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OPERATING-SYSTEM CONSTRUCTION

Material based on slides by
Olaf Spinczyk, Universität Osnabrück

Interrupts – Hardware

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

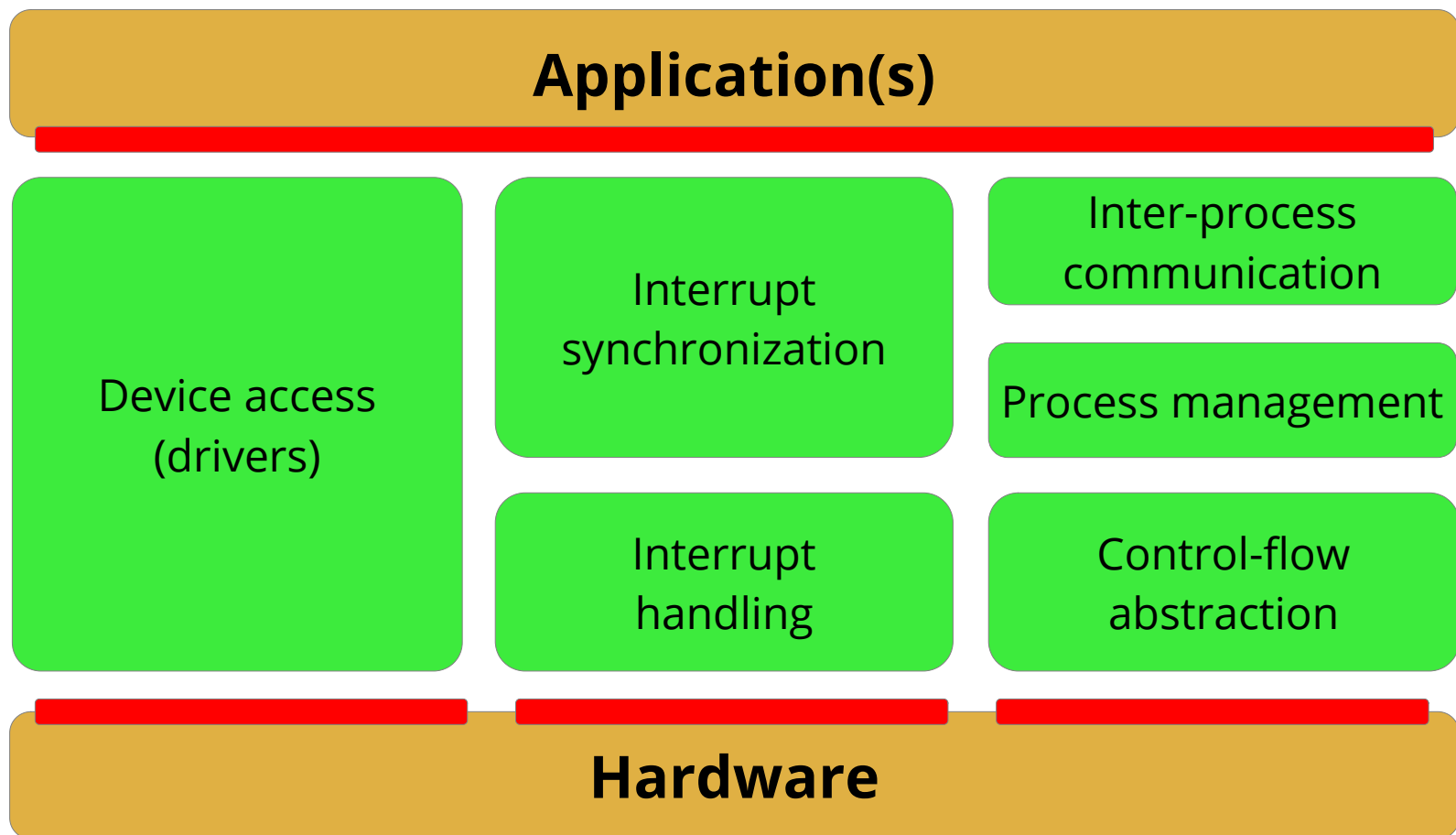
HORST SCHIRMEIER



<https://frag.jetzt/participant/room/OSC2022>

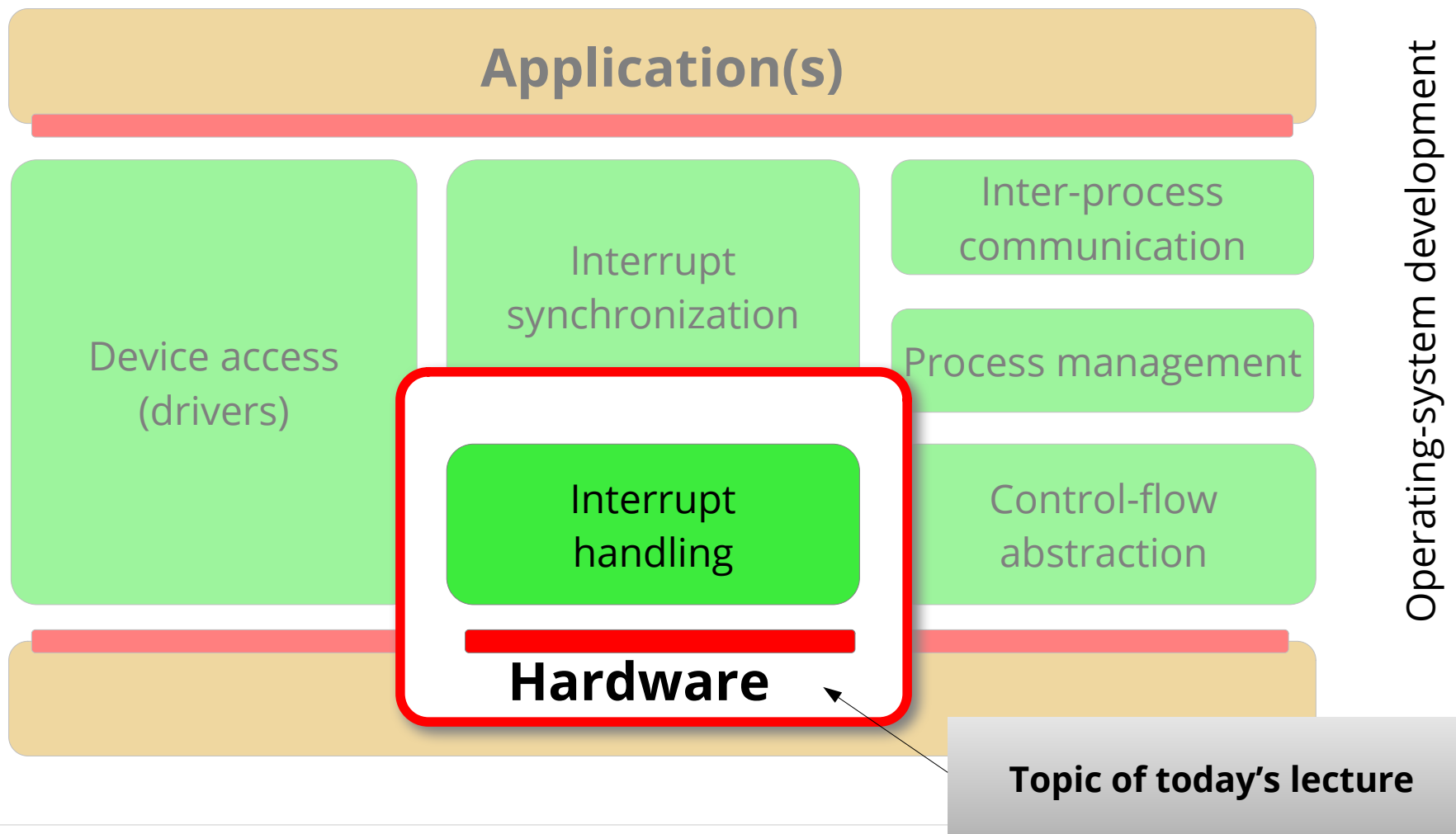
Overview: Lectures

Structure of the “OO-StuBS” operating system:



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Structure of the “OO-StuBS” operating system:



Overview

- Interrupts
 - Purpose
- General Discussion
 - Prioritization, Lost Interrupts, Dispatch, Saving State, Nested Interrupts, Interrupts in Multiprocessor Systems
- Hazards
 - „Spurious Interrupts“, „Interrupt Storms“
- Hardware-Architecture Examples
 - Motorola 68K, Pentium APIC

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Purpose of Interrupts

Looking back in history ...

- Overlapped I/O
 - Input: Wasting CPU cycles by (unpredictably long) **busy waiting**
 - Output: Autonomous device behavior (e.g. **DMA**) unloads CPU
- Time sharing
 - Timer interrupts allow the operating system to ...
 - **preempt processes**
 - run time-driven activities

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Prioritization

- **Problem:**
 - Multiple interrupt requests can be signaled **at once**. *Which one is more important?*
 - While the CPU handles the most important request, **further requests** can be signaled.
- **Solution:** a **prioritization mechanism** ...
 - **in software:** The CPU only has one IRQ (interrupt request) line and queries/services devices in a defined order.
 - **in hardware:** A prioritization circuit assigns priorities to devices and only forwards the most urgent request for handling.
 - **with static priorities:** each device statically gets assigned a priority
