```
            mov    ax,1
acquire:    xchg   ax,lock
            cmp    ax,0
            jne    acquire
```

- PowerPC: LL/SC (***load linked/store conditional***)

Discussion: Busy Waiting

Issue of the lock algorithms shown so far:
the actively waiting process (i.e., busy waiting)

- since the process is waiting, it cannot provoke a change in the condition it is blocked on
- therefore the waiting process unnecessarily restricts the progress of other processes
- thus ultimately also harms itself:
  - the longer the process keeps the processor to itself → the longer it has to wait for other processes to fulfill the condition it is blocked on

Disabling Interrupts

- note: only interrupts (e.g., timer) lead to the CPU revocation from a process during its execution of a critical section

```
/* enter critical section */
void acquire (Lock *lock) {
  asm ("cli");
}

/* leave critical section */
void release (Lock *lock) {
  asm ("sti");
}
```

`cli` and `sti` are used with Intel x86{,-64} processors to **disable** and **enable** interrupts

- this "solution" will affect all processes and the operating system itself (including device drivers)
  - **`sti`** and **`cli`** must therefore not be used in user mode

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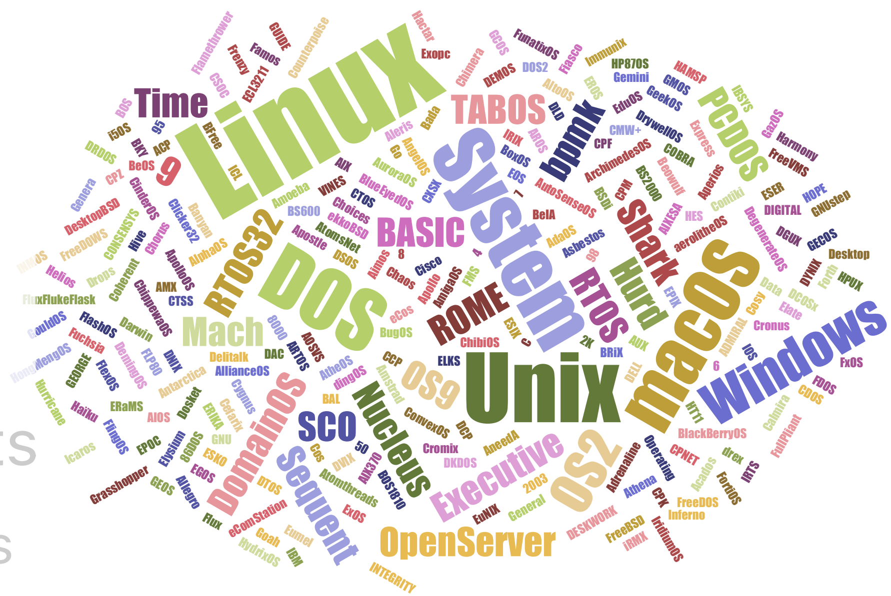

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Discussion: Passive Waiting

- processes yield control of the CPU while waiting for events to occur
  - in case of synchronisation a process "blocks itself" on an event
  - PCB of the process placed in a queue
  - if the event occurs, a process waiting for it is deblocked
- the waiting phase of a process is designed as a blocking phase (cf. I/O burst)
  - the schedule for the processes is updated (scheduling)
  - another, ready process is dispatched according to schedule (dispatching)
  - if no process is ready anymore, the CPU runs "empty" (idle phase)
- with the beginning of its blocking phase the CPU burst of a process also ends

Semaphore (dt. Semaphor {m})

- OS abstraction to implement synchronisation of processes using **passive waiting**

- semaphore: a "non-negative integer", for which two distinct atomic (**<u>indivisible operations</u>)** are defined:

  P (hol. prolaag, „decrement“; also: *down*, ***wait***)
  - if the semaphore has the value 0: the running process is blocked
  - else: the semaphore is *decremented* by 1

  V (hol. verhoog, „increase“; also: *up*, ***signal***)
  - if existing: another process which is blocked on the semaphore is deblocked
  - else: the semaphore is *incremented* by 1

- semaphore is an operating system abstraction for exchanging synchronisation signals between **concurrent processes**

Semaphore

```
/* Semaphore Implementation, Pseudo-Code */
Semaphore semaphore;

semaphore.wait() {
    if (counter == 0) {
      worker *self = scheduler.active(); /*
      enqueue(self);
      scheduler.block(self);
    }
    else
      counter--;
}

semaphore.signal() {
    worker *worker = dequeue();
    if (worker)
      scheduler.wakeup(worker);
    else
      counter++;
}
```

Semaphore provides a list of PCBs with the access methods **enqueue** and **dequeue**.

