KTH Informations- och kommunikationsteknik

IE1204 Digital Design

L1 : Course Overview. Introduction to Digital Technology. Binary Numbers

Elena Dubrova
KTH/ICT/ES
dubrova@kth.se

Lecturer

Elena Dubrova
School of Information and Communication Technology (ICT)
Department of Electronic Systems (ES)

dubrova@kth.se
http://people.kth.se/~dubrova

Course responsivble: William Sandqvist
william@kth.se

Course assistants

- Masoumeh Ebrahimi – lectures
- Giovanni Grandi – exersises
- Syed Jafri – exersises

About Elena Dubrova

- Professor at the School of ICT in Kista, Department of Electronic Systems
- Research area: Electronic Systems Design
- Teaches the following courses at KTH:
  - IE1204 Digital Design (P1)
  - IL2209 Advanced Logic Design (P2)
  - ID2218 Design of Fault-Tolerant Systems (P4)
  - FIL3001 The Art of Doctoral Research (P1-P4)

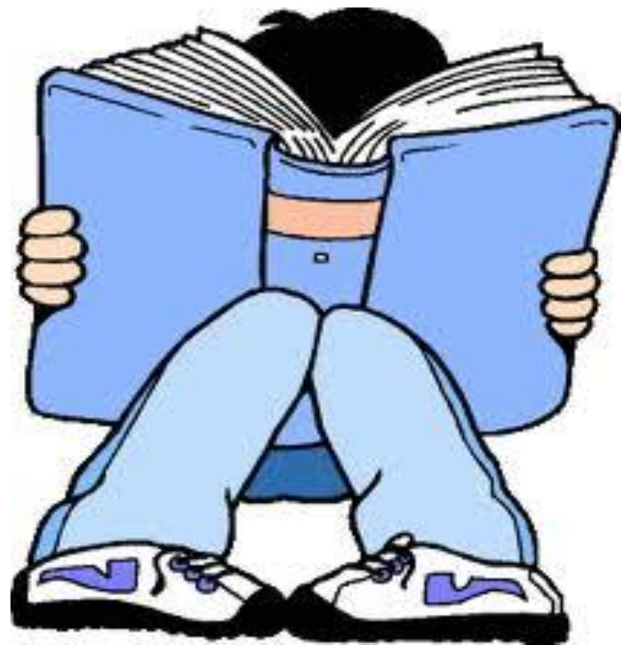
The teacher's role in education ...

- Do not forget that it is the student's job to learn new skills
- The teacher's task is to support learning

There is a course book…

- Brown/Vranesic, Fundamentals of Digital Logic with VHDL Design (3rd edition), Mc-Graw-Hill, 2009

Read it!



Studying at university …

- Is very different than in high school!
- Means that you take responsibility for your studies!
- An engineering degree provides excellent opportunities for a well-paid, fun and stimulating job, but first you have to get there!

Don’t forget…

- That the tempo is much higher at KTH than in a high school!
- An engineer has a great responsibility to society and must therefore have a solid education!

KTH Informations- och kommunikationsteknik

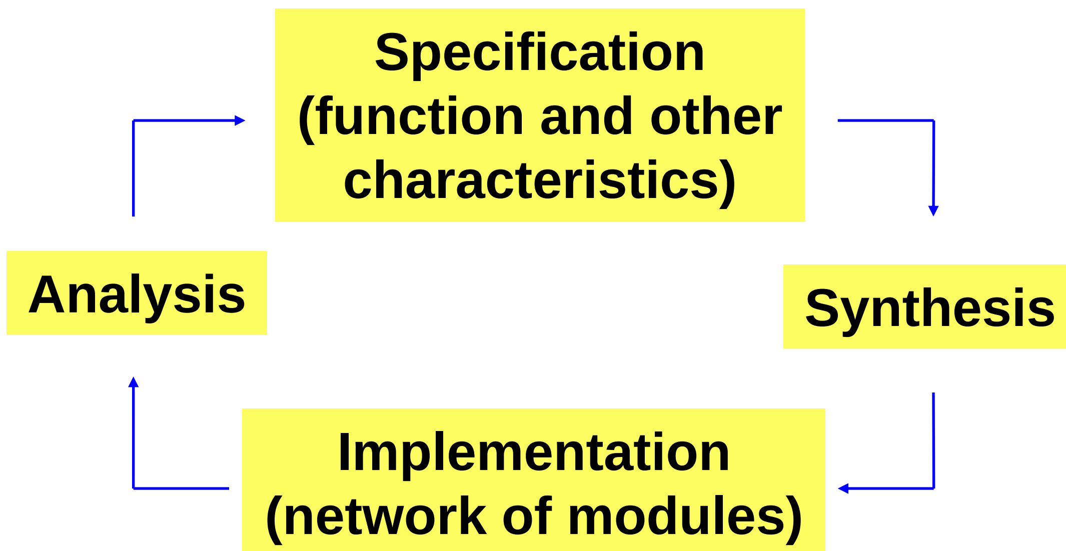
This course...

Course aims

- To teach the theoretical foundations for the analysis and synthesis of combinational and sequential digital circuits
- Through practical problem solving, provide an understanding of various design phases
  - to enable the students designing simple combinational and sequential digital systems

Course aims (cont)

- To teach the students a design methodology



- To confirm that this methodology enables the design of simple digital systems

Course aims (cont)

- Introduce students to English textbooks
  - All good literature on the subject is in English
  - English is the working language in all major Swedish international companies
  - Speaking English (reasonably) fluent is a prerequisite for a successful career as a civil engineer
- Therefore, we have chosen an English course book!

Course book

- Course book (abbreviated as BV at webpage)
  – Brown/Vranesic, *Fundamentals of Digital Logic with VHDL Design (3rd edition)*, Mc-Graw-Hill, 2009
- More material is available on website

  https://www.kth.se/social/course/IE1204/
- At present lecture slides from 2014 are posted on this website (in the schedule & lectures)
- I may replace them with updated slides shortly before or after the lecture, if there are changes (in lectures 2015 P1 for TCOMK eng. section)

Course content overview

- Specification of the digital functions and systems
- Digital building blocks
- Digital Arithmetic
- Synchronous circuits and state machines
- Asynchronous circuits and state machines
- Larger digital systems: processors and computers
- We will not go through VHDL to any great extent - it is a complete course by itself

Examination and structure

- Examination
  - LABA, 3.0 hp
    - Grade: G/U
  - TENA, 4.5 hp
    - Grade A-E/F
- Lectures - 28 h (14 x 2h)
- Exersices - 16 h (8 x 2h)
- Labs - 12 h (3 x 4h)

Final exam

- Thursday 29 Oct, 8:00-12:00, room 204
- Registration is required
  – No later than two weeks before the exam!

Labs

- Located in room 305
  - Registration is required and it is done via the Daisy system
    - https://daisy.ict.kth.se/
- Arrive in a good time to the first lab because your accounts may need to be activated

Knowledge control

- To get a lab you must first make a mandatory knowledge control (Web-based)
- You will find your "number" in Daisy
- The same "number" is then used for knowledge control for all three labs

Knowledge control

- Note that knowledge control and preparation for labs are very time consuming
- You are therefore advised to start working on these as soon as possible!

Contact with KTH-Personal

- The lecturer is available during the break and for some time after the lecture
  - Take advantage of this time
- Email
  - KTH staff is flooded by too many emails
  - If necessary, send a plain and clear message to the right person
  - Use your KTH mail address!
  - Put "IE1204: ...” is the subject of your message

More information is available on the web!

- It is not always possible to go through all the information during a lecture
- Visit the course web page often!

https://www.kth.se/social/course/IE1204

KTH Informations- och kommunikationsteknik

Why is digital technology important?

Our daily life is affected by digital technology



- Computers are everywhere and in all kinds of products
  - Did you that there are about 40 to 100 microprocessors in a new car?