 - **with dynamic priorities:** priorities can be changed dynamically, e.g. cyclic

Lost Interrupts

- **Problem:**
 - During interrupt handling, and/or while interrupts are disabled, the CPU **cannot handle new interrupts**.
 - Memory for IRQs is (very!) limited
 - usually 1 bit per interrupt line
- **Solution:** in **software**
 - Interrupt handler routine should be **as (temporally) short as possible** to minimize probability for lost interrupts.
 - Interrupts should **not be disabled** longer than necessary by the CPU.
 - A device driver must handle the situation that an interrupt **signals more than one completed I/O operation**.

Interrupt Dispatch

- **Problem:**
 - Determine with little effort **which device** triggered the interrupt
 - **Sequential querying:**
Time-consuming, modifies state of I/O buses and uninvolved devices
- **Solution: Interrupt vector**
 - Assign a number to each interrupt → index into vector
 - Vector number not necessarily related to priority
 - In practice, devices may have to share a vector number (**interrupt chaining**)
 - CPU-specific vector-table structure
 - Usually contains **pointers to functions**, rarely machine instructions

Saving State

- **Problem:**
 - After running the handler routine, we want to **return** to normal context
 - **Transparency:** Interrupt handling supposed to happen unnoticed
- **Solution: State save**
 - by hardware
 - Only essential state: e.g. return address and status register
 - State restore by special instruction, e.g. **IRET**, **RTE**, ...
 - by software
 - Interrupts may occur at any time → handler routine also must save and restore state

Nested Interrupt Handling

- **Problem:**

- To react promptly to important events, interrupt handlers should be **interruptible**.
- ... but we should avoid unlimited nesting. (Why?)

