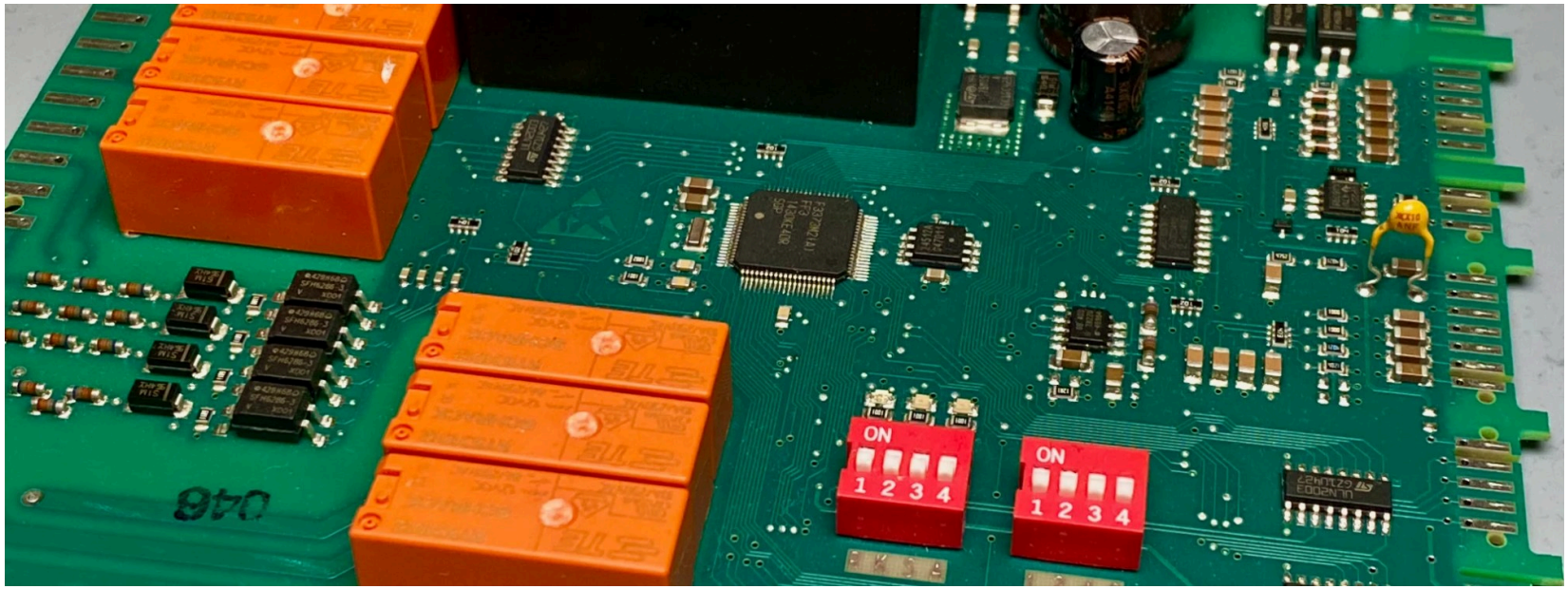
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# Introduction to the module and its content

DET-01 · Digital Electronics

# GUIDING QUESTIONS

- What awaits you in this module, and how will you show at the end what you can do?
- Why is 1 + 1 = 10 not a mistake?
- How can a heat pump that knows only two states, on and off, show the time 23:59, count 8 003 compressor starts and store an outside temperature of −7 °C?



Image by Qwen-Image 2.1

# INTENDED LEARNING OUTCOMES

- You know how the module is organized and what is expected of you.
- You understand how analogue and digital signals are related.
- You convert numbers between positional number systems.
- You represent signed numbers.
- You carry out binary arithmetic.




Image by Qwen-Image 2.1

# AGENDA

1. Studying successfully
2. Prior knowledge
3. How do I teach?
4. The examination
5. Introduction to digital electronics
6. Positional number systems
7. Base conversion
8. Binary arithmetic
9. Unsigned and signed numbers
10. Introduction to A/D and D/A conversion
11. What have you learnt?



