Transmitters and IO modules

Industrial control

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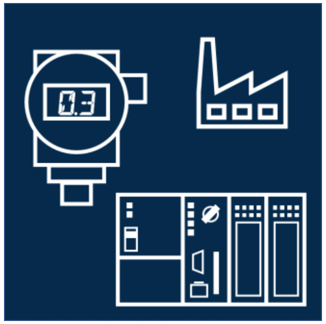
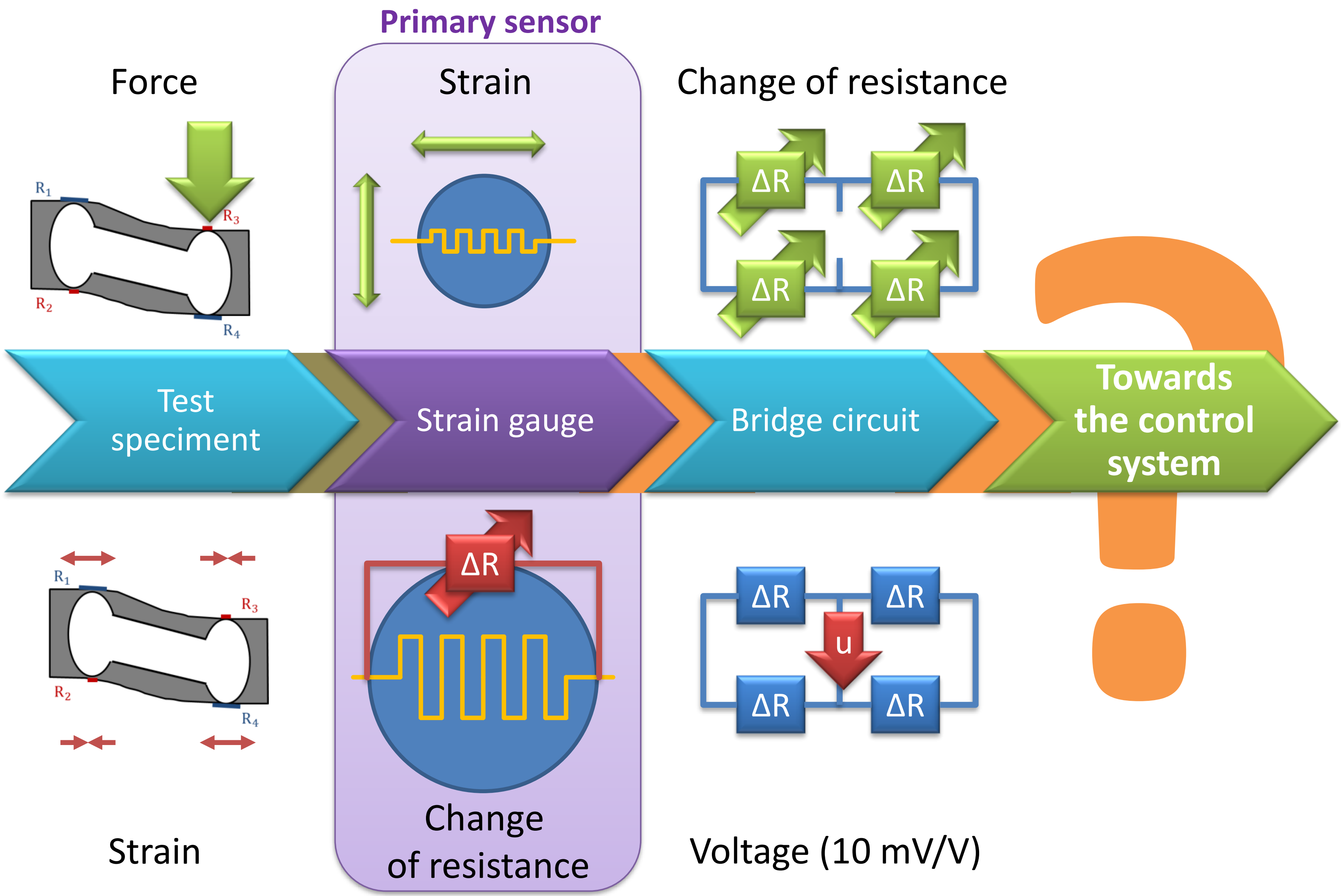


Sensor interfacing

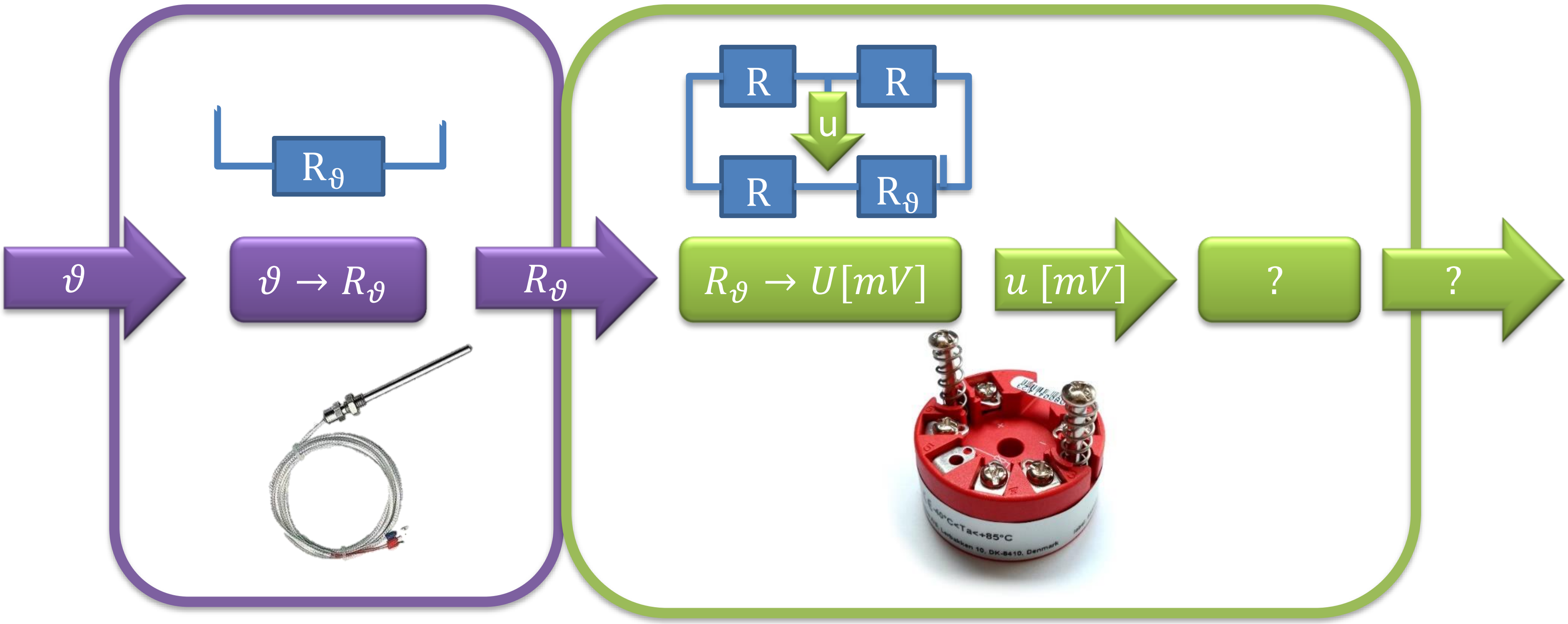


Output of sensors

- Sensors commonly provide a voltage output
- Output signal needs to be transmitted to a control or data acquisition device, possibly located in a long distance

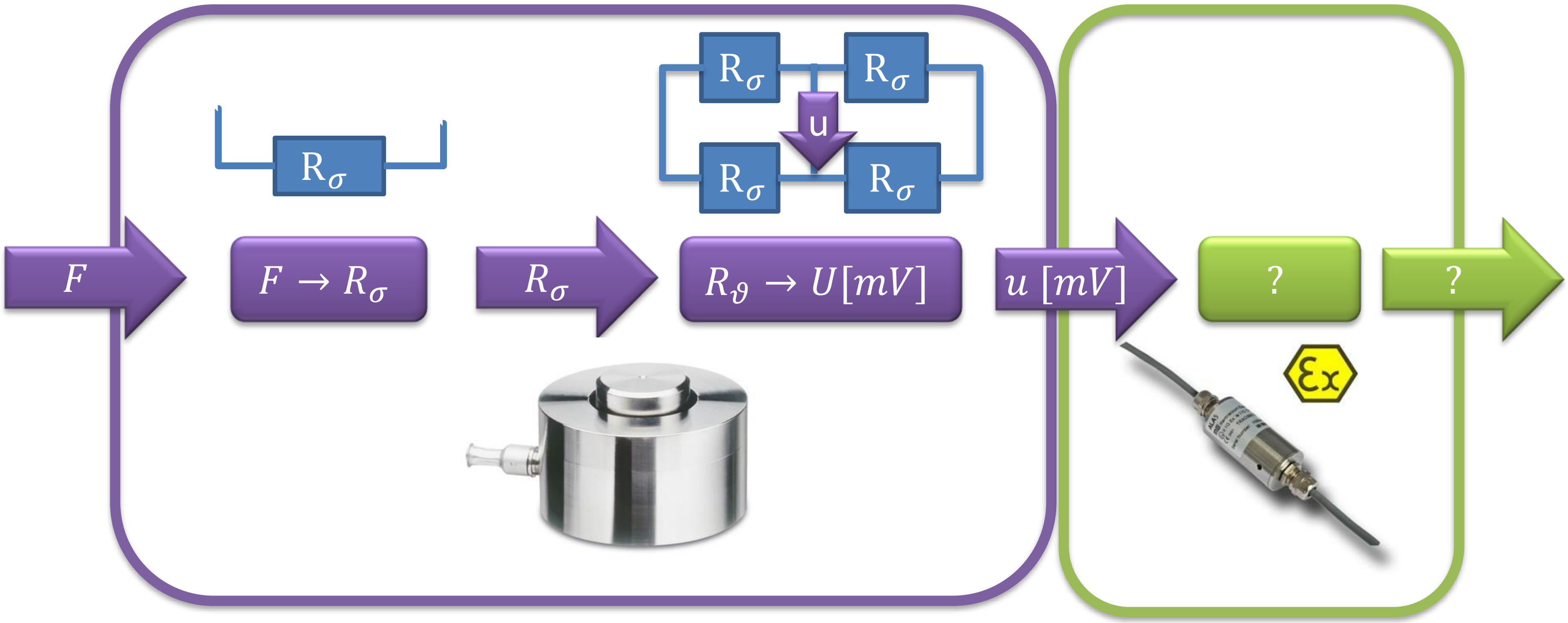
- A **transmitter** is a device capable of forwarding the continuous measured value in a standard electrical form

Sensors, transducers and transmitters



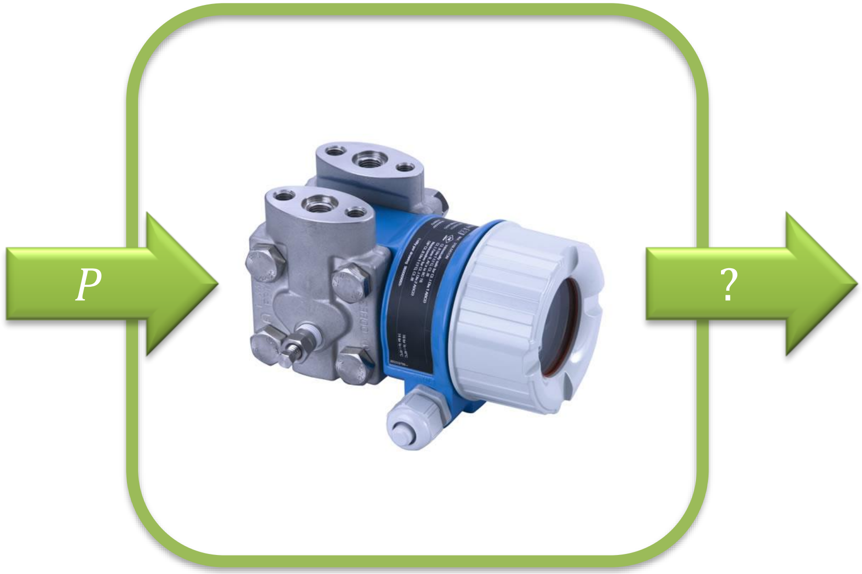
- Standardized sensors: interface circuitry included in the transmitter
  - RTDs
  - thermocouples

Sensors, transducers and transmitters



- Non-standardized but generic sensors with well-defined outputs: transmitter does not contain the primary interface circuitry (e.g. bridge circuit of load cells)

Sensors, transducers and transmitters



- Non-standardized, custom, manufacturer-specific devices: assembly which contains the transducer, the sensor and the device generating standardized electrical output is referred to as a transmitter

Parts of a transmitter

- Transducer
- Primary sensor
- Interface circuitry
- Signal conditioning
- Compensation
- **Output interface**

Pressure transmitter

- Diaphragm
- Strain gauge
- Bridge circuit
- **Output interface**

RTD transmitter

- Interface circuitry (e.g. active bridge)
- **Output interface**

Load cell transmitter

- **Output interface**

Analog transmitters

- Provides interface to the sensor
- Might provide analog compensation
- Analog output
  - early ages: no standard output range
  - pneumatic signals: 3-15 psi
  - standard electrical range: **4-20 mA current signal**

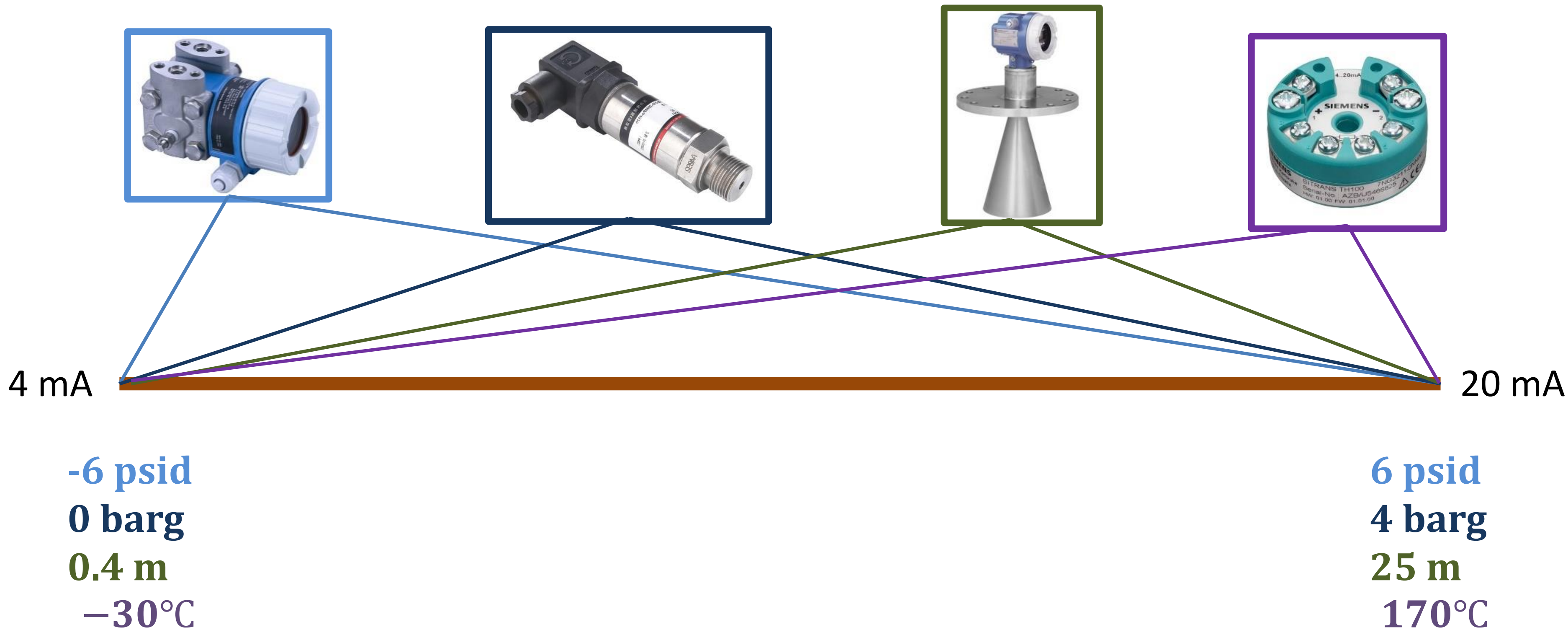
4-20 mA

- Current signal
  - less sensitive to noise than voltage
  - lead wires do not influence the current measured

- Live zero
  - current corresponding to the minimal value of the measurement range is 4 mA (not 0 mA)
  - open circuit errors can be easily detected

4-20 mA

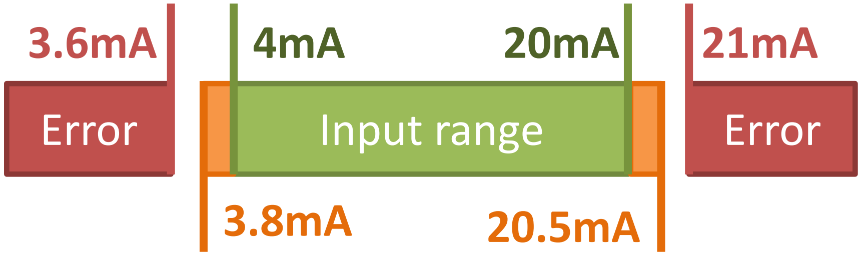
- What is the measured value represented by a given current value?
- There is no generic answer
- Each transmitter maps its own measurement range to the 4-20 mA current range



4(?) – 20(?) mA

- Values outside the 4-20 mA range might be used
  - value outside the input range of the sensor
  - error indication

- NAMUR NE43 standard
  - AO-LL : 3.8 mA
  - AO-HL : 20.5 mA
  - Values outside 4-20 mA represent measured values outside (below or over) the input range
  - values below 3.6 mA or over 21 mA indicate the failure of the transmitter



Linear characteristic transmitter

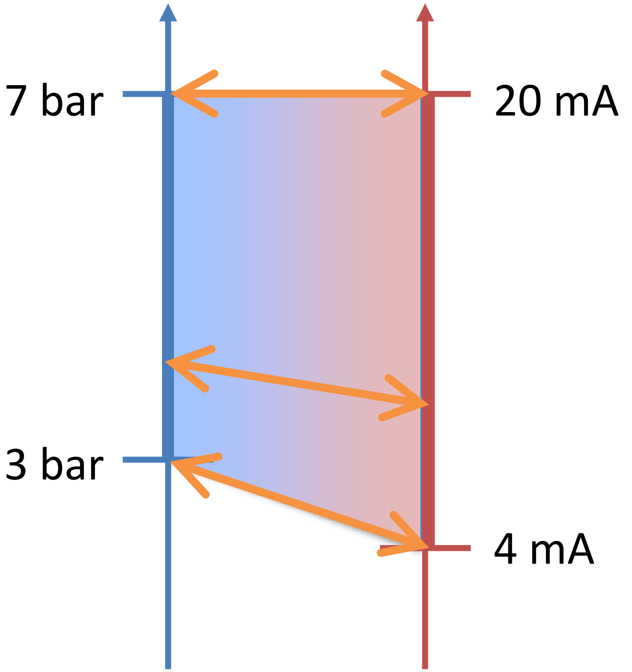
Mapping of the measured value to the 4-20mA range is linear:

$$I = 4 + \frac{Y - Y_{min}}{Y_{max} - Y_{min}} \cdot 16\ [\mathrm{mA}]$$

$$Y = Y_{min} + \frac{I - 4}{16} \cdot (Y_{max} - Y_{min})$$

Linear characteristic transmitters - Problem

- Input range of an absolute pressure transmitter with linear characteristics is 3-7 bars. Give the measured pressure if the output current of the transmitter is 8mA.



