Dependability and Fault Tolerance

in micro- and nano-electronic circuits and systems

Introduction

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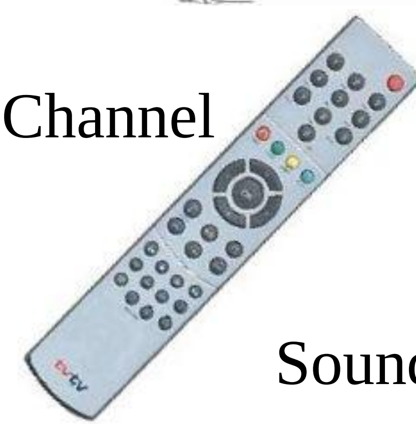
Outline

1. Everyday Experiences
2. Microelectronics Evolution
3. Errors and Dependability
4. Fault Tolerance and Self Repair
5. Re-configurable Systems
6. Outlook

1. Everyday Experiences

How to Control a TV Set

On /off button



Channel

Sound

Image

Cars

No electronics,
but operationable!

With up to about 120 embedded computers in control units a car of today is a multi-processor network !

.. but without electronics there is no emission control, no ABS (break control), no navigation system.

Automotive Electronics

….in Audi- Advertisement

Not possible without electronic traction control !!

Text Processing

Typewriter
(ca. 1970).

mechanical,
no SW

Muti-Media- PC (2010)

PC-System
(1985)

100 000 Trans.
10 MByte SW

10 000 000 Trans.
10 000 MByte SW

General Tendency

- For a large variety of technical systems, complex functions are not possible without embedded micro-electronic devices, processors, memory, **Software**.
- Tools, appliances, devices of everyday use are becoming increasingly more complex with respect to:

  -- structure

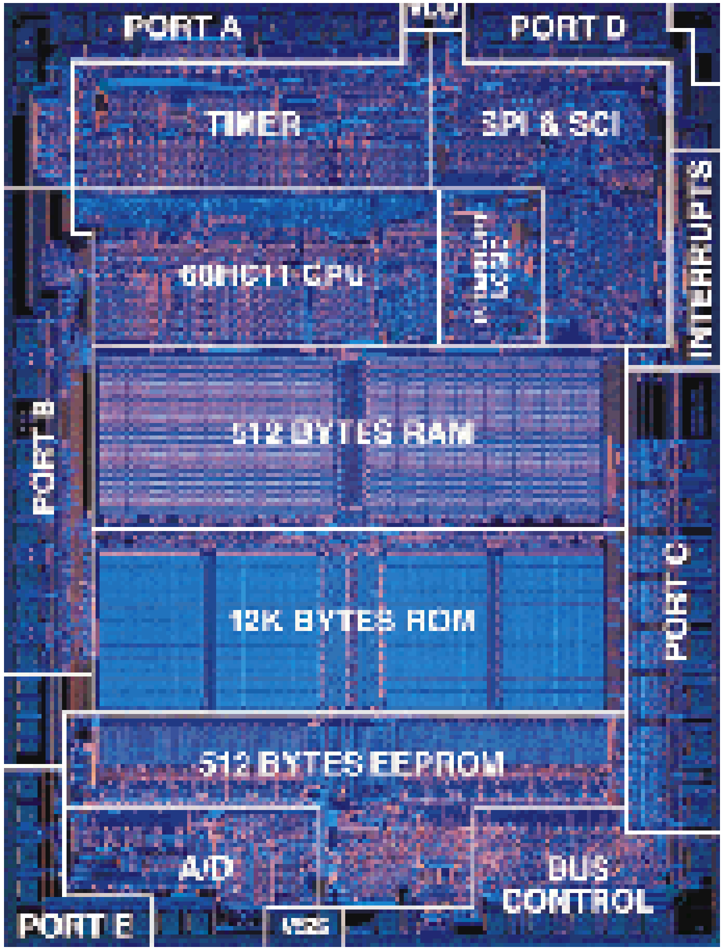
  -- handling

  -- maintenance / service

  -- reliability in operation.

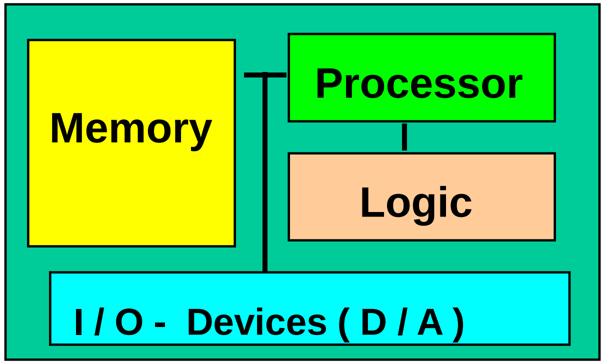
Where does complexity come from?? For what purpose??

2. Microelectronics as the Driver



Large-scale integrated circuits with embedded processors make „Systems on a Chip“ (SoCs)

Embedded Electronics



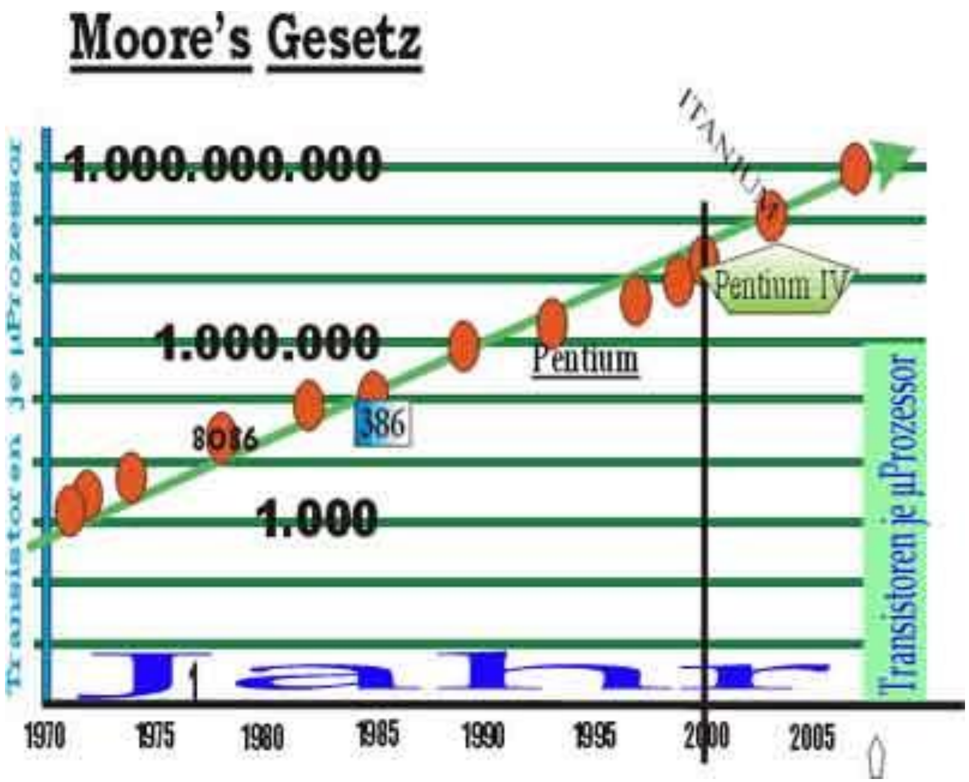
An embedded system consists of one or more processors, memory blocks (RAM, ROM), I / O devices. Typically it operates on fixed pre-defined software, typically

- in cars (motor control, break control, traction control, navigation)
- in PCs (keyboard, display, printer)
- in household appliances (washing machine, dish washer)

Evolution of Microelectronics

Year	Min. Struct. in nm	Trans. per cm^2	Clock frequ. MHz	Pins	Metal-Layers
1970	20 000	1000	1	16	1
1975	10 000	10 000	5	28	1
1980	5 000	20 000	10	50	1
1985	1 000	100 000	20	68	2
1990	500	1 000 000	50	200	3
1995	300	5 000 000	200	350	4
2000	130	50 000 000	1000	500	6
2005	65	200 000 000	3000	800	8
2010	30	1 000 000 000	4000	1000	10
2015	14	10 000 000 000	4000	15000	12