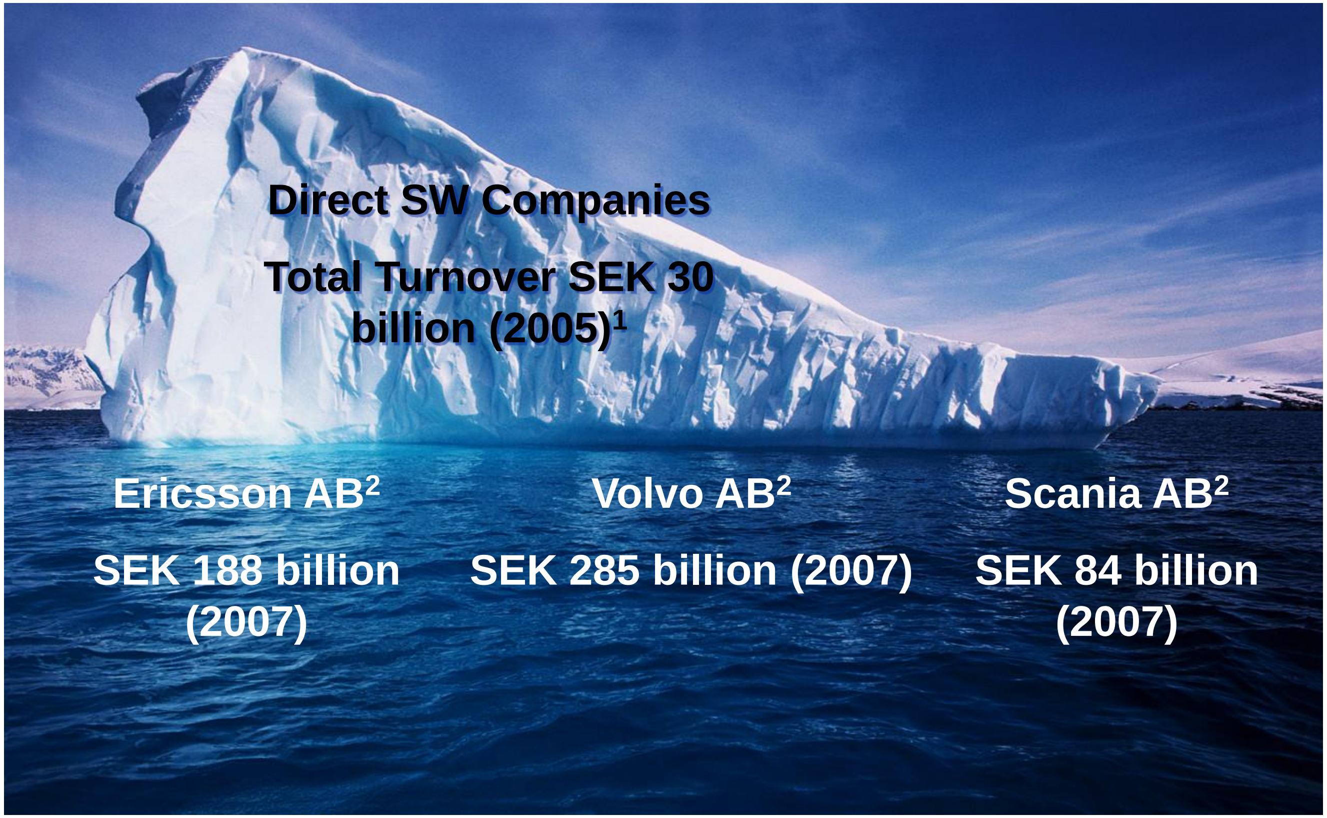
Industrial needs in embedded systems

DIRECT

Development of SW and services for direct sales to external customers

INDIRECT

SW is a critical part of the competitiveness of products, processes and services



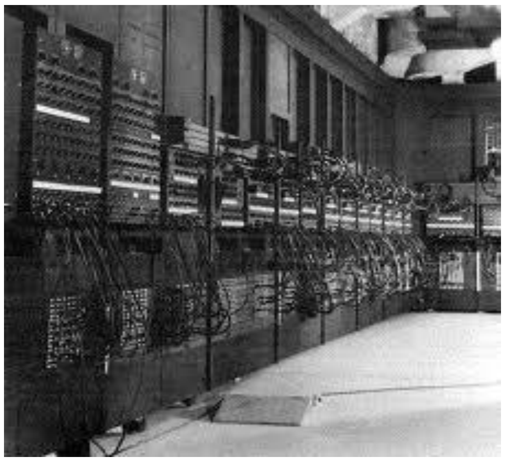
Competitiveness, volumes and value creation of “indirect” SW companies exceed that of “direct” SW companies

Source:

1. ***Redeye Advisory Services [2005]***
2. ***Reuters [2008]***

Development of electronics

Technological progress allows more and more functionality to be integrated on a single chip



ENIAC

(1946)

Apple II

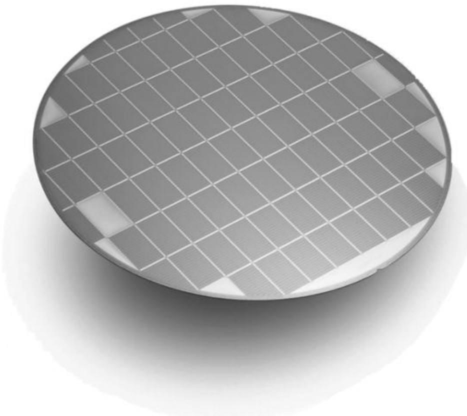
(1977)

iPhone 6

(2014)

The trend continues!

Advances in technology



The development goes amazingly fast ...

A sample of the International Technology Roadmap for Semiconductors.

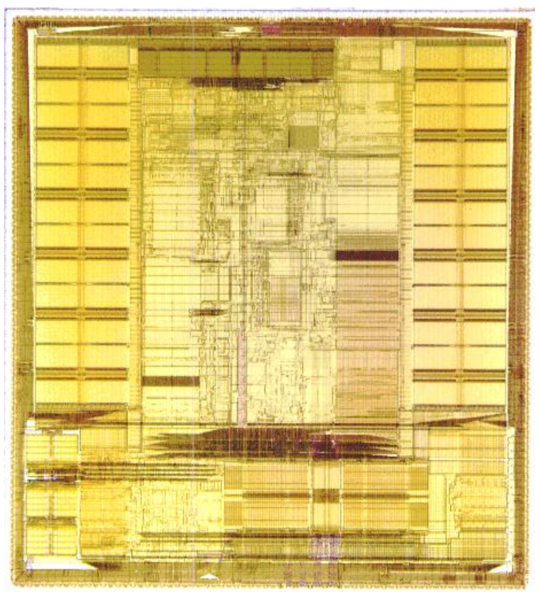
	Year					
	2006	2007	2008	2009	2010	2012
Technology feature size	78 nm	68 nm	59 nm	52 nm	45 nm	36 nm
Transistors per cm^2	283 M	357 M	449 M	566 M	714 M	1,133 M
Transistors per chip	2,430 M	3,061 M	3,857 M	4,859 M	6,122 M	9,718 M

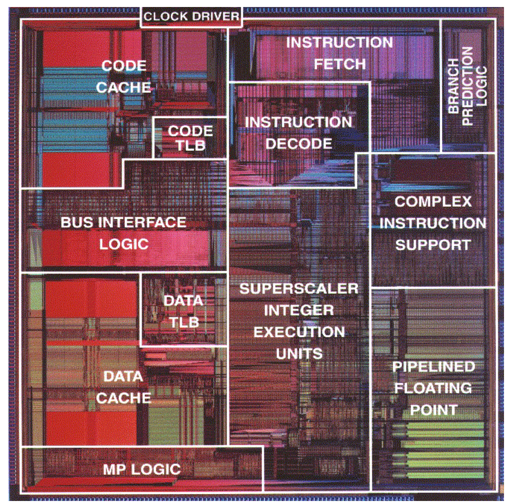
Examples of digital systems

VLSI Chip
(Alpha 21164)

Funktional block of
Pentium (Intel)