- **Solution:**

- CPU only allows interrupts with *higher* priority
- Current priority in status register
- Previous priority on a stack

Multiprocessor Systems

- **Problem:**
 - Each interrupt can only be handled by one CPU. But which one?
 - Additional interrupt category: **Inter-processor interrupts** (IPIs)
- **Solution:** More complex interrupt-handling hardware for multiprocessors; design variants:
 - **static** destination
 - **random** destination
 - **programmable** destination
 - destination depending on **current CPU load**
... and combinations thereof.

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Hazard: Spurious Interrupts

- **Problem:** Interrupt-handling mechanism can be presented with spurious* interrupts, caused e.g. by ...
 - Hardware errors
 - Incorrectly programmed devices
- **Solution:**
 - Avoid hardware and software errors 😊
 - Program OS “defensively”
 - expect spurious interrupts

* “spurious” \approx „falsch“, „unecht“

Hazard: Interrupt Storms

- **Problem:**
 - High interrupt frequency can overload or “freeze” a computer
 - **Cause:** Spurious interrupts, or too high I/O load
 - Can be mistaken for **thrashing** (similar symptoms).
- **Solution:** in the OS
 - Detect interrupt storms
 - Deactivate culprit device

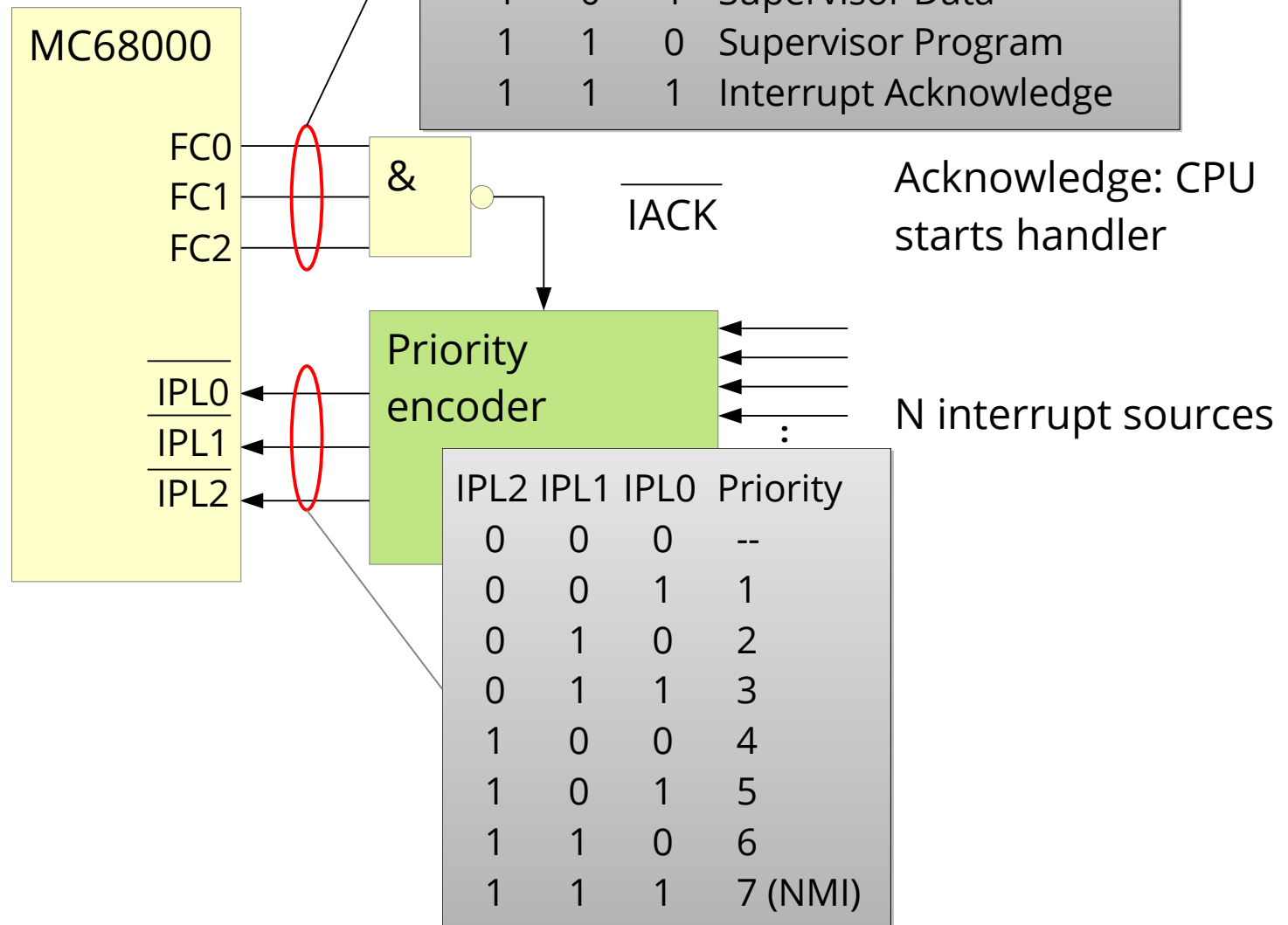
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Interrupts in the MC68000

