Operating Systems

Interrupts

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What do you already know?

Let's go to the survey again:
`https://pingo.coactum.de/977183`

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- What is a System Call?
- Which System Calls do you need to call to spawn a new process executing a new application?
- A global unitialized variable will be stored in which memory segment?

Some Analogies

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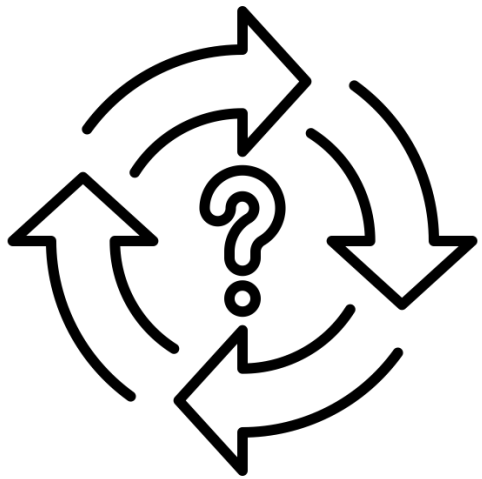
- I am giving an online presentation But forget to share my screen – what can you do?

Interrupts are essential

- An **interrupt** interrupts normal program execution for a certain purpose
- In practice no computer system can work without interrupts
- Without interrupts, preemptive multitasking is impossible
  - Preemptive multitasking means: The operating system can remove the CPU from a process before its execution is complete

Interrupts vs. Polling



Created by Path Lord
from Noun Project

- **Polling:** In order to detect the occurrence of an event a process has continuously to send requests
- **Interrupt:** On occurrence of an event an interrupt is generated

Interrupts from an Application Perspective

"Interrupts are an unpleasant fact of life; although they cannot be avoided, they should be hidden away, deep in the bowels of the operating system, so that as little of the operating system as possible knows about them."
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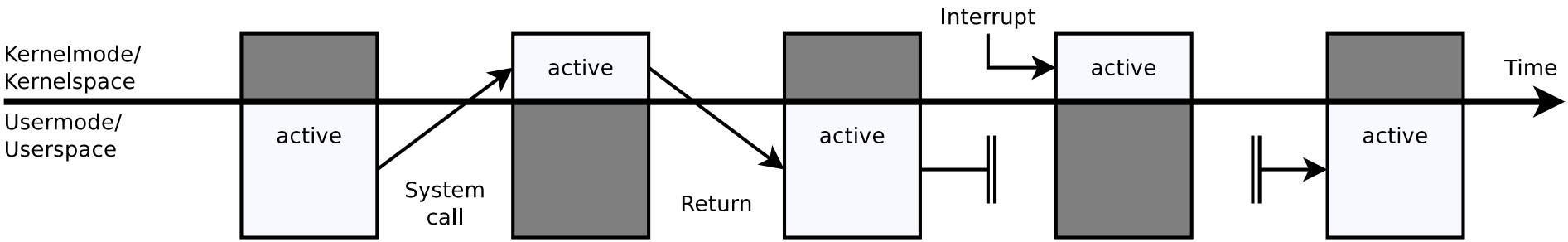
Comparison between system calls and interrupts

Interrupts are triggered by events outside user-mode processes



Agenda

- Interrupts, Exceptions, Traps
- Interrupt Handling

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What reasons (sources) for an interrupt can you imagine?

Terminology

Caution!

The terms *interrupt*, *exception*, or *trap* are used and defined slightly differently in the literature or documentation of the hardware manufacturers.

Interrupts and Exceptions

- In any computer system unpredictable events may (and will) occur at any time and must be handled
- Events that must be handled immediately are called **interrupts**
- Interrupts can be categorized into:
  - **Hardware** or **External Interrupts**
    - An I/O device provides feedback to a process

    $\Rightarrow$ Asynchronous interrupt
  - **Exceptions**
    - **Faults**

      Error situation (error caused by an arithmetic operation)
      Division by zero, floating point error, address errors, ...
    - **Trap** or **Software Interrupt**

      Triggered by a process $\Rightarrow$ synchronous interrupt
      Examples are the exception 0x80 to switch from user mode to kernel mode and the single-stepping mode during program test (debugging, trace)