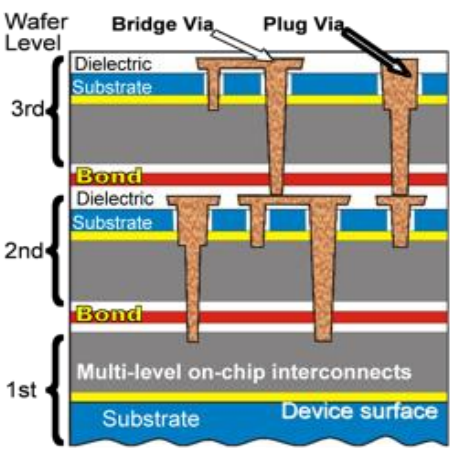
iPhone 6s



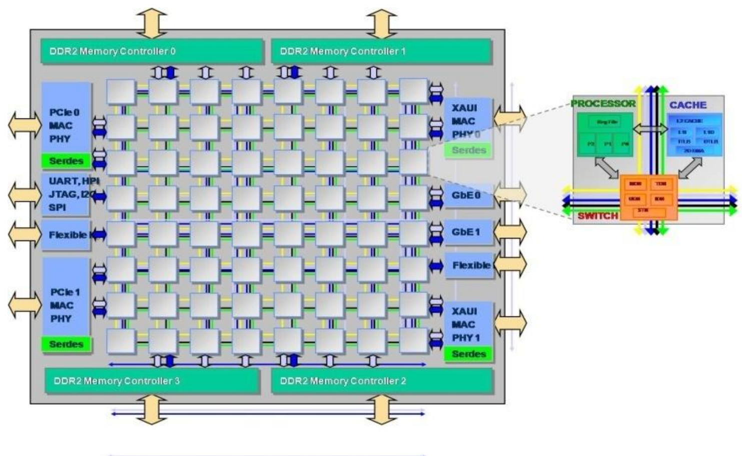


Examples of digital systems

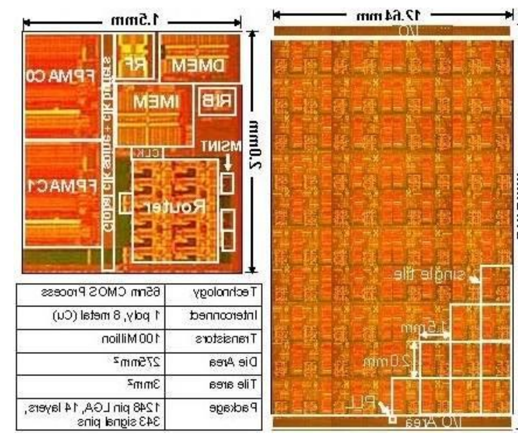
3D Integration



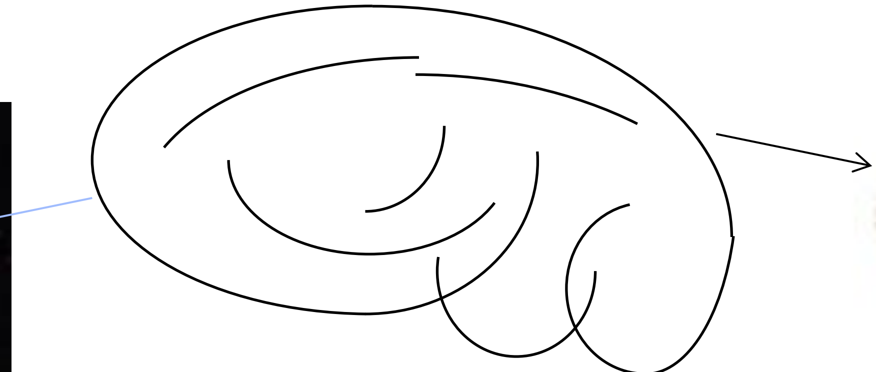
Tilera TilePRO64 (8x8 MPSoC)



Intel TeraFlop (8x10 MPSoC)

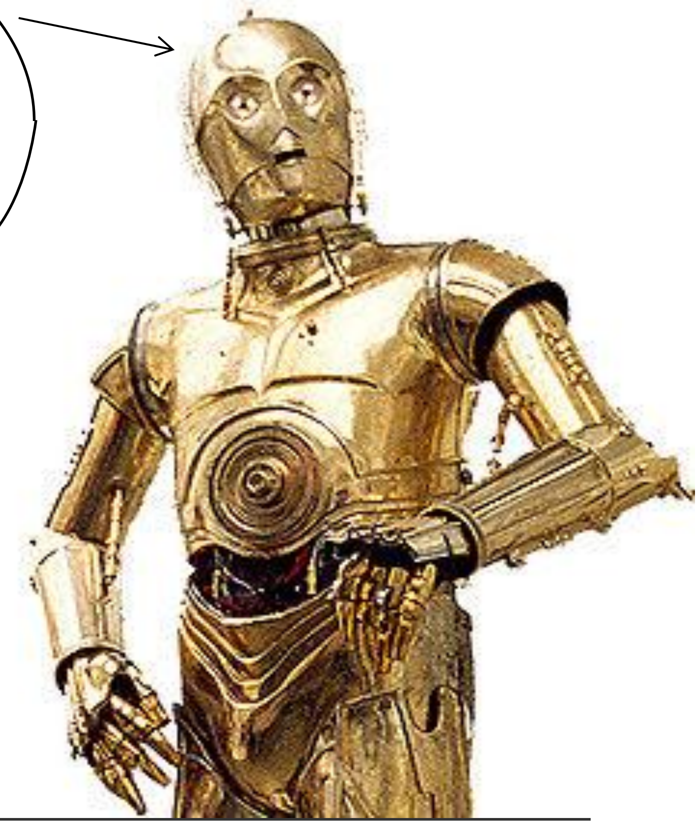


Examples of digital systems (2022)



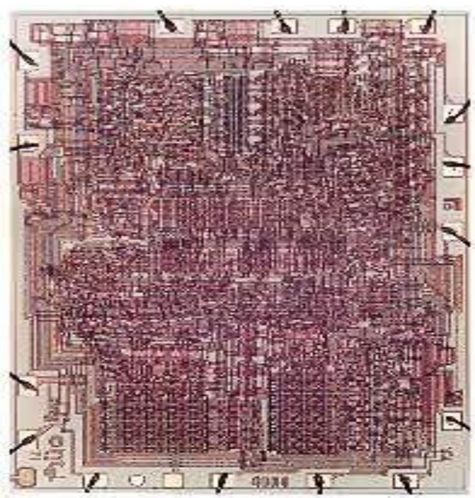
Robotic Brain

10x10x10 Chips containing a total of ~6350 Brain Processing Units (BPUs) & ~100 TB DRAM memory



Development of electronics

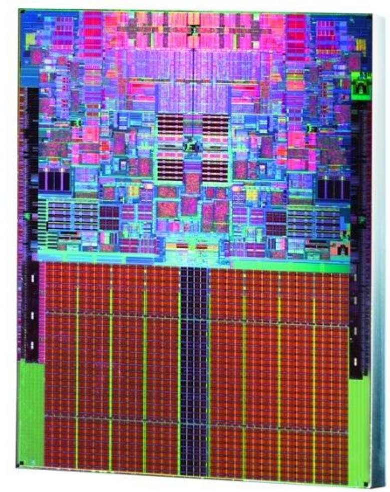
Intel 4004 (1971)



Intel Xeon 5400 (2008)

3.0 GHz
820 millions of transistors

108 KHz
2,300 transistors



If we had a corresponding development of cars, we would now be able to drive from San Francisco to New York in about 13 seconds (Intel).

Digital technology has created the basis for this development

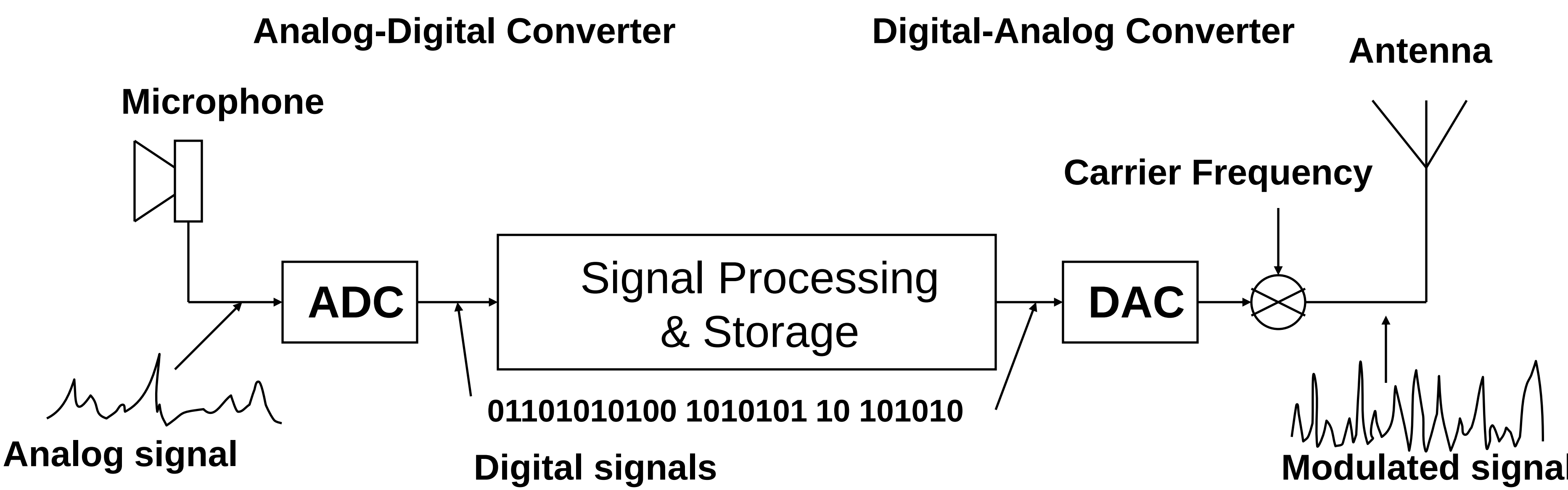
- Simple mathematical model
  - Just 1s and 0s as values
  - Boolean algebra (George Boole 1815-1864, English)
  - Interference-insensitive, efficient implementation of the mathematical model
- Transistor-based integrated circuits
  - Progress in semiconductor technology
  - Effective design methods and tools

KTH Informations- och kommunikationsteknik

Why binary?