- $Y = Y_{min} + \frac{I-4}{16}(Y_{max} - Y_{min})$
- $P = 3 + \frac{8-4}{16}(7-3) = 3 + 1 = 4 \text{ bar}$

Other characteristics

- Square root

$$I = 4 + \frac{16}{\sqrt{Y_{max} - Y_{min}}} \sqrt{Y - Y_{min}}\ [\mathrm{mA}]$$

$$Y = Y_{min} + \frac{(I-4)^2}{256} (Y_{max} - Y_{min})$$

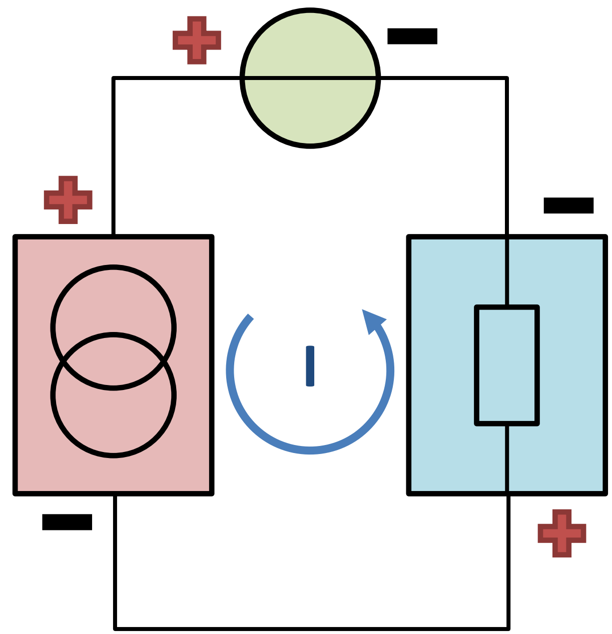
- Logarithmic

$$I = 4 + 16 \frac{\lg\left(\frac{Y}{Y_{min}}\right)}{\lg\left(\frac{Y_{max}}{Y_{min}}\right)}\ [\mathrm{mA}]$$

$$Y = \left(\frac{Y_{max}}{Y_{min}}\right)^{\frac{I-4}{16}} \cdot Y_{min}$$

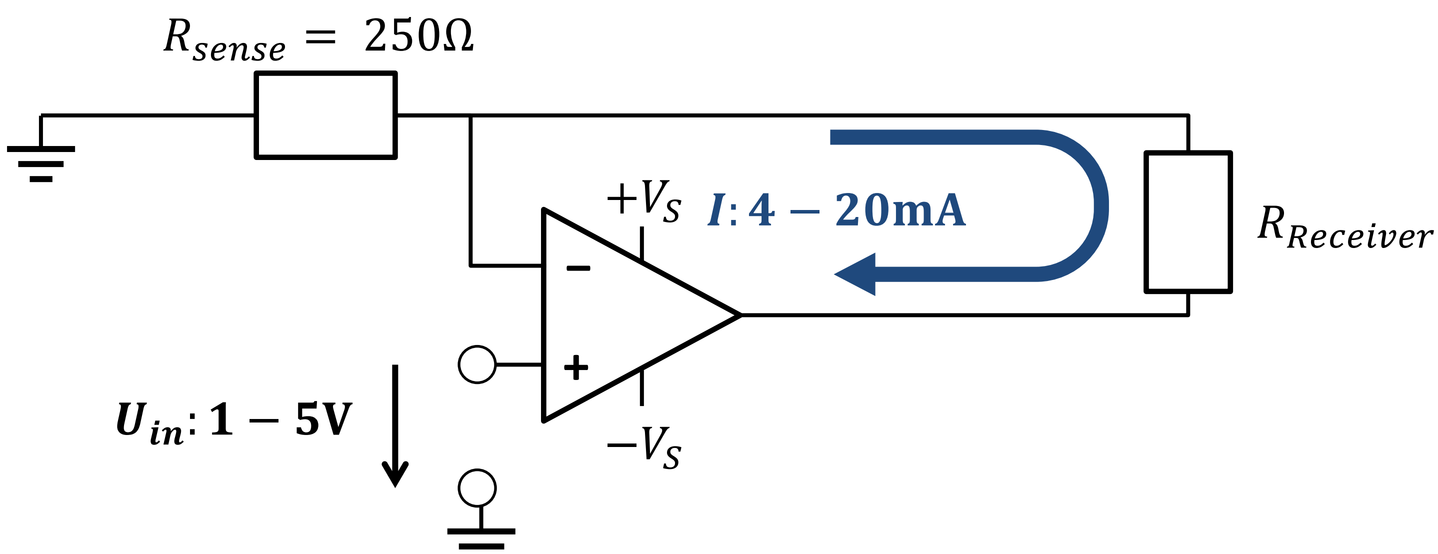
Two-wire current loop

- Components:
  - transmitter
  - receiver
  - power supply
- The loop might contain multiple receivers but only one single transmitter
- Power and signal transmitted by the same pair of wires
- Maximal loop length: ca 2000 m

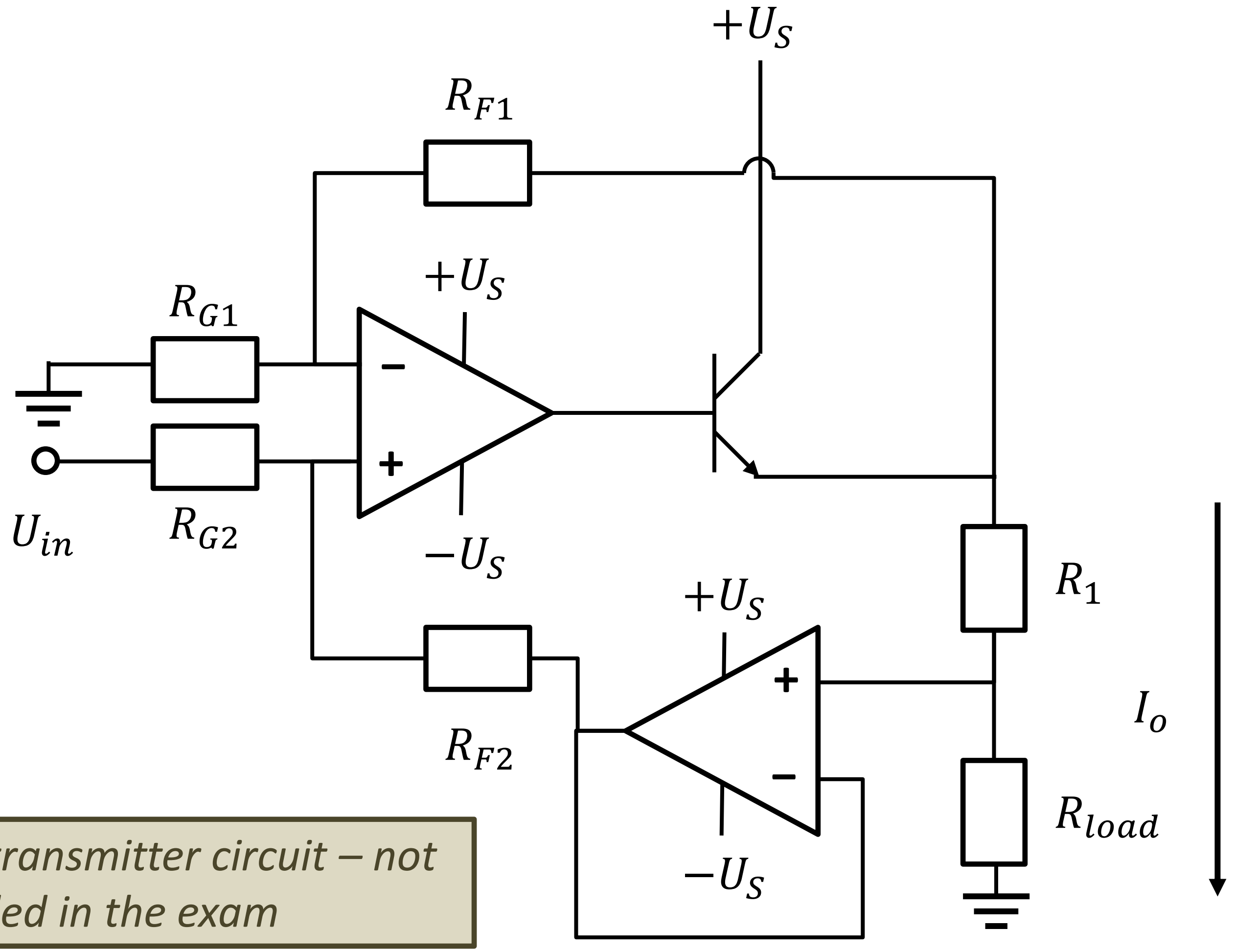


Transmitter

- The loop is powered by the power supply
- The transmitter modulates the current flowing through the loop
- Circuitry: current source energized by the power supply (V_S)

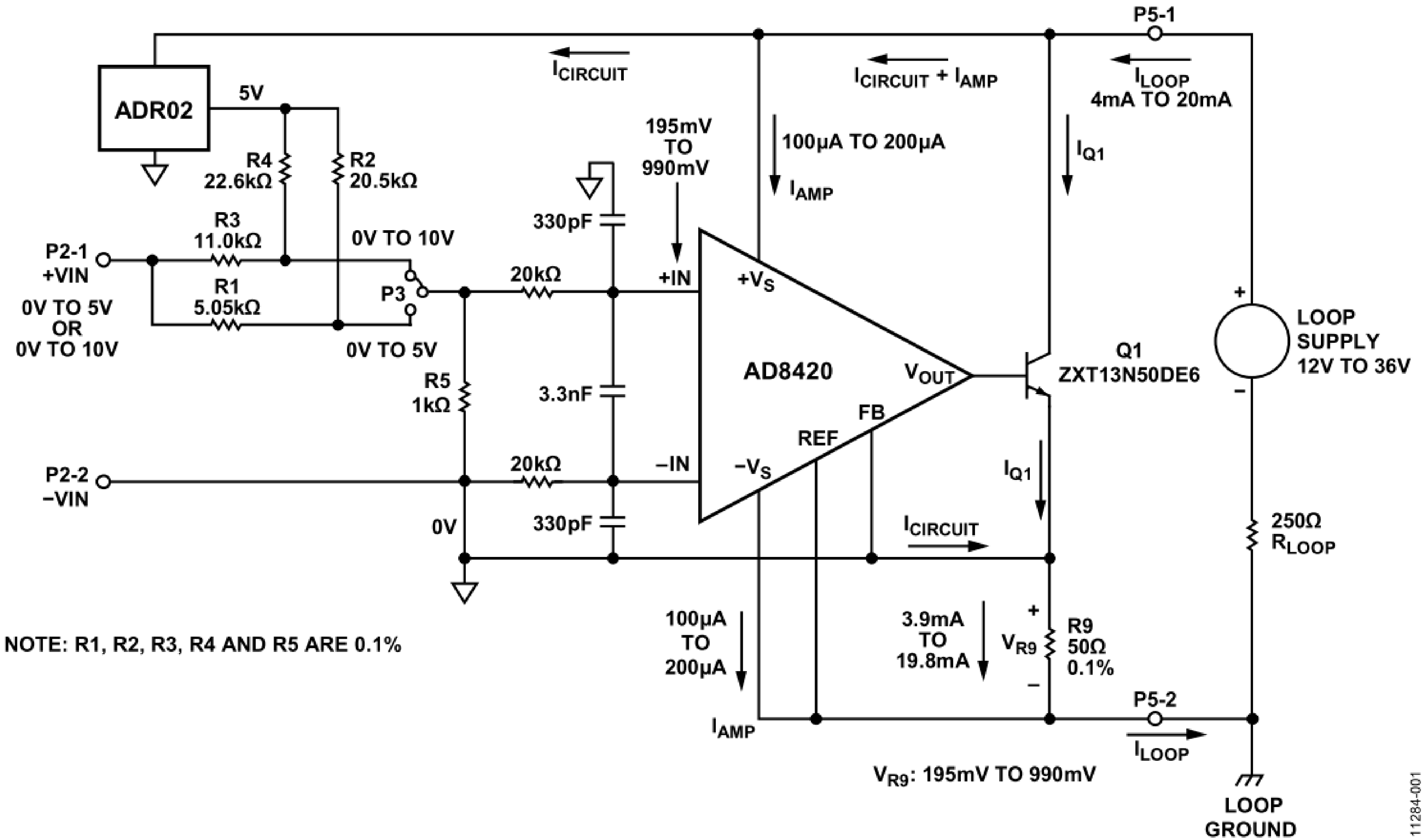


Current generator – real-life circuitry



Example of a transmitter circuit – not included in the exam

If $R_{F1} = R_{F2} = R_{G1} = R_{G2}$, then $I_o = U_{in}/R_1$



Transmitter circuitry - example

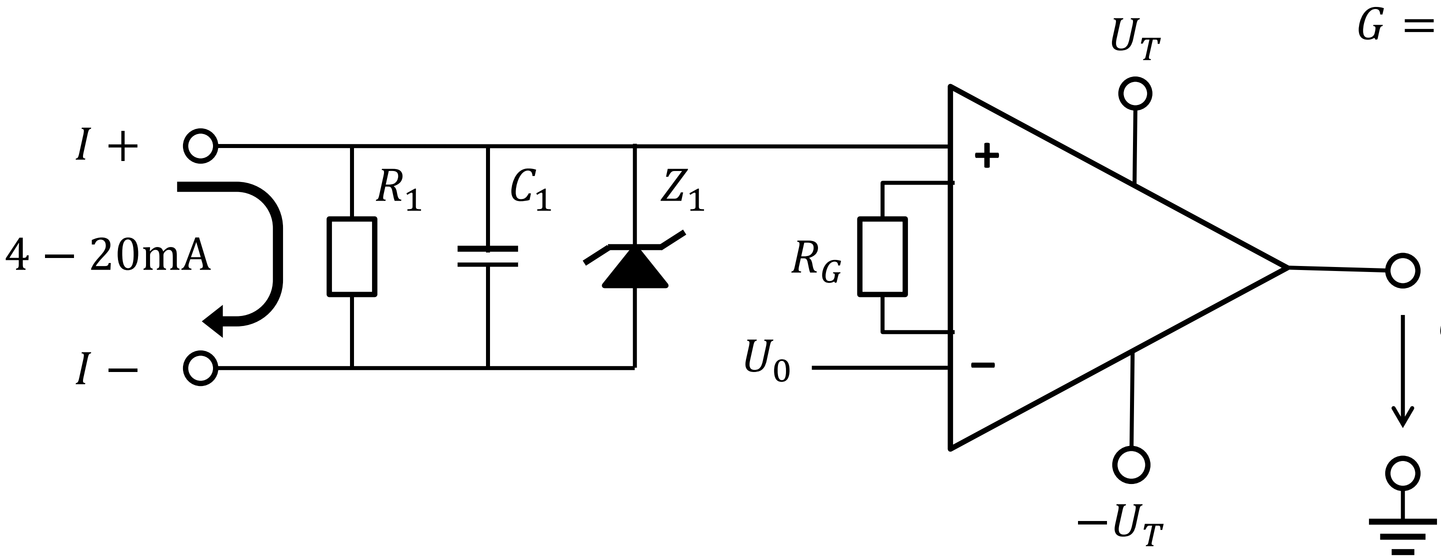
Example of a transmitter circuit – not included in the exam

Analog Devices Circuit Note CN-0314
http://www.analog.com/CN0314

Receiver

- Passive element
- Key is current-voltage conversion: precision resistor
  - $500\Omega \Rightarrow U = 2 - 10\mathrm{V}$
  - $250\Omega \Rightarrow U = 1 - 5\mathrm{V}$
  - $200\Omega \Rightarrow U = 0.8 - 4\mathrm{V}$
  - $100\Omega \Rightarrow U = 0.4 - 2\mathrm{V}$

Input stage of the receiver



$$U_0 = 4\text{mA} \cdot R_1$$

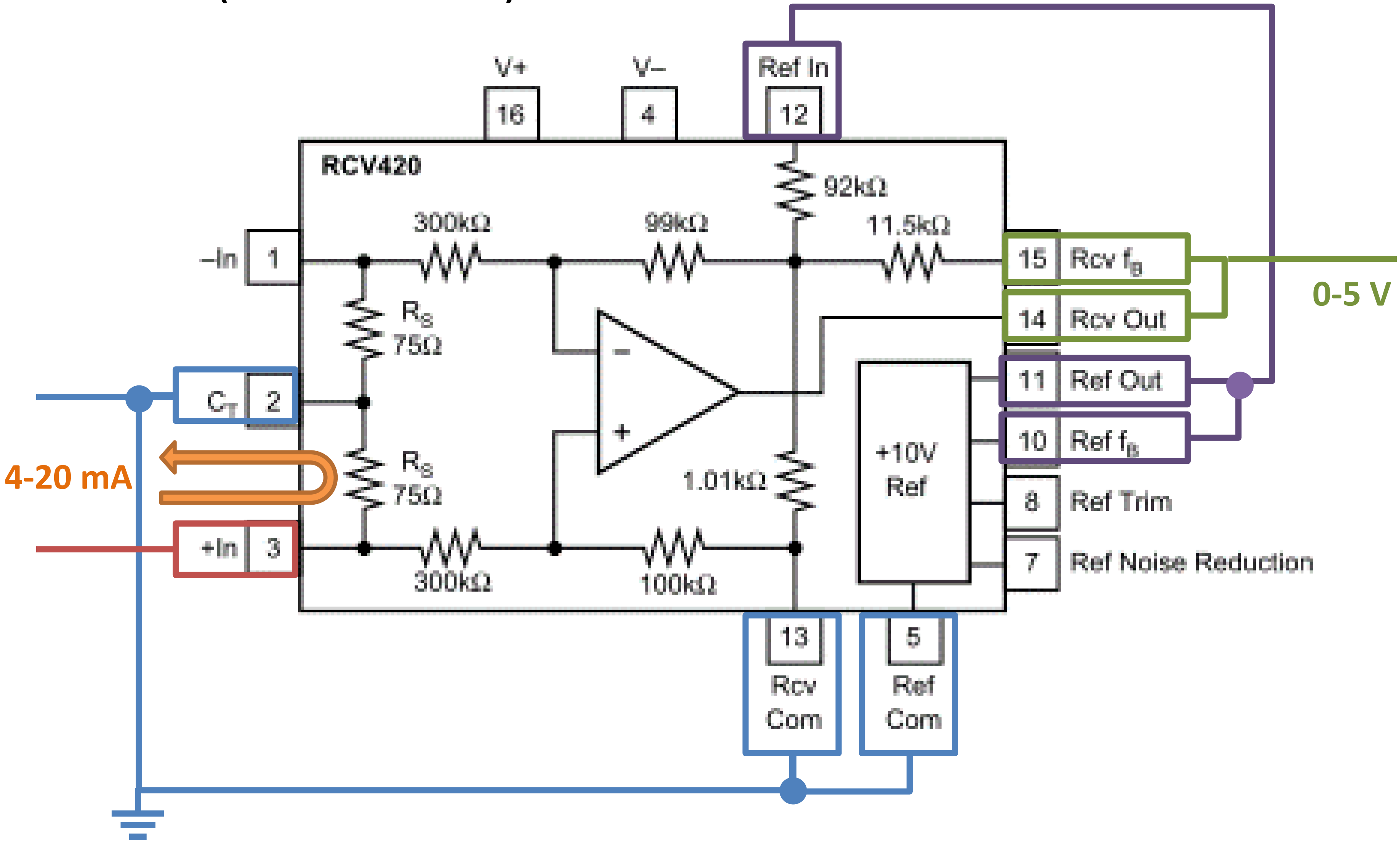
$$G = \frac{U_{max}}{16\text{mA} \cdot R_1}$$

$$U_{out} = G(IR_1 - U_0)$$

$$U_{out}: 0 \dots U_{max}$$

$$R_1 = 100\Omega, U_{max} = 10\text{V} \Rightarrow U_0 = 100 \cdot 4\text{ mV} = 0.4\text{V}, \text{G} = \frac{10}{0.016 \cdot 100} = \frac{10}{1.6} = 6.25$$

Burr-Brown (Texas Instruments) RCV420



Due to the voltage divider in the feedback path, the output range is 0-5V using 10V stabilized reference voltage

Example for a receiver IC – not included in the exam

Power supply

- DC power supply
- Role: supply the transmitter with power
  - needs to supply the voltage required by the transmitter
  - voltage is decreased by the resistance of the receiver(s) and lead wires

Power supply selection

- Power supply provides energy for
  - electronics of the transmitter (excl. current generator)
  - generating the 4-20mA current signal

- Voltage of the power supply:

$$\boldsymbol{U_S \geq U_{S,Transmitter} + 20\mathrm{mA} \cdot R_{Receiver} + 20\mathrm{mA} \cdot R_{Wiring}}$$

  $U_{S,Transmitter}$: minimal supply voltage of the transmitter

  $R_{Receiver}$: sum of receiver resistances

  R_{Wiring} : lead resistance of the current loop

It is recommended to use a power supply with a rated voltage 1.2-1.5 times higher than the minimally required voltage.

Power supply selection - Problem

Operating supply range of a transmitter is $V_S = 11 \ldots 36\text{V}$. The current loop includes two receivers with input resistance of 200Ω each. The lead resistance of the current loop is 10Ω. Give the minimal voltage of the power supply required for the application.

$$U_S \geq 11\text{V} + 2 \cdot 200\Omega \cdot 20\text{mA} + 10\Omega \cdot 20\text{mA}$$

$$U_T \geq 19.2\ \text{V}$$

Power consumption of the transmitter

- Power consumption of the transmitter is limited
- Its maximal current is less then 4 mA (3.8 mA for Namur NE43 transmitters)
- If the transmitter would consume more than 4 mA then the current flowing in the loop will be over 4mA even for the minimal measured value

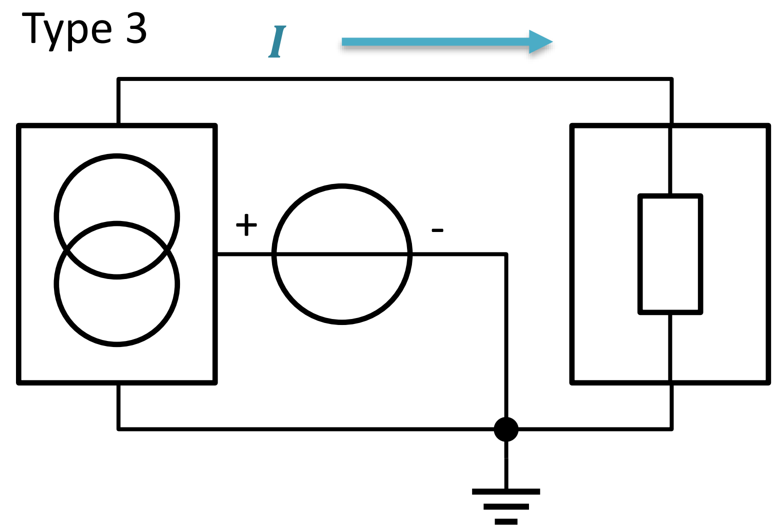
Power consumption of a transmitter - Problem

Operating supply range of a transmitter is $V_S = 11 \ldots 36$. The transmitter is Namur NE43-compliant with output range $3.8 \ldots 20.5\ \mathrm{m}A$. Give an upper bound for the transmitters power consumption.