Image by Qwen-Image 2.1

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# 1 Studying successfully

- What does ‘studying’ mean?

# WHAT DOES ‘STUDYING’ MEAN?

- *Studere*: to strive for something, to devote oneself to it
- Success comes from your behaviour: take part, prepare, follow up, practise
- Learn together, refresh your prior knowledge, keep the goals in sight

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# 2 Prior knowledge

- What you bring with you

# WHAT YOU BRING WITH YOU

- No formal prerequisites
- Mathematics: powers of two, place value, written addition and subtraction
- Physics and electrical engineering: voltage
- English: each technical term with its German equivalent
- Follow-up: question your prior knowledge

# 3 How do I teach?

- How a session works
- Like at a buffet
- Everyday example: the smartphone
- Industrial example: the heat pump
- The logic simulator
- The textbook

# HOW A SESSION WORKS

- Twelve sessions, Tuesdays from 16:00 to 19:00
- Lecture, followed by exercises
- Exercises: first on your own, then the solution together
- The script contains everything in full – ideally, you read it beforehand
- The slides structure and illustrate the content

# LIKE AT A BUFFET

- ‘Learning takes place through the active behavior of the student; it is what he does that he learns, not what the teacher does.’ – Ralph W. Tyler [6, p. 63]
- I cook tasty dishes from fresh ingredients and arrange them as appealingly as I can
- You take the right dishes in the right amount and order, so that you can digest them – your responsibility
- Choose, combine – and ask when something is unclear



Image by Qwen-Image 2.1

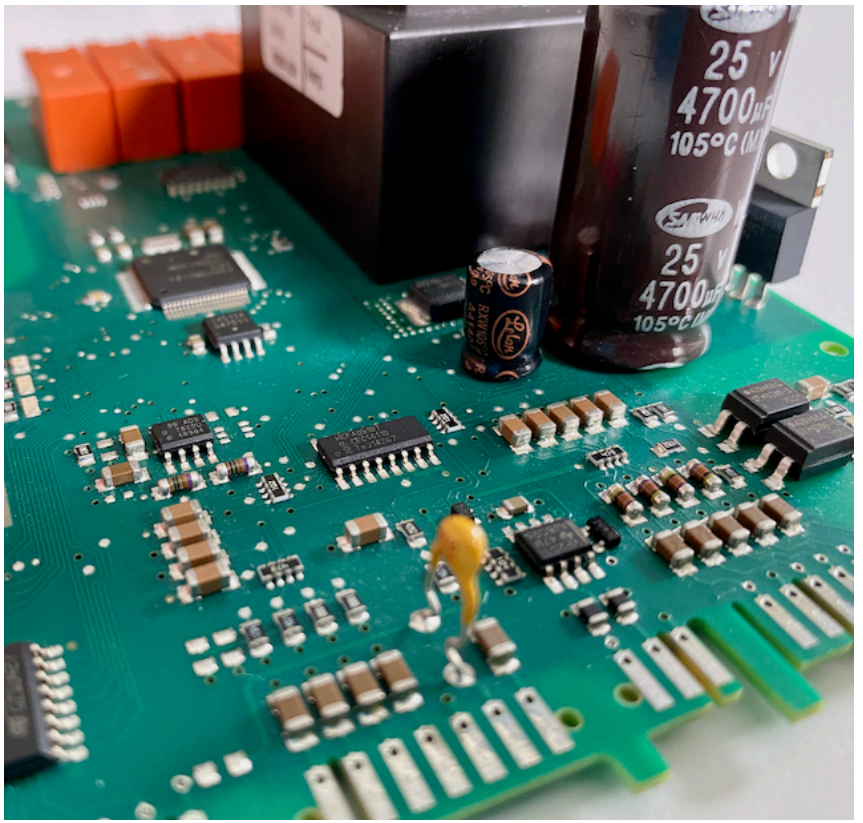
# EVERYDAY EXAMPLE: THE SMARTPHONE

- The obvious: cameras, flash with a light emitting diode (LED), buttons, display, microphones, loudspeaker
- The hidden: processor and memory that work only with 0 and 1
- Sensors and converters between the world and the bits