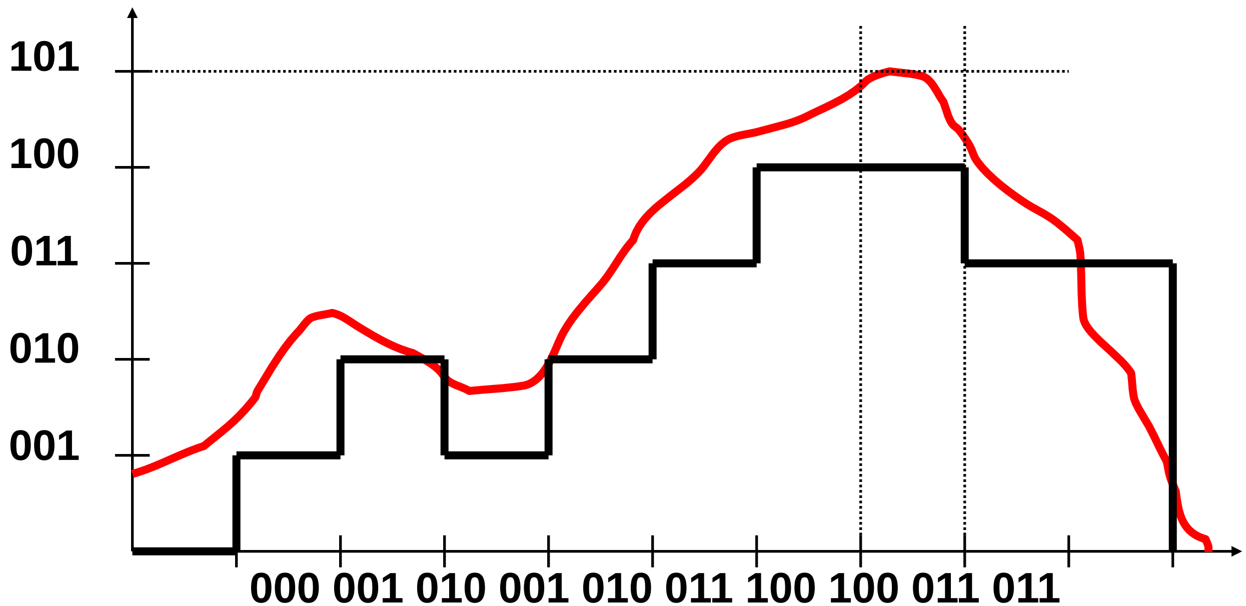
Analog & digital dignals

- Most of the signal processing today is done digitally

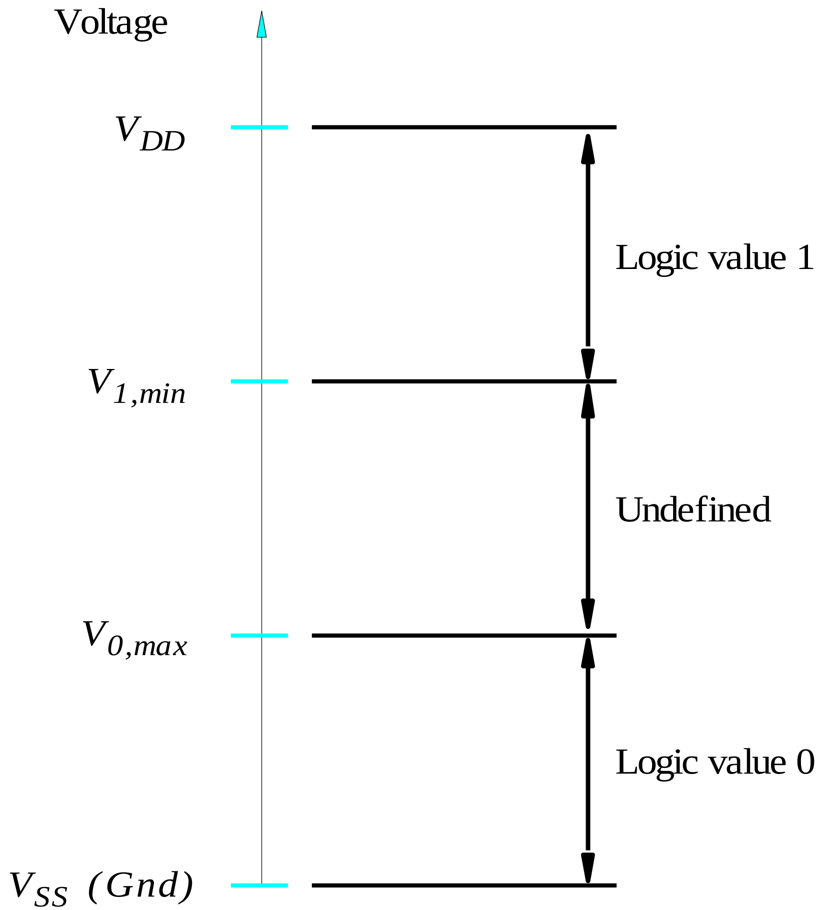


Analog vs. digital

- Instead of an analog signal that can assume *continuous* values, a digital signal only assumes *discrete* values



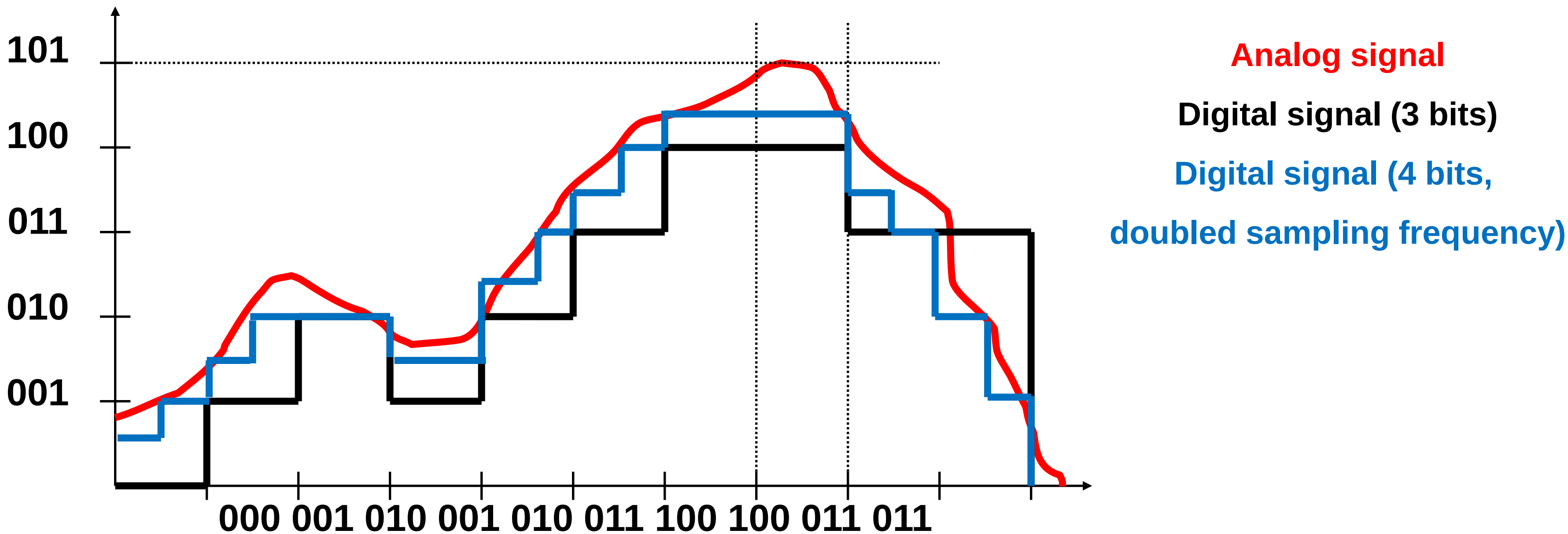
Digital technology is very insensitive to noise



- Not only *one* voltage value is interpreted as 1 or 0, but an *interval* of voltage values
- A deviation of a few mV can be very distracting in analog technology, but makes no difference in digital technology

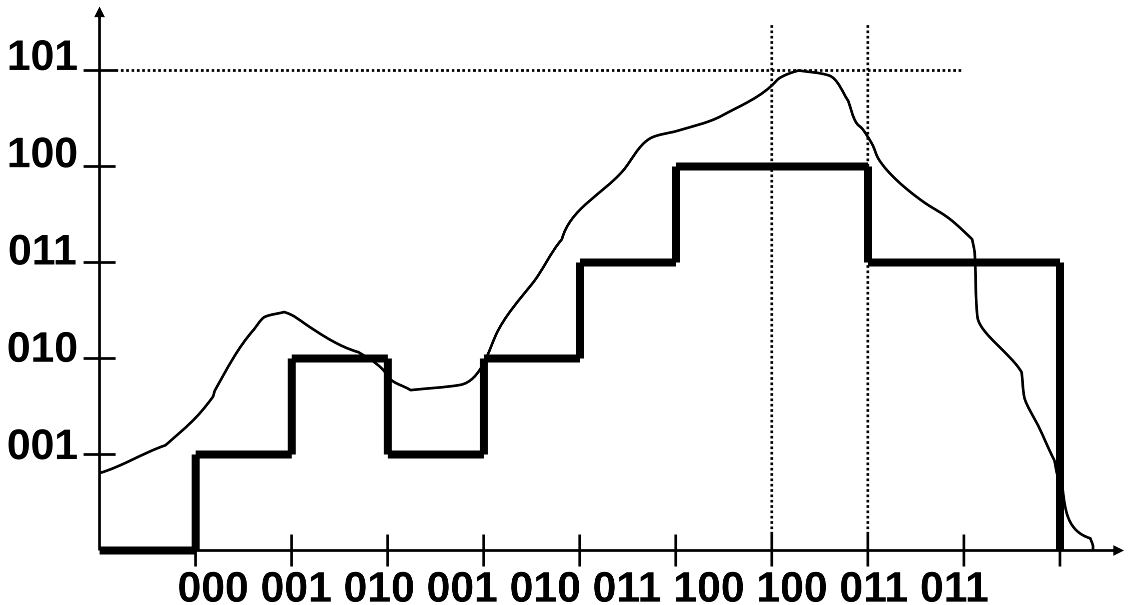
More bits and higher sampling increase signal quality