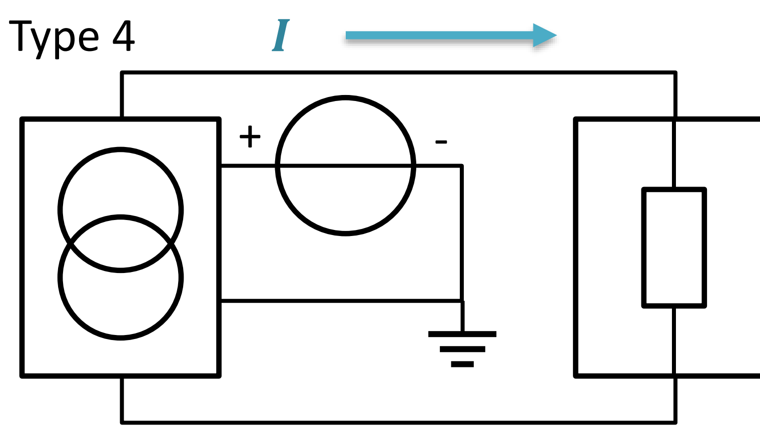
$$P < 11\mathrm{V} \cdot 3.8\mathrm{mA} = 41.8\mathrm{mW}$$

Connection of analog transmitters (ISA)

- Type 2: two-wire
- Type 3: three-wire
- Type 4: four-wire

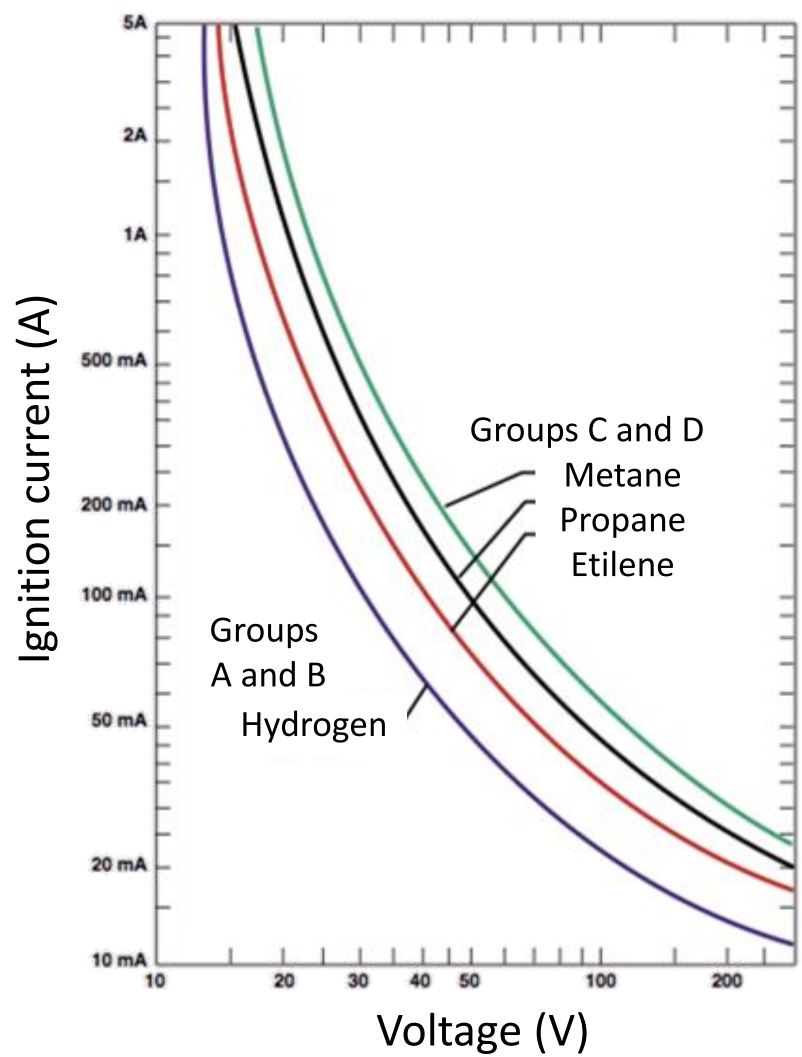


- Type 3 and Type 4 transmitters
  - pro: power consumption of transmitter is not limited
  - con: higher wiring cost



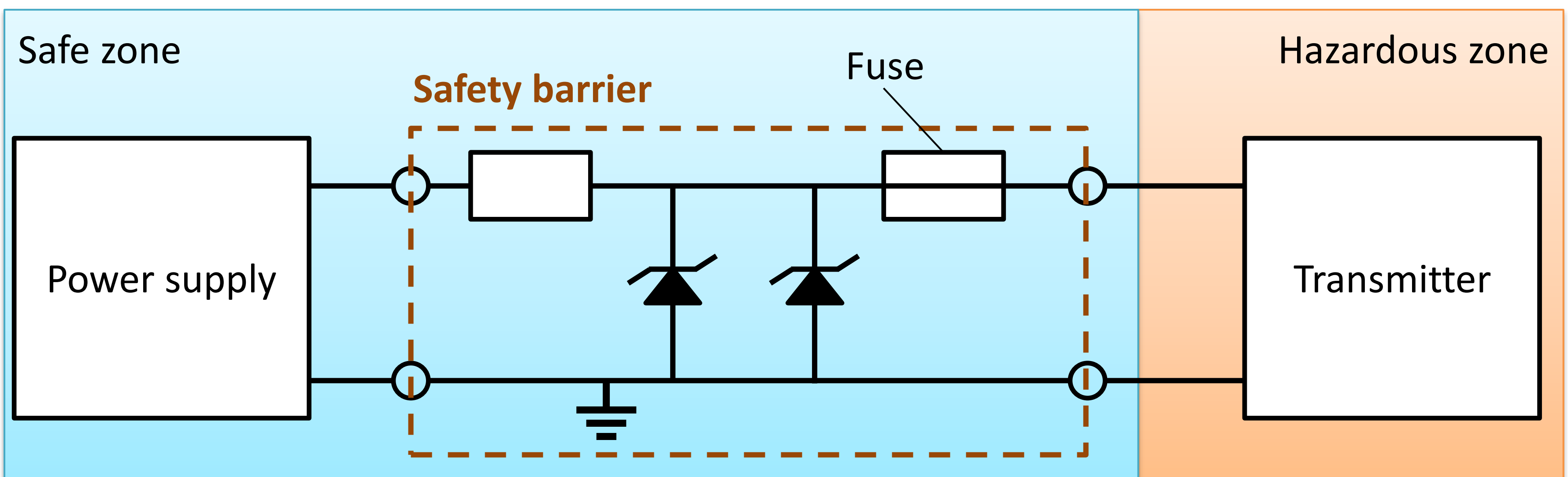
Intrinsic safety

- Electrical power of 4-20mA transmitters with 24V supply is not sufficient to induce explosion in hazardous locations
- No ignition spark can be formed inside the transmitter
- ***Intrinsic safety***: device is safe due to limited power

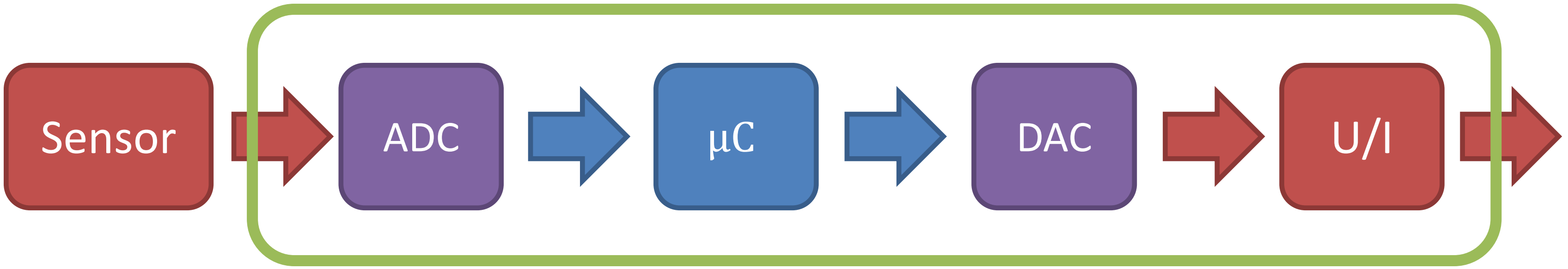


Safety barrier

- Signal levels during normal operation do not allow the generation of a spark
- Same power levels needs to be guaranteed for failure situations (e.g. short circuit) – power supply of the transmitter should also be limited
- Isolation of the transmitter: safety barrier
  - overcurrent protection: current limiting resistor and fuse
  - overvoltage protection: Zener diodes



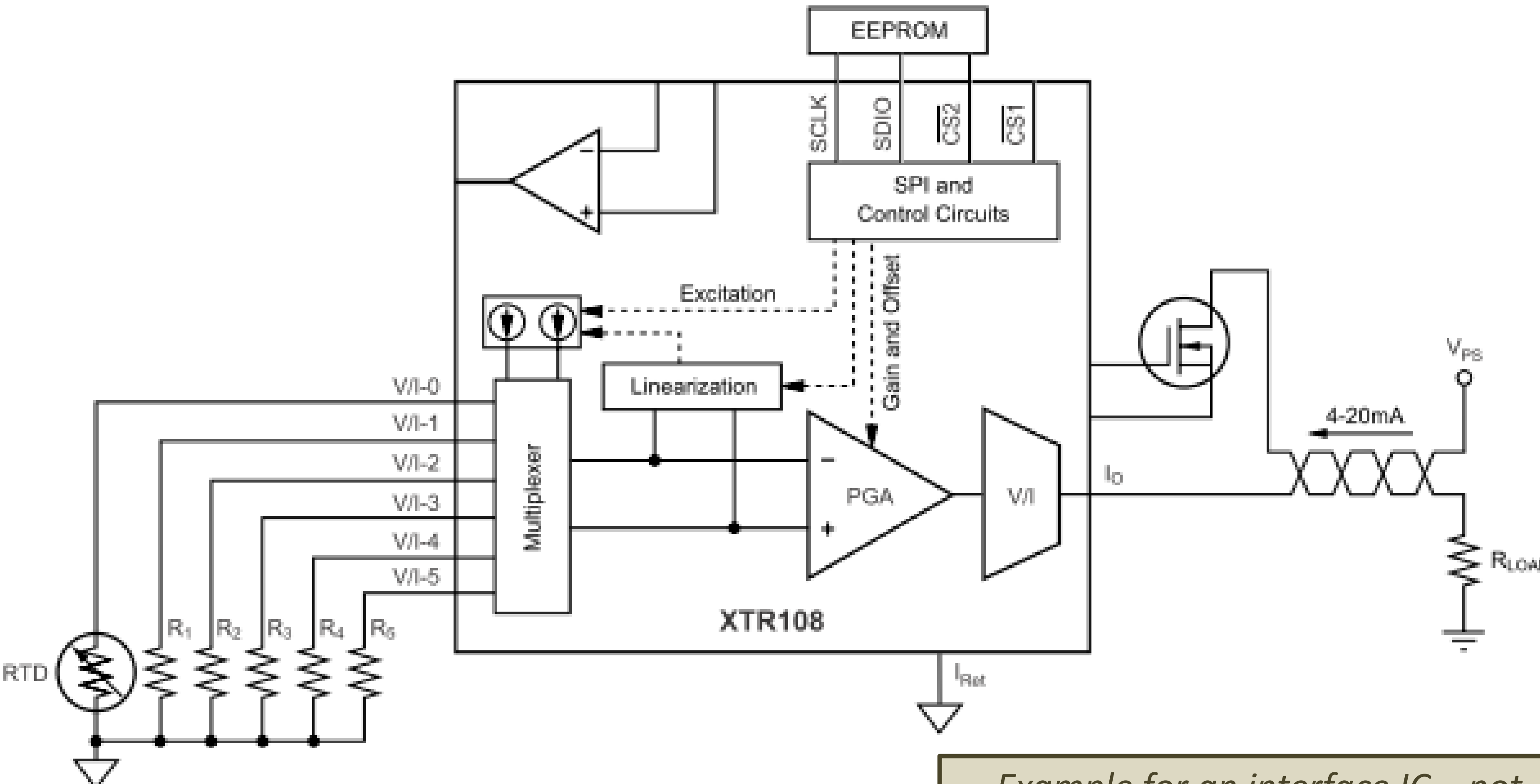
Digital transmitters with analog output



- Digital circuitry in the transmitter
  - same accuracy with lower cost
  - additional functions
  - complex compensating algorithms
- Output: analog 4-20 mA current signal (easy to interface with existing control systems)

Burr-Brown (Texas Instruments) XTR108

- RTD and bridge transmitter
- Digital calibration and compensation circuitry
- Analog current output



Example for an interface IC – not included in the exam

Common features of digital transmitters

- Offset, input range and output range settings
- Configurable correction and compensation
- Memory for storing minimal and maximal values
- Self-diagnostics

Local interface of digital transmitters

- Display + optional pushbuttons
- Displays the measured value in configurable units
- Allows parameter setting

HART

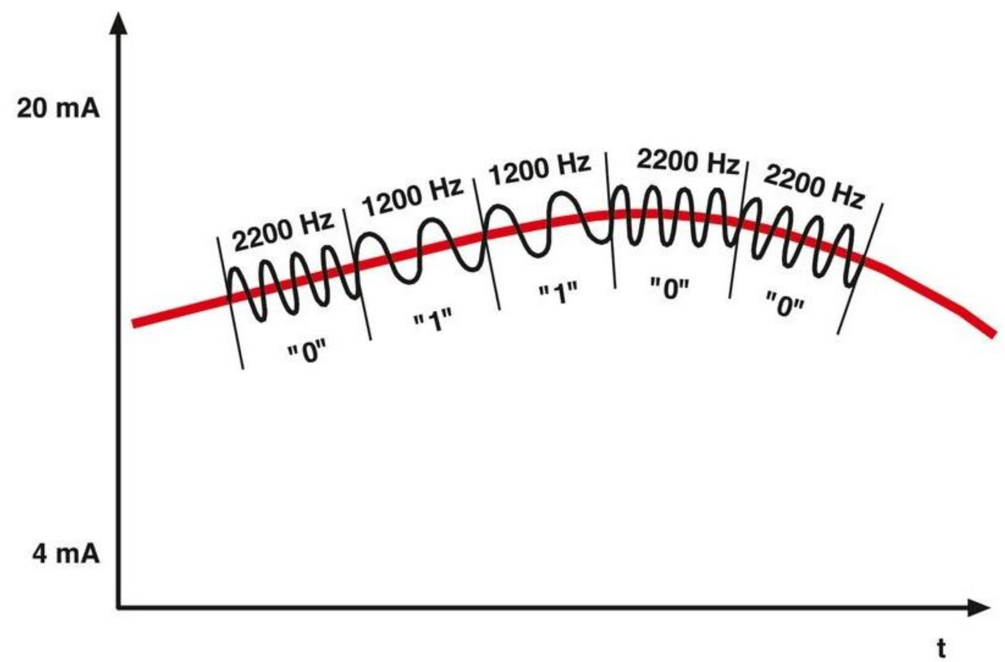
(Highway Addrassable Remote Transducer)

- Digital communication channel for transmitters using the current loop along with analog signals
- Developed by Rosemount Inc. (late 1980s)
- 1993: HCF – HART Communication Foundation
- Current version: 8

HART COMMUNICATION PROTOCOL

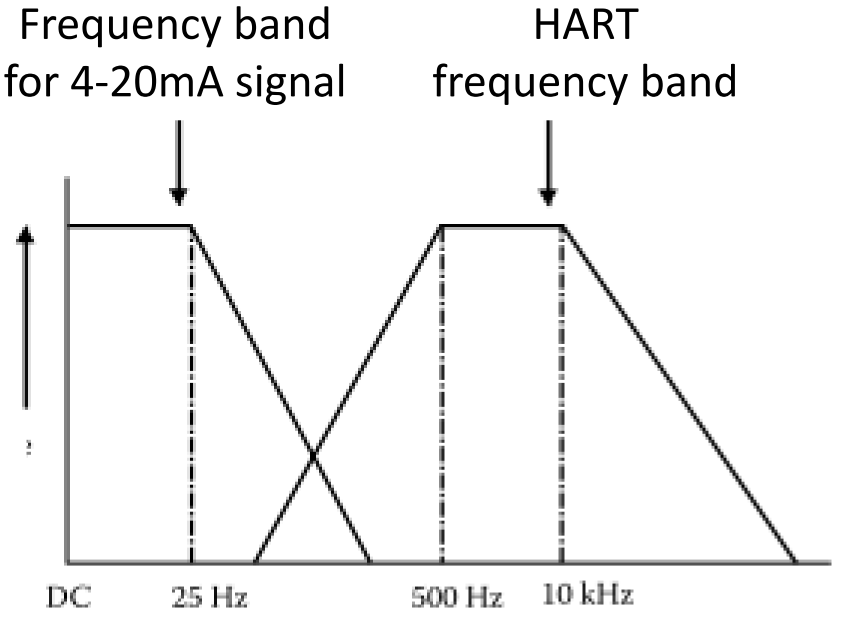
HART physical layer

- FSK modulated digital signal superposed to the 4-20mA analog signal
  - 1200Hz – 1
  - 2200Hz – 0
- Continuous-phase current signal with 0.5mA magnitude



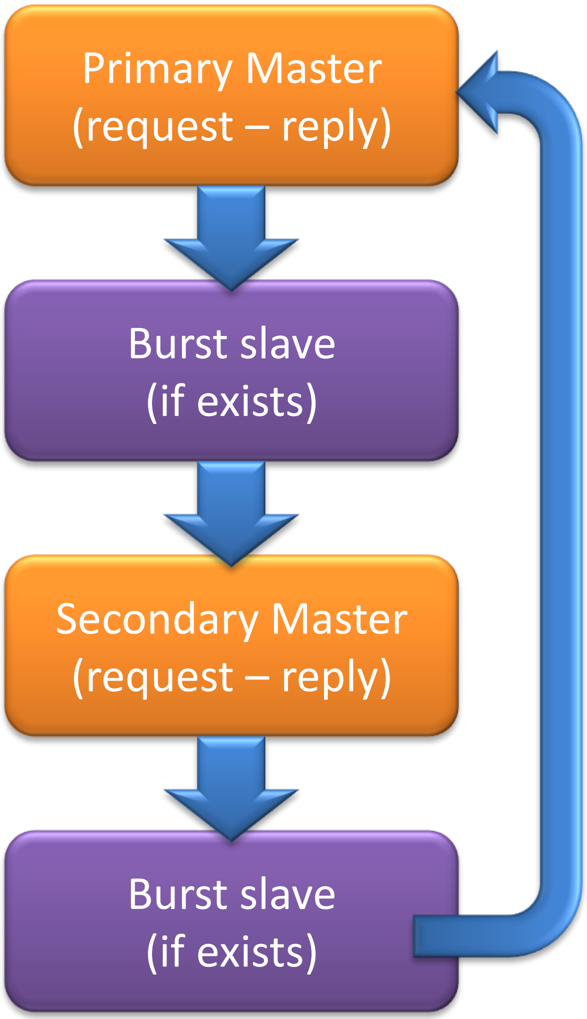
HART physical layer

- DC average of the signal is zero, so no DC component added to the analog signals
- Spectra do not overlap
- Use of input filters is recommended for non HART-compliant devices



HART communicaiton

- Master-slave model
  - 1 or 2 masters
  - 1…15 slaves
- Slaves reply to requests of the master only
- Burst mode: one single slave is allowed to transmit without request of the master
- Deterministic data transfer
- Response time: 0.5s



HART – multi-variable transmitters

- A transmitter can be connected to multiple sensors – up to 256 measured values
  - pressure
  - temperature
  - …
- Only one of these values can be transmitted as an analog 4-20mA signal
- Other values can be queried using HART

Transmitters with digital output

- Digital output connected to a bus
- Fieldbus networks
  - PROFIBUS PA
  - AS-i
  - DeviceNet
  - PROFINET
  - …
- Transmitter can be powered by the bus (e.g. AS-i)

