TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Informatik Institut für Systemarchitektur, Professur für Betriebssysteme

OPERATING-SYSTEM CONSTRUCTION

Material based on slides by Olaf Spinczyk, Universität Osnabrück

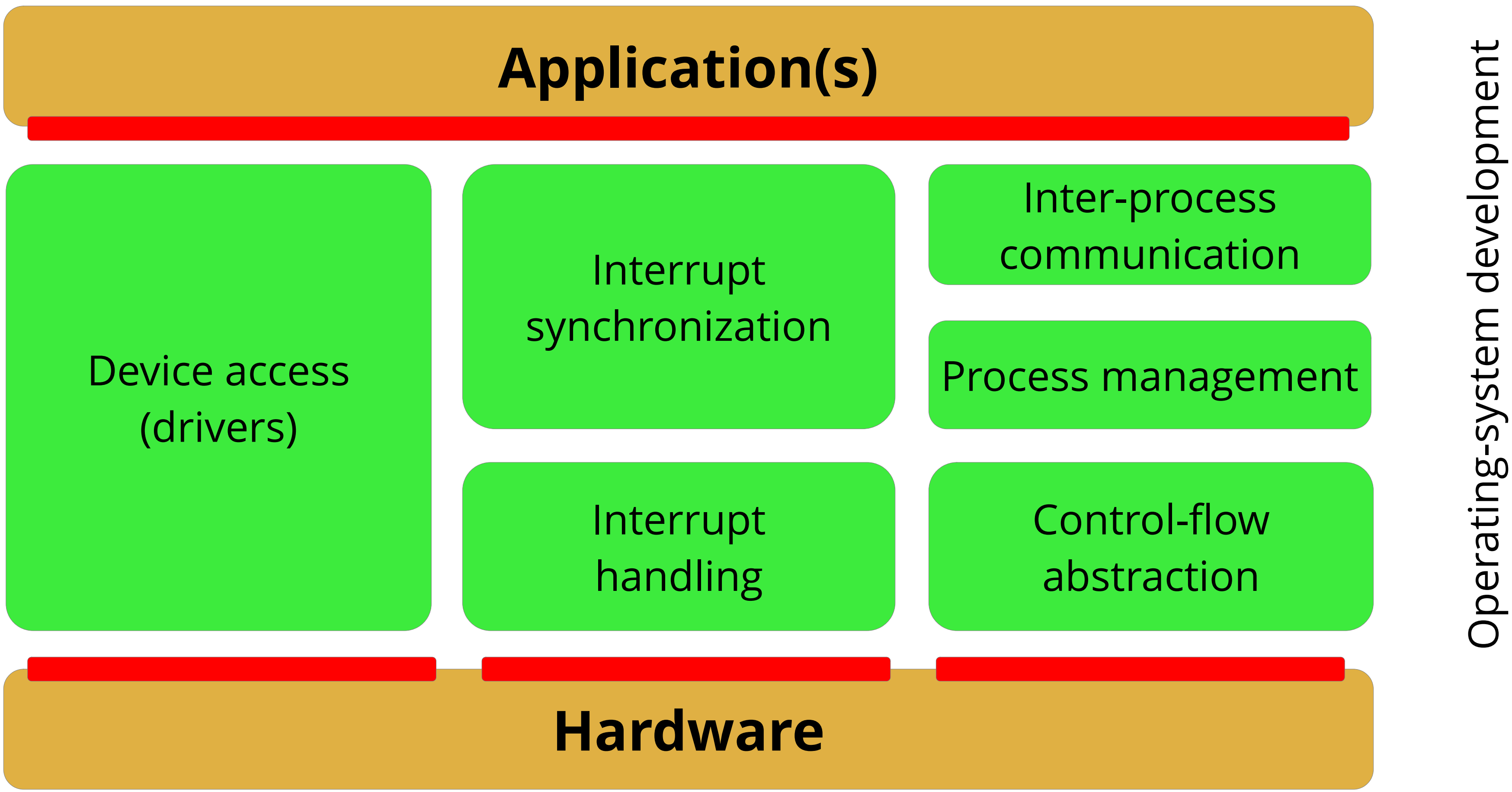
Thread Synchronization

https://tud.de/inf/os/studium/vorlesungen/betriebssystembau

HORST SCHIRMEIER

Overview: Lectures

Structure of the “OO-StuBS” operating system:



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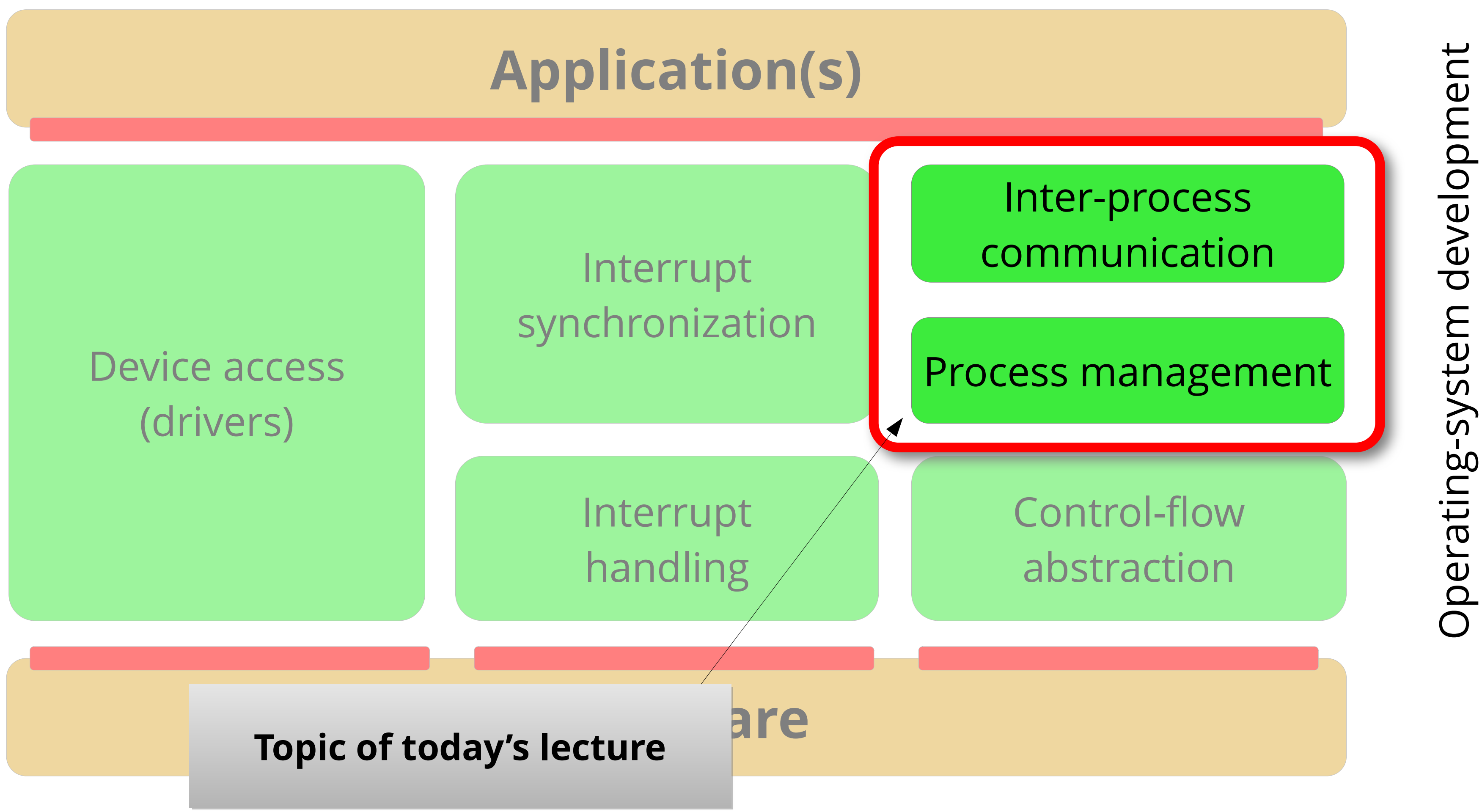

Agenda

- Motivation
- Control-flow Level Model with Threads
- Thread Synchronization
  - Constraints
  - Mutex, Implementation Variants
  - Concept of Passive Waiting
  - Semaphore
- Example: Synchronization Objects on Windows
- Summary

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Motivation: Scenario

- Given: Threads <f> and <g>
  - Preemptive round-robin scheduling
  - Both access a shared buffer **`buf`**

```
#include "BoundedBuffer.h"

extern BoundedBuffer buf;
```

```
void f() {
  ...
  char el;
  el = buf.consume();
  ...
}
```

```
void g() {
  ...
  char el = ...
  buf.produce( el );
  ...
}
```

Motivation: Consistency Issues

- Given: Threads <f> and <g>
  - **Problem: Buffer accesses can overlap**

```
char BoundedBuffer::consume() {
  int elements = occupied;
  if (elements == 0) return 0;
  char result = buf[nextout];
  nextout++; nextout %= SIZE;
```

resume

```
...
void BoundedBuffer::produce(char data) {
  int elements = occupied;
  if (elements == SIZE) return;
  buf[nextin] = data;
  nextin++; nextin %= SIZE;
  occupied = elements + 1;
}
...
```

resume

```
  occupied = elements – 1;
  return result;
}
```

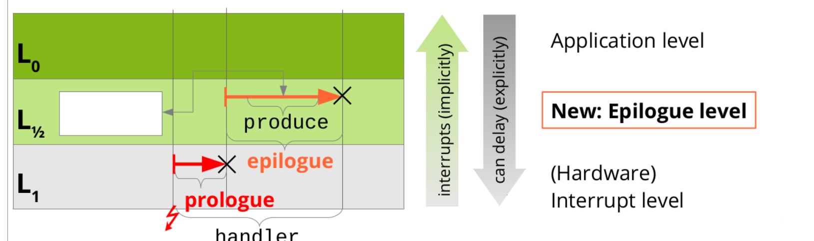
We’ve seen this before …

L05: Interrupt Synchronization

What is different this time?