Interrupt Example

- X and Y are processes which communicate via a network
  - Both processes are executed on different computers
  - On sending a message to the other process a reply is expected within a certain period of time
  - If the other process does not reply within that time the message must be sent again ($\rightarrow$ **timeout**)
    - **Reason**: The sender assumes that the message got lost

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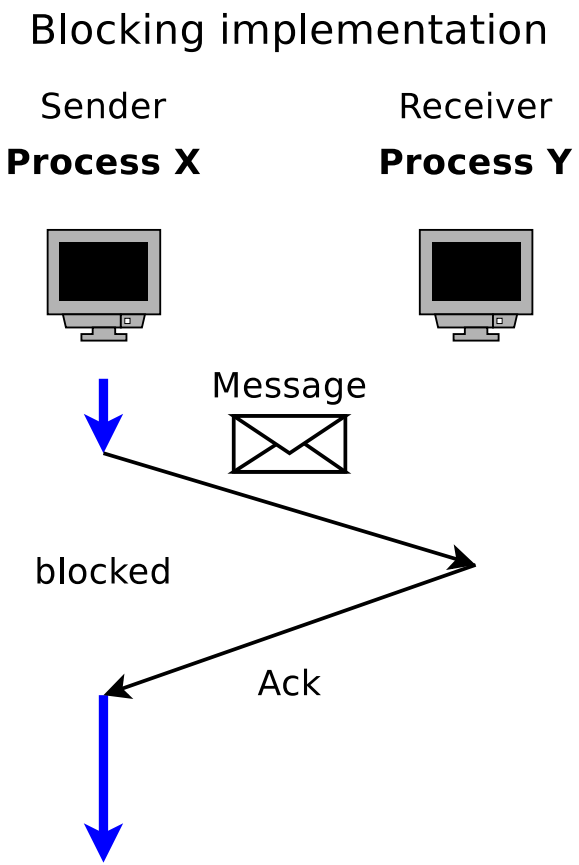
How could we implement this timeout for process X?

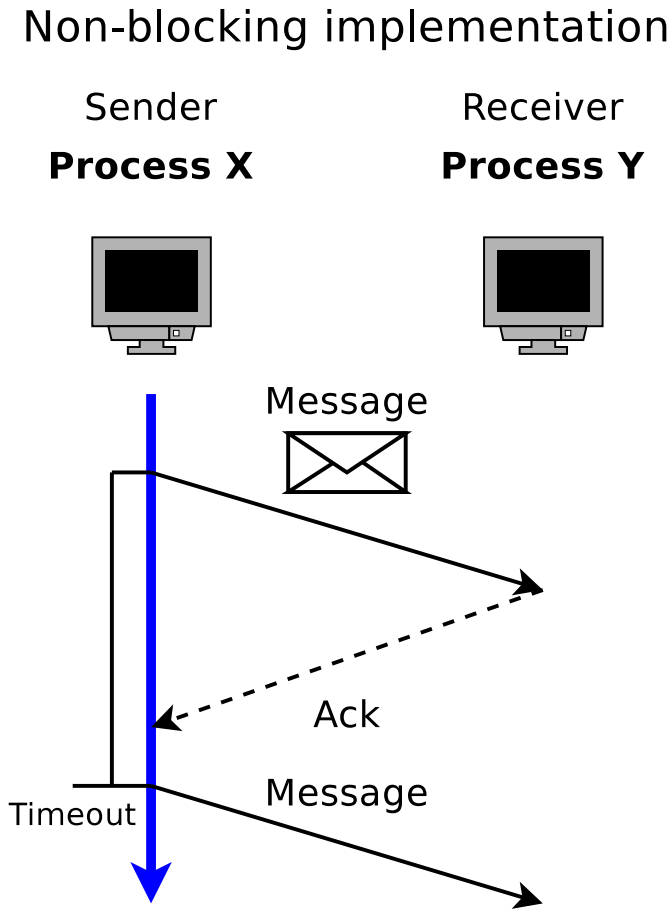
Blocking Implementation

- Process X gets **blocked** until the message is **acknowledged** or the **timeout** expires
- If the acknowledgement arrives, sender process X may continue
  - Otherwise, process X must send the message again
- Disadvantage: Long idle times for process X arise