Wireless transmitters

- Rival standards
  - Wireless HART
  - ISA100 Wireless
  - ZigBee Plus
- Mesh architecture providing redundancy
- Up to 100ms of range
- Advanced security solutions
- Fully wireless – no need for power lines!
  - battery-powered operation
  - periodic communication
  - energy harvesting
  - up to 10 years battery operation

IO modules of industrial control systems

Common signal types in industrial control systems

- Analog
  - voltage
  - current
  - frequency
  - (resistance)
- Digital
  - voltage (level/contact)
  - frequency

Typical types of IO modules

- Input modules
  - analog
    - voltage/current
    - temperature – RTD resistance, thermocouple voltage
  - digital
    - digital IO
    - fast counter
- Output modules
  - analog (voltage/current)
  - digital

Analog voltage and current signals

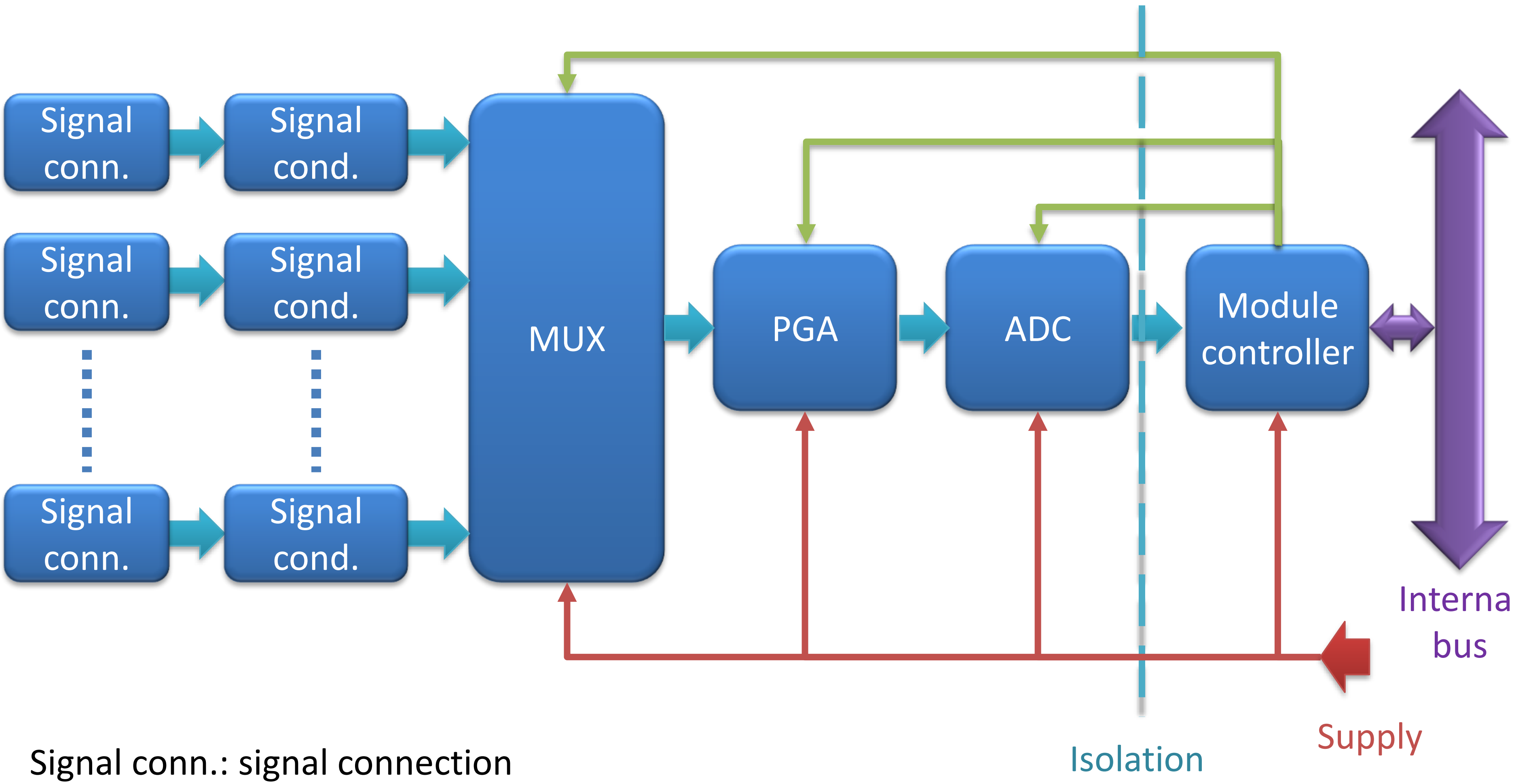
- Typical voltage ranges (input resistance $> 1\mathrm{M}\Omega$)
  - $0 - 10\mathrm{V}$
  - $0 - 5\mathrm{V}$
  - $\pm 10\mathrm{V}$
  - $\pm 5\mathrm{V}$
  - $\pm 2.5V$

- Typical current ranges (input resistance $< 300\Omega$)
  - $0 - 20\mathrm{mA}$
  - $4 - 20\mathrm{mA}$

Types of analog signals

- Single ended voltage
  - voltage is measured relative to a common level (ground)
  - needs $N + 1$ (common ground) terminals for N channels
- Differential voltage
  - voltage is measured as the difference between two terminals
  - needs $2N$ terminals for N channels
- Single ended current
  - current flowing through the module is measured
  - needs $2N$ terminals for N channels

Analog input module

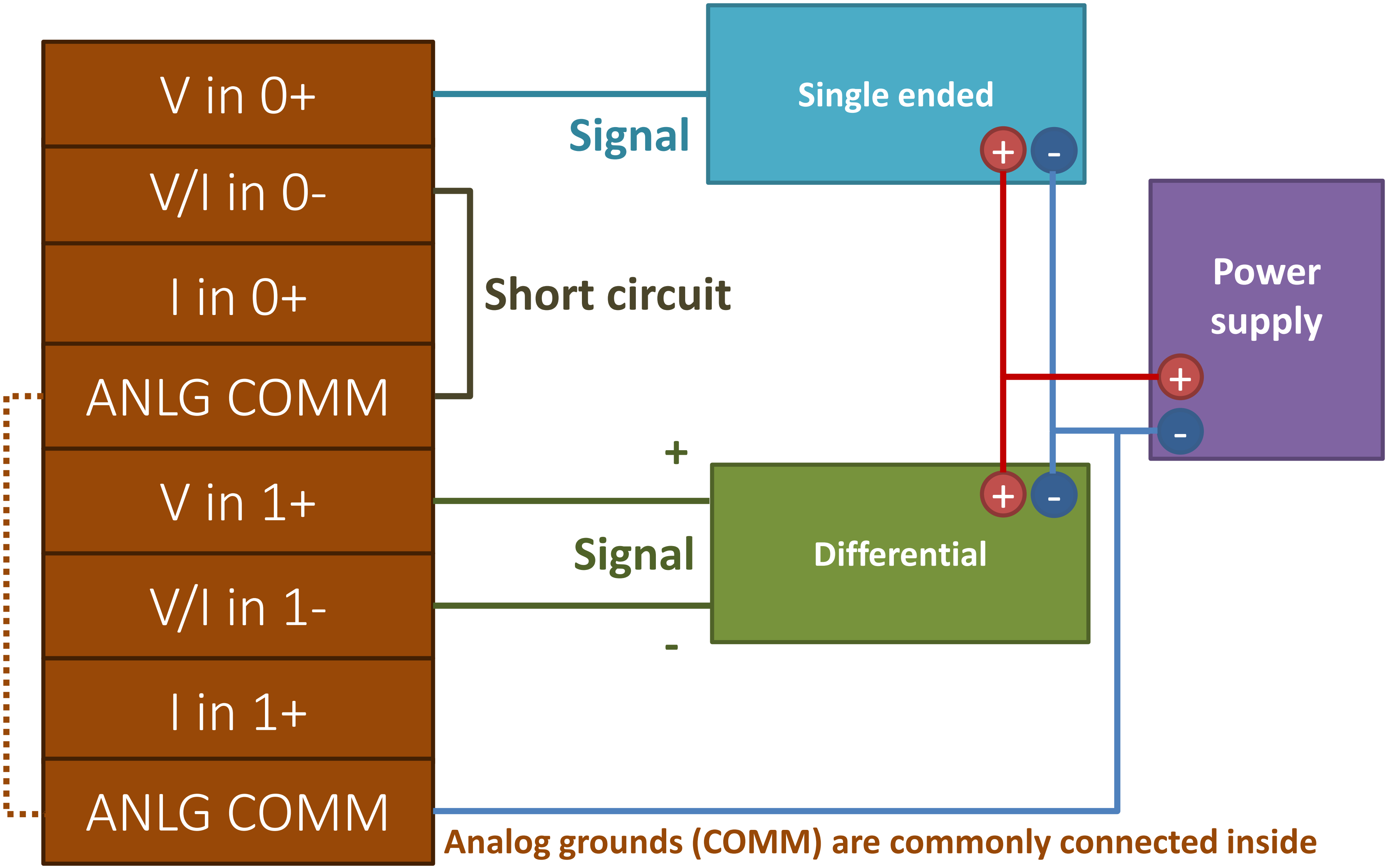


Signal conn.: signal connection
Signal cond.: signal conditioning

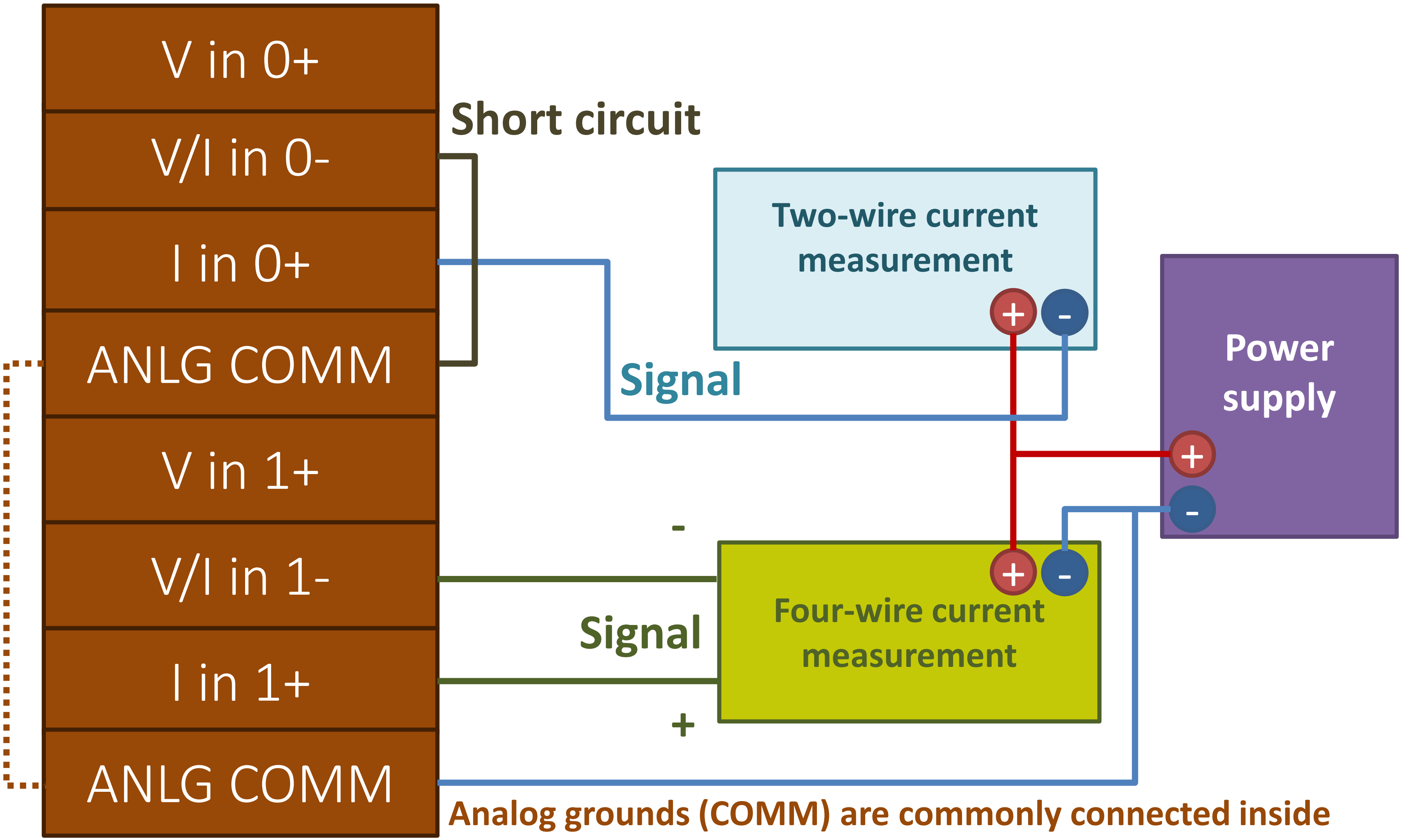
Signal connections of an input module

- Voltage input
  - one terminal per channel for single ended measurements (e.g. V IN 0)
  - positive and negative terminals for differential measurements (e.g. V IN 0+, V IN 0-)
- Current input
  - one of the terminals is common with the voltage input of the same channel (V/I IN +), other is dedicated to current measurement (I IN -)
  - reference resistor between the two terminals ($50 - 250\Omega$)
- Reference (ground): COM, RTN
  - multiple terminals
  - some or even all reference terminals might be connected internally – always check the datasheet!

Analog voltage input



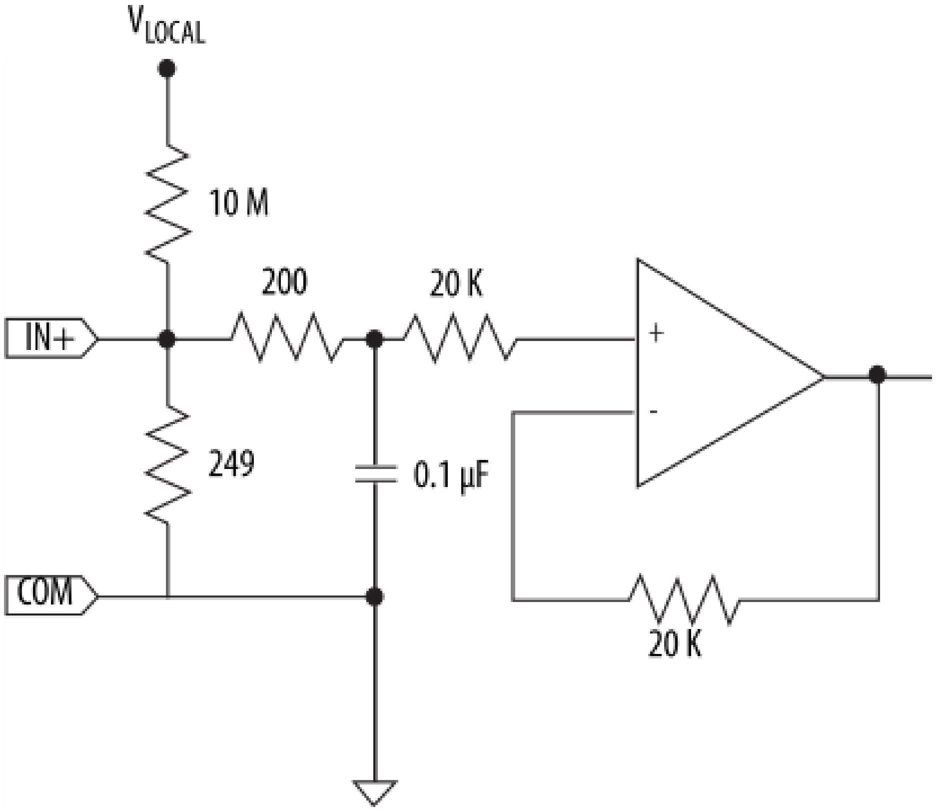
Analog current input



Signal conditioning

- Current/voltage conversion (reference resistor)
- Voltage divider
- Filter
- Circuit protection (optional)

Signal conditioning circuit of input module Rockwell 1769-IF16C



Example for signal conditioning circuit – exact circuitry not included in the exam

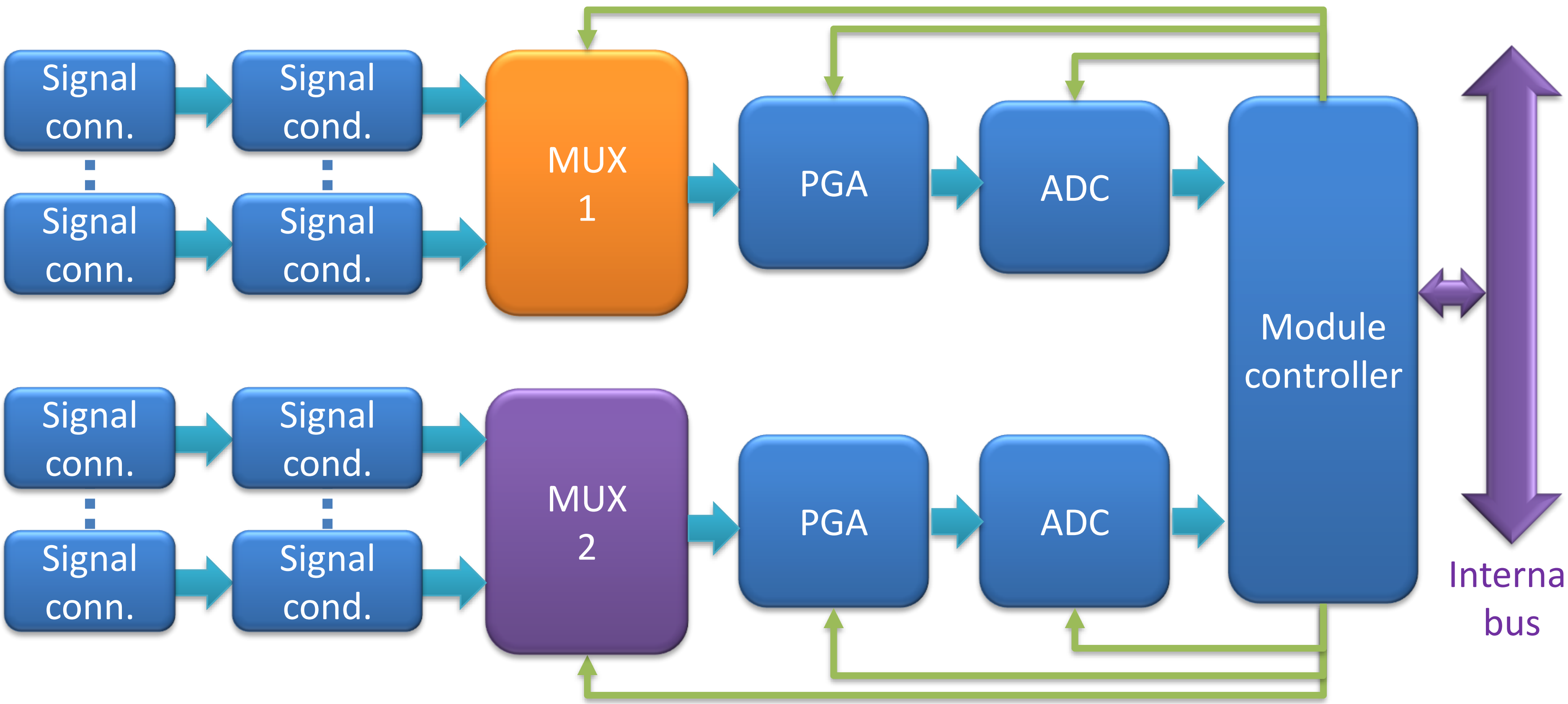
Multiplexer

- Analog multiplexer
- Switches and transmits the signal of the channel selected by the module controller
- Is it really necessary?
  - each channel can be equipped with dedicated amplifier and ADC
  - cost of a good quality amplifier and ADC is high
- Types of multiplexers
  - solid state (MOSFET)
  - relay
  - switched capacitor

Drawbacks of multiplexing

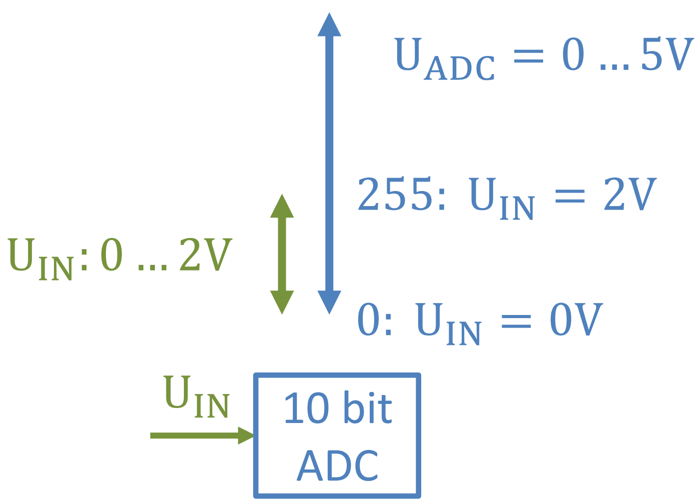
- Only one channel can be sampled simultaneously
- Sampling time rises with the number of channels used
- Samples of different channels are not taken exactly at the same time (jitter)
- Field grounds are interconnected if solid state multiplexer is used
- Common solution: multiplexing not all channels but groups of 4-8 channels