Prologue/Epilogue Model – Approach

- **Idea:** We insert **another level $L_{½}$** between application level L_0 and the interrupt-handling levels $L_{1...n}$
  - IH is divided into ***prologue*** and ***epilogue***
    - **Prologue** runs on interrupt level $L_{1...n}$
    - **Epilogue** runs on (software) level $L_{½}$ (**epilogue level**)
  - State resides (as far as possible) on epilogue level
    - actual interrupt handling is only disabled briefly

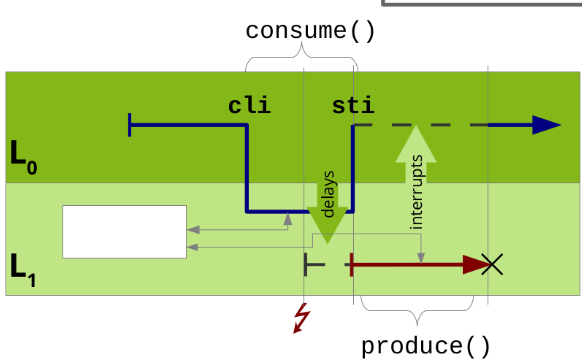


Bounded Buffer – Hard Synchronization

Access "from above" is synchronized hard.
(For the execution of consume(), the control flow switches to L_1.)

```
char consume() {
  cli();
  ...
  char result = buf[nextout++];
  ...
  sti();
  return result;
}
```

```
void produce(char data) {
  // nothing to do here
  ...
  buf[nextin++] = data;
  ...
  // nothing to do here
}
```



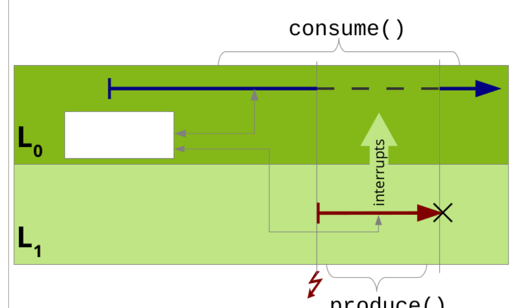
State (logically) resides on L_1.

Bounded Buffer – Nonblocking Sync.

State (logically) resides on L_0

```
void produce(char data) {
  ?
}
```

```
char consume() {
  ?
}
```



Access "from below" is synchronized in a nonblocking manner.
(consume() yields a correct result even if during its execution produce() was executed.)

First Conclusion

- Before: Synchronization of accesses by control flows from **different levels**
  - State was logically assigned to one specific level
  - Synchronization either “from above” (hard) or “from below” (non-blocking)
  - Implicit sequentialization within the same level

- Now: Synchronization of accesses by control flows from the **same level**
  - Threads can be preempted by other threads at any time.

That’s the point of threads!

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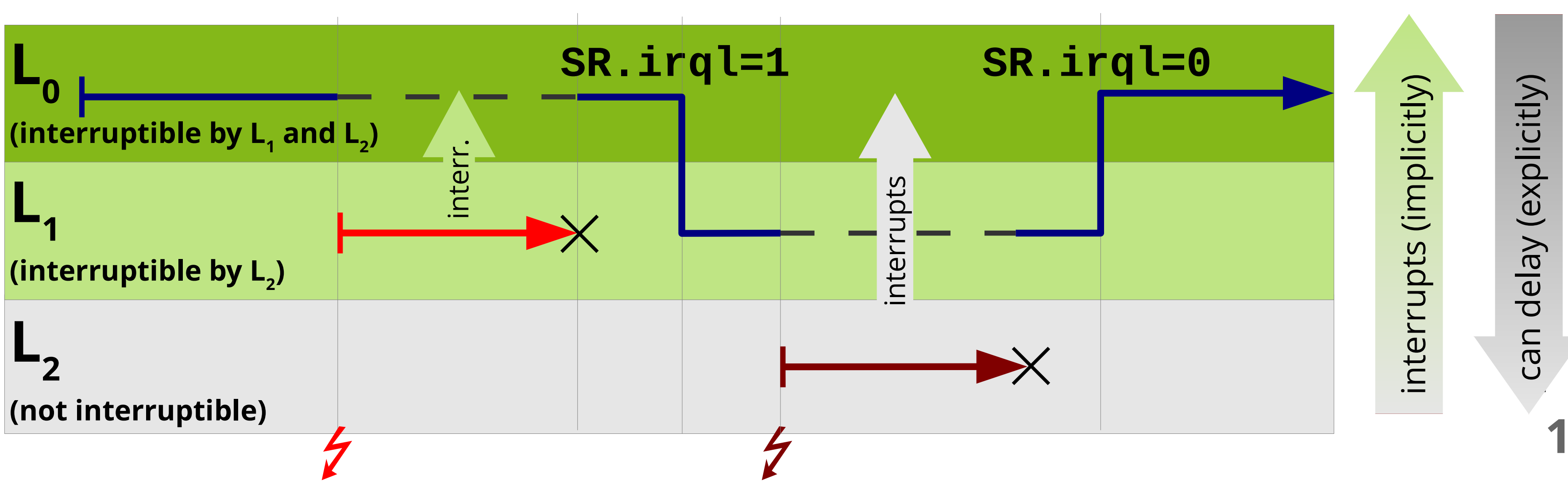
Control-Flow Level Model: so far