Complexity in Microelectronics



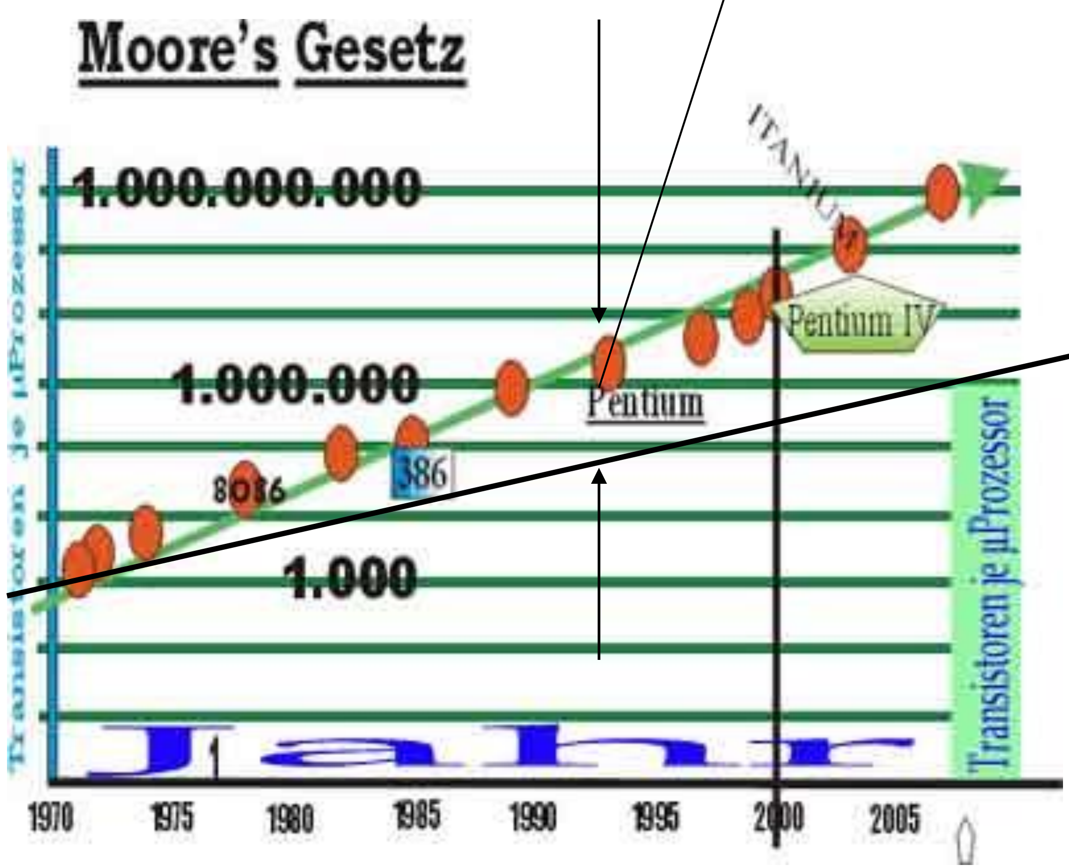
The number of transistors on the same chip area duplicates about every 18 months !

... and there must be somebody to use it and pay for it !!

Fundamental Wisdom About Microelectronics

- Many complex functions in cars, tools, airplanes, manufacturing etc. are not possible without microelectronics and software.
- Complex ICs can economically be produced only in large volumes. For nano-circuits, the volume is in multi-millions. „Old“ technologies may allow production volumes in hundreds of thousands.
- Mobile phones are the „technology driver“. Manufacturers compete for the lowest price per transistor.
- Aspects of reliability and operational life time are not a strong issue in mobile phones !! They become dominating if nano-technologies have to be used for long-living systems in safety-critical applications !

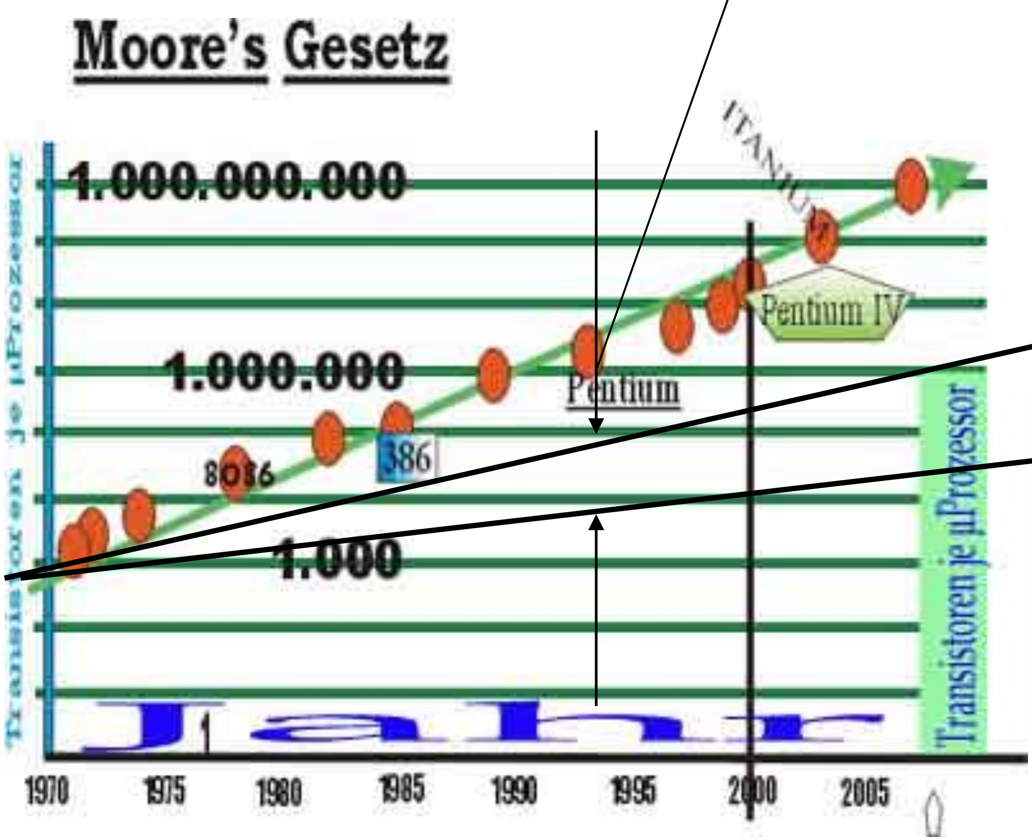
The „Design Gap“



The number of transistors that a HW-designer can „use“ per working day in system Design.

Way out :
Software!!

The Validation Gap



The number of transistors whose correct design a person can validate per day is even much lower !

Was Out :

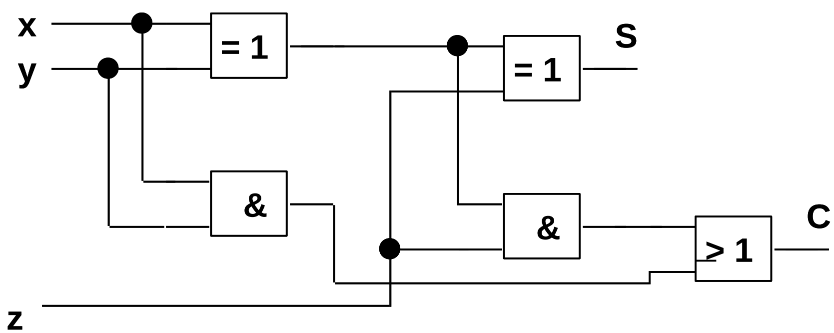
Software?? No!!

Digital hardware people can partly „prove" design correctness, SW people can not !