Channel groups

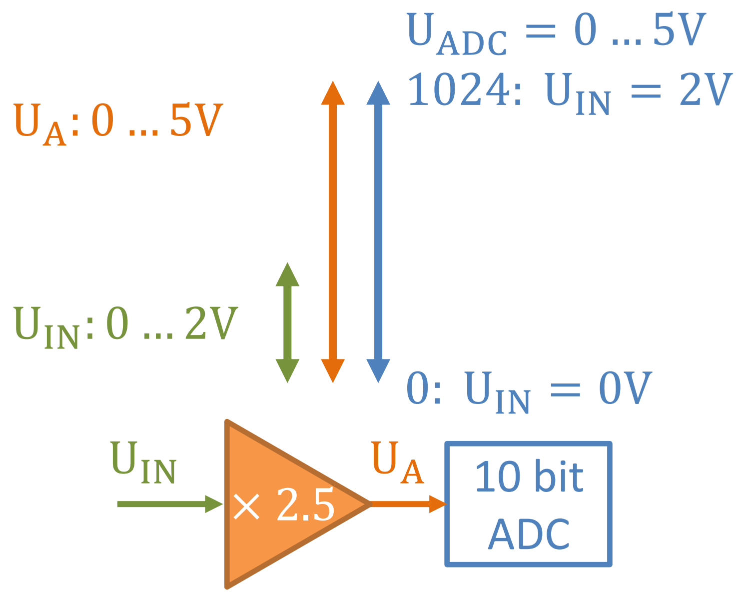


Amplifier

- Role: scaling the signal to the input range of the ADC
- Aim: input range should „fill in” the input range of the ADC
- Various input voltage ranges (0-5V, 0-10V, $\pm$10V…)



Resolution $\approx$ 5mV



Resolution $\approx$ 2mV

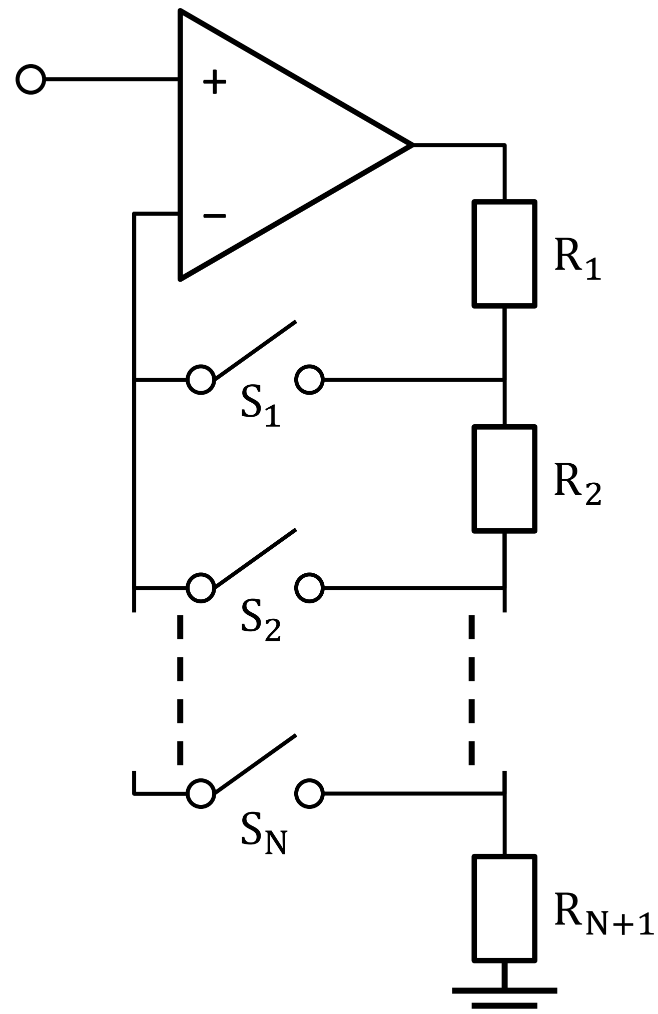
Programmable Gain Amplifier (PGA)

Gain can be set to discrete values:

- S_1 is closed: $G = 1 + \frac{R_1}{R_2 + \cdots + R_{N+1}}$
- S_2 is closed: $G = 1 + \frac{R_1 + R_2}{R_3 + \cdots + R_{N+1}}$

  $\cdots$

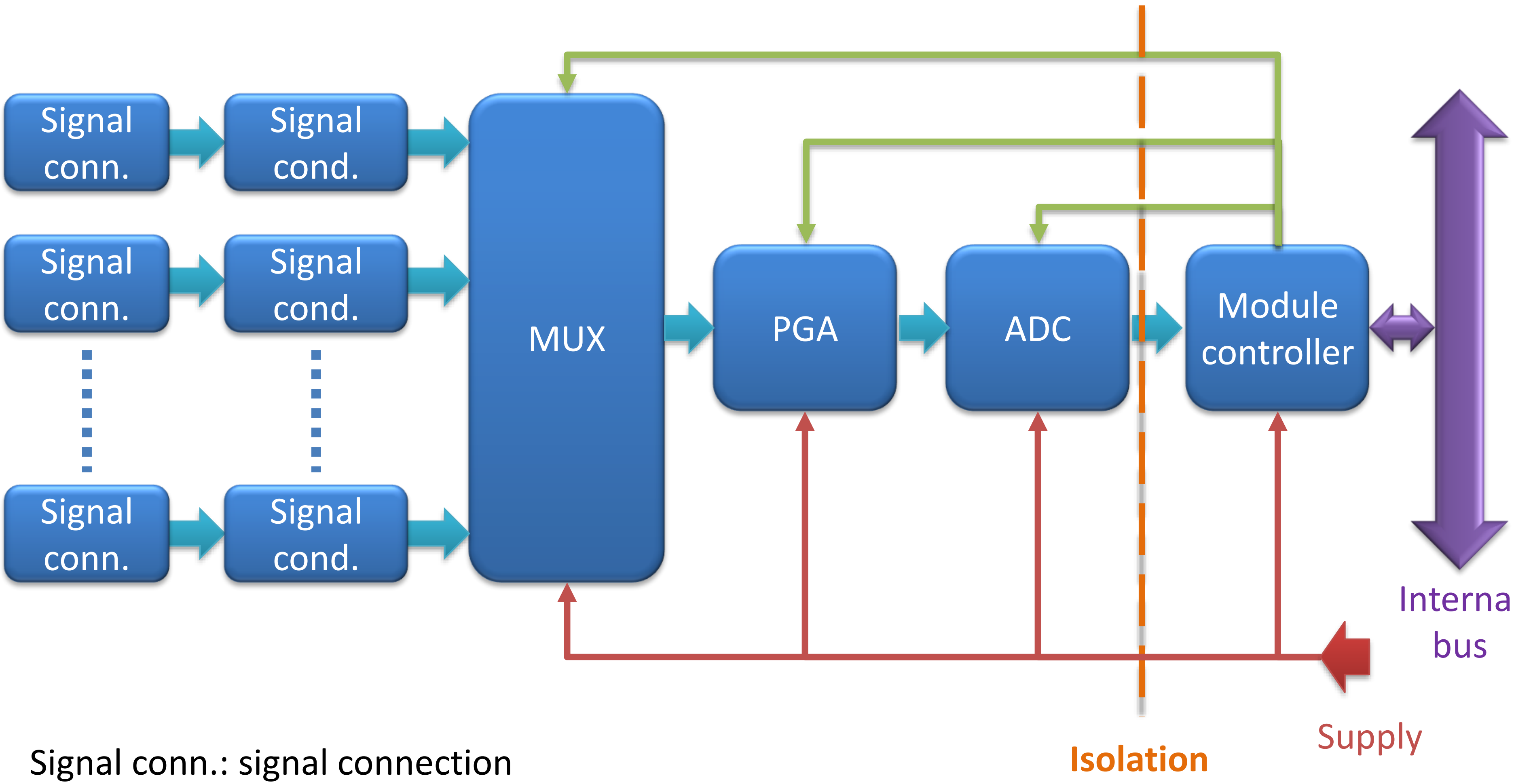
- S_N is closed: $G = 1 + \frac{R_1 + R_2 + \cdots + R_N}{R_{N+1}}$



Analog-Digital Converter (ADC)

- Typical resolution: 16-24 bits
- Typical types
  - ΣΔ
  - dual slope
  - successive approximating

Isolation



Signal conn.: signal connection
Signal cond.: signal conditioning

Isolation

- Aim: protection of the control device
- Galvanic isolation of the module controller
  - both for measurement and control signals
  - isolation by optocoupler
- Supply isolation – optional DC-DC converter
- Typical isolation voltage: 1000V

Module controller

- Coordinates operation of the input module
  - channel selection (MUX control)
  - scaling (PGA control)
  - starting the conversion (ADC control)
  - correction, conversion and buffering the measurements
  - communication with the CPU via the internal bus

- Typical features
  - sampling and buffering
  - filtering
  - self calibration
  - alarm and failure detection

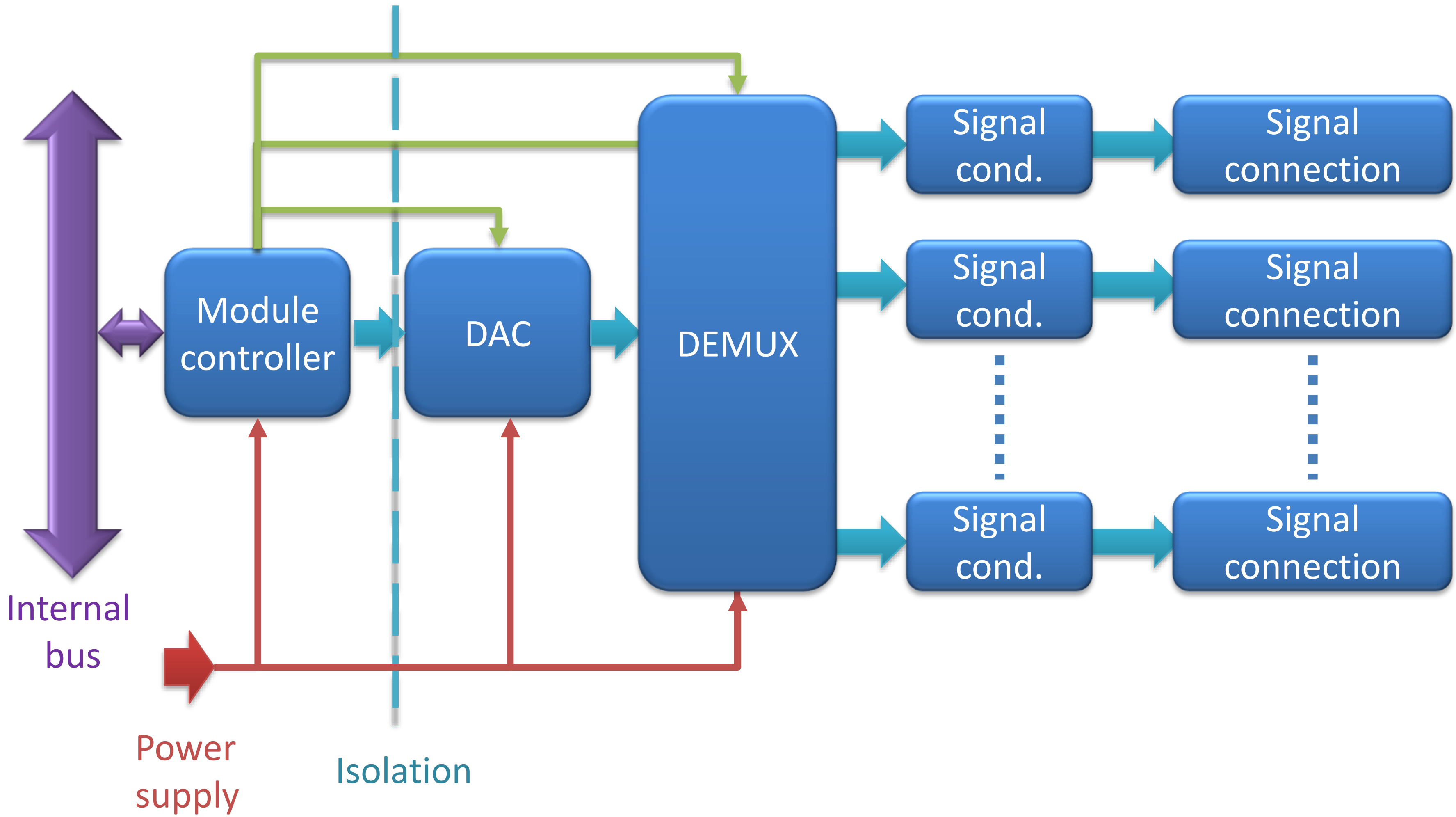
Special input module: isolated inputs

- Channels are galvanically isolated
- Dedicated PGA and ADC for each channel
- High cost
- Galvanic isolation of field grounds

Special input modules for temperature measurement

- RTD input
  - current generator
  - voltage measurement
  - supports 3- and 4-wire configurations
- Thermocouple input
  - voltage measurement
  - cold junction compensation by software
- Low signal levels (< 100mV)
- Isolation of channels

Analog output module



Module controller

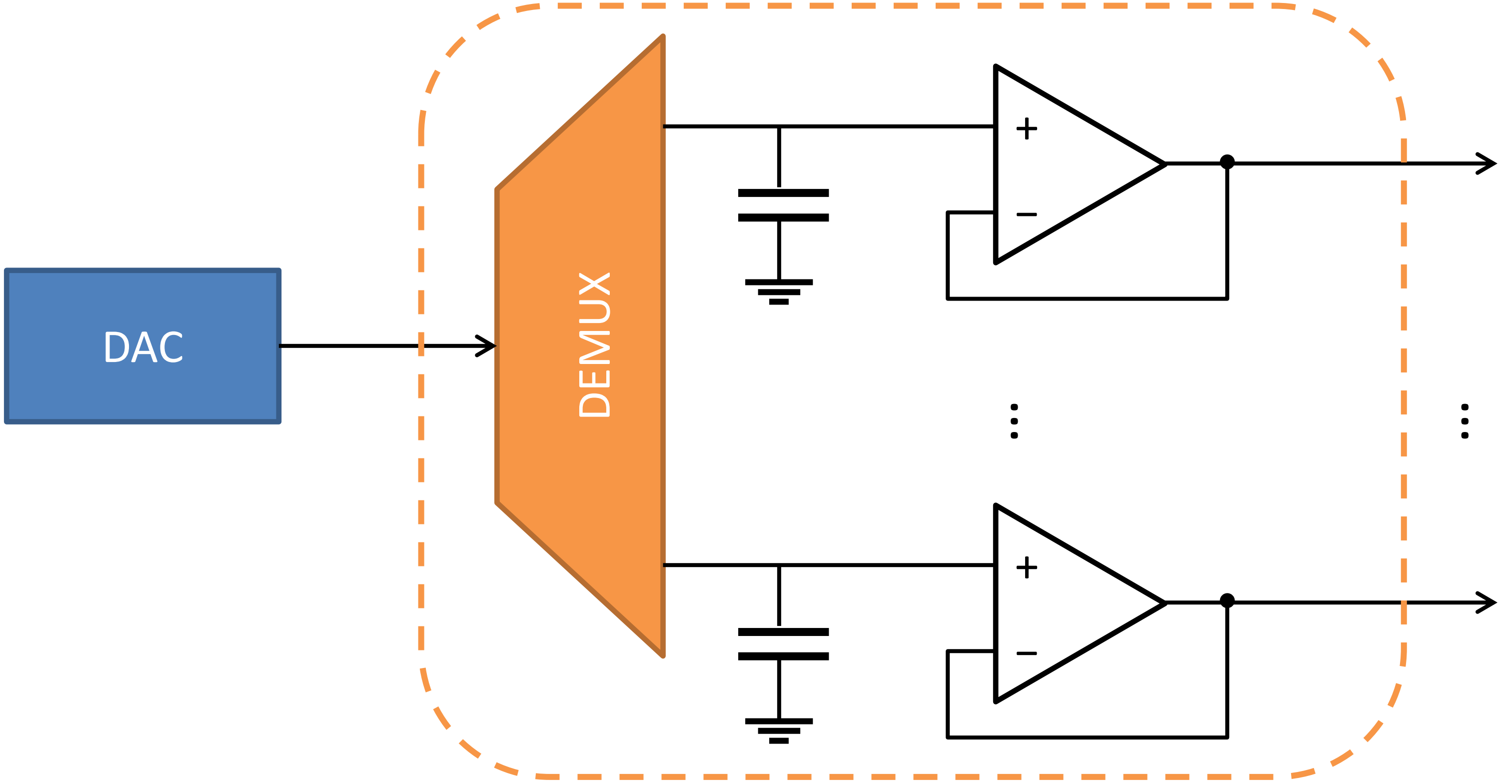
- Coordinates operation of the output module
  - communication with the CPU via the internal bus
  - storing output data received from the CPU
  - channel selection (DEMUX control)
  - start of conversion (DAC control)

Digital/analog converter

- Resolution: 16-24 bits
- Sample-and-hold (zero order hold)
- Output range can be set
- Filter (ramp) might also be configured

Demultiplexer

- Connecting the output of DAC to the appropriate channel
- Sample-and-hold feature: capacitor and op-amp buffer
- No need for demultiplexers if dedicated DACs are used for each channel



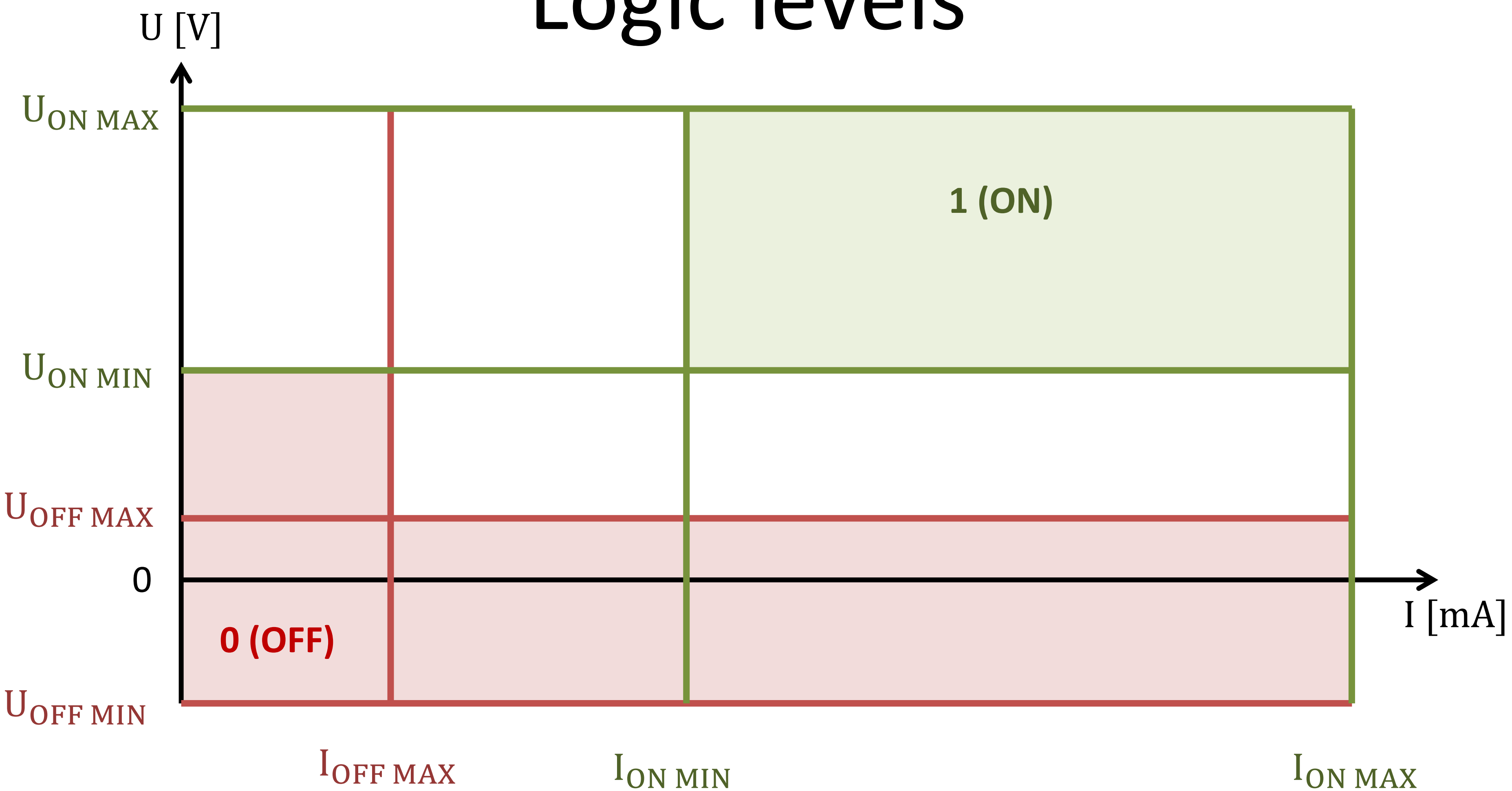
Signal conditioning

- Typical setup: output of the DAC is directly used
- Optional isolation at the output (rare)
- Current output modules
  - DAC followed by voltage/current conversion
  - standard 4-20 mA current level