# INDUSTRIAL EXAMPLE: THE HEAT PUMP

- Example device: Stiebel Eltron WPL 24 A – in the picture, its control board, the WPMsystem
- The obvious: compressor, fan, values in the web browser
- The hidden: microcontroller, relays, dual in-line package (DIP) switches, Controller Area Network (CAN) bus
- All values stored and processed as binary numbers

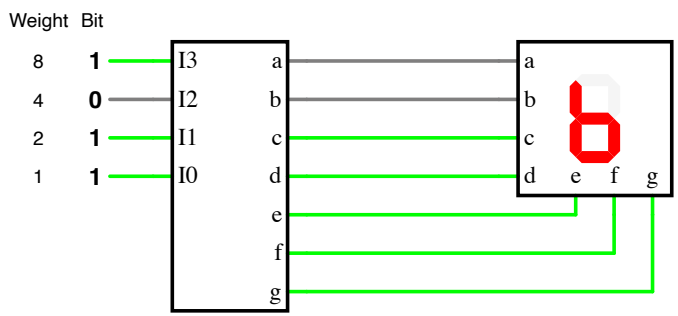



Control board of the heat pump

# THE LOGIC SIMULATOR

- A teaching tool: I use it again and again so that you can follow how circuits work – and you can use it yourself
- CircuitJS at sim.wattsinside.eu
- The link opens the circuit in a new tab
- Switch inputs, change the circuit, import and export it as text

Open in the simulator



# THE TEXTBOOK

- LaMeres: Introduction to Logic Circuits & Logic Design with VHDL [5]
- For anyone who wants more than the script: a second explanation and many exercises
- Full text on Springer Link: university network or virtual private network (VPN)
- Videos on most sections and concept checks for self-testing

# 4 The examination – your stage

- The eAssessment

# THE EASSESSMENT

- Location and duration: ILIAS eAssessment in the computer room on the Gütersloh campus, 60 minutes
- Examination period: 2 to 9 January 2027
- Aid: non-programmable calculator of the Casio FX-82 series
- Mock exam: DET-12 on 22 December 2026, computer room G105, Gütersloh campus



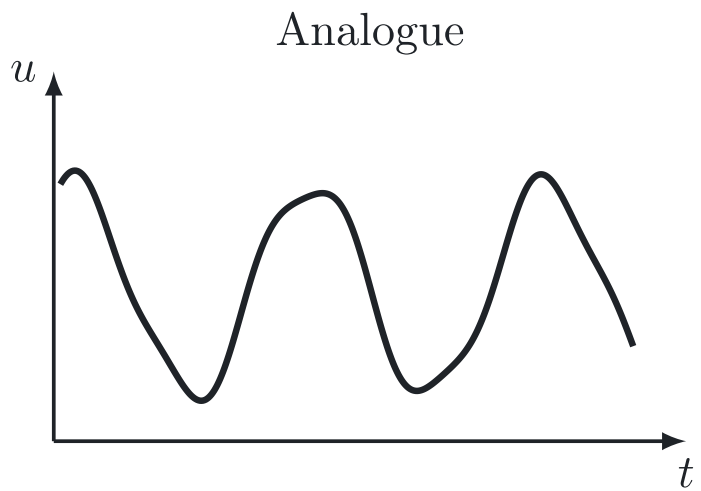
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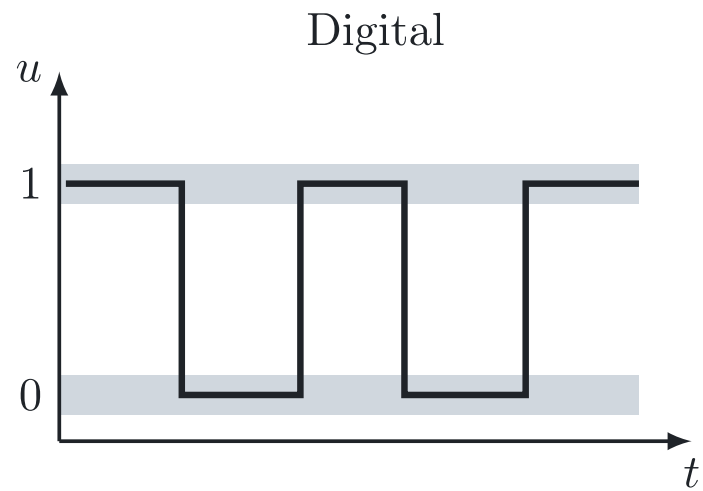
# 5 Introduction to digital electronics