The scheduler must provide 3 operations:

- **active:** provides PCB of the running process
- **block:** puts a process into the BLOCKED state
- **wakeup:** puts a blocked process back on the ready list

Semaphore: Simple Interaction Patterns

- **unilateral synchronisation** (dt. einseitige Synchronisation)

```
/* shared memory */
Semaphore elem;
struct list l;
struct element e;
```

```
void producer() {
  enqueue(&l, &e);
  signal(&elem);
}
```

```
void consumer() {
  struct element *x;
  wait(&elem);
  x = dequeue(&l);
}
```

```
/* initialisation */
elem = 0;
```

- example: producer/consumer relationship between threads
- only consumer may block (i.e., when no consumable resource is available)
- blocked consumers resume when consumable resources are available (i.e., when a producer calls `signal()`)

Semaphore: Simple Interaction Patterns

- **multilateral synchronisation** (dt. mehrseitige Synchronisation)

```
/* shared memory */
Semaphore resource;
```

```
/* initialisation */
resource = N; /* N >= 1 */
```

modus operandi:
as with mutual exclusion

- example: threads share reusable resources (e.g., buffers), only a limited number of the shared resource is available for simultaneous use
- access to/allocation of the shared resource must be synchronized between all threads involved
- all threads are potentially blocked if all available resources have already been spent

Semaphore: Interactions

- example: **the first readers-writers problem**

As with mutual exclusion, a critical section should be protected in this example. However, there are **two classes** of competing processes:

- **writer**: they change data and must therefore get mutual exclusion guaranteed
  - concurrent writes are unsafe
- **reader**: they access data read-only and therefore multiple readers may enter the critical section at the same time
  - concurrent reads are safe

Semaphore: Interactions

- example: **the first readers-writers problem**

```
/* shared memory */
Semaphore mutex;
Semaphore writer;
int readcount;
```

```
/* initialisation */
mutex     = 1;
writer    = 1;
readcount = 0;
```

```
/* writer */
wait (&writer);

/* write operations */
signal (&writer);
```

```
/* reader */
wait(&mutex);
readcount++;
if (readcount == 1)
  wait(&writer);
signal(&mutex);

/* read operations */
wait(&mutex);
readcount--;
if (readcount == 0)
   signal(&writer);
signal(&mutex):
```

Semaphore: Discussion

- **semaphore extensions and variants**
  - binary semaphore or ***mutex***
  - non-blocking `wait()`
  - timeout: `wait()` with expiration (e.g., 500 ms)
  - counter arrays (several semaphores)
- **pitfalls and sources of error**
  - risk of deadlocks
  - complex synchronisation patterns become difficult

    dependence of cooperating processes
    - all processes must follow the protocols strictly
  - semaphore usage is *not* enforced

→ monitor concept: programming language support

Putting a Semaphore to Good Use

mutual exclusion: a semaphore initialized with 1 semaphore can act as a lock variable

```
Semaphore lock; /* = 1; semaphore as locking variable */

/* example code: enqueue */
void enqueue (struct list *list, struct element *item) {
  item->next  = NULL;

  wait (&lock);

  *list->tail = item;
  list->tail  = &item->next;

  signal (&lock);
}
```

- the first process that **enters** the critical section **decreases** the counter **to 0**
- all subsequent **processes block**

- when **leaving** either
  (I) a blocked **process** is **woken** up *or*
  (II) the counter is **increased to 1** again

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⏭ Summary and Outlook

- **summary**
  - uncontrolled, concurrent data access leads to errors
    - **synchronisation** methods ensure coordination
    - necessary for: **cooperation** (producer/consumer) and **competition** (concurrent use of system resources)
  - **ad-hoc method:** busy waiting
    - **waste of resources**, in particular previous CPU time
  - synchronisation methods with **hardware** and **operating system support**
    - **mutual exclusion** using **atomic operations**
    - **semaphores, unilateral** and **multilateral synchronisation**
    - flexible but sensitive to errors when **synchronisation protoco**l is violated
- **outlook: deadlocks**
  - **process deadlocks:** mutual blocking of concurrent but independent control flows
  - deadlock **prevention**, **avoidance**, **detection**

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.
https://www4.cs.fau.de/~wosch/glossar.pdf