Non-blocking Implementation

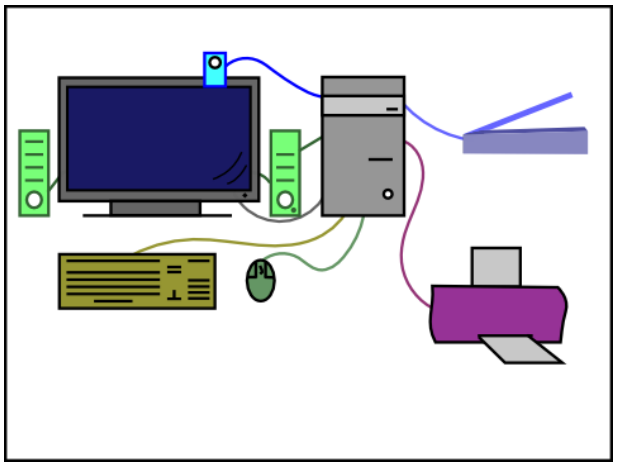
- After process X sent the message it continues to operate normally
  - If a timeout expires because of a missing acknowledgment the OS suspends the process
- The → **context** of the process is saved and a procedure for interrupt handling is called
  - In the example the procedure would send the message again
  - If the execution of the procedure has finished the process becomes reactivated



Subprograms without return value are typically called **procedures**. Subprograms with return value are called **functions** or **methods**.

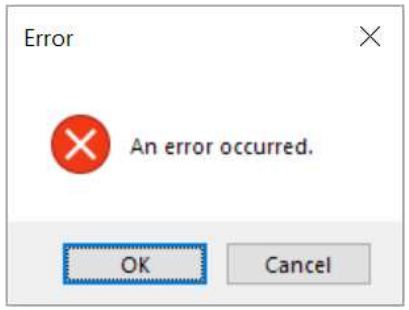
Hardware Interrupts

- Asynchronous
- A device signals an event
- Potential sources:
  - External devices like a keyboard (event → keypress)
  - Internal devices like a clock (event → timer tick)
  - Notifications of another processor
- The OS maintains a list of interrupt vectors (IV)
  - Each IV maps an interrupt source to the according handler
  - The entire list is called interrupt vector table (IVT)



Exceptions

- Exceptions are caused by a running process
- When an exception occurs the CPU is interrupted and an handler in the kernel is activated
- A serious error has occurred, e.g.,:
  - Division by zero
  - Floating point operation without a **FPU (floating point unit)**
  - Invalid instruction
  - Segmentation fault (memory access violation)
  - Hardware failure