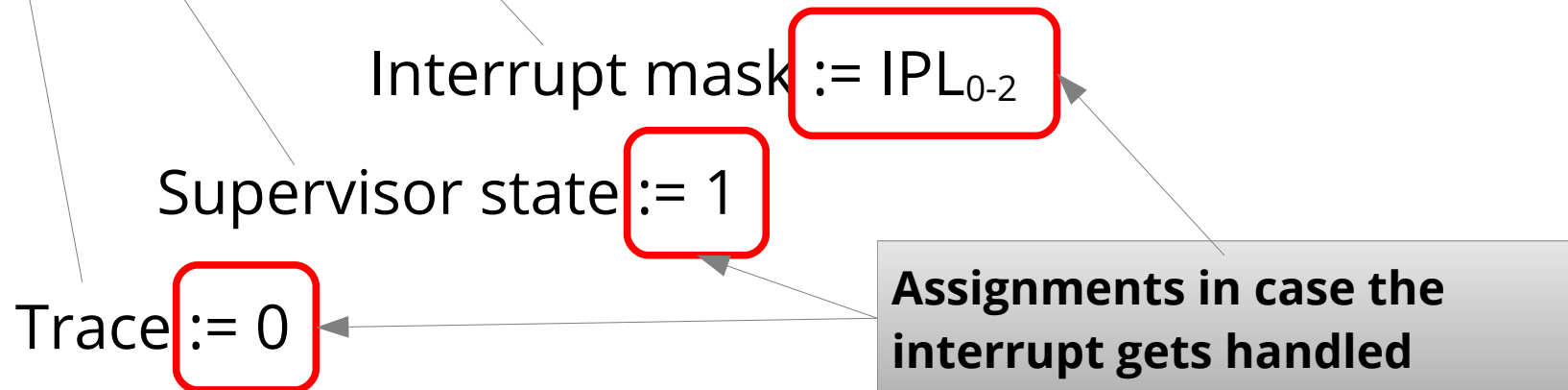
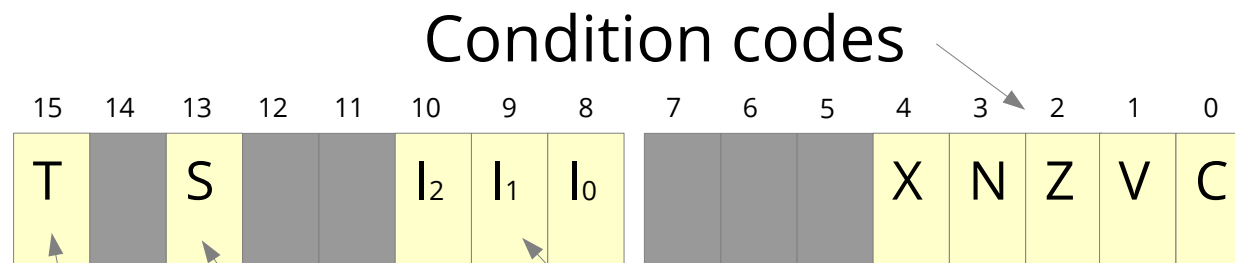


Interrupts in the



MC68000 Status Register (SR)

- Contains current **interrupt mask** (among other things)
 - Interrupt → CPU tests whether $IPL_{0-2} > I_{0-2i}$
No? → Interrupt is inhibited (for now).
 - However, interrupt with $IPL_{0-2} = 7$ is always handled (NMI)