- If you have enough bits and sufficiently high sampling frequency, a digital signal can efficiently mimic the analog signal



Quantization and digitalization

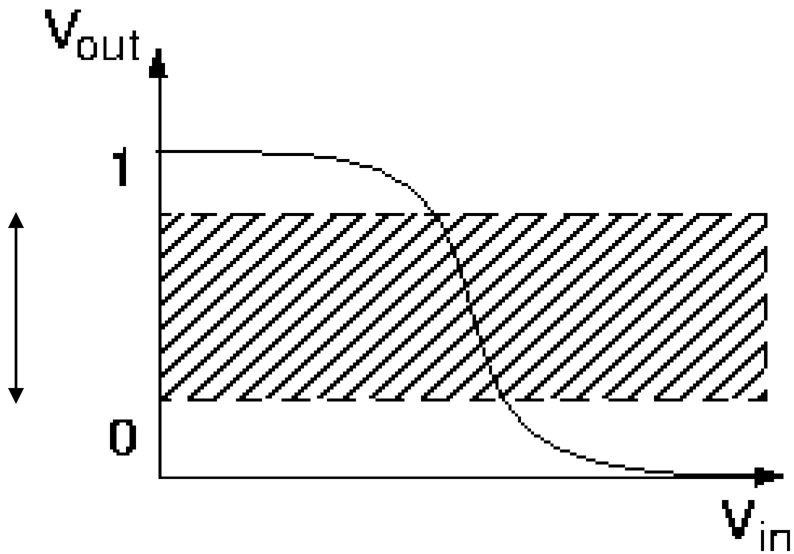
Quantization Levels

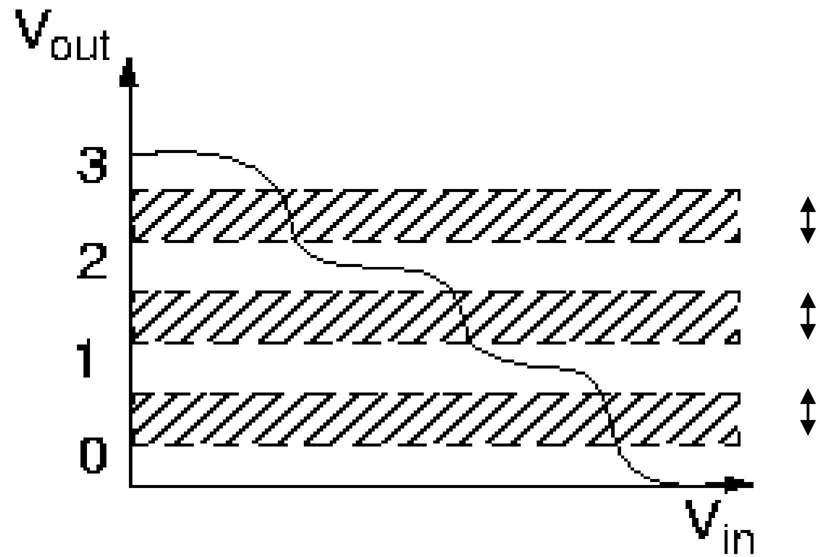


Digital signal sequence

Noise margins of digital levels

= Noise margins



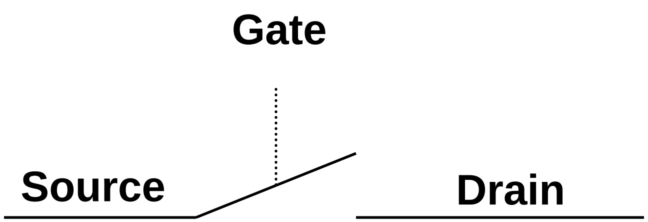


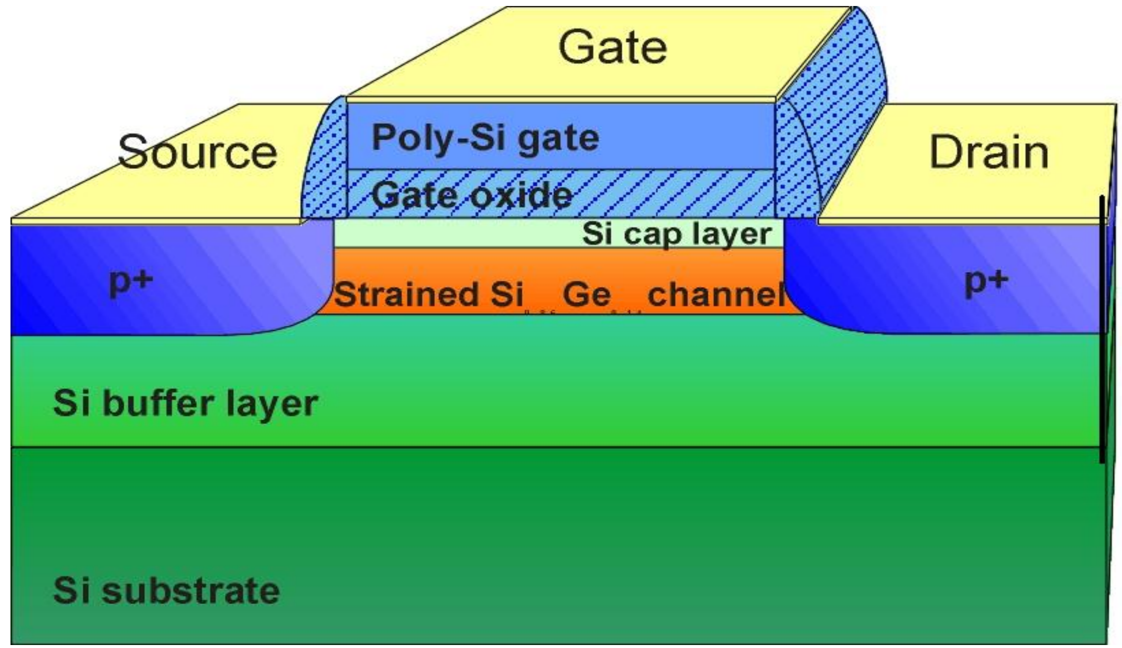
Why binary?

- CMOS transistors are
  - Cheap (made from ordinary sand)
  - Reliable
  - Efficient

- It is easy to make a transistor work as a switch

Transistor - switch with no moving parts





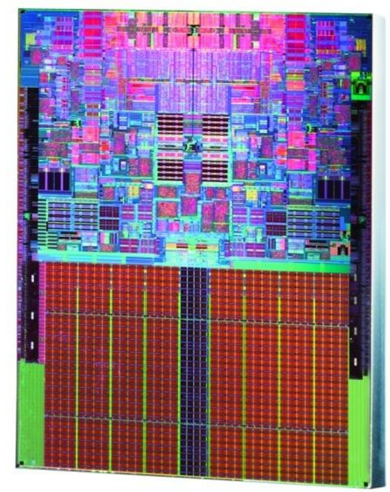
Schematic diagram of the SiGe transistor (KTH)

KTH Informations- och kommunikationsteknik

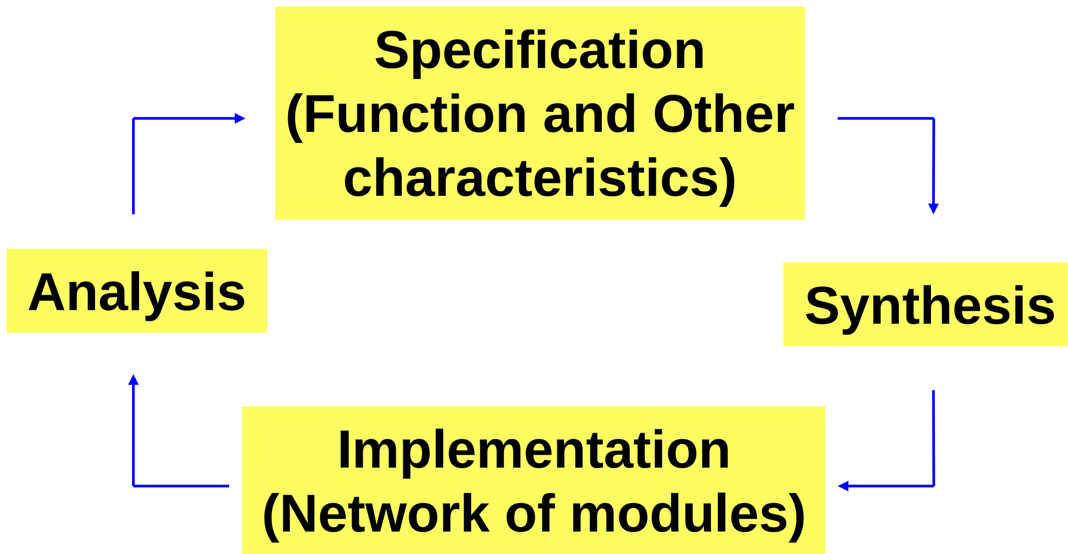
How does we design a digital system?