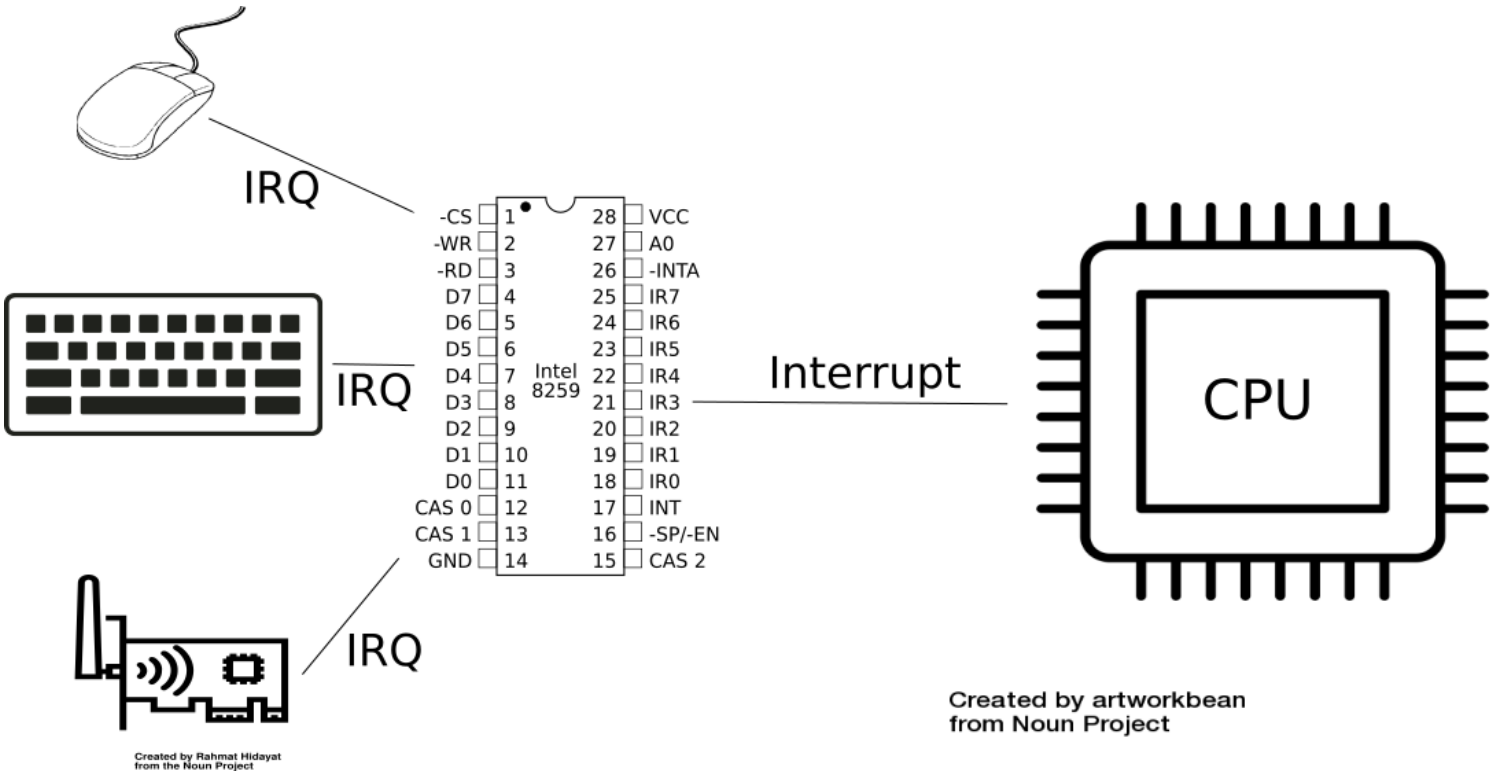
- Exceptions can be used to generate an interrupt in software → trap
  ⇒ Synchronous interrupt

Traps

- **Software instruction** which causes an (intended) change of operation mode
- $\longrightarrow$ System calls
- **processor synchronous**

How is an Interrupt generated?

- An interrupt source generates an **Interrupt Request (IRQ)**
- IRQs are received by a **Programmable Interrupt Controller (PIC)** (for ARM CPUs **Vectored Interrupt Controller (VIC)**)
- This controller determines the maximum number of different IRQs
  - **Shared IRQs** are possible
- It also manages and **prioritizes** the interrupts



Interrupt Conflicts

- Two potential issues during interrupt handling:
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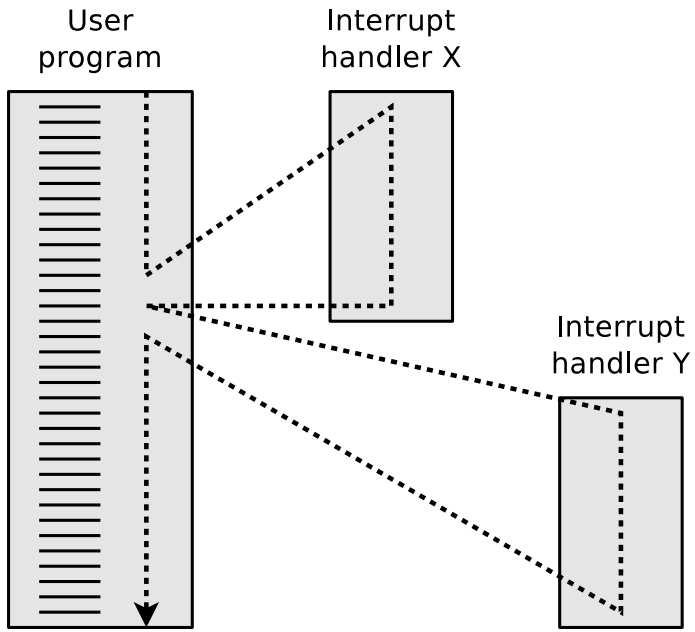
What can we do?