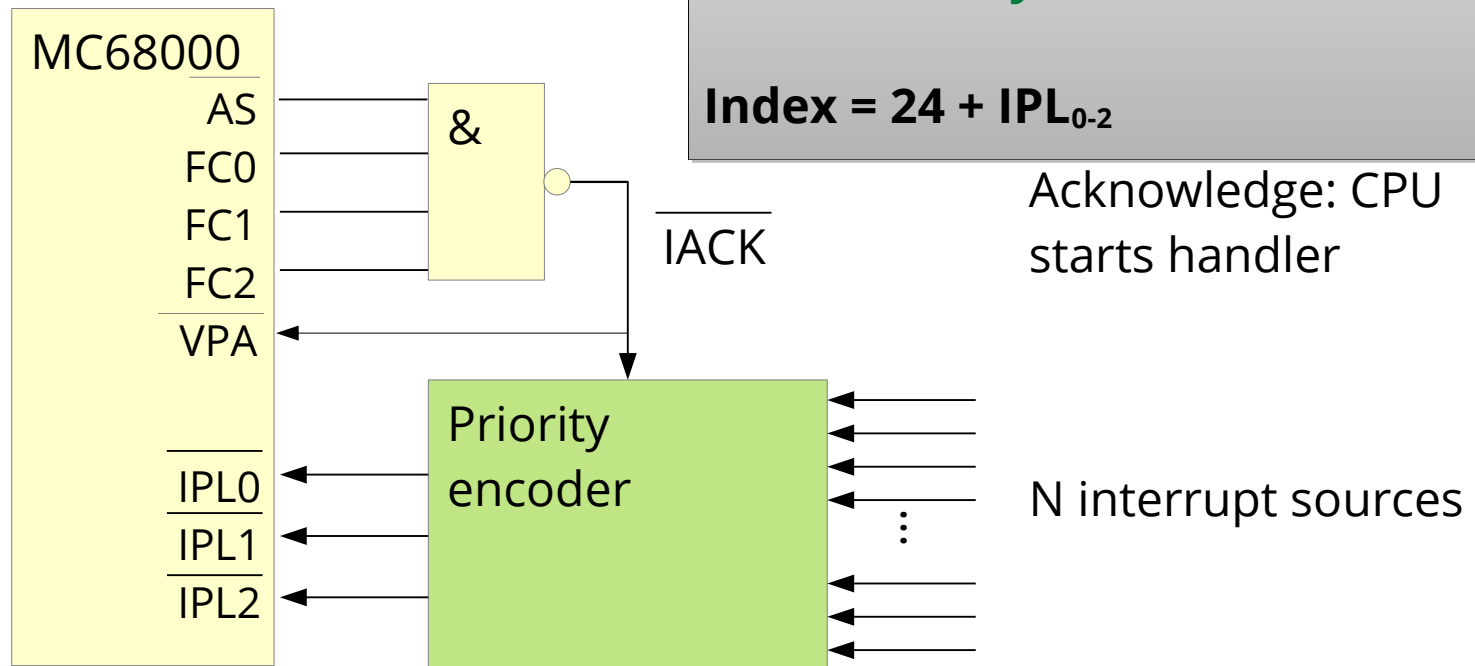
MC68000 Interrupt Vectors

Index	Address	Assignment
0	0x000	Reset: Initial Supervisor Stack Pointer
1	0x004	Reset: Initial PC
2	0x008	Bus Error
3	0x00c	Address Error
4	0x010	Illegal Instruction
5	0x014	Zero Divide
...		
24	0x060	Spurious Interrupt
25	0x064	Level 1 Interrupt Autovector
26	0x068	Level 2 Interrupt Autovector
...		
30	0x078	Level 6 Interrupt Autovector
31	0x07c	Level 7 Interrupt Autovector (NMI)
32-47	0x080	TRAP Instruction Vectors
48-63	0x0c0	<i>reserved</i>
64-255	0x100	User Interrupt Vectors

Autovectorized Interrupts

External circuitry signals via **VPA** that the CPU should calculate the vector number **automatically**:

$$\text{Index} = 24 + \text{IPL}_{0-2}$$



Acknowledge: CPU starts handler

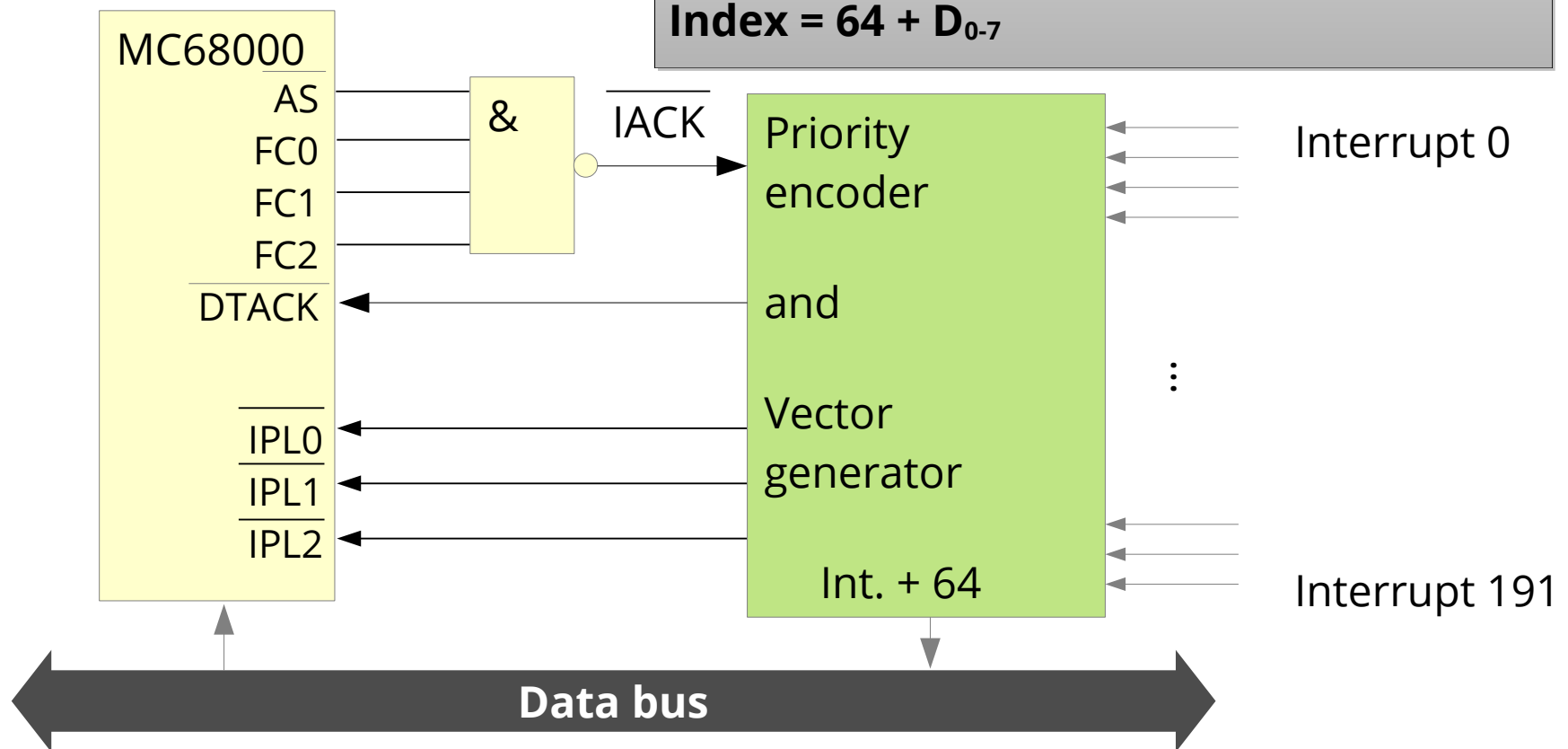
N interrupt sources

Problem: Only 6 vectors available. With more devices, **sharing** is unavoidable.