- Control flows on L_f are
  - **interrupted anytime** by control flows on L_g (for $f < g$)
  - **never interrupted** by control flows on L_e (for $e \leq f$)
  - **sequentialized** with other control flows on L_f
- Control flows can switch levels
  - by special operations (here: modifying the status register)



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Control-Flow Level Model: so far

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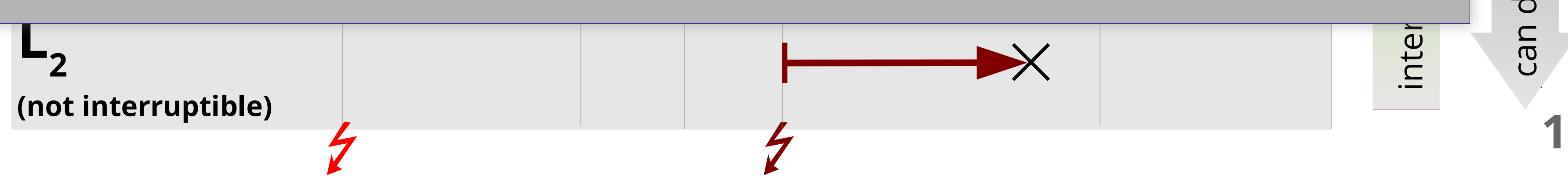
  - **sequentialized** with other control flows on L_f
- Control flows can switch levels

By supporting **preemptive threads** we cannot sustain this **assumption** any longer!

- No ***run-to-completion*** semantics anymore
- State accesses (from the same level) are **not** implicitly sequentialized anymore
- True for all levels that allow preemption of control flows; usually this is the application level L_0



Control-Flow Level Model: new

- Control flows on L_f are
  - **interrupted anytime** by control flows on L_g (for $f < g$)
  - **never interrupted** by control flows on L_e (for $e \leq f$)
  - **sequentialized** with other control flows on L_f (for $f > 0$)
  - **preempted** by other control flows on L_f **(for $f = 0$)**

L_0 → Thread level **(interruptible, preemptible)**
L_1 → Epilogue level **(interruptible, not preemptible)**
L_2 → Interrupt level **(not interruptible, not preemptible)**

Control flows on level L_0 (thread level) are **preemptible**.

To maintain consistency on this level, we need additional mechanisms for **thread synchronization**.

Thread Synchronization: Assumptions

- Threads can be preempted **unpredictably**
  - at any time (also by external events)
    - interrupts
  - by any other thread
    - of higher, same or lower priority (progress guarantee!)
- Typical assumptions for desktop computers
  - *probabilistic*, *interactive*, *preemptive*, *online* CPU scheduling
  - We do not consider other scheduling variants here.

Primarily, **progress guarantee** is causing the trouble here.

In purely priority-driven systems with sequential thread processing within one priority level, we can simply extend the interrupt-handling control-flow level model to thread priorities, and synchronize with comparable mechanisms (explicit level switch, algorithmic).
(→ event-driven real-time systems)

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Thread Synchronization: Overview

- Goal (for the user):
  Coordination of **resource accesses**
  - Coordinating exclusive access to reusable resources → **Mutex**
  - Interacting with / coordinating consumable resources → **Semaphore**
- Implementation approach (for the OS developer):
  Coordination of CPU allocation of **threads**
  - Particular threads are **not scheduled** temporarily.
    → "Waiting" as an OS concept

In the following, we focus on the OS developer's perspective.

Mutex – Mutual Exclusion

- In general:
  An algorithm for enforcing mutual exclusion in a critical section
- Here:
  A system abstraction `class Mutex`
- Interface:
  - `void Mutex::lock()`
    - Enter and lock the critical section
    - Thread can block
  - `void Mutex::unlock()`
    - Leave and unlock the critical section
- Correctness condition: $0 \leq \sum_{exec} \texttt{lock()} - \sum_{exec} \texttt{unlock()} \leq 1$
  - At every point in time, there is at maximum one thread in the critical section.

Mutex: Usage

```
#include "BoundedBuffer.h"
#include "Mutex.h"
extern BoundedBuffer buf;
extern Mutex mutex;
```

```
void f() {
  ...
  char el;
  mutex.lock();
  el = buf.consume();
  mutex.unlock();
  ...
}
```

```
void g() {
  ...
  char el = ...
  mutex.lock();
  buf.produce( el );
  mutex.unlock();
  ...
}
```

Mutex: with Busy Waiting

- Implemented purely at user level; approach:
  - store state in boolean variable (0=free, 1=locked)
  - wait busily in `lock()` until variable is 0

```
// __atomic_test_and_set is a gcc builtin for
// (CPU specific) test-and-set
class SpinningMutex {
  char locked;
public:
  SpinningMutex() : locked (0) {}
  void lock(){
    while (__atomic_test_and_set(
           &locked, __ATOMIC_RELAXED))
      ;
  }
  void unlock() {
    locked = 0;
  }
};
```

```
lock:
     mov      $1,%dl
L2:  mov      %edx,%eax
     xchg     %al,(%rdi)
     test     %al,%al
     jne      L2
     ret

unlock:
     movb     $0, (%rdi)
     ret
```

Assessment: Mutex with Busy Waiting

- **Advantages**
  - Maintains consistency, satisfies correctness condition
    - under the assumption of progress guarantee for all threads
  - Synchronization without involving the OS
    - No system calls necessary
- **Disadvantages**
  - Busy waiting wastes a lot of CPU time
    - at least until the time slice is used up
    - quite significant for time slices of 10–800ms!
    - Scheduler may "penalize" thread

Busy Waiting is, if at all, only an alternative on multiprocessor machines.