Digital voltage signals

- DC
  - 0-24 V
  - 0-5 V (TTL) – rare
  - …
- AC
  - 115V/230V – rate
  - …

Logic levels



OFF: $U_{OFF\ MIN} \leq U \leq U_{OFF\ MAX}$ OR $(U_{OFF_{MIN}} \leq U \leq U_{ON\ MIN}$ AND $I \leq I_{OFF\ MAX})$

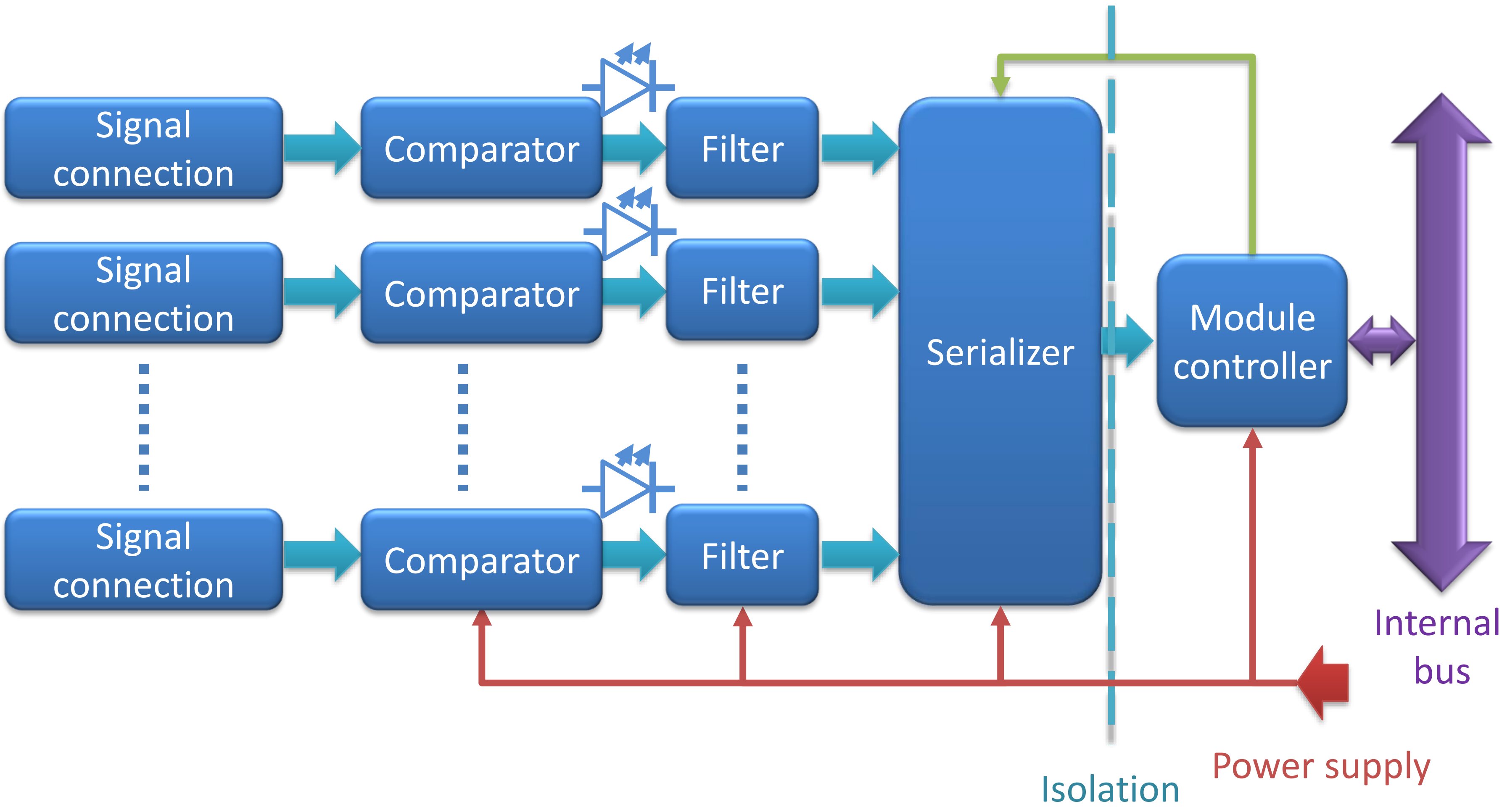
ON: $U_{ON\ MIN} \leq U \leq U_{ON\ MAX}$ AND $I_{ON\ MIN} \leq I \leq I_{ON\ MAX}$

Digital signals

- Level / contact signal
  - information represented by voltage/current level
  - low frequency
  - e.g. limit switch

- Frequency / pulse signals
  - information represented by frequency of pulse width
  - possibly high frequency
  - e.g. encoder

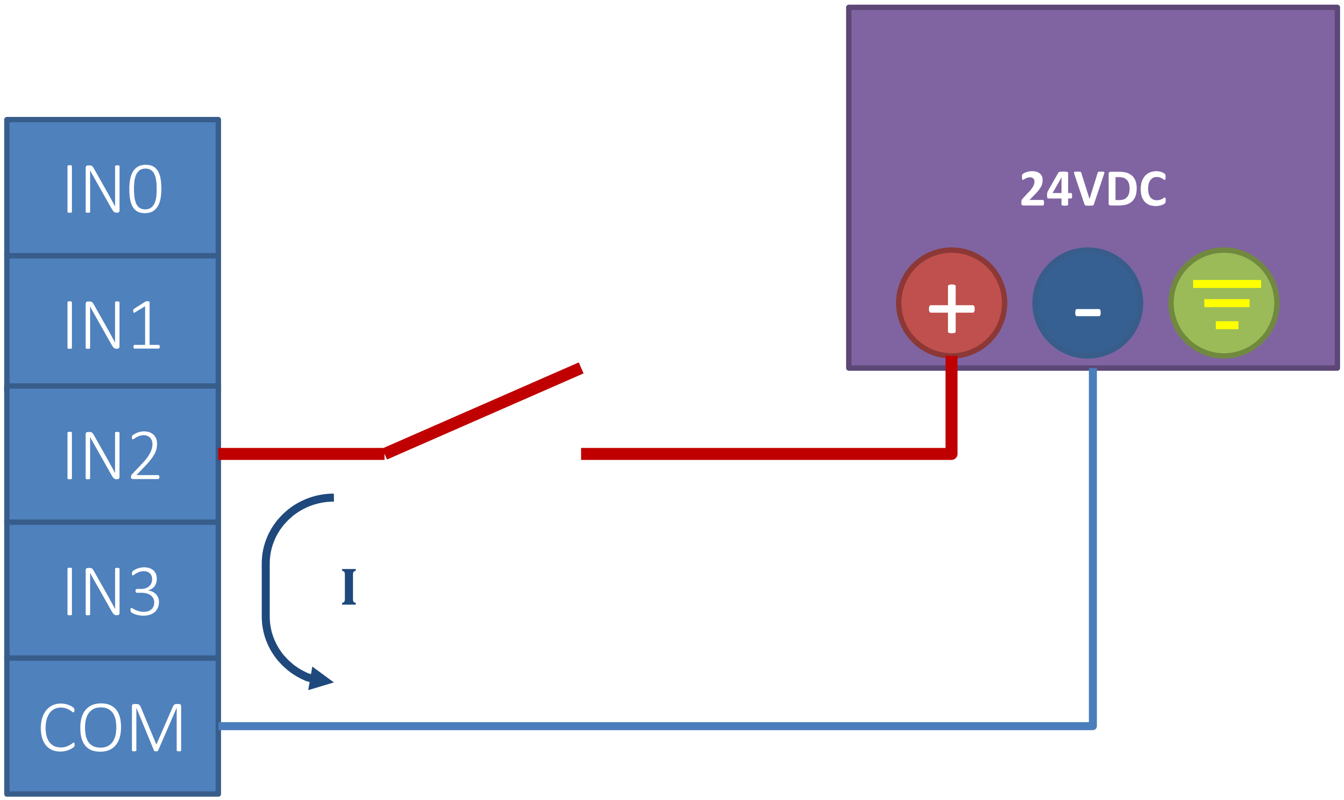
Digital input module



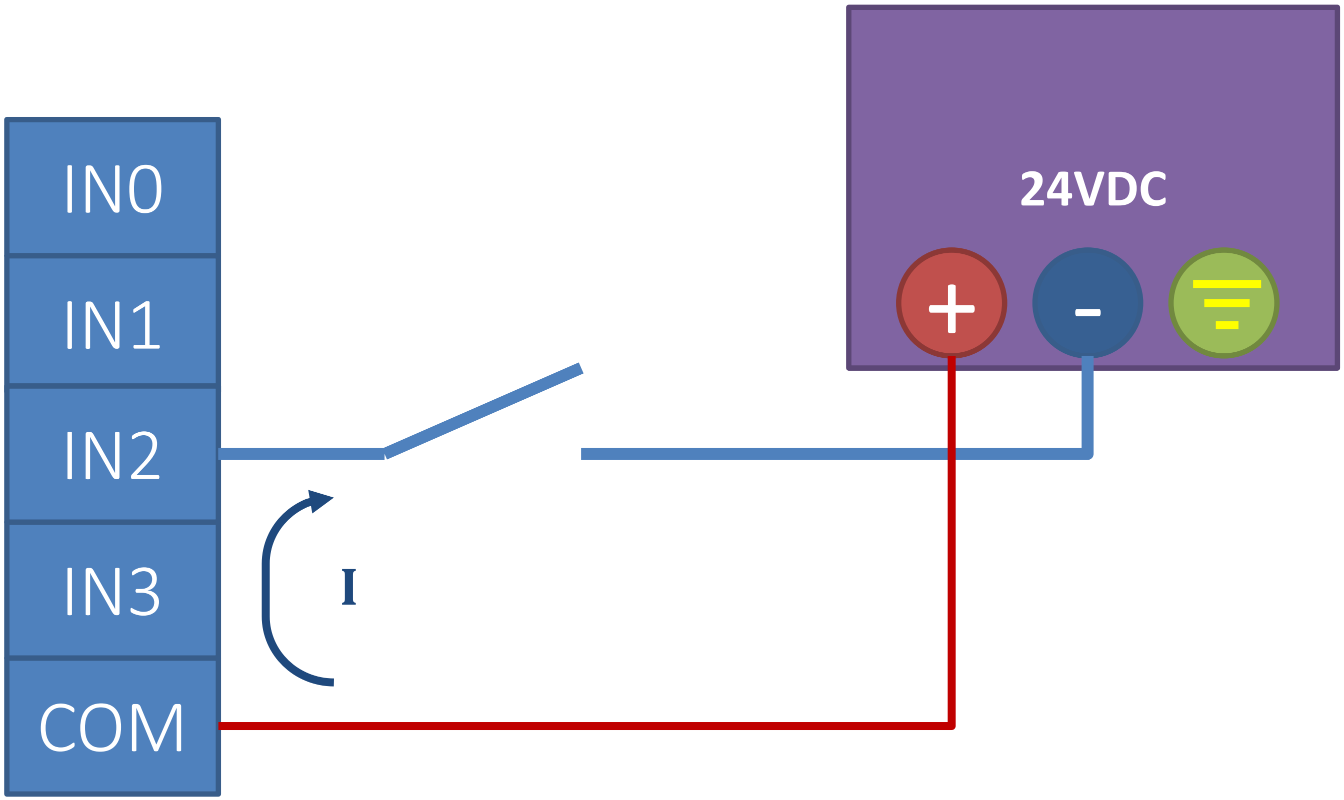
Signal connections

- Input: IN-*n*, I*n*
- Common (ground): COM, GND
  - reference for levels
  - isolated module: dedicated ground for each channel (high cost, rare)
  - channel ground: common ground for 4 / 8 input channels

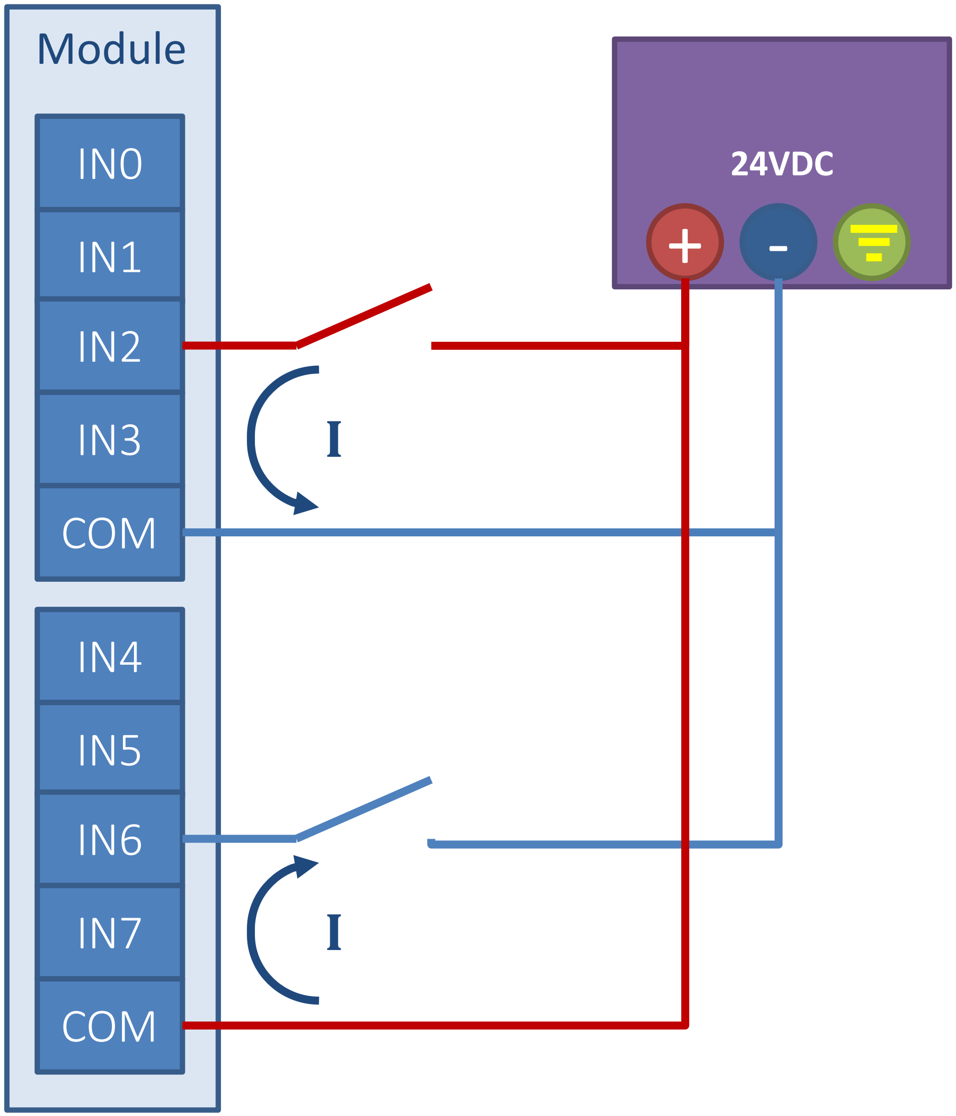
Sink input – positive logic



Source input – negative logic



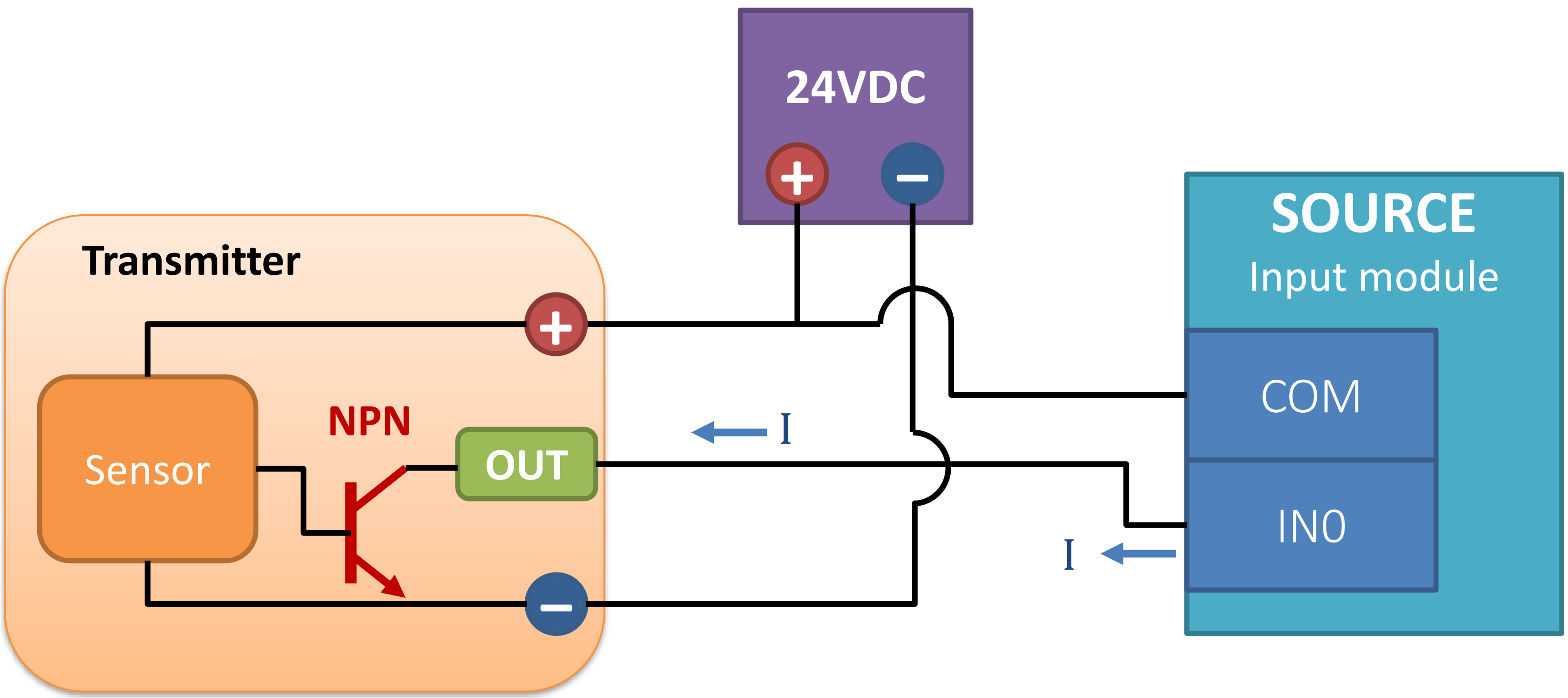
Sink / Source input



- Able to operate in both configurations
- Each channel of a channel group (with common reference signal) operates either in sink or source configuration

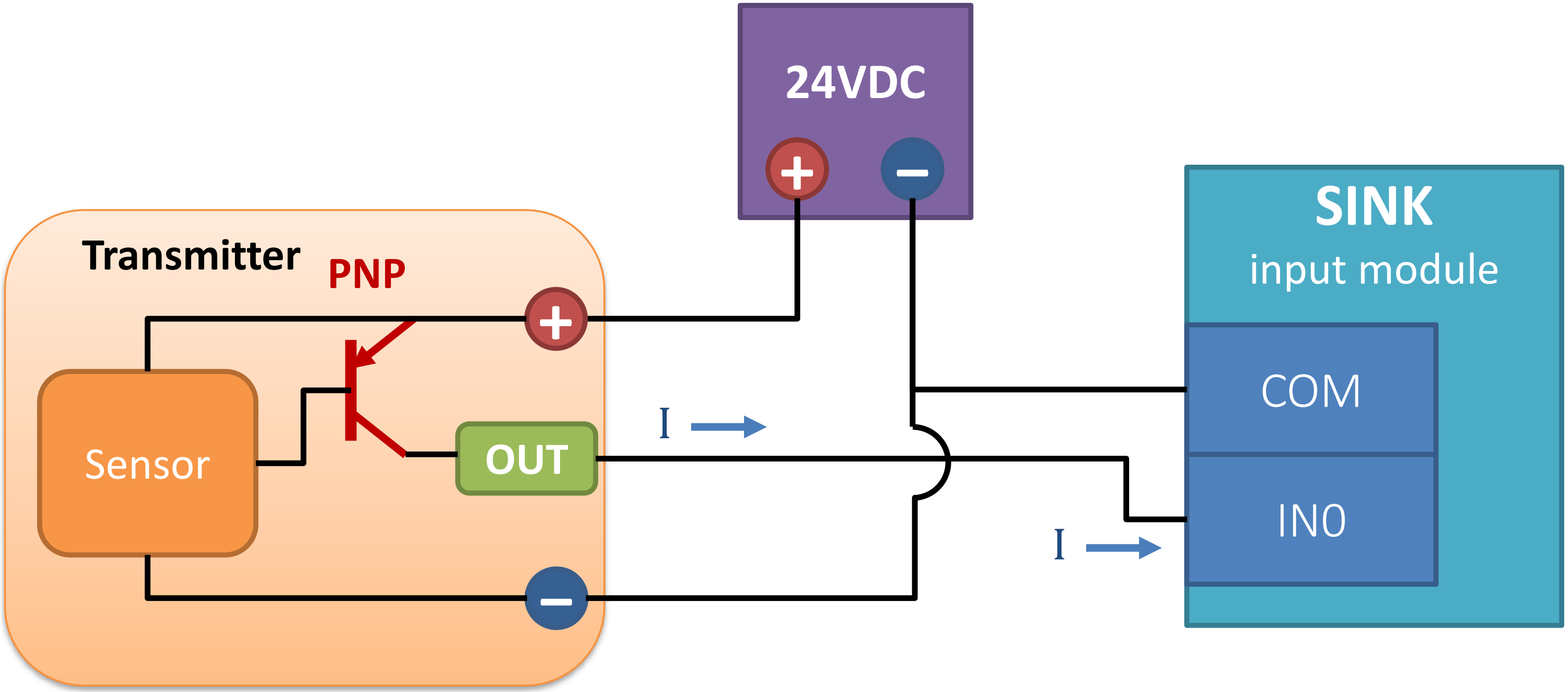
NPN transmitters

- NPN output transmitter (current sink)
- Can be connected to a source input module