Non-Autovectored Interrupts

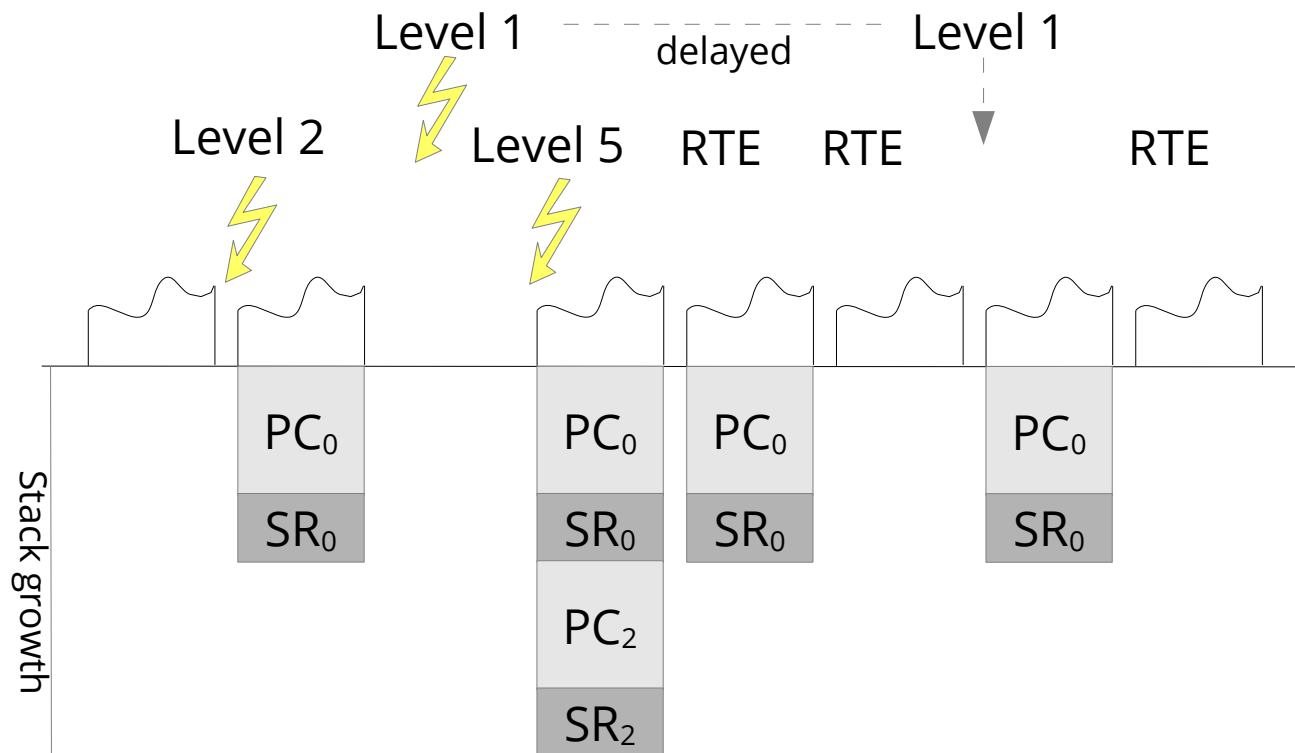
External circuitry signals via **DTACK** that the CPU should read the vector number **from the data bus**.

$$\text{Index} = 64 + D_{0-7}$$



MC68000 State Save

- Previous SR value and PC are saved on supervisor stack
- **RTE** instruction restores state



MC68000 – Summary

- **6 priority levels** for hardware interrupts + NMI
 - Interrupt level 1–6, NMI level 7
 - Masking possible via status register I_{0-2}
- Only interrupts with **higher priority** and NMI can interrupt running interrupt handler
 - Status register is adapted automatically
- **Automatic state save** on supervisor stack, **nested handling** possible
- Vector number generation ...
 - either autovectored: Index = Priority + 24
 - or non-autovectored (by external hardware): Index = 64 ... 255
- No multiprocessor support