Mutex: with “Hard Synchronization”

- Implementation with “hard thread synchronization”
  - Approach:
    - Deactivate multitasking before entering the critical section
    - Reactivate multitasking after leaving the critical section
  - Necessitates a way to disable preemption
    - Special operations: forbid(), permit()

```
class HardMutex {
public:
  void lock(){
    forbid();    // disable multitasking
  }
  void unlock(){
    permit();    // enable multitasking
  }
};
```

Mutex: with “Hard Synchronization”

- Implementation of forbid() and permit()
  - e.g. in the scheduler
    - special, non-preemptible “real-time priority”
    - own priority level L¼ for the scheduler
    - resume() simply switches back to the caller
- or simply on epilogue level
  - Context switching usually resides on epilogue level
    - Epilogue-level control flows are sequentialized
    - As long as a thread is on epilogue level, it cannot be preempted
  - Consequence: Sequentialization also with epilogues!

```
void forbid(){
  enter();
}
void permit(){
  leave();
}
```

Assessment: Mutex with “Hard Synchronization”

- **Advantages**
  - Maintains consistency, satisfies correctness condition
  - Simple to implement
- **Disadvantages**
  - Broadband effect
    - Across-the-board delay of all threads (and potentially even epilogues!)
  - Priority violation
    - We delay control flows with higher priority.
  - Pessimistic
    - We put up with the disadvantages, although the collision probability is very low.

Assessment: Mutex with “Hard Synchronization”

- **Advantages**
  - Maintains consistency, satisfies correctness condition
  - Simple to implement
- **Disadvantages**
  - Bro
    - logues!)
  - Pric
    - We delay control flows with higher priority.
  - Pessimistic
    - We put up with the disadvantages, although the collision probability is very low.

> **Thread synchronization on epilogue level** has many disadvantages. It is, however, appropriate for very short, seldomly entered critical sections – or if we need to synchronize with epilogues anyways.

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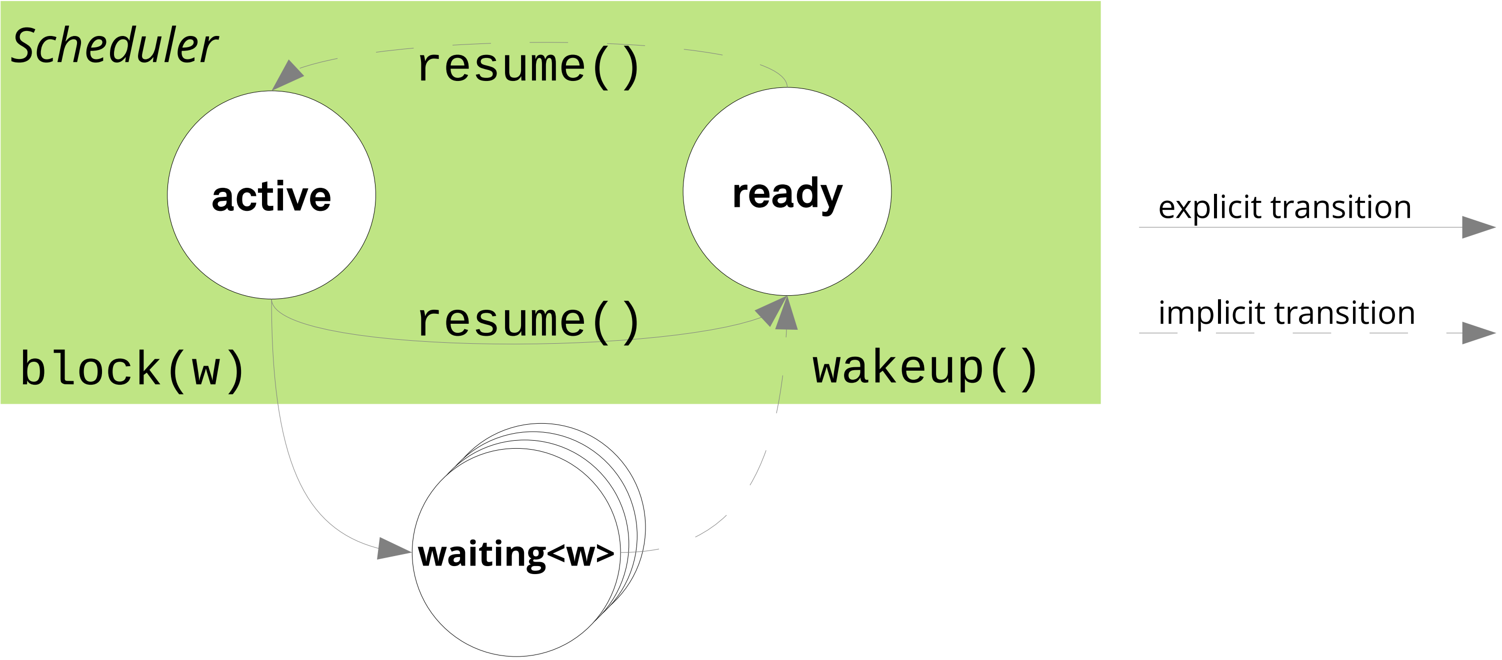
Passive Waiting