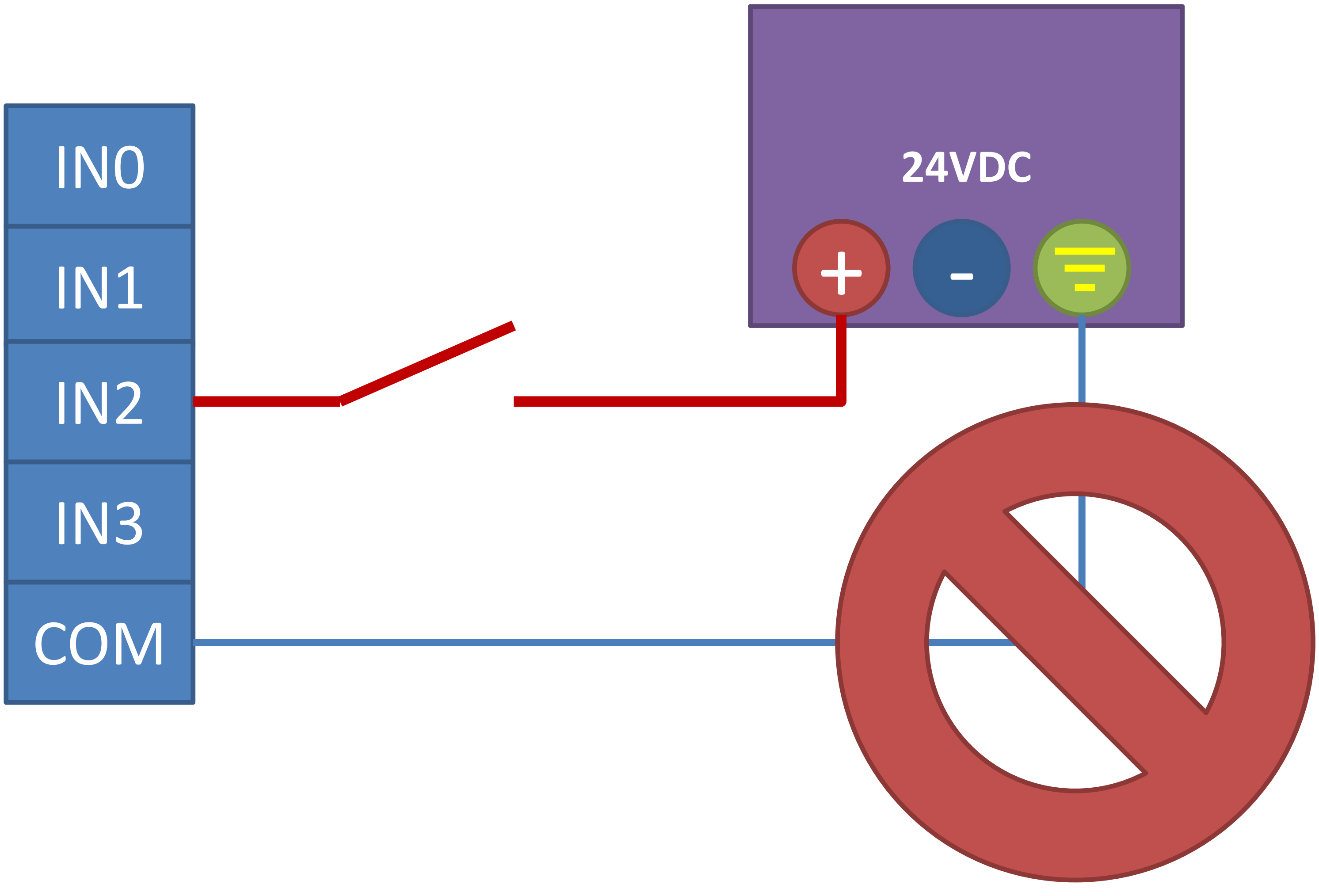


PNP transmitter

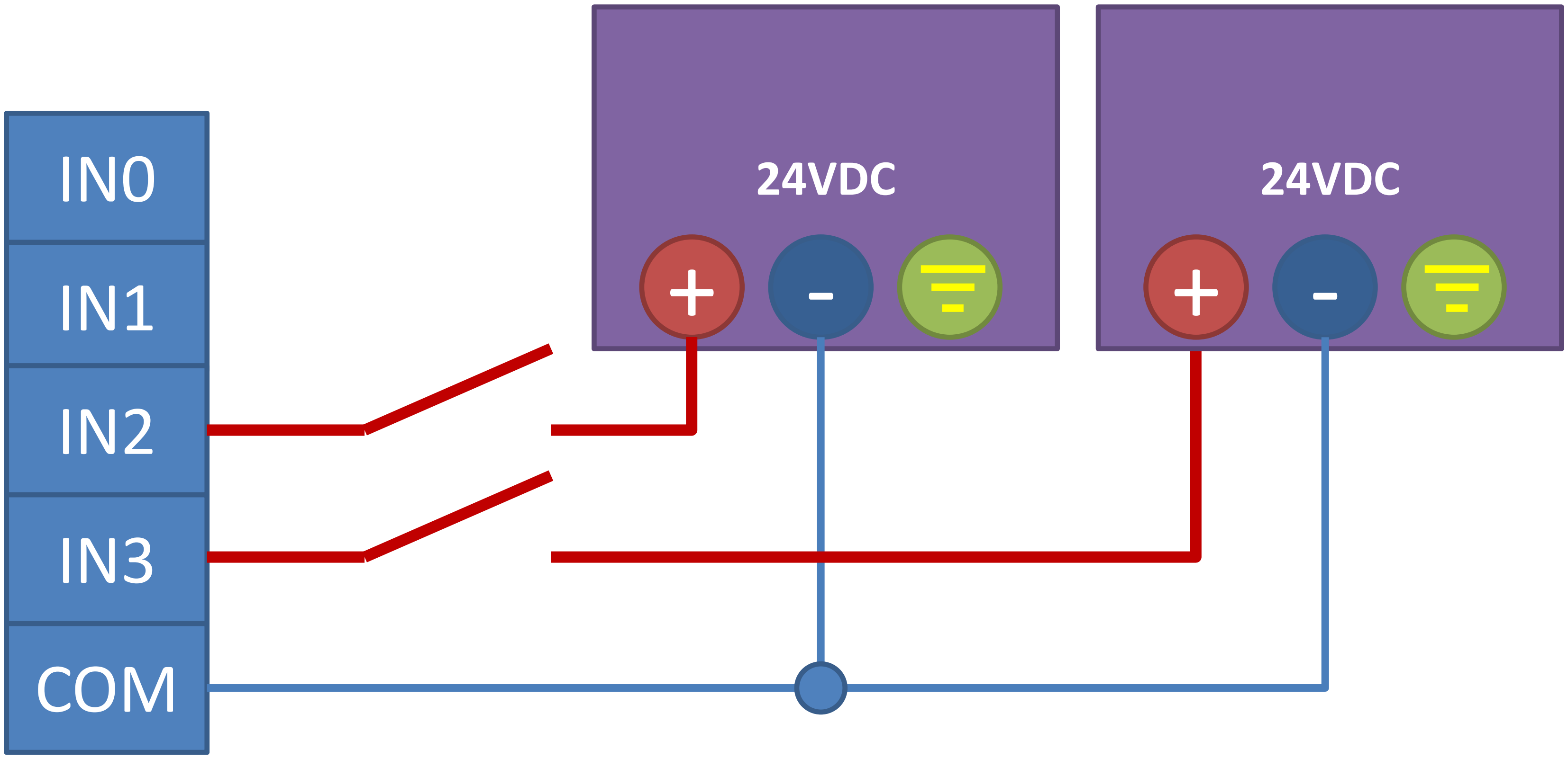
- PNP output transmitter (current source)
- Can be connected to a sink input module



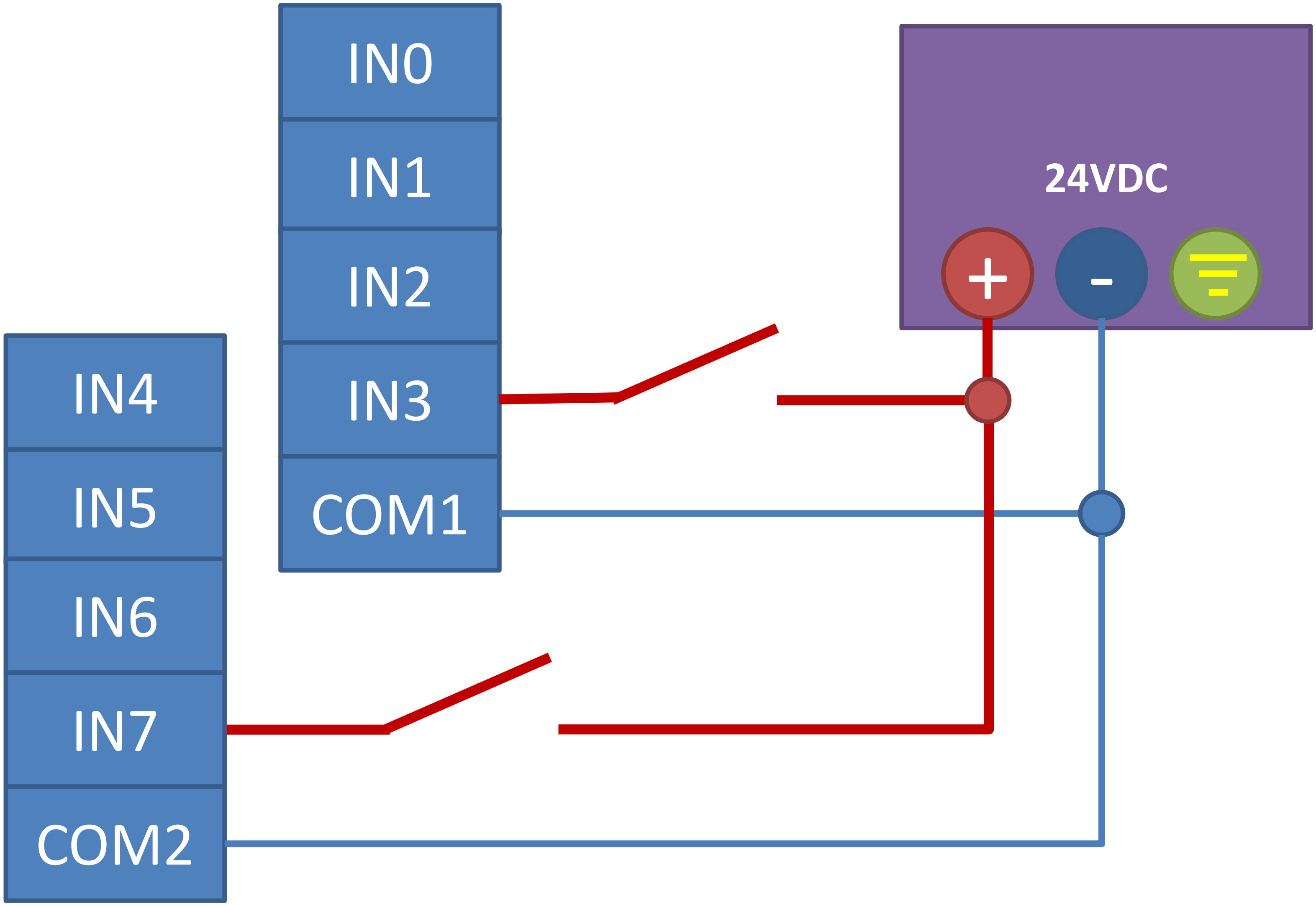
COM ≠ PE



Let the common be common!



Connecting reference if multiple channels share the same PSU

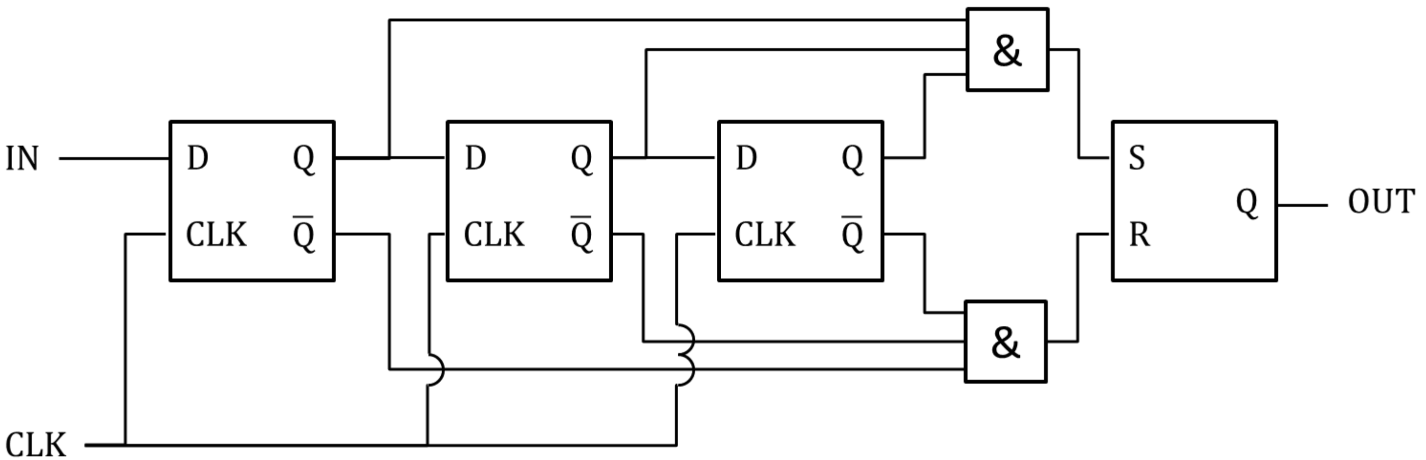


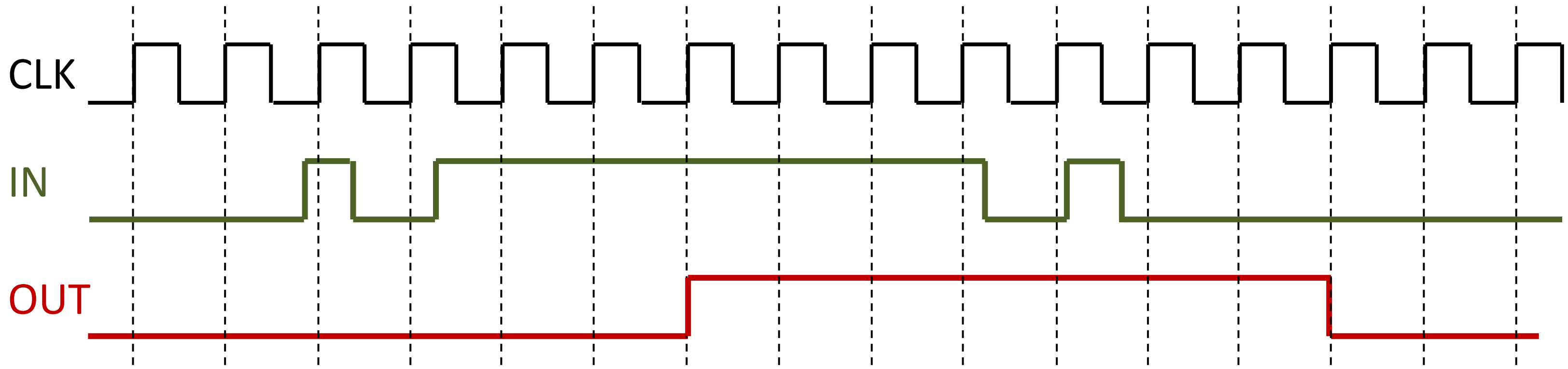
Comparator

- Logic level of the signal is determined based both on its voltage AND current
- LEDs
  - connected directly to the output of the comparator
  - help in troubleshooting
- Optional optocoupler isolation at the output of the comparator

Filter – debouncing

- Some models allow configuration of window length

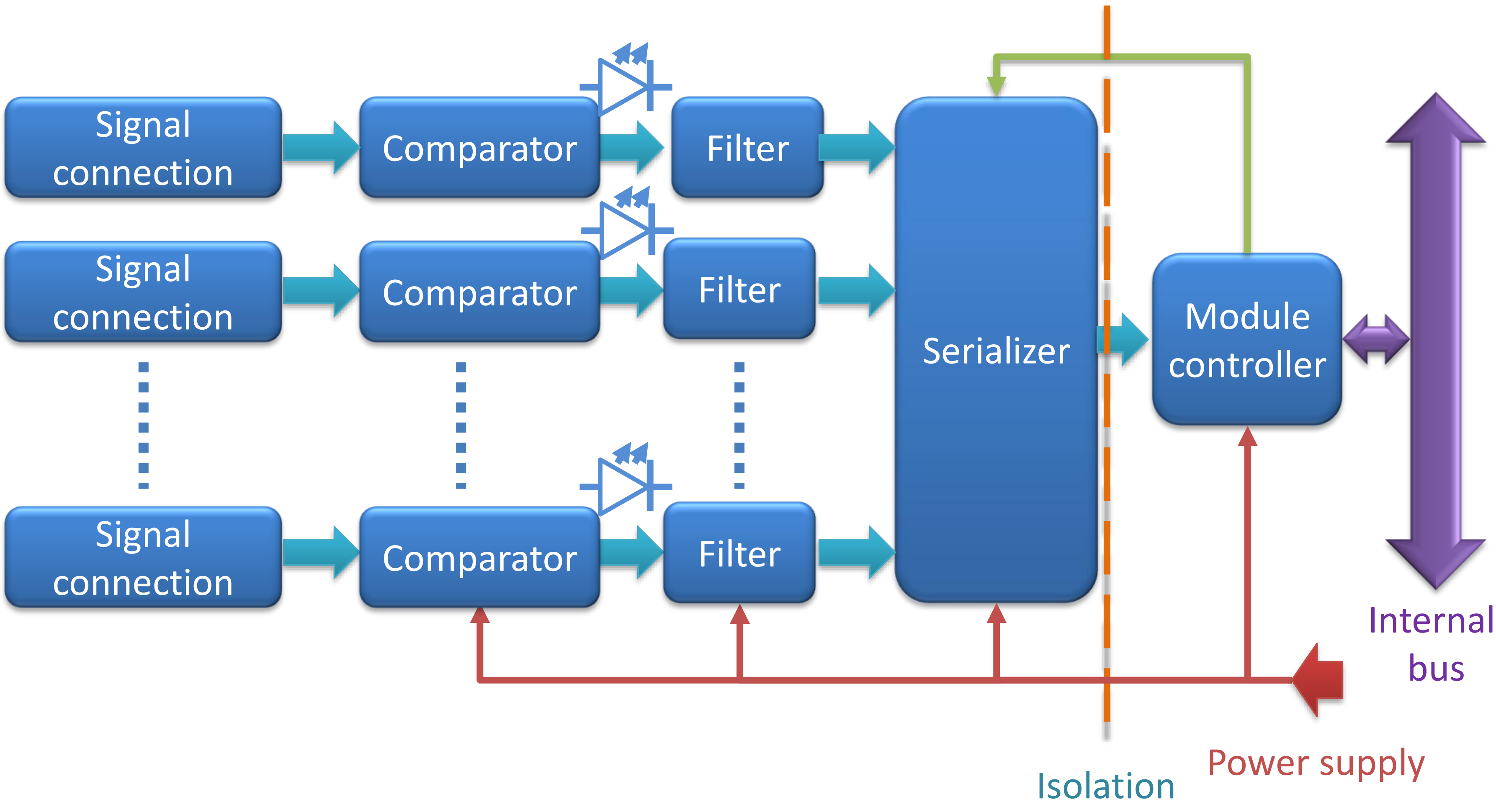




Serializer

- Role: serialize signals of parallel input channels
- Practically a parallel loaded shift register
- Channel values optionally extended with parity / CRC
- Decreases number of lines to isolate
- Available as an IC together with signal connection and comparator