- Analogue and digital
- Why digital?
- Our leading character: the bit
- The module at a glance

# ANALOGUE AND DIGITAL

- Analogue: continuous, maps the information directly
- Digital: encoded, discrete values 0 and 1, each with its own voltage range



# WHY DIGITAL?

## Benefits

- Noise immunity: noise changes nothing as long as the signal stays within its range
- Simple circuits: a switch produces 0 or 1
- Low power consumption in complementary metal oxide semiconductor (CMOS) technology
- Storage without degradation
- Programmable: new functions by a software update

## Challenges

- Converters at the border to the physical world
- Every digital value is only an approximation of the analogue one
- Timing: short false pulses, called hazards

# OUR LEADING CHARACTER: THE BIT

- Bit = binary digit: 0 or 1
- Logic level: HIGH in the upper, LOW in the lower voltage range
- Positive logic: LOW = 0; HIGH = 1
- $n$ bits give $2^n$ combinations
- The supply voltage depends on the logic family – transistor–transistor logic (TTL) or CMOS

| Logic family | Technology | Supply voltage |
|---|---|---|
| 7400 series (classic) | TTL | 5 V |
| 4000 series (classic) | CMOS | 3 V to 18 V |
| 74HC series | CMOS | 2 V to 6 V |
| 74HCT series, TTL-compatible inputs | CMOS | 4.5 V to 5.5 V |
| 74LVC series | CMOS | 1.65 V to 3.6 V |

# THE MODULE AT A GLANCE

- DET-02 Logic operations
- DET-03 and DET-04 Representation and minimization of logic functions
- DET-05 Codes, code converters and standard components
- DET-06 to DET-09 Latches, flip-flops, delay and clock, counters, finite state machines
- DET-10 Programmable logic devices and microcontrollers
- DET-11 Further applications in mechatronics
- DET-12 Exam preparation with mock exam

# 6 Positional number systems

- Positional number systems
- The decimal system
- The binary system
- The octal system
- The hexadecimal system