Interrupts in x86 CPUs

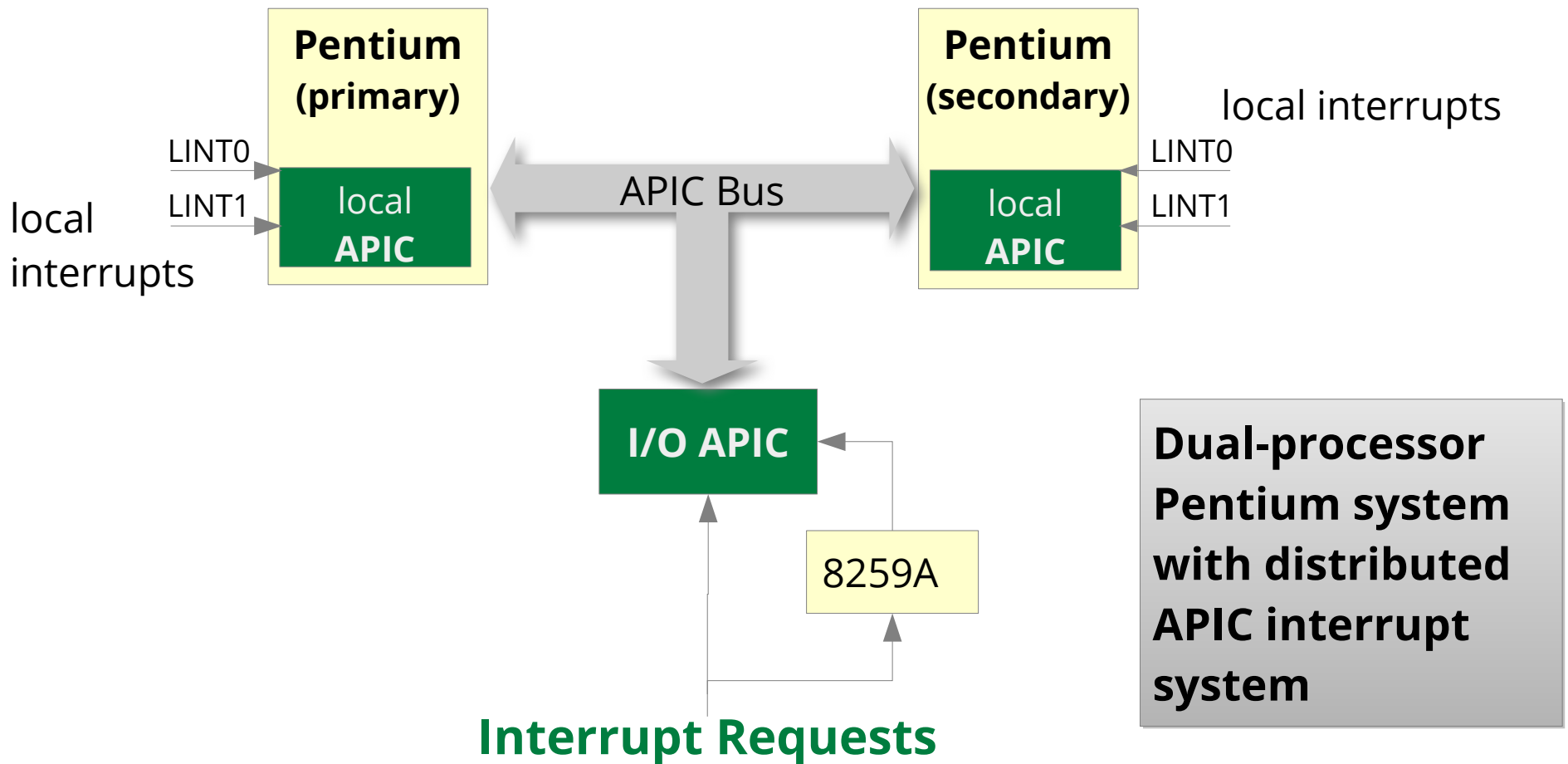


Interrupts in x86 CPUs

- Up and including i486, x86 CPUs had only 1 IRQ and 1 NMI line
- External hardware: prioritization, vector number generation
 - by a chip named **PIC 8259A**
 - 8 interrupt lines
 - 15 lines when cascading 2 PICs
 - no multiprocessor support
- Today's x86 processors contain the much more capable "Advanced Programmable Interrupt Controller" (**APIC**)
 - necessary for **multiprocessor systems**
 - completely superseded classic PIC 8259A
 - Compatibility: PIC interface still available in chipsets

APIC Architecture

- APIC interrupt system: **Local APIC** on each CPU, **I/O APIC**



I/O APIC

- Typically integrated in PC chipset's Southbridge
- Usually 24 interrupt lines
 - cyclic sensing (round-robin prioritization)
- **Interrupt Redirection Table:**
64-bit entry for each interrupt line
 - Describes interrupt signal
 - Used for generating APIC bus message