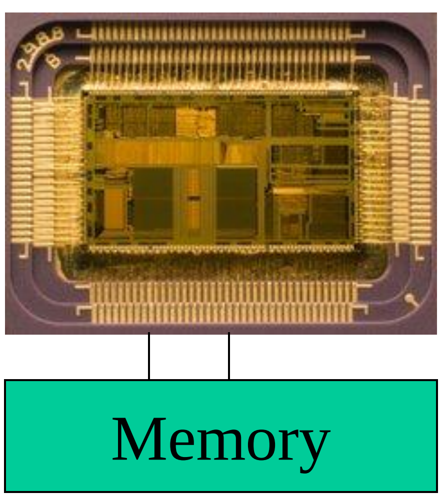
Microelectronics

- Microelectronics is the driver of complexity.
- Complex functions are impossible to implement without embedded processors and software.
- The transition from hardware to software-based functions typically means a jump in complexity by factor of 100 and more..
- Formal proof a software correctness is not possible for real-life systems.
- But for test and error handling we need to go to hardware details !

How to Design and Build an Adder



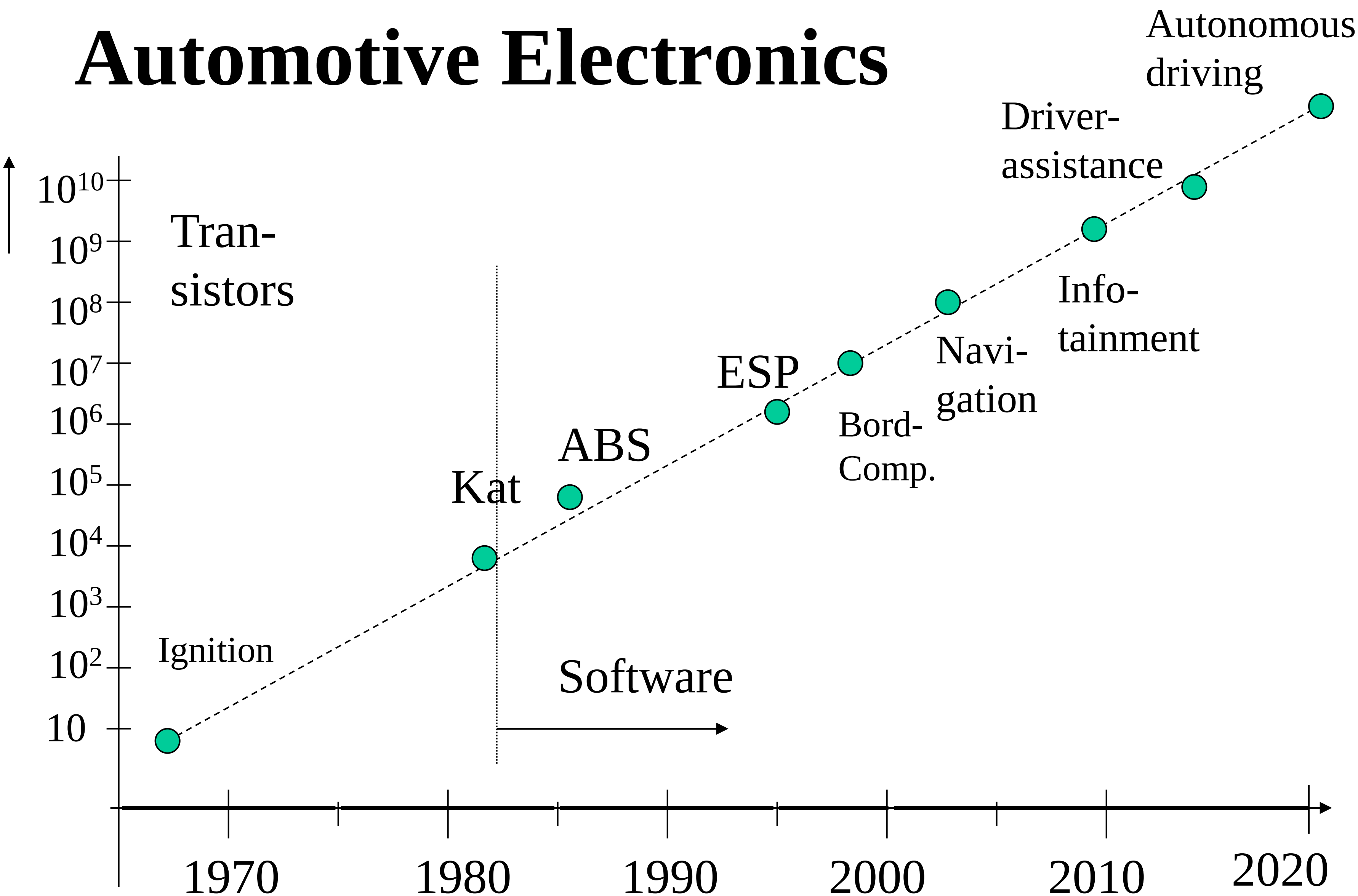
From pure Hardware:
ca. 100 – 1 000 Transistors



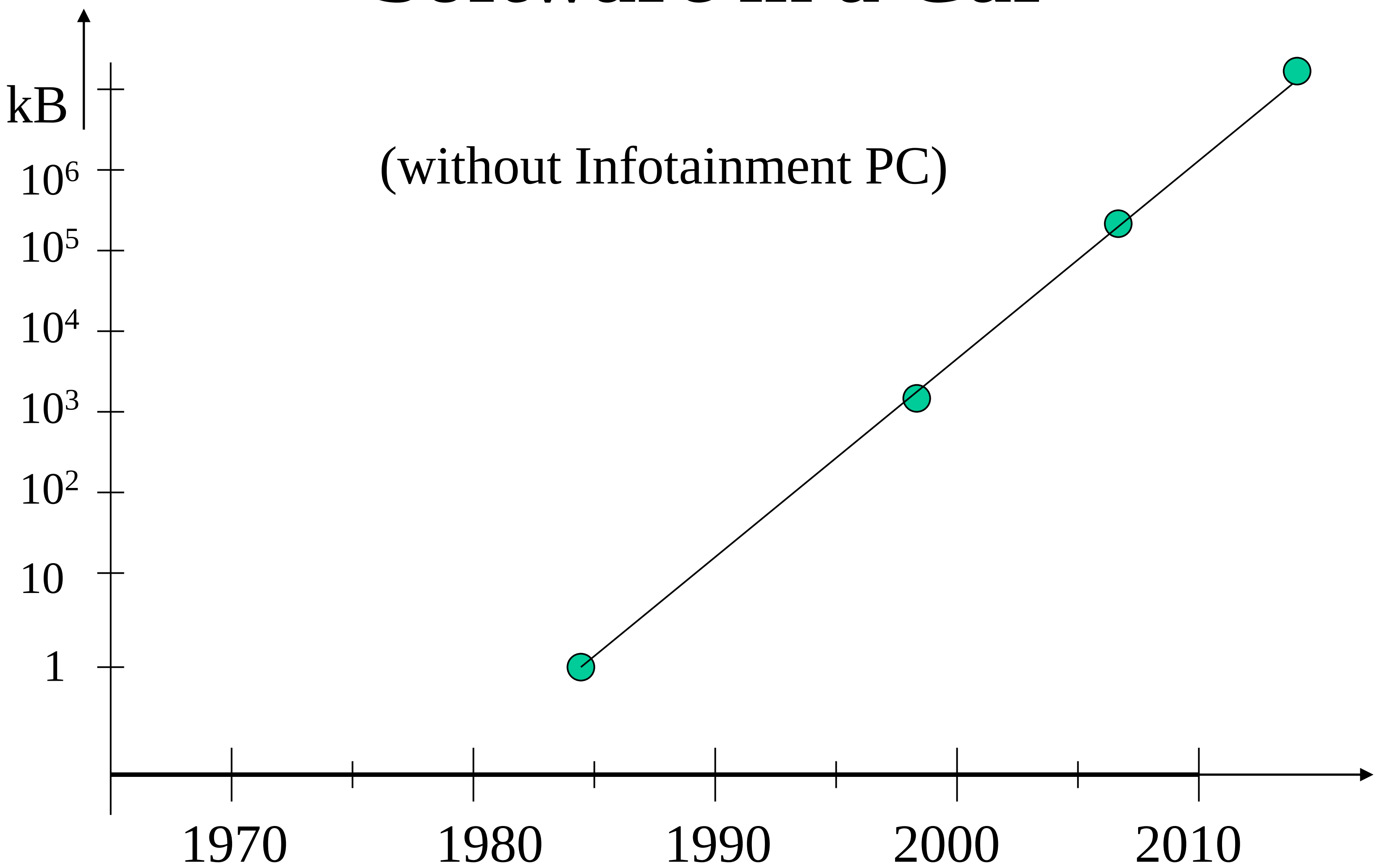
From Processor + Software:
ca. 30 000 bis 100 000 Transistors!