# POSITIONAL NUMBER SYSTEMS

- The value of a digit depends on its position
- Digits, base, weight

$$N = \sum_{i=0}^{n-1} d_i \cdot b^i$$

- One rule for decimal, binary, octal and hexadecimal

# THE DECIMAL SYSTEM

- Decimal: from Latin *decem*, ‘ten’ – base 10, digits 0 to 9

$$N = \sum_{i=0}^{n-1} d_i \cdot 10^i$$

$$8\,003 = 8 \cdot 10^3 + 0 \cdot 10^2 + 0 \cdot 10^1 + 3 \cdot 10^0$$

- The language of people: a bottling plant shows its count in decimal



Image by Qwen-Image 2.1

# THE BINARY SYSTEM

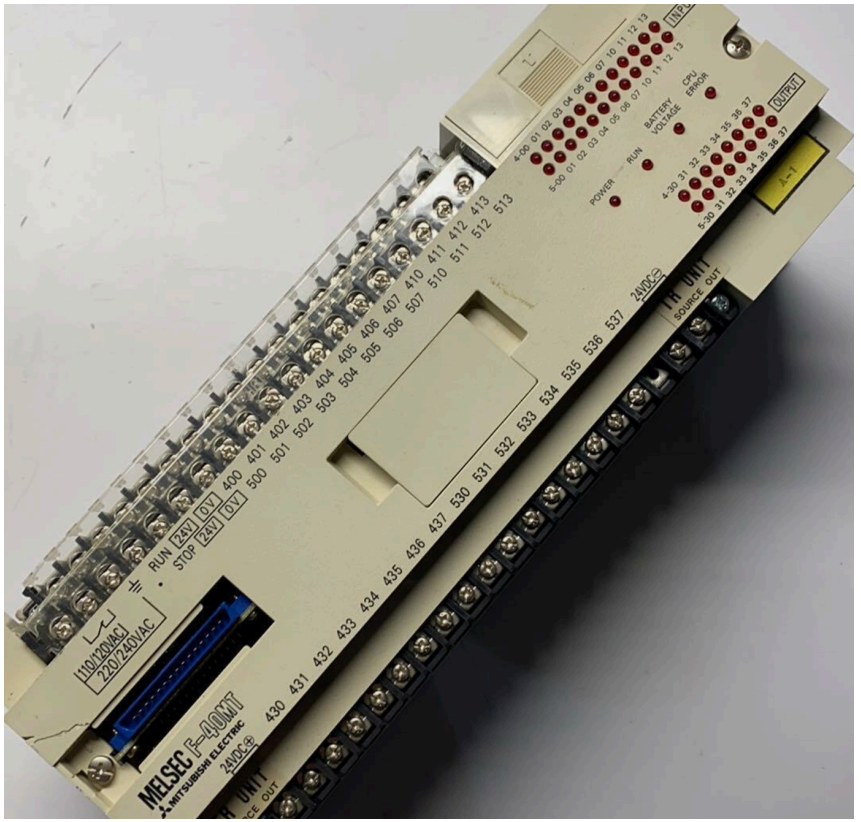
- Binary: from Latin *binarius*, ‘consisting of two’ – base 2, digits 0 and 1
- Weights 1, 2, 4, 8, 16, …
- Nibble = 4 bits, byte = 8 bits, words
- Most significant bit (MSB) on the left, least significant bit (LSB) on the right
- Light barrier at a programmable logic controller (PLC) input: one bit



Image by Qwen-Image 2.1

# THE OCTAL SYSTEM

- Octal: from Latin *octo*, ‘eight’ – base 8, digits 0 to 7
- One octal digit = three bits
- Mitsubishi MELSEC-F: inputs X0 to X7, then X10 to X17 [7]
- In the picture: inputs 400 to 407, then 410 – there is no 408




Mitsubishi MELSEC F-40MT

# THE HEXADECIMAL SYSTEM

| Decimal | Binary | Octal | Hexadecimal |
|---|---|---|---|
| 0 | 0000 | 0 | 0 |
| 1 | 0001 | 1 | 1 |
| 2 | 0010 | 2 | 2 |
| 3 | 0011 | 3 | 3 |
| 4 | 0100 | 4 | 4 |
| 5 | 0101 | 5 | 5 |
| 6 | 0110 | 6 | 6 |
| 7 | 0111 | 7 | 7 |
| 8 | 1000 | 10 | 8 |
| 9 | 1001 | 11 | 9 |
| 10 | 1010 | 12 | A |
| 11 | 1011 | 13 | B |
| 12 | 1100 | 14 | C |
| 13 | 1101 | 15 | D |
| 14 | 1110 | 16 | E |
| 15 | 1111 | 17 | F |

- Hexadecimal: from Greek *hex*, ‘six’, and Latin *decem*, ‘ten’ – base 16
- Digits 0 to 9 and A to F
- One hexadecimal digit = four bits, two digits = one byte
- CAN bus: an identifier of 11 bits fits into three hexadecimal digits [8]

# 7 Base conversion

- Binary to decimal
- Octal to decimal
- Hexadecimal to decimal
- Decimal to binary
- Decimal to octal
- Decimal to hexadecimal
- Binary, octal and hexadecimal

# BINARY TO DECIMAL

- Multiply each bit by its weight, a power of 2, and add up the products

$$N = \sum_{i=0}^{n-1} d_i \cdot 2^i$$

$$1100100_2 = 1 \cdot 2^6 + 1 \cdot 2^5 + 0 \cdot 2^4 + 0 \cdot 2^3 + 1 \cdot 2^2 + 0 \cdot 2^1 + 0 \cdot 2^0 = 64 + 32 + 4 = 100_{10}$$

$$10111_2 = 1 \cdot 2^4 + 0 \cdot 2^3 + 1 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0 = 16 + 4 + 2 + 1 = 23_{10}$$