- Previously shown Mutex implementations are not ideal
  - Mutex with **busy waiting:** wastes CPU time
  - Mutex with **hard synchronization:** coarse-grained, violating priorities
- Better approach: **Exclude thread from CPU scheduling** as long as the mutex is locked
- Necessitates new OS concept: **passive waiting**
  - Threads can “wait passively” for an event
    - Wait passively → be excluded from CPU scheduling
    - New thread state: **waiting** (for an event)
  - Occurrence of an event triggers leaving the waiting state
    - Thread is included in CPU scheduling
    - Thread state: **ready**

OS Concept: Passive Waiting

- Necessary abstractions:
  - Scheduler operations: **`block()`**, **`wakeup()`**
  - Synchronization object: **`Waitingroom`**
    - represents the event to wait for
    - usually a waiting queue of waiting threads



OS Concept: Passive Waiting

- Scheduler operations
  - **`block(Waitingroom& w)`**
    - enqueue active thread (caller) in queue of synchronization object w
    - activate another thread (from ready list)
  - **`wakeup(Customer& t)`**
    - enqueue t in ready list
- Waitingroom operations
  - **`enqueue(Customer*)`**
  - **`Customer* dequeue()`**

It makes sense to manage the queue with the **same prioritization strategy** as the scheduler's ready list!

Mutex: with Passive Waiting

```
class WaitingMutex : public Waitingroom {
  char locked;
public:
  WaitingMutex() : locked(0) {}
  void lock() {
    while (__atomic_test_and_set(&locked, __ATOMIC_RELAXED))
      scheduler.block(*this);
  }
  void unlock() {
    locked = 0;
    // fetch possibly waiting thread and wake it up
    Customer *t = dequeue();
    if (t)
      scheduler.wakeup(*t);
  }
};
```

This solution still has one remaining problem ...

Mutex: with Passive Waiting

```
class WaitingMutex : public Waitingroom {
  char volatile locked;
public:
  WaitingMutex() : locked(0) {}
  void lock() {
    mutex.lock();
    while (locked == 1)
      scheduler.block(*this);
    locked = 1;
    mutex.unlock();
  }
  void unlock() {
    mutex.lock();
    locked = 0;
    // fetch possibly waiting thread and wake it up
    Customer *t = dequeue();
    if (t) scheduler.wakeup(*t);
    mutex.unlock();
  }
};
```

lock() and **unlock()** are critical sections themselves

Can we protect these critical sections with a Mutex?

Mutex: with Passive Waiting

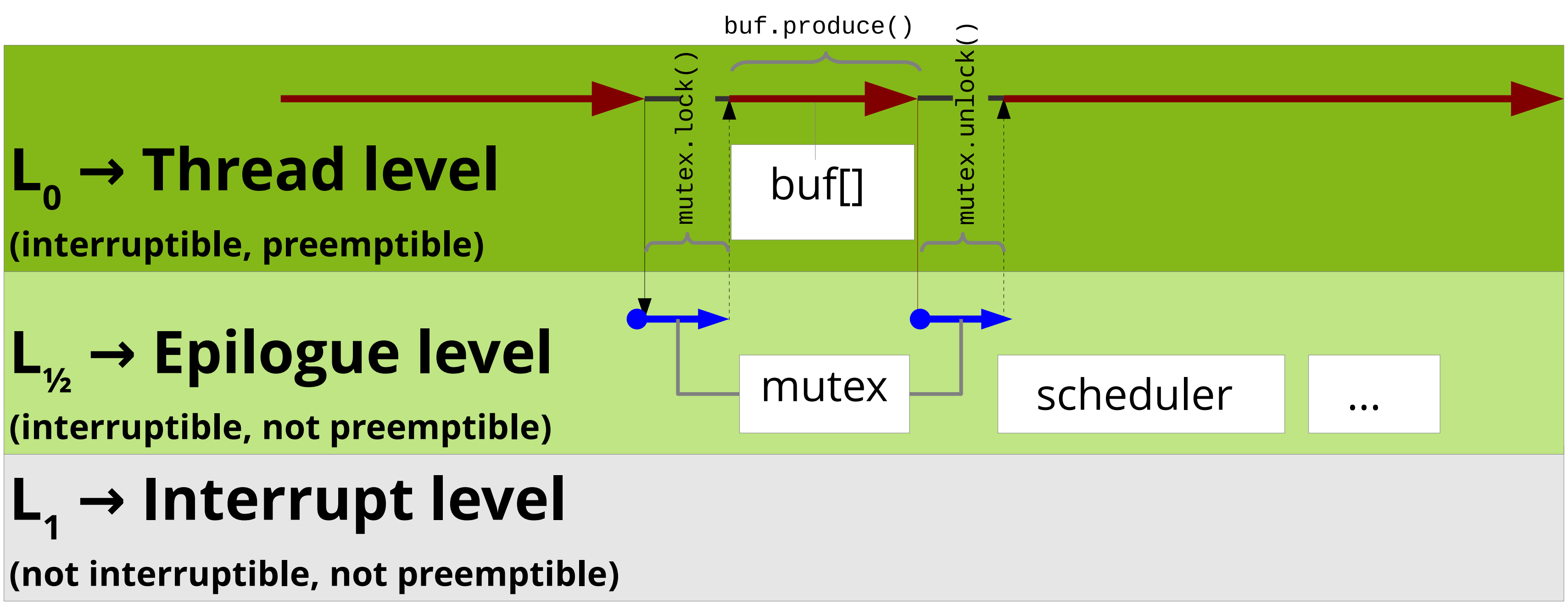
```
class WaitingMutex : public Waitingroom {
  char volatile locked;
public:
  WaitingMutex() : locked(0) {}
  void lock() {
    enter();
    while (locked == 1)
      scheduler.block(*this);
    locked = 1;
    leave();
  }
  void unlock() {
    enter();
    locked = 0;
    // fetch possibly waiting thread and wake it up
    Customer *t = dequeue();
    if (t) scheduler.wakeup(*t);
    leave();
  }
};
```