Typically the transition of a function from hardware to software means *100 in complexity!

Automotive Electronics



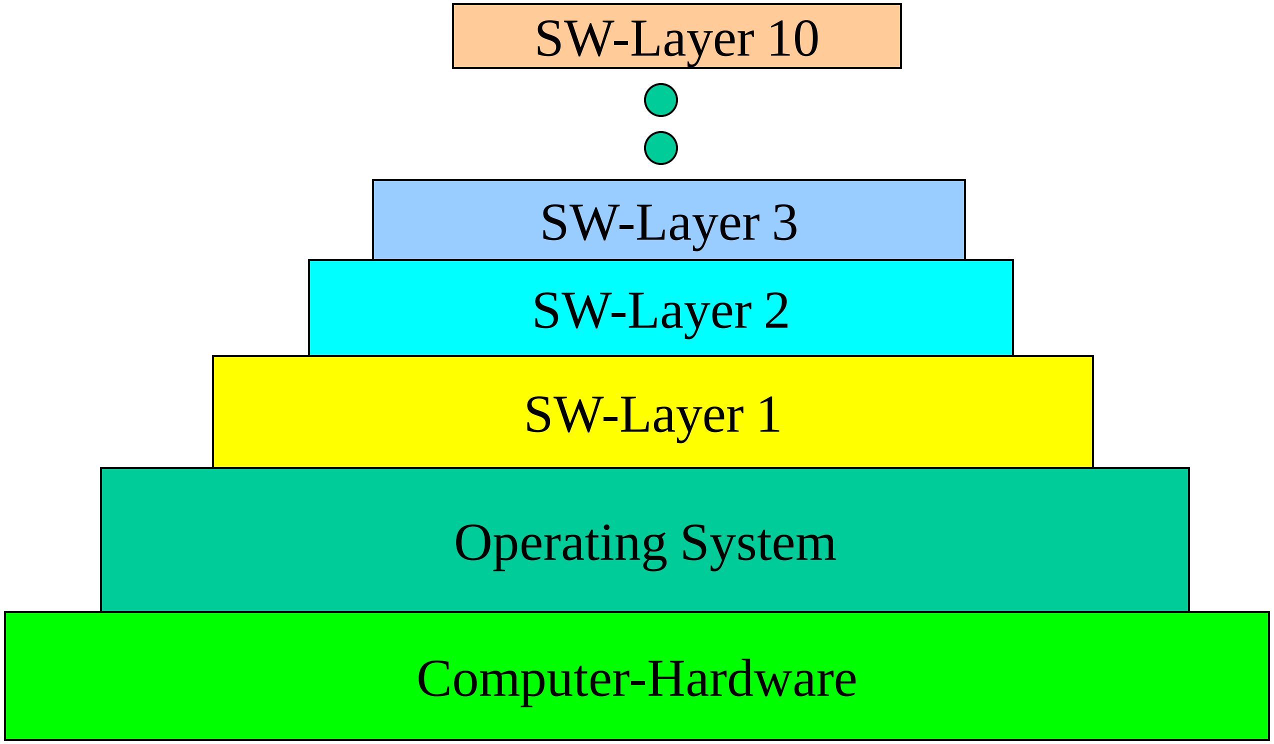
Software in a Car



Audi again....

Computation of tractive control may need several processors and a lot of software !

Software Complexity Organisation



... and every „higher“ level assumes that the lower levels work correctly !!

Migrating to Software

- As ICs in advanced technologies can be produced economocally only in volumes of millions, few types of ICs and functional implementation by software becomes the dominating tendency.
- System design is often based on specification, automatic software generation and final compilation.
- As system design tries to avoid problems of hardware design, it inherits all types of software !! SECURITY !!
- Some application areas such as automotive electronics and avionics have strict standards and regulations which cannot be met by „smart phone“-oriented nano-technologies.

3. Faults, Errors and Reliability

Complexity as such is not a problem, as long as you can control it.

But complexity also results in new sources of errors ....

Defects / Faults /Errors in Cars

- until 1975: Mechanics, hydraulics, electrics (battery!!)
- since 1975: Electronics, sensors
- since 1990: Software
- since ca. 2000: ICs, Interconnects, networks
- since ca. 2014: Security on automotive networks

There has been a dramatic increase in possible sources of faults and errors due to networking of heterogeneous computing units !
diverse in character or content.

Computer scientists have problems enough with parallel computing on regular and homogenoeus networks !
of the same or a similar kind or nature

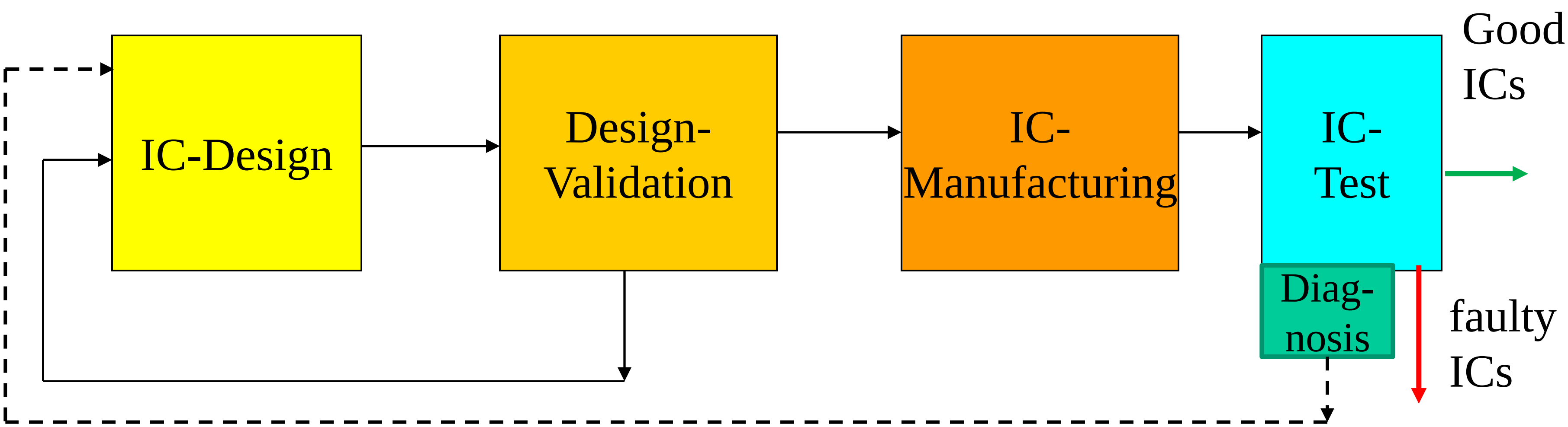
Faults /Errors in Electronic Systems

Level of Verifyability

	handable	limited	very poor
Faulty Specification			●
Faulty Design (Software)			●
Faulty Design (Hardware)		●	
Manfacturing Defects		● *	
Errors in Operation (transient HW errors)	● *		
Faults / errors due to aging and over-stress			●

* May cost a lot !

The Test Gap



$$\text{Manufacturing Yield: } \frac{\text{Fault-free Chips}}{\text{All Chips}}$$

The Test Gap

The ratio of of transistors on a single chip that can be:

manufactured over

validated (Hardware) over

tested is about:

100 : 10 : 1 !!!

.. unless digital circuits and systems are designed fo testability !

Can Electronics be Fault-Free ??