# OCTAL TO DECIMAL

- Multiply each digit by its weight, a power of 8, and add up the products

$$N = \sum_{i=0}^{n-1} d_i \cdot 8^i$$

$$17_8 = 1 \cdot 8^1 + 7 \cdot 8^0 = 8 + 7 = 15_{10}$$

$$377_8 = 3 \cdot 8^2 + 7 \cdot 8^1 + 7 \cdot 8^0 = 192 + 56 + 7 = 255_{10}$$

# HEXADECIMAL TO DECIMAL

- Multiply each digit by its weight, a power of 16; A = 10 to F = 15

$$N = \sum_{i=0}^{n-1} d_i \cdot 16^i$$

$$1\mathrm{F}43_{16} = 1 \cdot 16^3 + 15 \cdot 16^2 + 4 \cdot 16^1 + 3 \cdot 16^0 = 4\,096 + 3\,840 + 64 + 3 = 8\,003_{10}$$

$$7\mathrm{FF}_{16} = 7 \cdot 16^2 + 15 \cdot 16^1 + 15 \cdot 16^0 = 1\,792 + 240 + 15 = 2\,047_{10}$$

# DECIMAL TO BINARY

- Repeated division by 2: the remainders are the bits, read from bottom to top

$$N = q \cdot 2 + r, \quad 0 \leq r < 2$$

| Division | Quotient | Remainder |
|---|---|---|
| 23 / 2 | 11 | 1 (LSB) |
| 11 / 2 | 5 | 1 |
| 5 / 2 | 2 | 1 |
| 2 / 2 | 1 | 0 |
| 1 / 2 | 0 | 1 (MSB) |

- $23_{10} = 10111_2; 59_{10} = 111011_2$

# DECIMAL TO OCTAL

- Repeated division by 8: the remainders are the octal digits, read from bottom to top

$$N = q \cdot 8 + r, \quad 0 \leq r < 8$$

| Division | Quotient | Remainder |
|---|---|---|
| 15 / 8 | 1 | 7 |
| 1 / 8 | 0 | 1 |

- $15_{10} = 17_8; 100_{10} = 144_8$

# DECIMAL TO HEXADECIMAL

- Repeated division by 16: remainders from 10 to 15 become A to F

$$N = q \cdot 16 + r, \quad 0 \leq r < 16$$

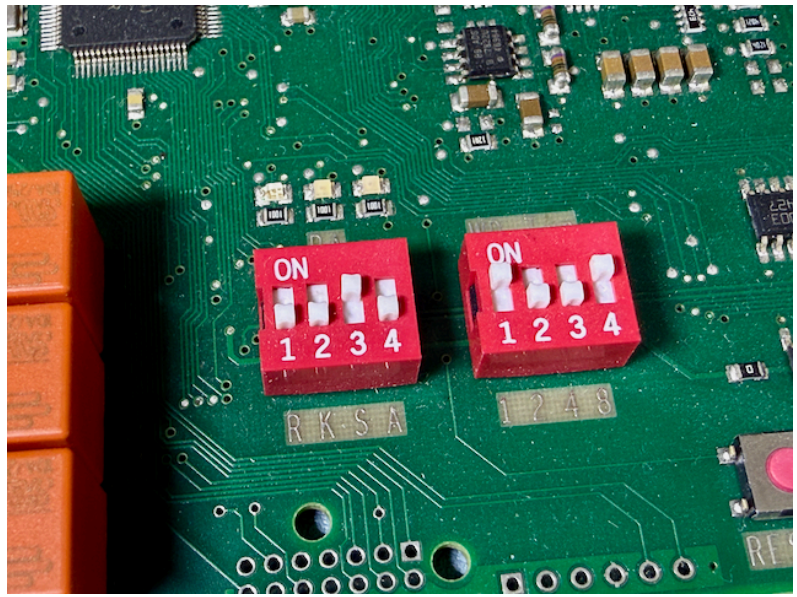
| Division | Quotient | Remainder |
|---|---|---|
| 8 003 / 16 | 500 | 3 |
| 500 / 16 | 31 | 4 |
| 31 / 16 | 1 | 15 = F |
| 1 / 16 | 0 | 1 |