Interrupt Conflicts

- Two potential issues during interrupt handling:
  - During interrupt handling, further interrupts occur
  - Multiple interrupts occur at the same time
- Two possible solutions:
  - Sequential interrupt processing
  - Nested interrupt processing

Sequential Interrupt Processing

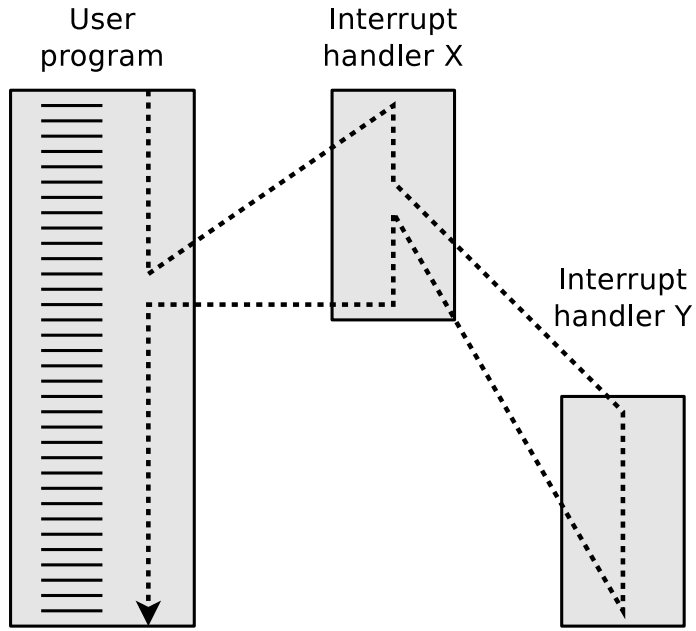
- Interrupts are strictly processed one after the other
- Interrupts are never interrupted
- Advantage: Simpler software design
- Drawback: Priorities and time-critical reactions are ignored



Source: William Stallings. Betriebssysteme. Pearson Studium. 2003

Nested Interrupt Processing

- Priorities are specified for the interrupts
- Interrupt handlers can be interrupted, when an interrupt with higher priority occurs
- Interrupts with lower priority are delayed until all interrupts with a higher priority are handled
- Drawback: Interrupts with a low priority may be significantly delayed



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The real-time operating systems QNX Neutrino and Windows CE 5.0 both support nested interrupts

`http://www.qnx.com/developers/docs/660/topic/com.qnx.doc.neutrino.sys_arch/topic/kernel_Nested_interrupts.html`
`http://msdn.microsoft.com/de-de/library/ms892539.aspx`

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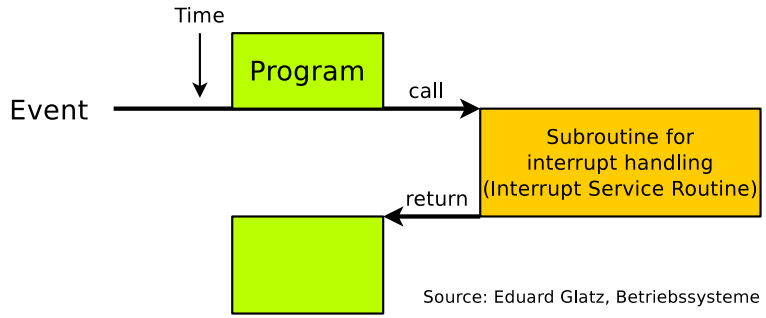
Interrupt Handling