- Typically, specifications are not complete in a formal sense and may even contain implicit contradictions.
- Neither hardware nor software design is error-free. But, for example, formal verification of processor designs is possible.
- According to general experience, software design is erron-prone. Debugging is done by testing, which is not complete in a formal sense. Typically, software bugs seem to be in rarely-used functions.
- Integrated circuits may suffer from manufacturing defects. They have to be found by production testing. Repair is sometimes done, mainly for memories.

- Transient hardware errors of otherwize correctly working circuits in normal operation become more likely with smaller features and lower operating voltage.

4. Fault Tolerance and Self Repair

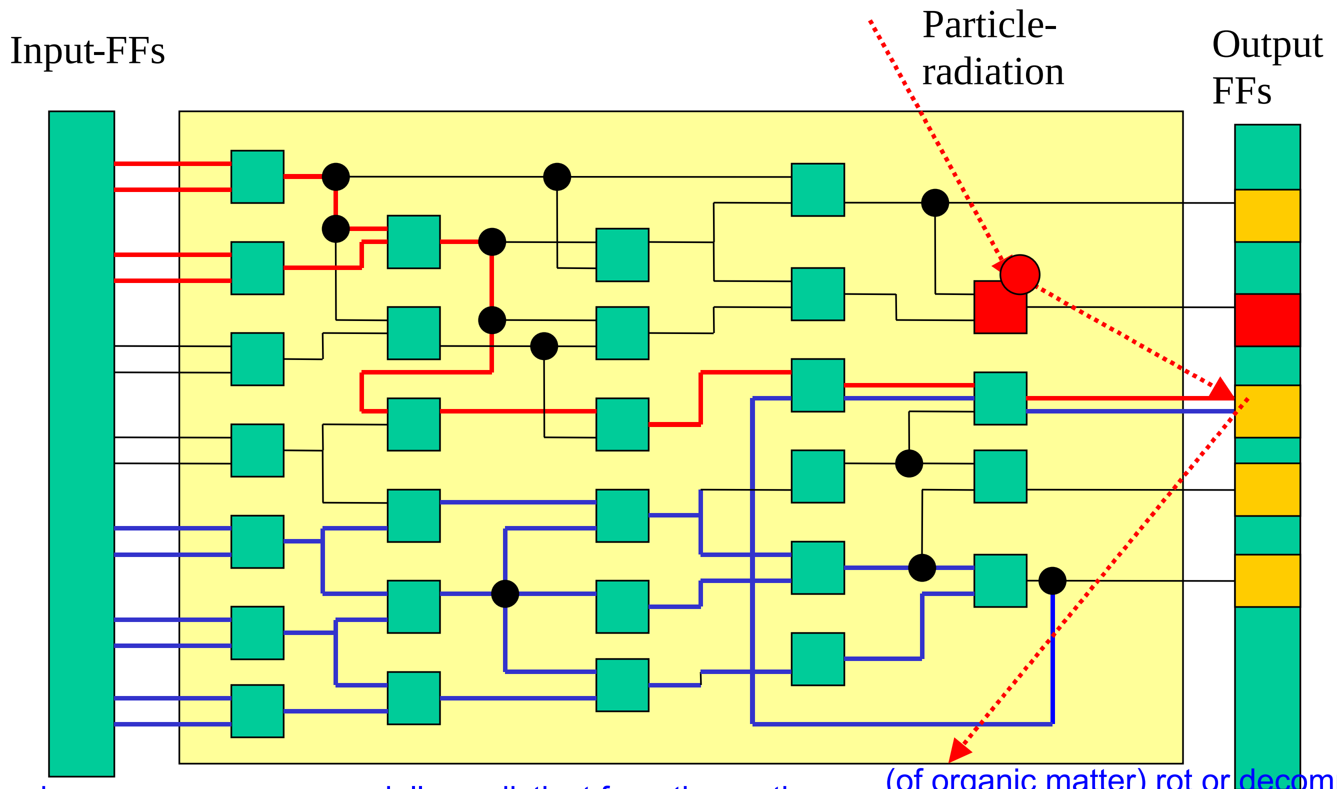
Faults are everywhere. You can fight them.

But then you have to know first where and when they occur ...

Mikroelectronics for Cars

Year	min. feature in nm	Trans. pro cm^2	Clock frequency MHz	Pins	Metall-layers	VDD/ V
1970	20 000	1000	1	16	1	10
1975	10 000	10 000	5	28	1	10
1980	5 000	20 000	10	50	1	5
1985	1 000	100 000	20	68	2	5
1990	500	1 000 000	50	200	3	3
1995	300	5 000 000	200	350	4	2
2000	130	50 000 000	1000	500	6	1
2005	65 250	200 000 000	3000	800	8	1
2010	30	1 000 000 000	4000	1000	10	1
2015	65	-automotive electronics trails behind !				

Transient Hardware Faults



relating to the universe or cosmos, especially as distinct from the earth

(of organic matter) rot or decompose through the action of bacteria and fungi.

Particles from cosmic radiation and from atomic decay may hit electronic devices and trigger (mainly) transient and (much less often) permanent faults.

relating to, denoting, or using the energy released in nuclear fission or fusion

Some Recent Data*

Cray XT5, Oak Ridge, Tennessee, „Jaguar“

Memory size: 360 terabytes, all ECC-protected

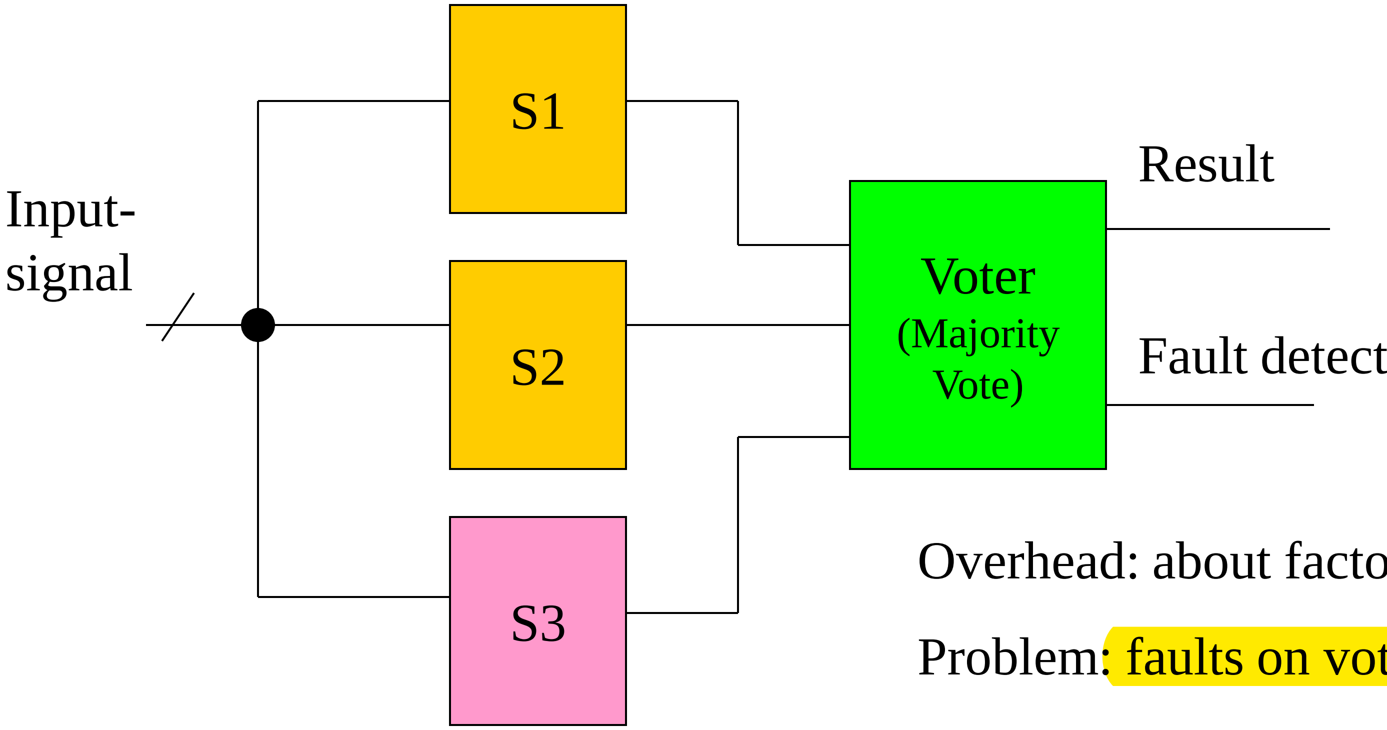
ECC error rate: 350 per minute (single bit errors)
1 per 24 hours (double bit errors)

This corresponds to one single bit error on a 1 GByte-memory about every 16 hours !