I/O APIC

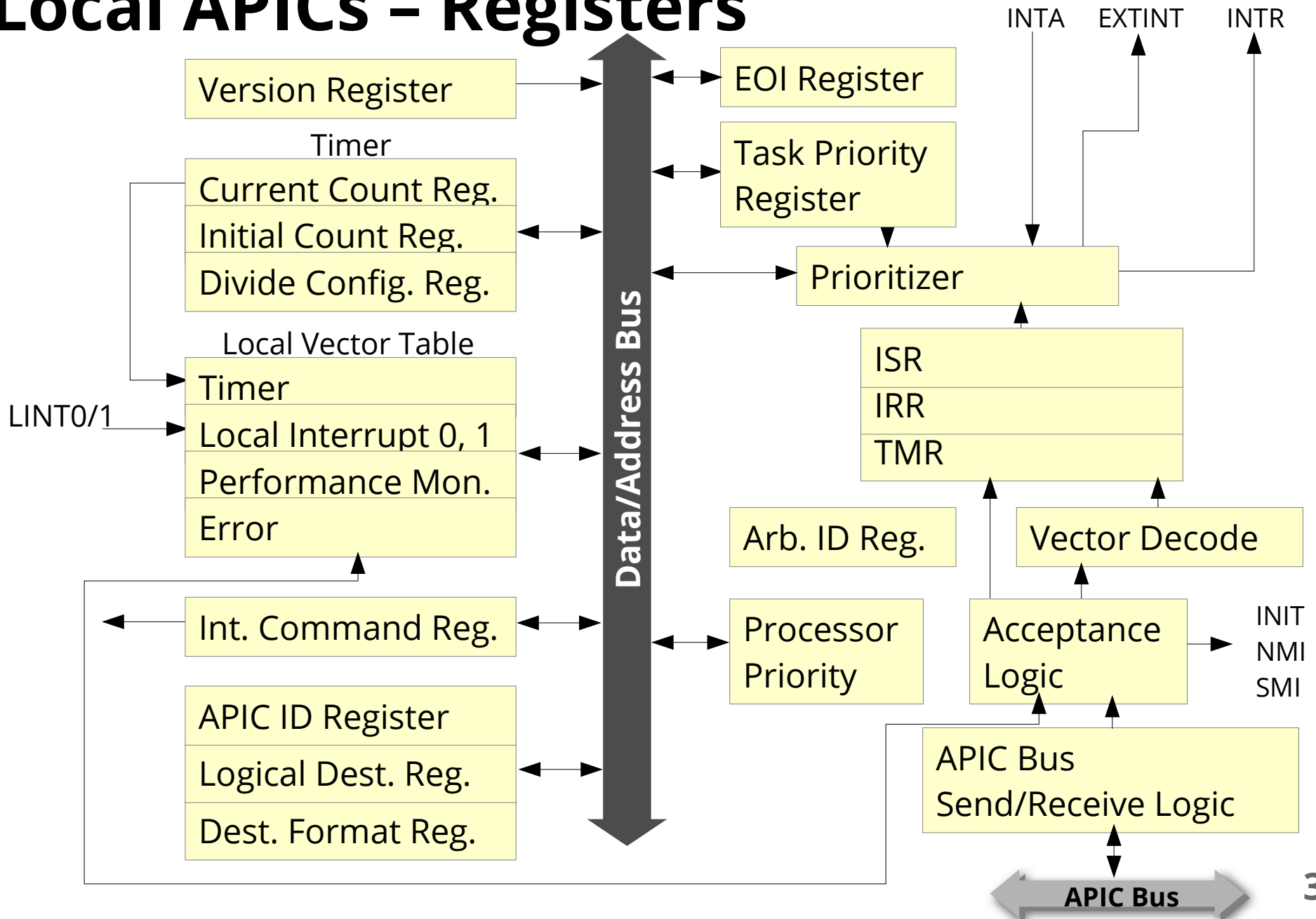
Structure (bits) of an *Interrupt Redirection Table* entry

63:56	Destination Field – R/W. 8-bit destination address depending on bit 11: APIC ID of a CPU (physical mode) or CPU group (logical mode)
55:17	<i>reserved</i>
16	Interrupt Mask – R/W. 1 = Do not forward this interrupt to a CPU.
15	Trigger Mode – R/W. 0 = Edge sensitive, 1 = Level sensitive
14	Remote IRR – RO. Type of received acknowledgment
13	Interrupt Pin Polarity – R/W. Signal polarity (high/low is active)
12	Delivery Status – RO. Interrupt message in flight?
11	Destination Mode – R/W. 0 = Physical mode, 1 = Logical mode
10:8	Delivery Mode – R/W. Affects destination APIC
	000 – Fixed Deliver to all destination CPUs
	001 – Lowest Priority Deliver to CPU with currently lowest priority
	010 – SMI System Management Interrupt
	100 – NMI Non-Maskable Interrupt
	101 – INIT Initialize destination CPUs (reset)
	111 – ExtINT Answer to PIC 8259A
7:0	Interrupt Vector – R/W. 8-bit Vector number between 16 and 254

Local APICs

- Receive IRQs through APIC bus
- Also select/prioritize
- Can directly handle two local interrupts (lint0/lint1)
- Contain further functionality
 - Built-in timer, performance counters, thermal sensor
 - Command register:
 - Send own APIC messages
 - especially Inter-Processor Interrupt (IPI)
- Programmable via 32-bit registers (starting at 0xfee00000)
 - memory mapped (no external bus cycles)
 - Each CPU programs its own Local APIC

Local APICs – Registers



APIC Architecture – Summary

- Flexible IRQ distribution to CPUs in x86 MP system
 - fixed, groups, lowest task priority
 - multiple IRQs at once: prioritization with vector number
- Vector numbers 16–254 can be freely assigned
 - should be enough to avoid sharing
- Local APIC expects explicit EOI
 - Software must take care of this!
- With APIC, x86 in principle also supports priority levels
 - System software must act accordingly
(re-enable interrupts, possibly use task priority register)

IRQ Sharing

- In practice, 24 IRQ lines proved to be insufficient
- ... especially 4/8 lines for PCI devices:

PIRQ Line	#A	#B	#C	#D	#E	#F	#G	#H
AGP slot	shared							
PCI 1						shared		
PCI 2							used	
PCI 3					used			
PCI 4								shared
PCI 5						shared		
PCI 6			shared					
1. USB 1.1	shared							
2. USB 1.1				used				
3. USB 1.1			shared					
USB 2.0								shared
AC-97 Sound						shared		

- **Message-Signalled Interrupts** (MSIs) finally resolved this.

Summary

- Interrupt-handling hardware implements ...
 - Prioritization
 - Dispatch/execution of a handler routine
 - State save and nested execution
- Modern interrupt-handling hardware can ...
 - freely assign interrupt vectors,
 - avoid sharing vectors,
 - flexibly dispatch interrupts in multiprocessor systems.
- The operating system must ...
 - expect problems (spurious interrupts, interrupt storms)
 - pass on the signaled event to higher levels and finally to the application process.