A processor contains many gates ...

- Very inefficient to describe it by drawing a network of gates
- We need other methods to describe a system!



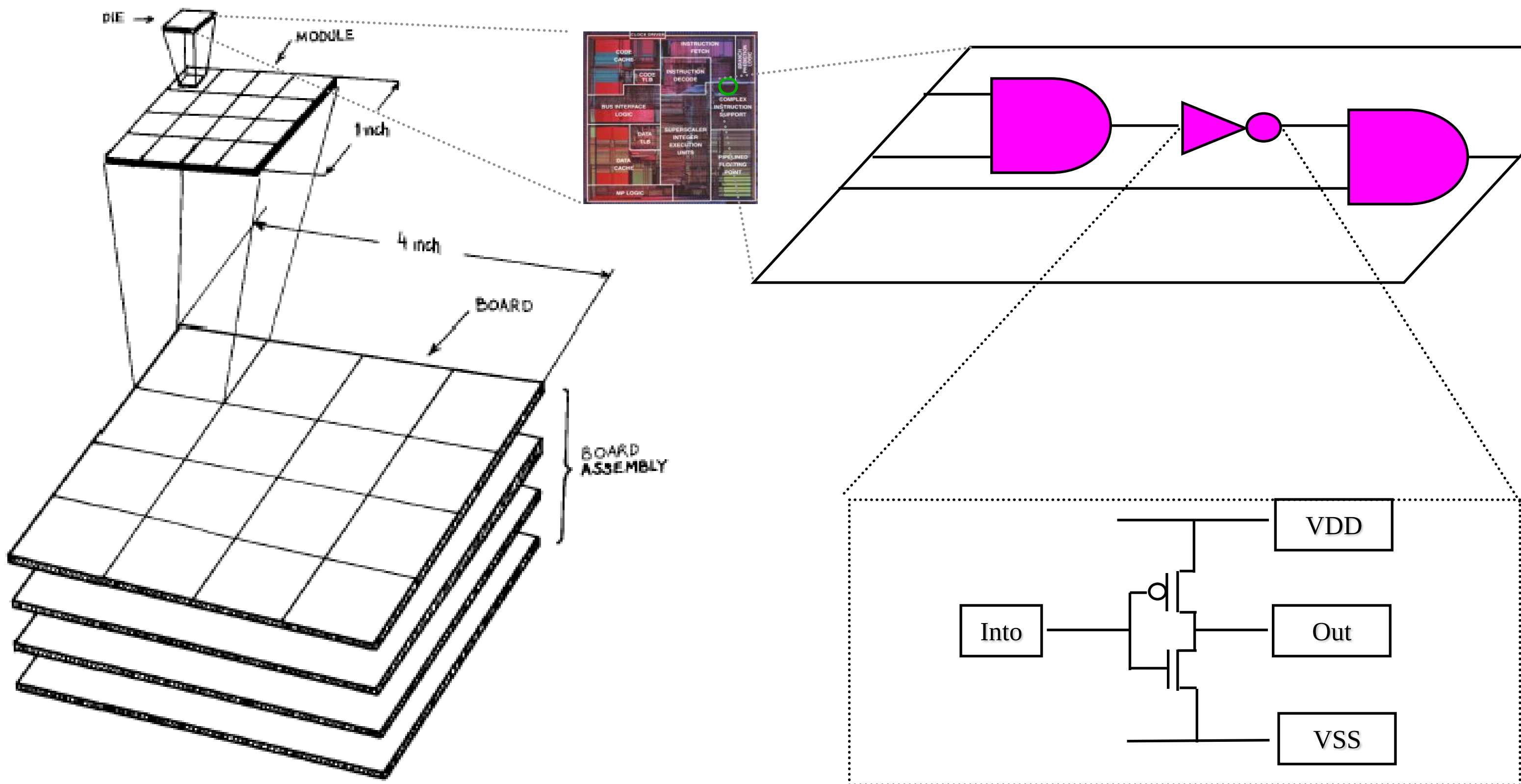
Design Methodology



Hierarchy and levels of abstraction

- Hierarchy: Looking at things that are composed of various smaller and (hopefully) simple things
- Abstraction: When we are looking at a specific level, we do not need to know all the details at the lower levels

Hierarchy in a digital system



Source: H.B. Bakoglu, Circuits, Interconnections and Packaging of VLSI, 1990

Digital hardware in a computer

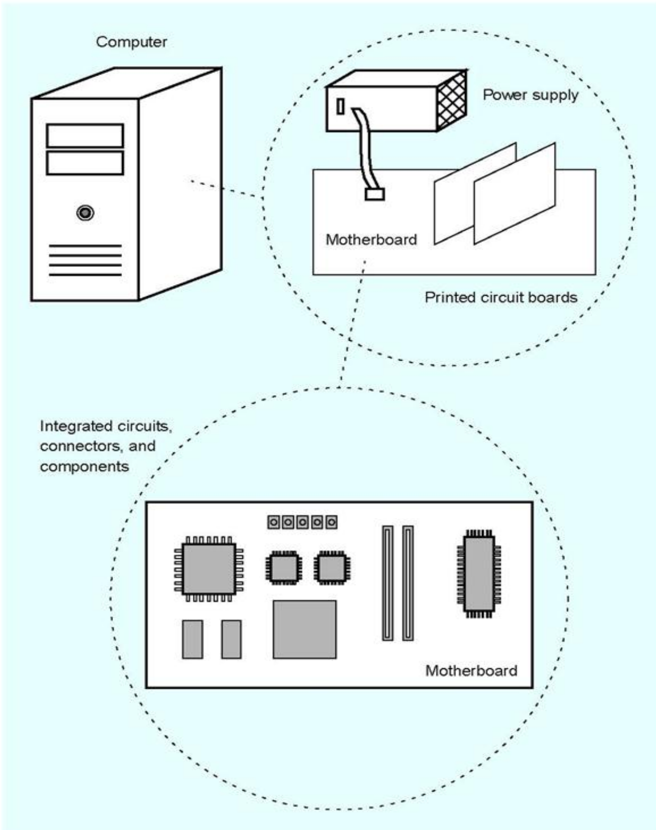


Figure 1.5. A digital hardware system (Part *a*).