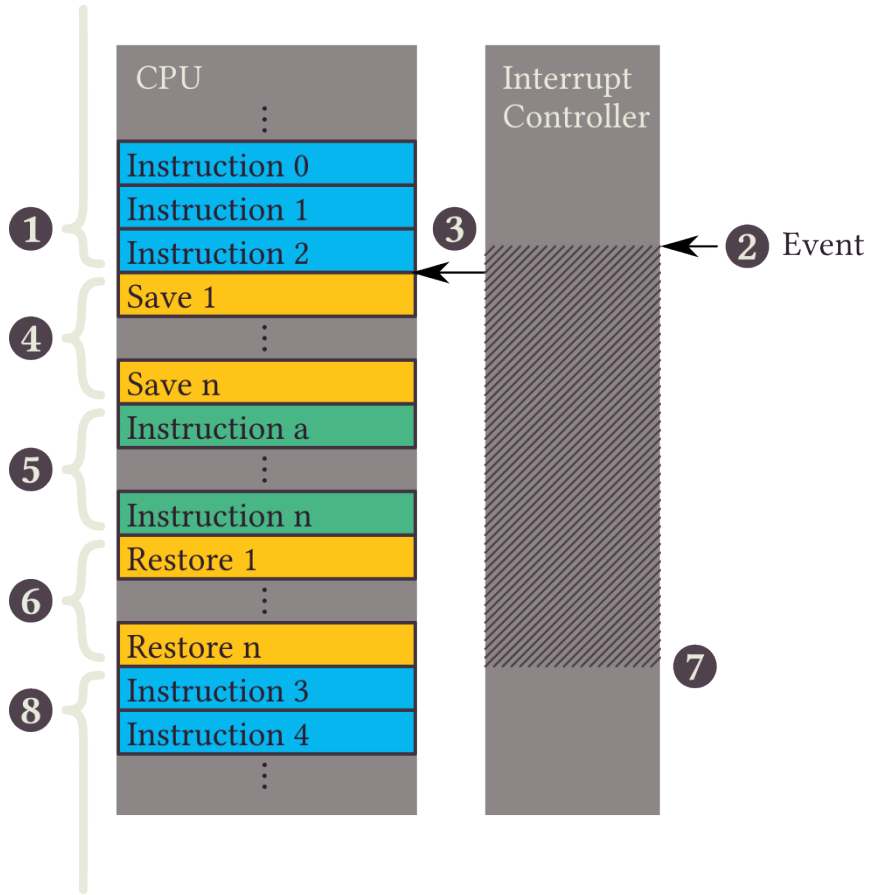
An interrupt request (IRQ) indicates an event and the operating system provides an **event handler**, the so called interrupt service routine (ISR)



- The CPU is interrupted and for interrupt handling, the ISR of the kernel is called
  - The value of the **program counter** register is set to the address of the ISR which is executed next
  - The operating system stores the process context and restores the process context after the execution of the ISR has finished

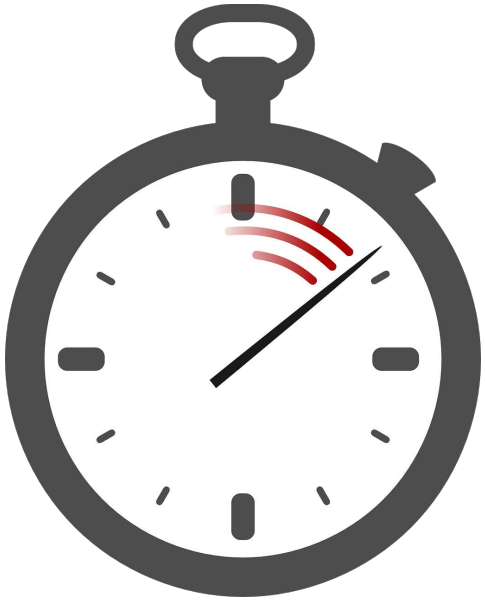
Interrupt Handling Procedure

- The common pattern is:
  - Save the state
  - Prepare ISR execution
  - Select the correct ISR
  - ISR execution
  - Potentially restore the state



ISR Properties

- Short runtime
- No blocking operations
- Low memory footprint
- **thread-safe**



Delayed Interrupt Handling

- Only the most necessary is done in the ISR itself
- All more expensive operations are postponed (outside the interrupt context)
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Example: character transmission

- Assume that characters are received on a certain line
- The application program proesses entire lines
- The ISR must save the characters
- The application program should be notified only when the first linebreak has been detected

Interrupt desired?

- Most interrupts can be deactivated (**masked**)
- Critical interrupts (e.g., exceptions) are not maskable ($\rightarrow$ non-maskable interrupt (NMI))
- Masking an interrupt may be necessary to allow for concurrency

Problems of Interrupt Handling

- Concurrency
- Time criticality
- Hard to debug
- Nesting is possible (priorities)
- Compiler optimizations ($\rightarrow$ **volatile**)
- Non-reentrant functions

You should now be able to answer the following questions:

- Why does any computer system need interrupts?
- What is the difference between hardware interrupts, exceptions, and traps?
- How are interrupts handled?