It works with a **`HardMutex`**!

The common solution is indeed to protect **`lock()`** and **`unlock()`** on the **epilogue level**, as shown here.

Conclusion: Implementing Waiting

- Mutex state resides **in the kernel** on epilogue level
  - more precisely: on the same level as the scheduler state
- This is a **generic principle**
  - Implementation of synchronization mechanisms for L_0 control flows is synchronized on $L_{½}$



Semaphore

- Semaphore is *the* classic synchronization object
  - Edsger W. Dijkstra, 1962 [2]
  - in many OSs: Basis for all other synchronization objects
  - for us: semaphore := synchronization object + counter
- Operations
  - 2 standard operations (with various names [2,3,5])
  - **`prolaag()`**, **`P()`**, **`wait()`**, **`down()`**, **`acquire()`**, **`pend()`**
    - if counter > 0, decrease counter
    - if counter ≤ 0, **wait** until counter > 0 and retry
  - **`verhoog()`**, **`V()`**, **`signal()`**, **`up()`**, **`release()`**, **`post()`**
    - increase counter
    - if counter = 1, **wake up** possibly waiting thread
- Many variants

Implementation of the standard variant in the exercises.

Semaphore: Usage

- Semaphore semantics are particularly suitable for implementing producer/consumer scenarios
  - i.e. coordinated access to **consumable resources**
    - Characters from the keyboard
    - Signals that are supposed to be processed further on thread level
    - …
  - Internal counter represents the resource count
    - Producer calls **`V()`** for each produced element.
    - Consumer calls **`P()`** to consume an element, possibly waits.

`P()` can block on thread level, **`V()`** never blocks!

Hence, a control flow on **epilogue** or **interrupt level** can also be a **producer** (assuming appropriate synchronization of the internal semaphore state.)

Semaphore vs. Mutex

- Mutex is often understood as a **two-valued semaphore**
  - Mutex → Semaphore with initial counter value 1
  - `lock()` → `P()`, `unlock()` → `V()`
- However, the semantics are different:
  - A locked mutex (implicitly or explicitly) has an **owner**
    - Only this owner may call `unlock()`.
    - Mutex implementations e.g. on Linux or Windows check this.
  - A mutex can (usually) also be **locked recursively**.
    - Internal counter: The same thread may call `lock()` multiple times; after a matching number of `unlock()` calls, the mutex is unlocked again.
  - In contrast, a semaphore can be incremented or decremented by any thread.

In many operating systems, the semaphore is the **basic abstraction** for synchronization objects. It is used as an **implementation basis** for mutexes, condition variables, reader-writer-locks, …

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Synchronization on Windows

- Windows takes the idea of waiting objects quite far
  - Every kernel object is also a synchronization object
    - explicit synchronization objects: Event, mutex, timer, semaphore
    - implicit synchronization objects: File, socket, thread, process, …
  - Waiting semantics depends on the object
    - Thread waits for “signaled” state
    - State is, if applicable, modified by successful waiting
- Uniform system interface for all object types
  - Kernel object is represented by a HANDLE
  - **`WaitForSingleObject(hObject, dwMillisec)`**
    - Wait for synchronization object with timeout
  - **`WaitForMultipleObjects(nCount, hObjects[], bWaitAll, dwMillisec)`**
    - Wait for one or more synchronization objects with timeout (“and”/“or” waiting, depending on bWaitAll = true/false)