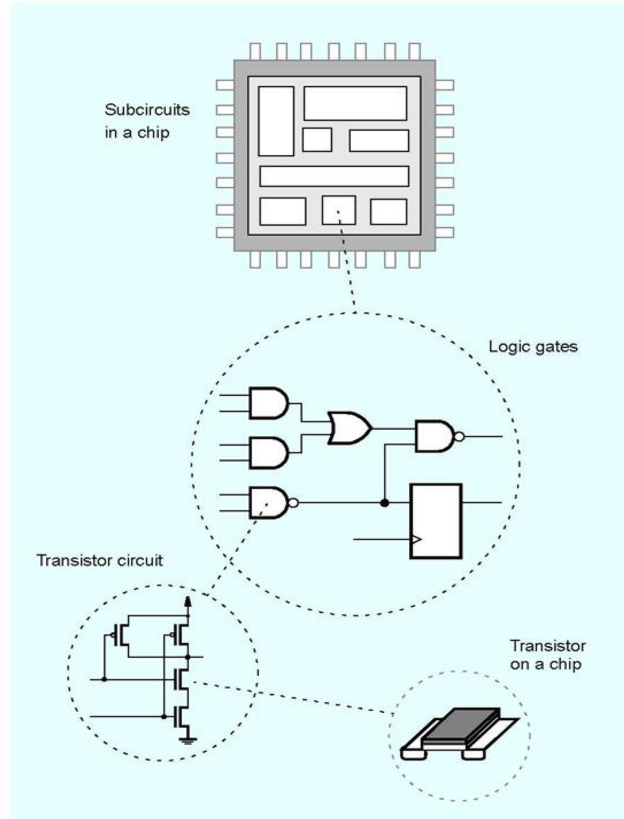
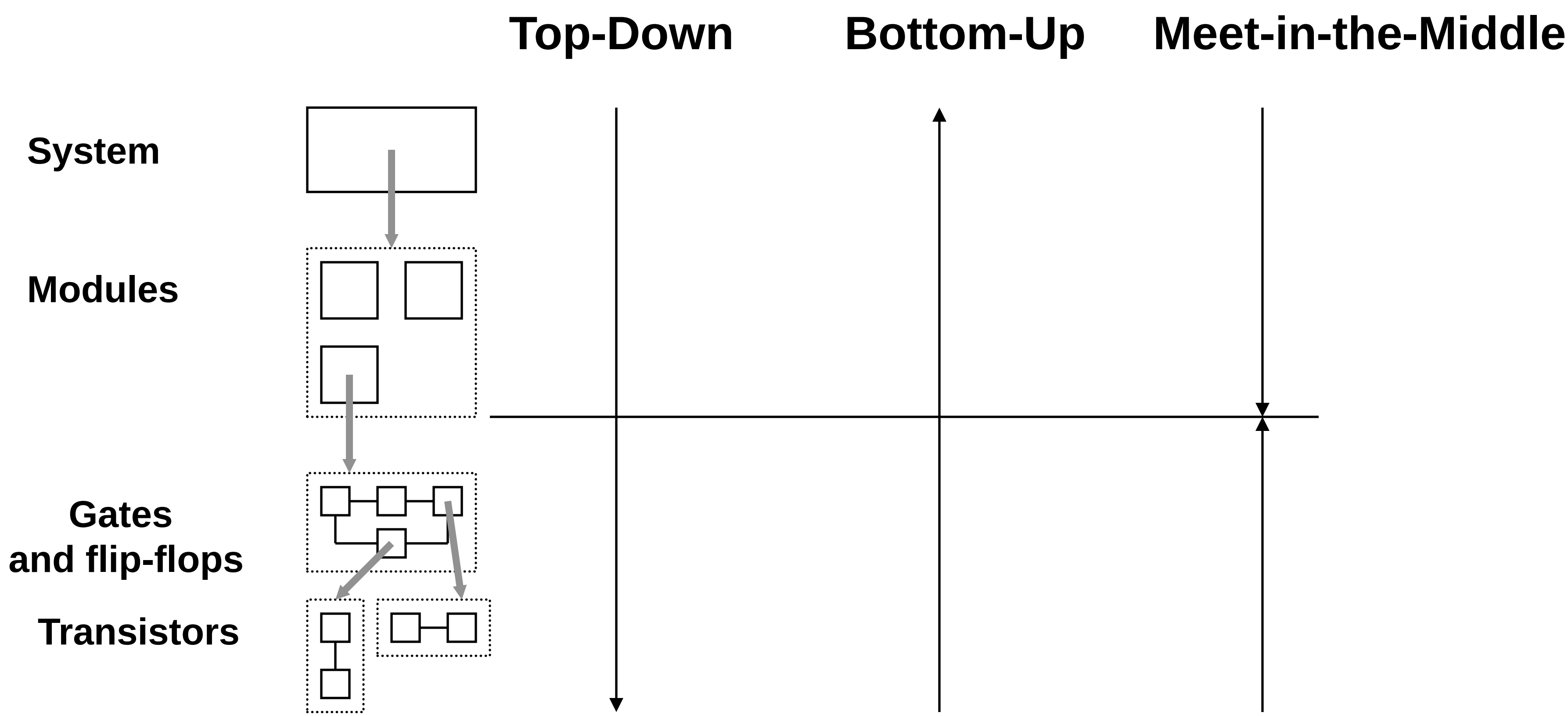
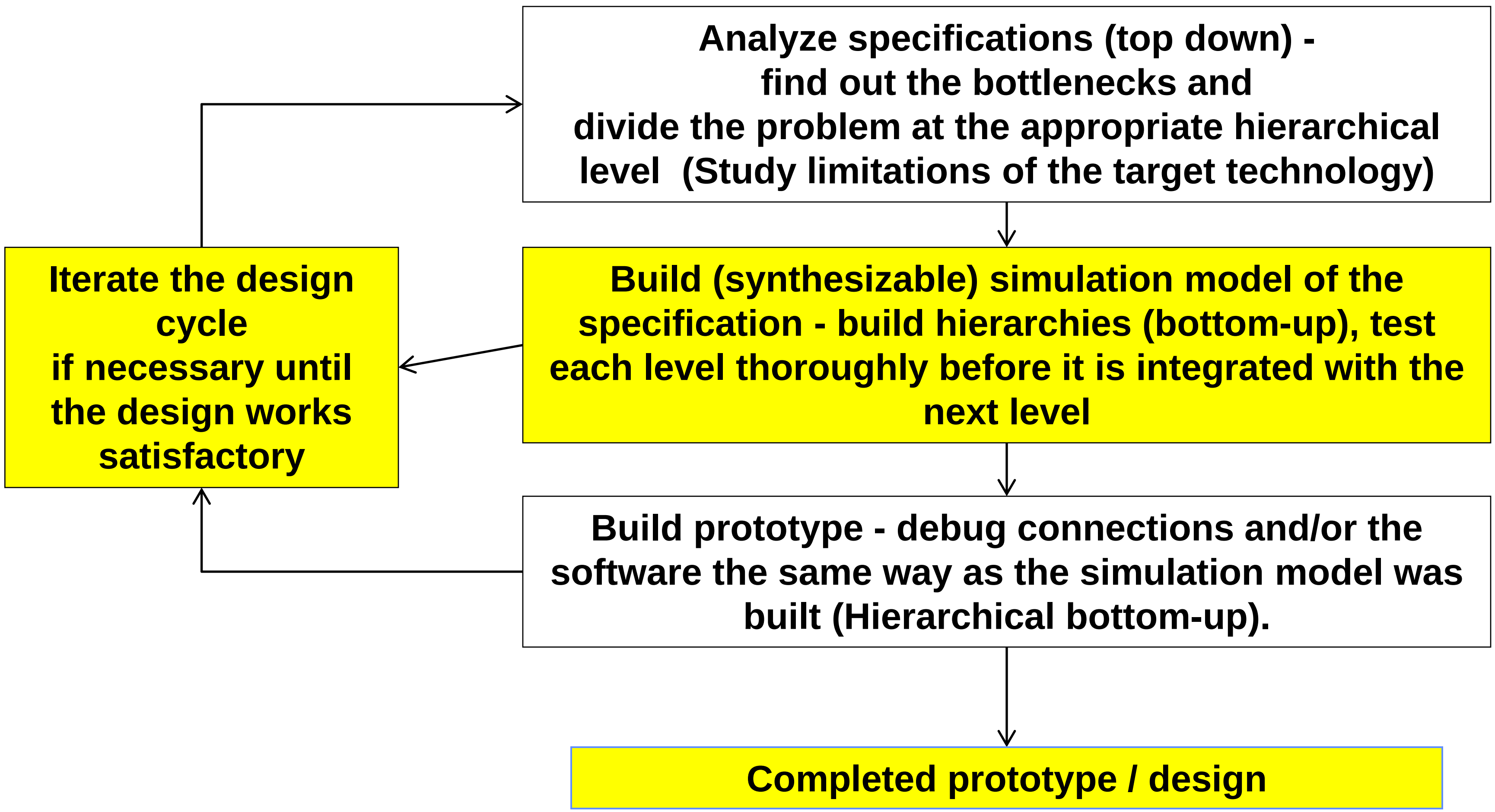


Figure 1.5. A digital hardware system (Part *b*).