Radiation- induced „hits“ causing permanent damages were also measured, but much less frequently !

*IEEE Spectrum, March 2016, pp. 28-31

Fault Detection by Active Redundancy



Overhead: about factor 3-4

Problem: faults on voter

„Self-checking Checker“

Dependable Hardware

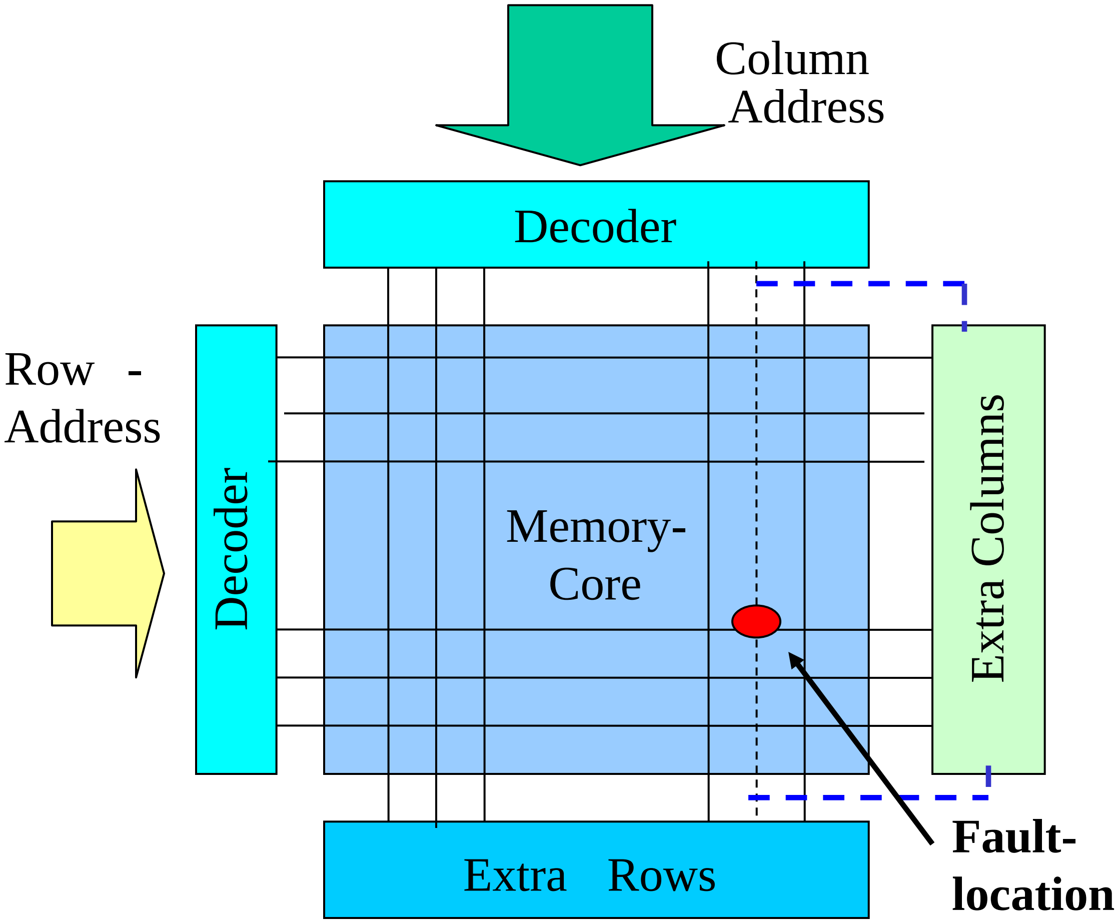
- Error detection and – compensation for transient errors in running operation. Often using code-based methods or re-execution.

  Has been the focus of related research for decades. Relatively well investigated. Requires extra hardware, often time, and always extra energy.

- Error detection and correction of permanent faults in running operation. Some stategies like re-execution fail. Requires „Built-in Self Repair"- BISR.

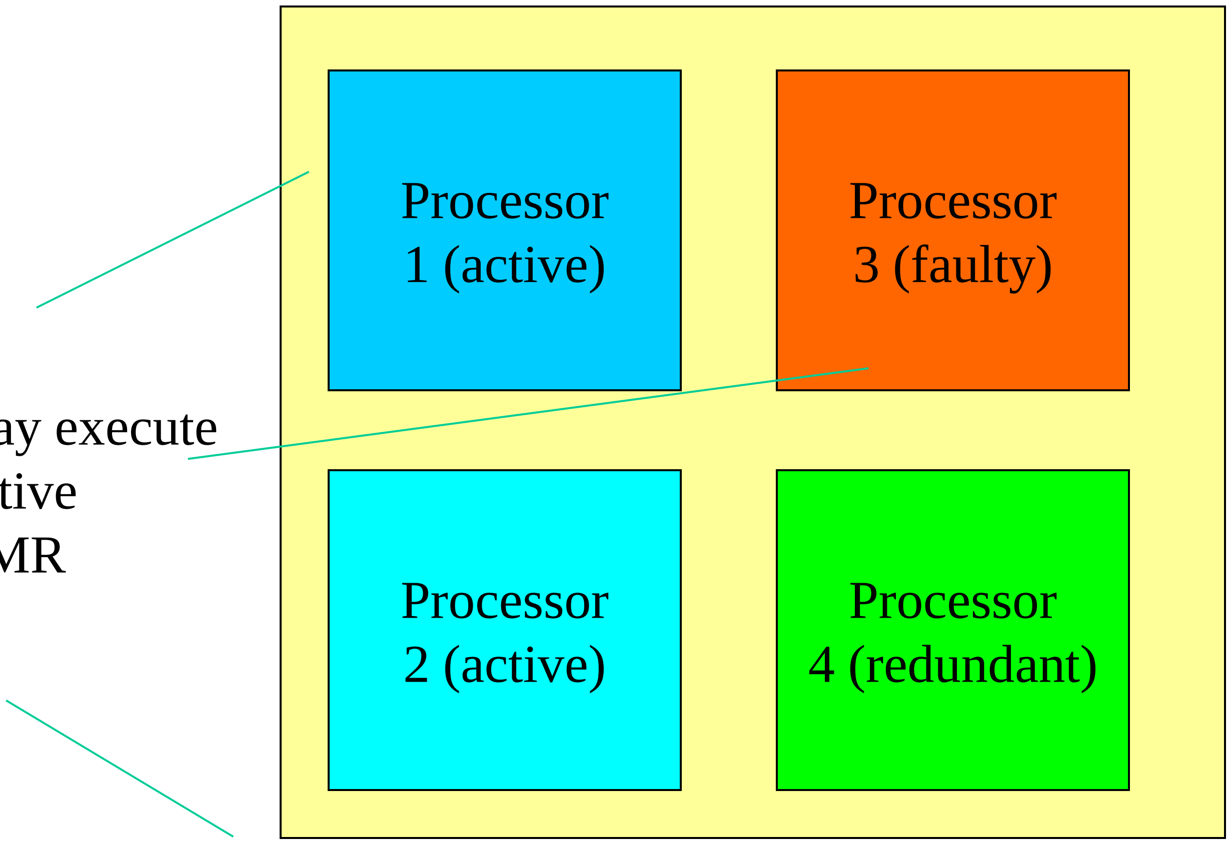
  BISR seems to work nicely for regular structures like memory blocks, Is much more difficult to apply to irregular logic.