- $8\,003_{10} = 1\mathrm{F}43_{16}; 255_{10} = \mathrm{FF}_{16}$

# BINARY, OCTAL AND HEXADECIMAL

- Group the bits from the right in threes (octal) or fours (hexadecimal)

| Colour | Red | Green | Blue |
|---|---|---|---|
| Hexadecimal | 28 | 4B | 63 |
| Binary | 0010<br>1000 | 0100<br>1011 | 0110<br>0011 |
| Decimal | 40 | 75 | 99 |




DIP switches on the control board of the heat pump

- Switches with the weights 8 and 1
  ON: $1001_2 = 9_{16}$

# 8 Binary arithmetic

- Addition with carries
- Subtraction with borrows

# ADDITION WITH CARRIES

| A | B | Sum | Carry |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 1 |

- $1 + 1 = 10_2$: the carry moves to the next position

$$\begin{array}{rcccccccc} & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ + & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ \text{carry} & 1 & 1 & 1 & 1 & 1 & 1 & 0 & \\ \hline = & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{array}$$

- ‘There are 10 kinds of people: those who understand binary and those who don't.’

# SUBTRACTION WITH BORROWS

- Minuend − subtrahend = difference
- Borrow from the next higher position: $10_2 - 1_2 = 1_2$

$$\begin{array}{rcccc} & 1 & 1 & 0 & 1 \\ - & 0 & 1 & 1 & 0 \\ \text{borrow} & 1 & 1 & 0 & \\ \hline = & 0 & 1 & 1 & 1 \end{array}$$

- And $6 - 13$? A negative result needs a new representation

# 9 Unsigned and signed numbers

- Unsigned numbers
- Signed magnitude and one's complement
- Two's complement

# UNSIGNED NUMBERS

$$0 \leq N \leq 2^n - 1$$

- $N$: value of the unsigned number, $n$: number of bits

| Value | Range | Bits needed |
|---|---|---|
| Hour of the heat pump's clock | 0 to 23 | 5, since $2^5 = 32$ |
| Minute | 0 to 59 | 6, since $2^6 = 64$ |
| Battery level of the smartphone in per cent | 0 to 100 | 7, since $2^7 = 128$ |
| Compressor starts of the heat pump so far | 0 to 8 003 | 13, since $2^{13} = 8\,192$ |

# SIGN BIT AND ONE'S COMPLEMENT

- Goal: extend the range to negative numbers – such as the outside temperature of −7 °C
- Sign bit: 0 positive, 1 negative
- Signed magnitude: sign bit plus magnitude
- One's complement: invert all bits
- Weakness of both: two codes for 0

| Code | Signed magnitude | One's complement | Two's complement |
|---|---|---|---|
| 0000 | +0 | +0 | 0 |
| 0001 | +1 | +1 | +1 |
| 0010 | +2 | +2 | +2 |
| 0011 | +3 | +3 | +3 |
| 0100 | +4 | +4 | +4 |
| 0101 | +5 | +5 | +5 |
| 0110 | +6 | +6 | +6 |
| 0111 | +7 | +7 | +7 |
| 1000 | −0 | −7 | −8 |
| 1001 | −1 | −6 | −7 |
| 1010 | −2 | −5 | −6 |
| 1011 | −3 | −4 | −5 |
| 1100 | −4 | −3 | −4 |
| 1101 | −5 | −2 | −3 |
| 1110 | −6 | −1 | −2 |
| 1111 | −7 | −0 | −1 |