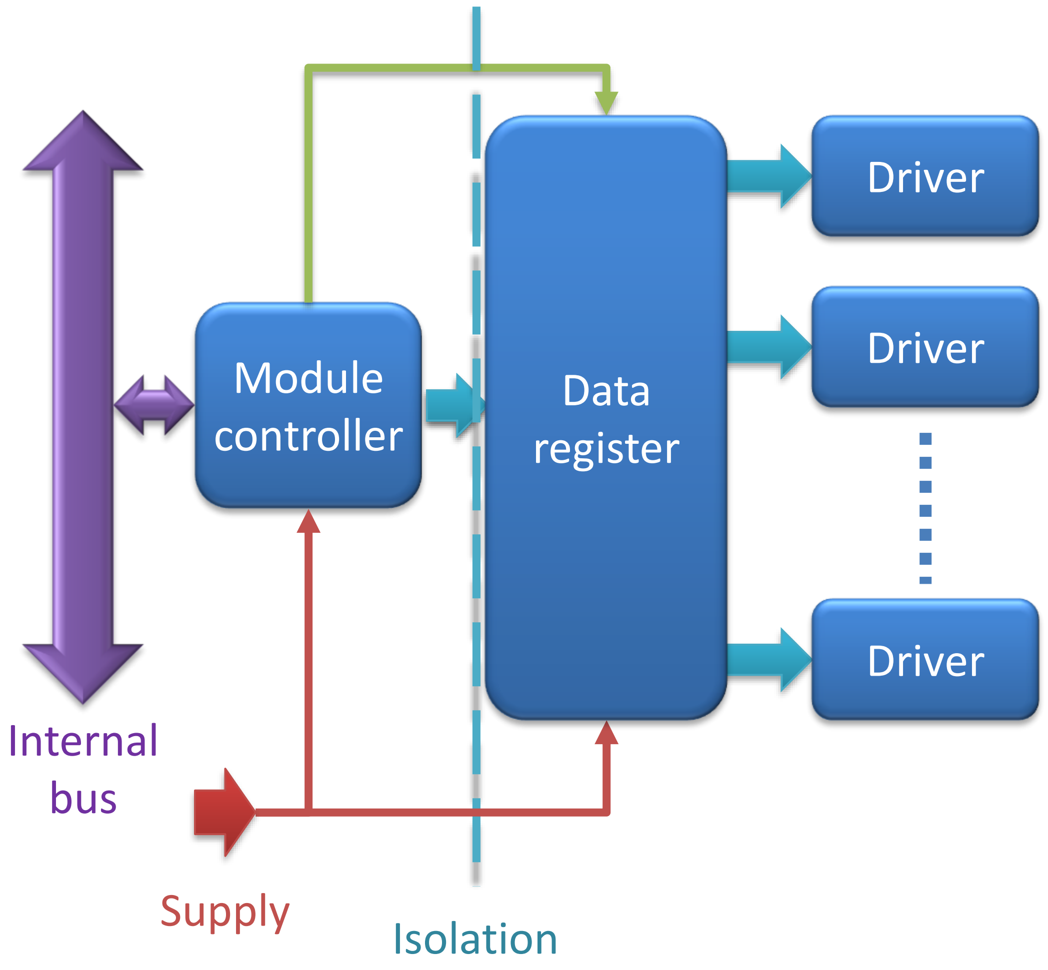
Isolation


Signal connection
Comparator
Filter
Signal connection
Comparator
Filter
Signal connection
Comparator
Filter
Serializer
Module controller
Internal bus
Power supply
Isolation

Module controller

- Reads serialized values of input channels
- Stores values
- Sends values to the CPU if requested
- Edge detection
- Diagnostics
- Configuration

Digital output module



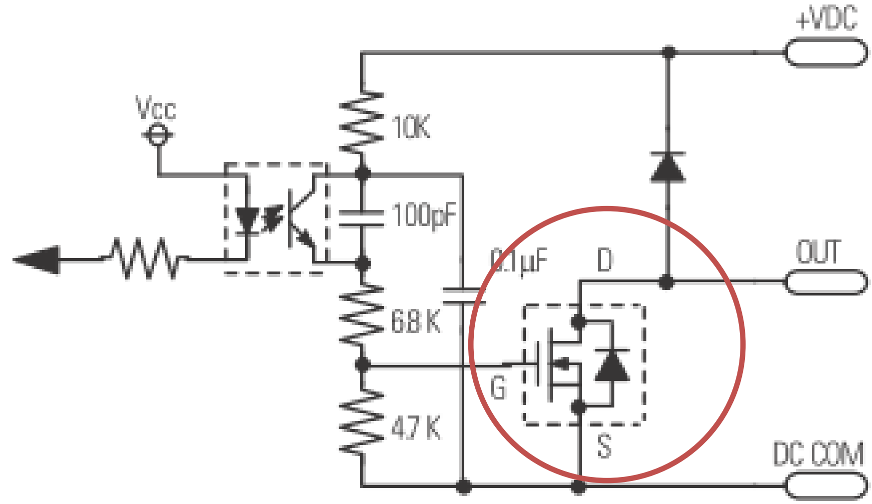
Digital output module

- **A digital output module supplies no power!**
- Acts only as a switch between the power supply and the load (e.g. valve, motor)
- Signal connections
  - Out-n, Qn: output
  - COM, GND: reference (ground or supply voltage)

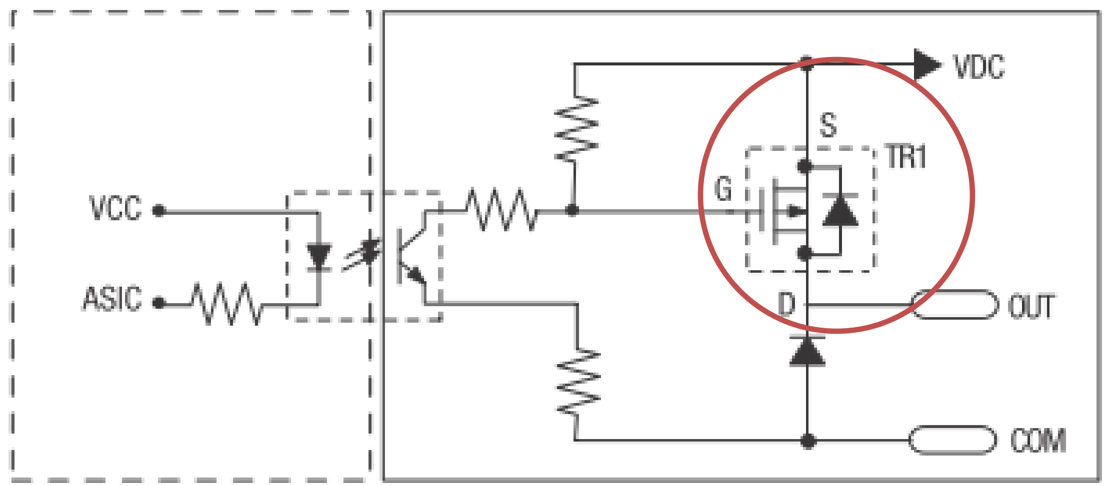
Semiconductor digital outputs

- Most common type
- DC output: MOSFET
- AC output: triac
- Source or sink type

Sink output – N channel MOSFET

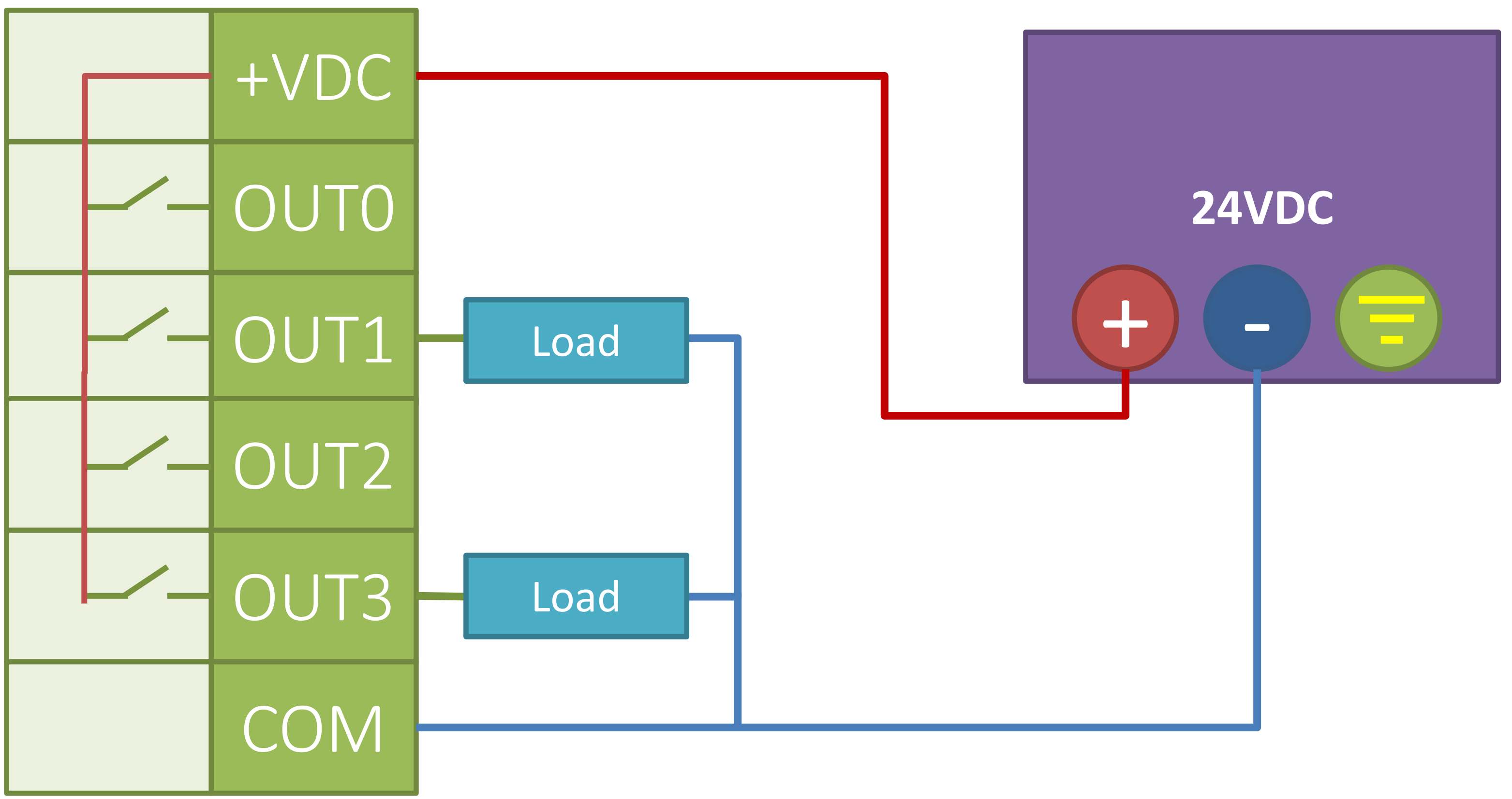


Source output – P channel MOSFET

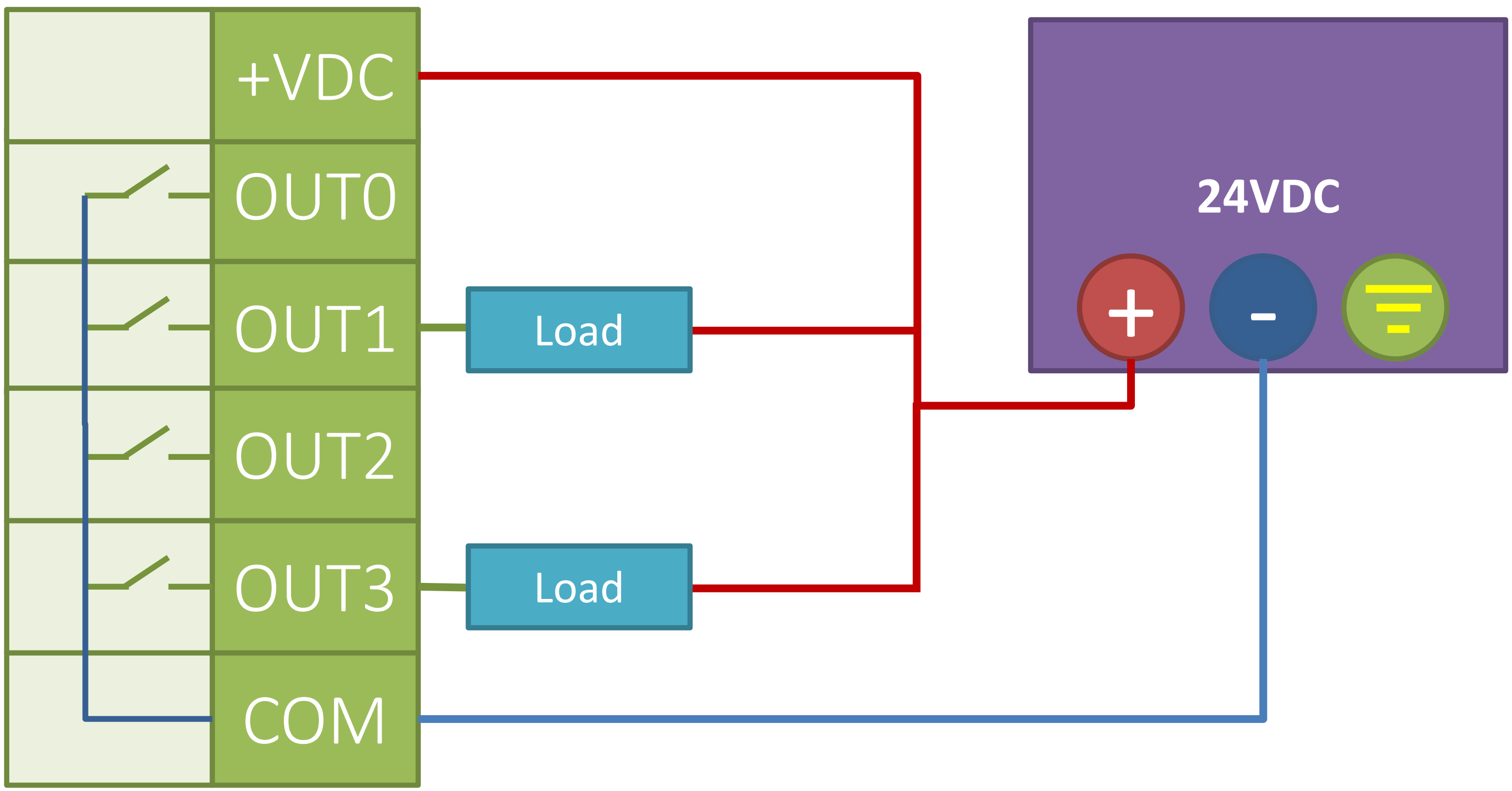


Examples for digital output circuits – exact circuitry not included in the exam

Source output



Sink output



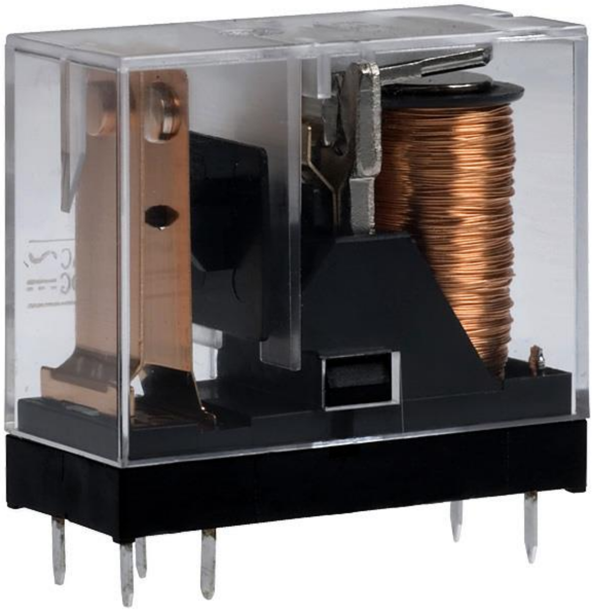
Semiconductor output module - Load

- Maximal output current $\approx 500\mathrm{mA}$

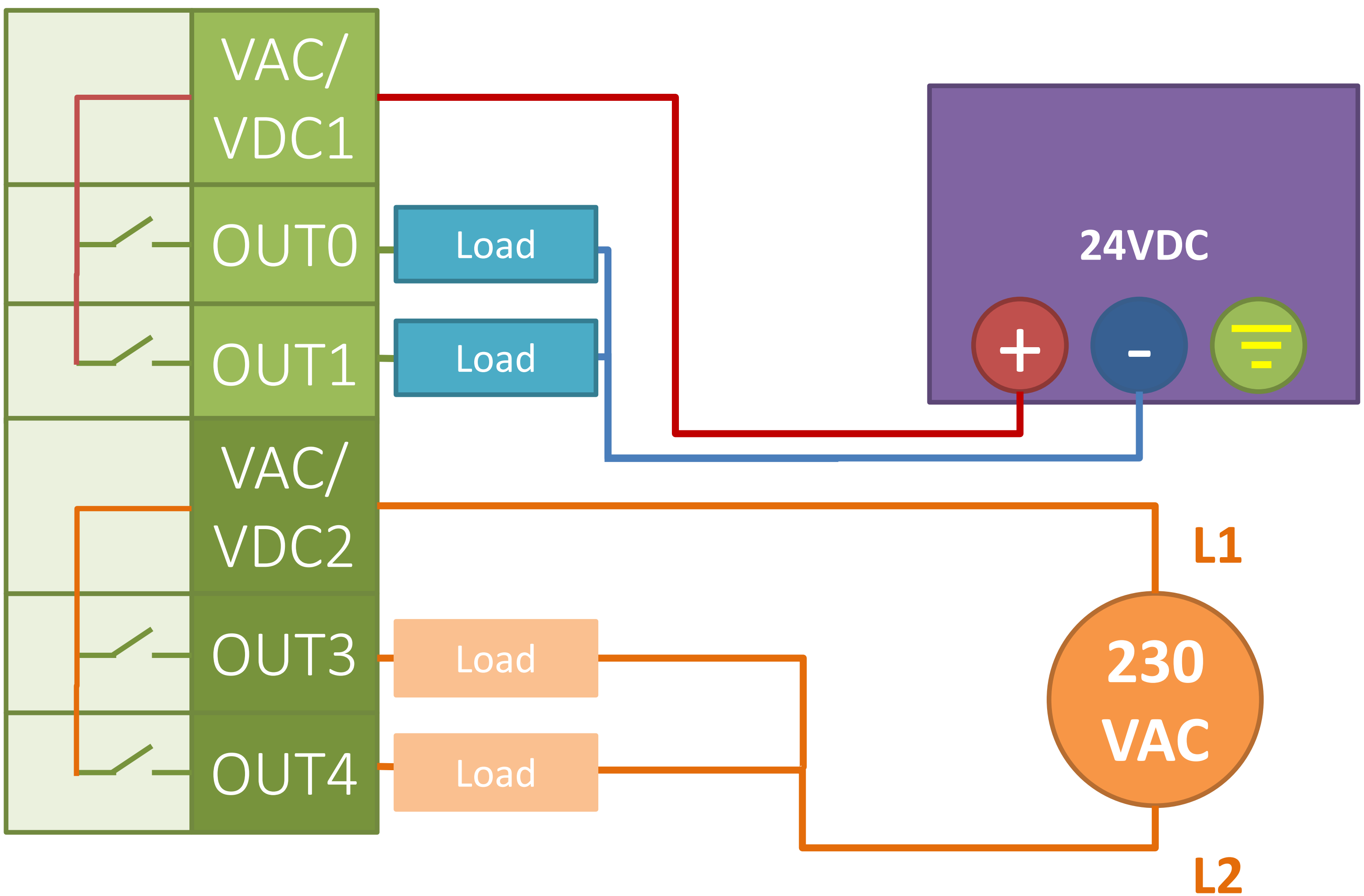
- Sensitive to inductive loads
  - transient voltage is high when switching on
  - internal protection: Zener diode – not enough!
  - auxiliary protection: diode or TVS diode in parallel with the load

Relay digital output module

- Outputs are switched by relays integrated to the module
- Less common, narrow selection
- Can operate both in source and sink configurations
- Able to switch both AC and DC voltages



Relay digital output module



Relay vs semiconductor outputs

	Relay output	Semiconductor output
Switched voltage	**both AC and DC**	AC (triac) or DC (MOSFET)
Configuration	**both source and sink**	source or sink
Galvanic isolation	**Yes**	no
Maximal output current	**1-2 A**	500 mA
Sensitivity to inductive load	**less sensitive**	Sensitive
Lifespan	limited (10^7 switch)	**unlimited**
Switching time	1-2 ms	**1 μs**
Switching frequency	-	**100 kHz**

Relay or semiconductor?

- Both has unique advantages:
  - semiconductor: unlimited lifespan, fast switching
  - relay: galvanic isolation, high power, less sensitive to inductive load

- Why not use both?
  - semiconductor output module
  - auxiliary (external) relays on selected channels