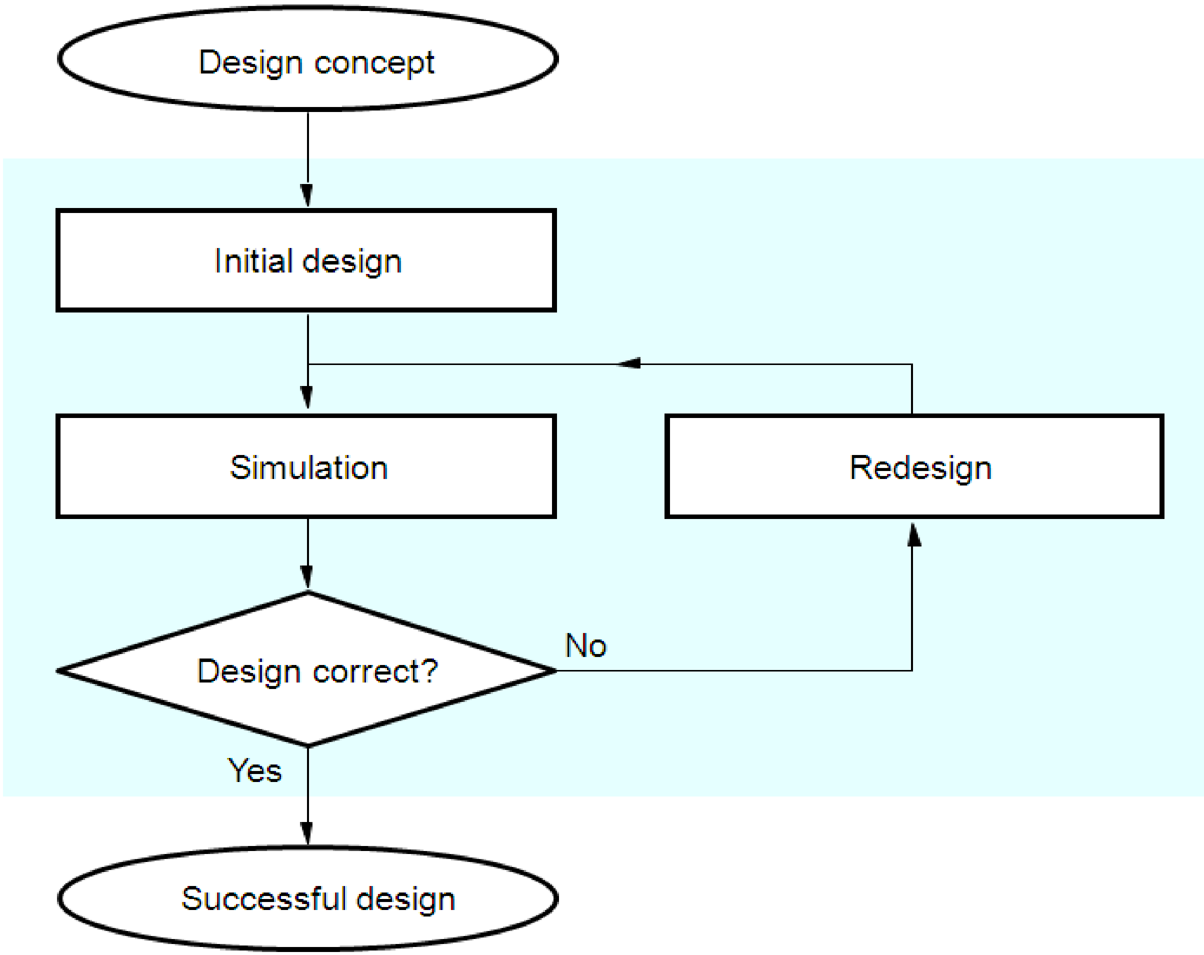
Three typical design methodologies



Meet-in-the-middle methodology



Simplified Design Process



KTH Informations- och
kommunikationsteknik

Have we can handle millions of transistors in a design?

CAD tools

- CAD tools are capable of handling the complexity (in term of the total number of transistors)
- They help us to design highly efficient integrated circuits for a broad spectrum of applications
  - Computers
  - Telecommunications (switches, routers, mobile)
  - Transport industry (aerospace, automotive)
  - The entertainment industry
  - ...

What is a CAD tool?

- A CAD tool is a program that helps an engineer to design (e.g. an integrated circuit)
- CAD tools can be fully automated or interactive
- CAD tools are based on algorithms that define the order of steps to be applied

Other types of CAD tools

- CAD tools are not only used for synthesis of circuits, but also for the analysis of circuits
  - E.g. to simulate a circuit description in order to analyze its time delays, how much power it draws, etc..

Hardware description language (HDL)

- Hardware Description Languages (HDLs) is a programming language that makes it possible to describe the hardware features in a natural way
- In contrast with normal programming languages, like C, where a code is executed sequentially, HDL languages execute a code in parallel
- HDL descriptions can be used as an input to a "synthesizer", a type of compiler which produces”executable code” for hardware

KTH Informations- och kommunikationsteknik

But now we take it from the beginning ...

Binary numbers

- Digital technology uses only two numerical symbols: 0 and 1
  - Easy to implement - each value corresponds to a voltage level, e.g.
    - 0 volts correspond to 0
    - 3 volts correspond to 1

How can we represent ordinary decimal numbers?

Decimal number system

- Decimal number system has 10 different numeric symbols: 0-9
- A decimal number is represented with a sequence of numeric symbols
  - The position in the sequence gives the digit weight which is multiplied by a power of 10 (*base* in the decimal system is 10)

$$(653)_{10} = 6 \cdot 10^2 + 5 \cdot 10^1 + 3 \cdot 10^0$$

Decimal number system

- Representation of an integer in decimal

$$N_{10} = x_{m-1} \cdot 10^{m-1} + x_{m-2} \cdot 10^{m-2} + \ldots + x_1 \cdot 10^1 + x_0 \cdot 10^0$$

$$(653)_{10} = 6 \cdot 10^2 + 5 \cdot 10^1 + 3 \cdot 10^0$$

- Representation of a number with ”comma”

$$N_{10} = x_{m-1} \cdot 10^{m-1} + x_{m-2} \cdot 10^{m-2} + \ldots + x_1 \cdot 10^1 + x_0 \cdot 10^0 + x_{-1} \cdot 10^{-1} + x_{-2} \cdot 10^{-2} + \ldots$$

$$(6.53)_{10} = 6 \cdot 10^0 + 5 \cdot 10^{-1} + 3 \cdot 10^{-2}$$

Binary system

- The binary system works in the same way as the decimal system, but uses base 2 instead of 10

$$N_2 = x_{m-1} \cdot 2^{m-1} + x_{m-2} \cdot 2^{m-2} + \ldots + x_1 \cdot 2^1 + x_0 \cdot 2^0 + x_{-1} \cdot 2^{-1} + x_{-2} \cdot 2^{-2} + \ldots$$

$$(110)_2 = 1 \cdot 2^2 + 1 \cdot 2^1 + 0 \cdot 2^0 = (6)_{10}$$

$$(11.01)_2 = 1 \cdot 2^1 + 1 \cdot 2^0 + 0 \cdot 2^{-1} + 1 \cdot 2^{-2} = (3.25)_{10}$$

Octal number system

- The octal number system uses base 8 and numerical symbols 0-7

$$N_8 = x_{m-1} \cdot 8^{m-1} + x_{m-2} \cdot 8^{m-2} + \ldots + x_1 \cdot 8^1 + x_0 \cdot 8^0 + x_{-1} \cdot 8^{-1} + x_{-2} \cdot 8^{-2} + \ldots$$

$$(65.3)_8 = 6 \cdot 8^1 + 5 \cdot 8^0 + 3 \cdot 8^{-1} = (53.375)_{10}$$

Hexadecimal number system

- The hexadecimal number system uses base 16 and numerical symbols 0-9 and letters A to F

$$N_{16} = x_{m-1} \cdot 16^{m-1} + x_{m-2} \cdot 16^{m-2} + \ldots + x_1 \cdot 16^1 + x_0 \cdot 16^0 + x_{-1} \cdot 16^{-1} + x_{-2} \cdot 16^{-2} + \ldots$$

$$(\mathrm{AE.8})_{16} = 10 \cdot 16^1 + 14 \cdot 16^0 + 8 \cdot 16^{-1} = (174.5)_{10}$$

Number systems with base *b*

- A general formulation can be obtained for the base *b*

$$N_b = x_{m-1} \cdot b^{m-1} + x_{m-2} \cdot b^{m-2} + \ldots + x_1 \cdot b^1 + x_0 \cdot b^0 + x_{-1} \cdot b^{-1} + x_{-2} \cdot b^{-2} + \ldots$$

Integers in different number systems

2	8	10	16
0	0	0	0
1	1	1	1
10	2	2	2
11	3	3	3
100	4	4	4
101	5	5	5
110	6	6	6
111	7	7	7

2	8	10	16
1000	10	8	8
1001	11	9	9
1010	12	10	A
1011	13	11	B
1100	14	12	C
1101	15	13	D
1110	16	14	E
1111	17	15	F
10000	20	16	10

Conversion between decimal and binary numbers

- Conversion from binary to decimal is trivial
- Conversion from decimal to binary can done by repeatedly dividing by 2
  - The remainder gives us the numerical value
  - The numbers are in reverse order - Least Significant Bit (LSB) comes first

$$
\begin{aligned}
53 \div 2 &= 26*2+1 &\Rightarrow\quad & x_0 = 1\,(\mathrm{LSB}) \\
26 \div 2 &= 13*2+0 &\Rightarrow\quad & x_1 = 0 \\
13 \div 2 &= 6*2+1 &\Rightarrow\quad & x_2 = 1 \\
6 \div 2 &= 3*2+0 &\Rightarrow\quad & x_3 = 0 \\
3 \div 2 &= 1*2+1 &\Rightarrow\quad & x_4 = 1 \\
1 \div 2 &= 0*2+1 &\Rightarrow\quad & x_5 = 1\,(\mathrm{MSB})
\end{aligned}
$$

Summary

- There are many different number systems
- Digital technology uses the binary number system
- It is possible to convert numbers between different number systems

Summary

- **Design Methodology**
  - **Meet-in-the-middle**
    - Analyze the specification and the target technology top-down
    - Build hierarchies and test bottom-up
  - **CAD tools**
    - Necessary to manage the complexity of large designs
  - **Hardware description language (HDL)**
    - It takes too long to construct a gate-level circuit ”by hand”
    - By describing a circuit at a higher level, we increase the productivity level (gates/hour) of a designer.