# TWO'S COMPLEMENT

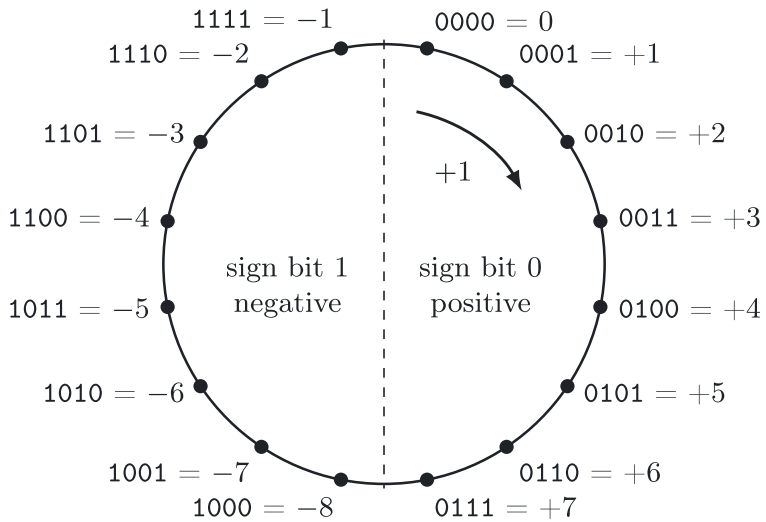
- Extends the binary numbers to negative values, without a double zero

$$C = 2^n - |N|$$

- Quicker: invert all bits and add 1

| Step | Bits |
|---|---|
| Positive number +7 | 0000 0111 |
| Invert all bits | 1111 1000 |
| Add 1: −7 | 1111 1001 |

$$-2^{n-1} \leq N \leq 2^{n-1} - 1$$




- $N$: value of the signed number, $C$: code of a negative $N$, $n$: number of bits

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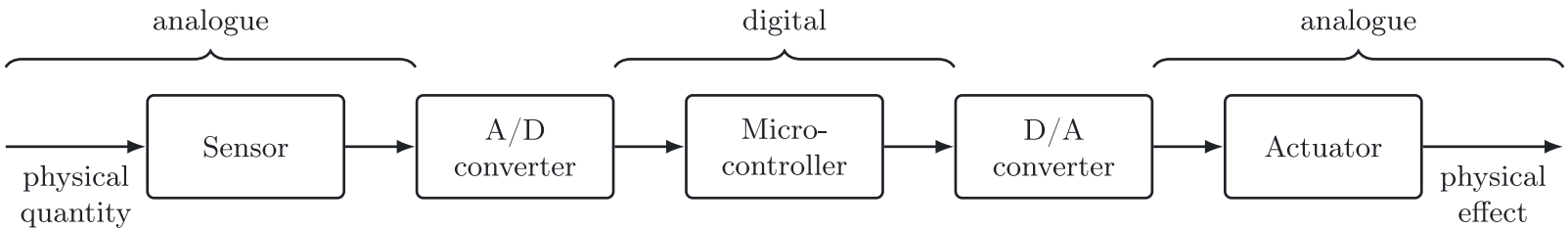
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# 10 Introduction to A/D and D/A conversion

A brief first look: how analogue quantities become bits – and back

- From sensor to actuator

# FROM SENSOR TO ACTUATOR




- Analogue-to-digital (A/D) converter: voltage → number
- Digital-to-analogue (D/A) converter: number → voltage
- In detail in DET-11

# 11 What have you learnt?

- The building blocks of knowledge
- Answers to the guiding questions

# WHAT YOU HAVE LEARNT

- Organization and assessment in this module
- Analogue and digital, the bit, logic levels
- Positional number systems: decimal, binary, octal, hexadecimal
- Base conversion: weights, repeated division, groups of bits
- Binary arithmetic: carries and borrows
- Signed numbers: one's complement and two's complement

# ANSWERS TO THE GUIDING QUESTIONS

- What awaits you? From the bit to programmable devices – and an eAssessment of 60 minutes
- Why is 1 + 1 = 10 not a mistake? In binary, $10_2$ means two
- Heat pump: 23:59 as $10111_2$ and $111011_2$; 8 003 starts in 13 bits; −7 °C in two's complement



Image by Qwen-Image 2.1

# Your turn: first on your own, then together.