Self Repair for Memory Blocks



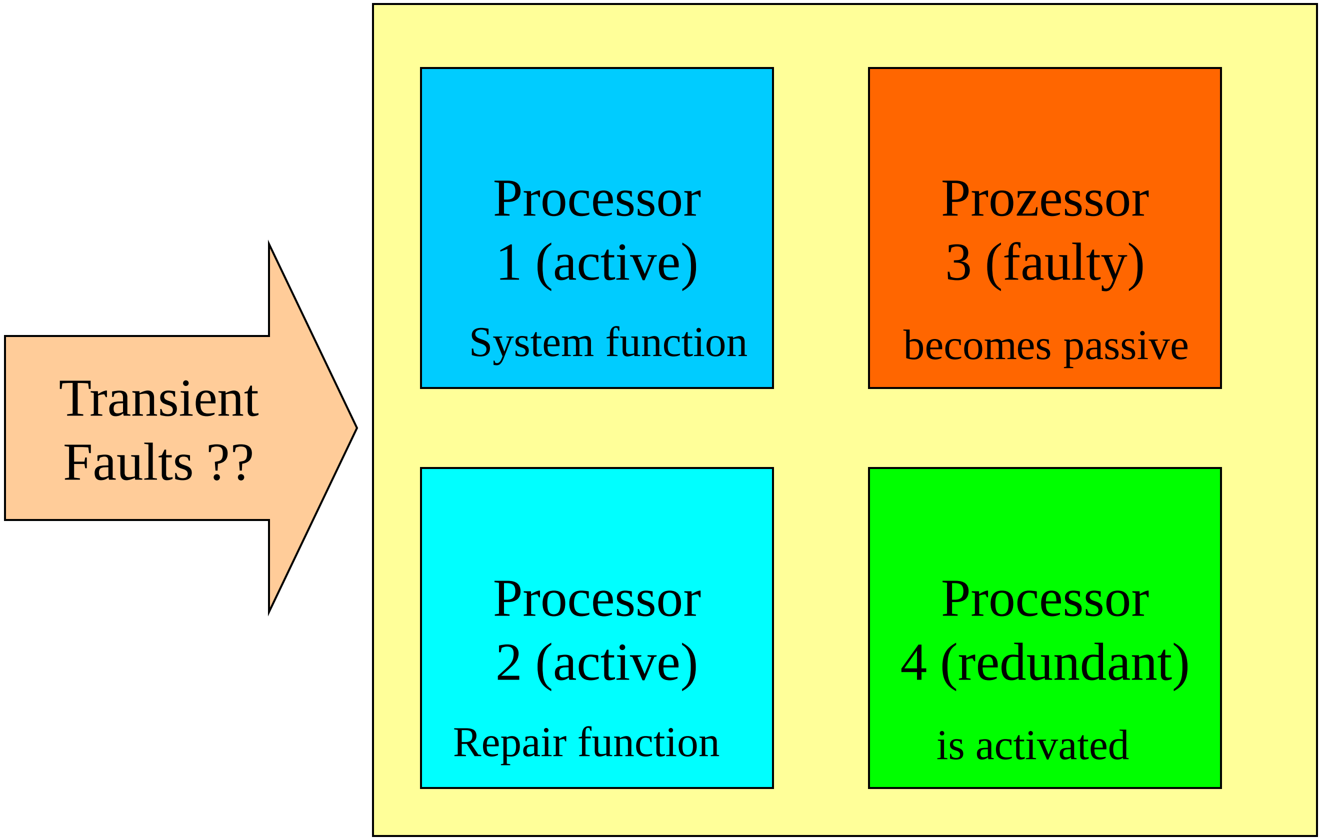
... seems to work reasonably well and is in practical use (e. g. for cashes).

Self Repair by Redundancy



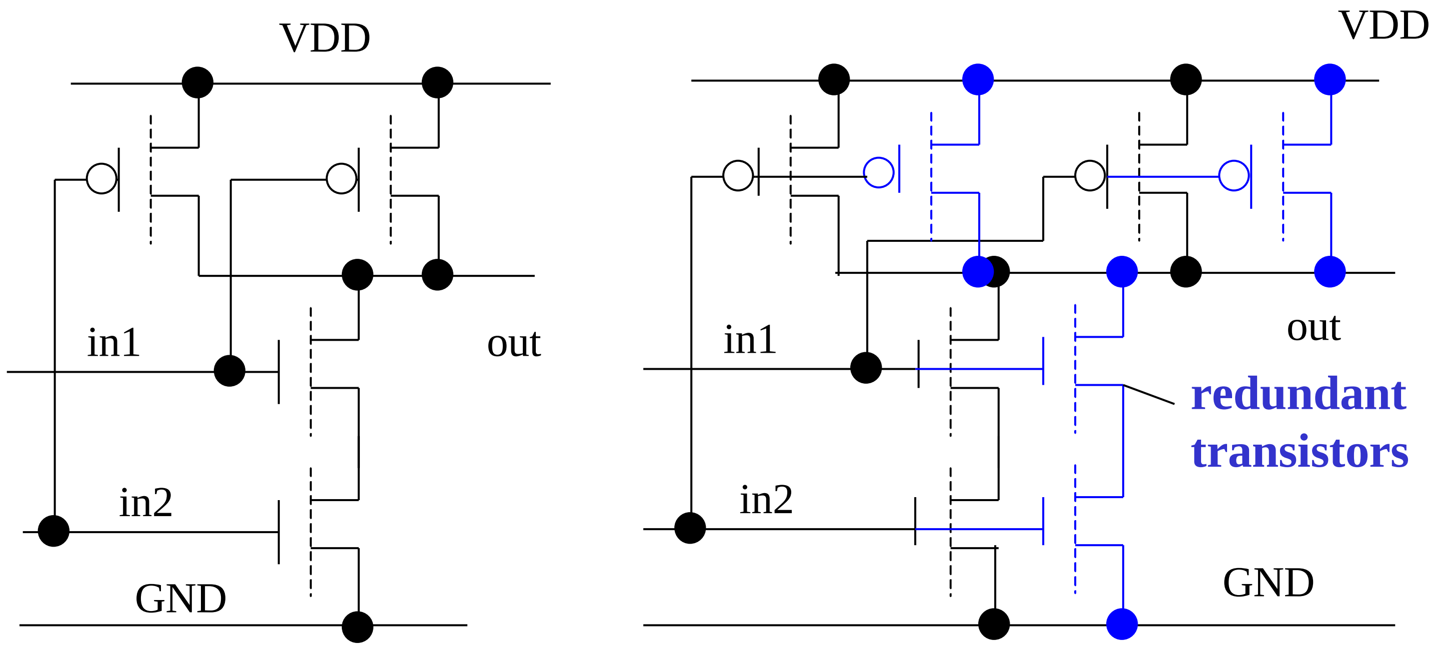
may execute
active
TMR

Coarse-Grain Self Repair



... works only as long as the supply of spare parts is not exhausted !

Fine-Grain Self Repair



Repair at the transistor level is not feasible due to the large overhead necessary to organisze the repair process.