Synchronization Objects on Windows

Object Type	Signaled when	Successful waiting results in
Event	Explicit state change (SetEvent()/ResetEvent())	Event reset (for AutoReset events)
Mutex	Mutex is available	Mutex is owned
Semaphore	Semaphore counter > 0	Semaphore is decreased by 1
Waitable timer	Specific point in time reached	Timer reset (for AutoReset timers)
Change notification	Specific change in the file system	–
Console input	Input data available	–
Process	Process has terminated	–
Thread	Thread has terminated	–
File	An asynchronous file op. finished	–
Serial device	Data available / file op. finished	–
Named pipe	An asynchronous op. finished	–
Socket	An asynchronous op. finished	–
Job (Win 2000)	All processes of the job terminated	–

Synchronization and Costs

- Synchronization objects are managed in the kernel
  - Critical data structures → protection
  - Internal synchronization on epilogue level → consistency
- This can make their use very costly:
  - We need to switch to the kernel for each state change
  - User/kernel mode transitions are very expensive.
  - IA-32/x86-64: several hundred cycles!
- These costs are particularly pronounced for mutexes:
  - The time needed for locking/unlocking mutexes is often a multiple of the time the critical section is locked.
  - Actual contention (thread wants to enter an already locked section) rarely occurs.

Synchronization and Costs

- Approach: Manage mutex as far as possible in **user mode**
  - Minimize the normal-case cost
    - Normal case: critical section is free
    - Special case: critical section is locked
- Introduce a **fast path** for the normal case
  - Test, locking and unlocking in user mode
    - Ensure consistency algorithmically / with atomic CPU instructions
  - Wait in kernel mode
    - We need the kernel for the transition to the passive waiting state
  - Further optimization for multiprocessor machines
    - Busily wait for limited amount time before waiting passively
    - High probability that the critical section is free before

Windows: CRITICAL_SECTION

- Structure for a **fast mutex** in user mode [8]
  - Internally uses an Event (kernel object) in case we must wait
  - Lazy (on-demand) Event creation
- Specific system-call interface
  - **`EnterCriticalSection(pCS)`** / **`TryEnterCriticalSection(pCS)`**
    - Lock critical section (blocking) / try locking critical section (non-blocking)
  - **`LeaveCriticalSection(pCS)`**
    - Leave critical section
  - **`SetCriticalSectionSpinCount(pCS, dwSpinCount)`**
    - Define number of tries for busy waiting (multiprocessor systems only)

```
typedef struct _CRITICAL_SECTION {
  LONG LockCount;      // Number of waiting threads (-1 when free)
  LONG RecursionCount; // Number of successful EnterXXX calls
  DWORD OwningThread;  // Owner thread
  HANDLE LockEvent;    // Internal synchronization object, created on demand
  ULONG SpinCount;     // On MP systems: number of busy-wait tries until we
                       // passively wait in the kernel
} CRITICAL_SECTION, *PCRITICAL_SECTION;
```

Windows: CRITICAL_SECTION

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  HANDLE LockEvent;    // Internal synchr
  ULONG SpinCount;     // On MP systems:
                       // passively wait in the kernel
} CRITICAL_SECTION, *PCRITICAL_SECTION;
```

With ***Futexes*** (*Fast user-mode mutexes*), Linux 2.6 introduced a comparable but much more powerful concept. [7,6]

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Summary

- Threads can be preempted at any time
  - Preemptive, probabilistic multitasking
  - No run-to-completion semantics
  - Access to shared state must be separately synchronized
- Thread synchronization: Many variants
  - Mutex for mutual exclusion
  - Semaphore for producer/consumer scenarios
  - Many other abstractions possible: reader/writer locks, semaphore vectors, condition variables, timeouts, ...
- Based on an OS concept for passive waiting
  - Fundamental thread property: They can wait.
  - Busy waiting and “hard” thread synchronization only make sense in exceptional cases.

Bibliography

[1] K. R. Apt. *Edsger Wybe Dijkstra (1930 – 2002): A Portrait of a Genius.* http://arxiv.org/pdf/cs.GL/0210001, 2002.

[2] E. W. Dijkstra. *Multiprogrammering en de X8*, 1962. [4].

[3] E. W. Dijkstra. *Cooperating Sequential Processes.* Technical report, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 1965. (Reprinted in *Great Papers in Computer Science*, P. Laplante, ed., IEEE Press, New York, NY, 1996).

[4] E. W. Dijkstra. *EWD Archive: Home.* http://www.cs.utexas.edu/users/EWD, 2002.

[5] P. B. Hansen. *Betriebssysteme.* Carl Hanser Verlag, erste Edition, 1977. ISBN 3-446-12105-6.

[6] Ulrich Drepper. *Futexes are tricky.* http://people.redhat.com/drepper/futex.pdf, 2005

[7] Hubertus Franke, Rusty Russell, Matthew Kirkwood. *Fuss, futexes and furwocks: Fast Userlevel Locking in Linux*, Ottawa Linux Symposium. https://www.kernel.org/doc/ols/2002/ols2002-pages-479-495.pdf, 2002.

[8] Matt Pietrek, Russ Osterlund. *Break Free of Code Deadlocks in Critical Sections Under Windows.* MSDN Magazine https://docs.microsoft.com/en-us/archive/msdn-magazine/2003/december/..., 2003