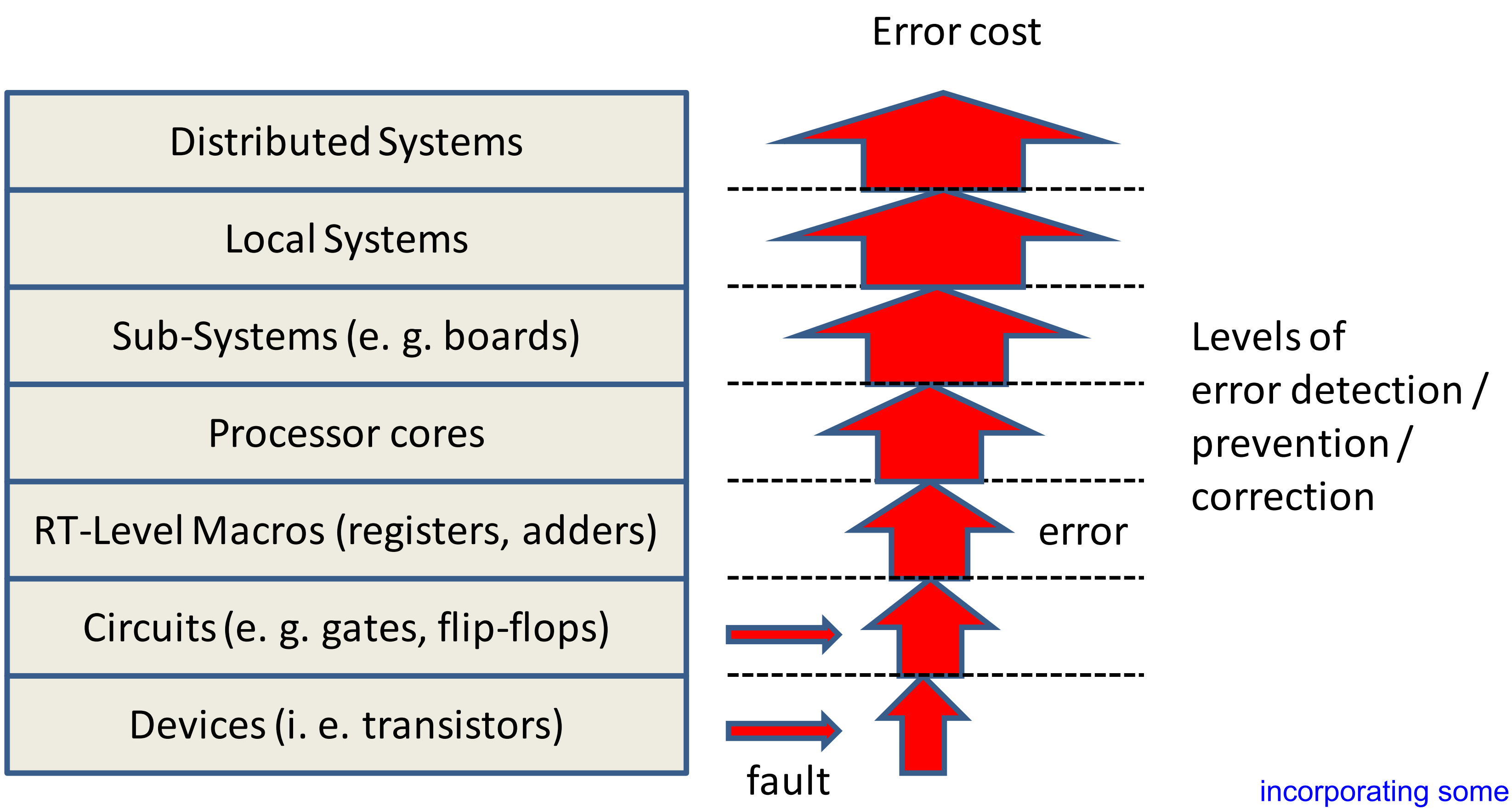
Dependable Hardware ??

- Microelectronics circuits and devices show a remarkably high level of reliability, even over a long life time (about 15 years in cars).
- Microelectronics circuits and devices based on nano-technologies with a feature size below about 30 nm may need extra care.
- Control of hardware- related faults and errors in digital circuits and systems is relatively well understood. Sensors seem to make major problems.

Hardware: P8 of 1906,
up to 60 years in service.

ICE ??

Error Resilience



incorporating some feature for automatically counteracting the effect of an anticipated possible source of failure

The real objective is to achieve „**error resilience**“ by keeping low- level / local errors from propagating to higher levels. Systems should be „fail-safe“ even under local error conditions ! *This does not necessary mean total error correction* !

Dependable Software??

Software gets „mature“ while being in use over time (Banana-Effect).

That is why parts of the software, which are rarely used (such as software for error management) are most likely to be and remain faulty!!!

At least there are new ways that show interactions in large-scale software systems (Software-Tomography).

5. Reconfigurable Systems

the living together of two dissimilar organisms in more or less intimate association or close union.

Hardware and Software make some sort of a symbiosis by (re-) programmable hardware structures such as FPGAs (field-programmable gate arrays).

This gives new opportunities on system design, but there are also new risks.

The FPGA-synthesis-software may contain bugs or Trojans!

How Softies see the World of Hardware

- Hardware always works.

  Almost correct, but only almost........

- Hardware is hard and cannot be modified.

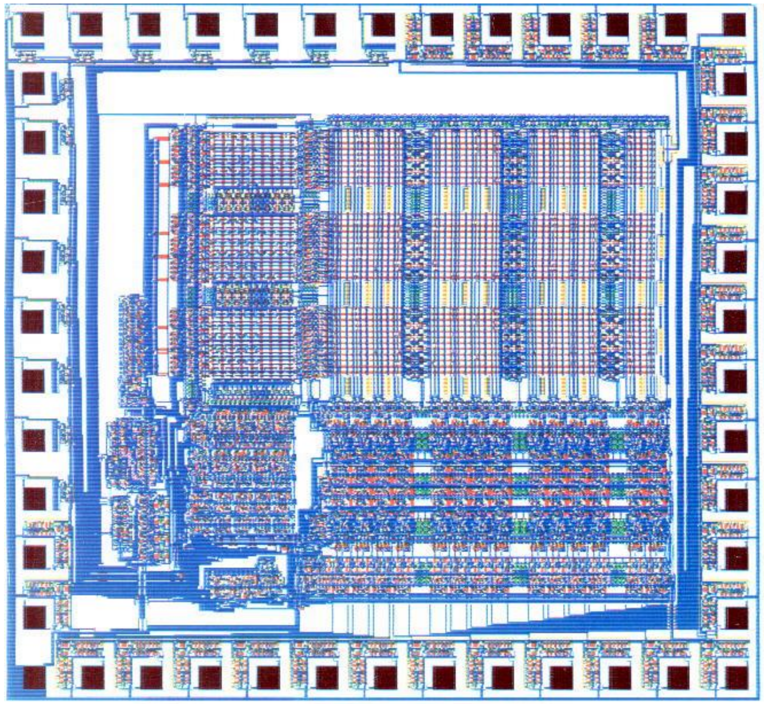
  No longer correct. Hardware may become soft.

What Softies do not see:

- Hardware can become faulty without a total breakdown. See transient faults !
- Hardware ages and does not become better when getting older (no banana effect).
- There are software-based solutions for hardware error management, but they are costly in terms of either etra hardware, power, or timing !

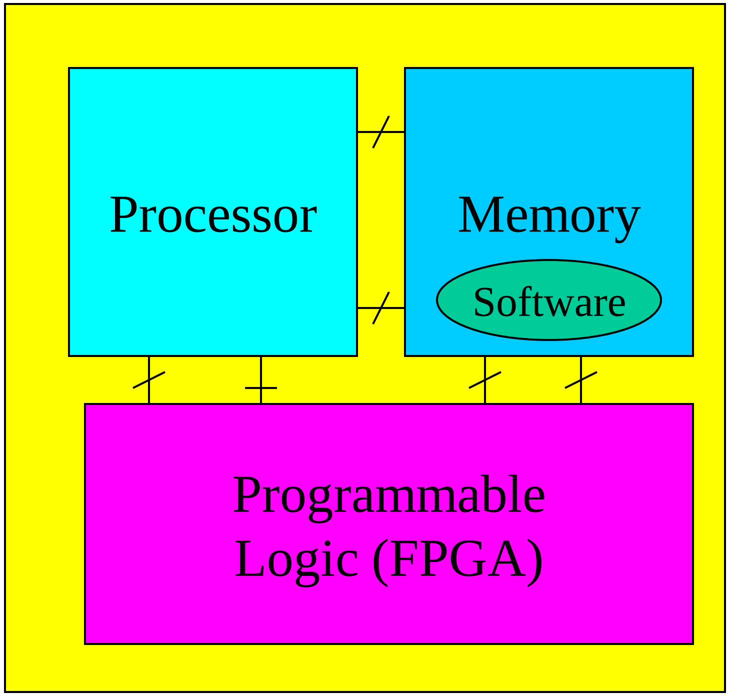
From „hard“ Chip to „soft“ FPGAs

Application specific IC (ASIC)



Function fixed!

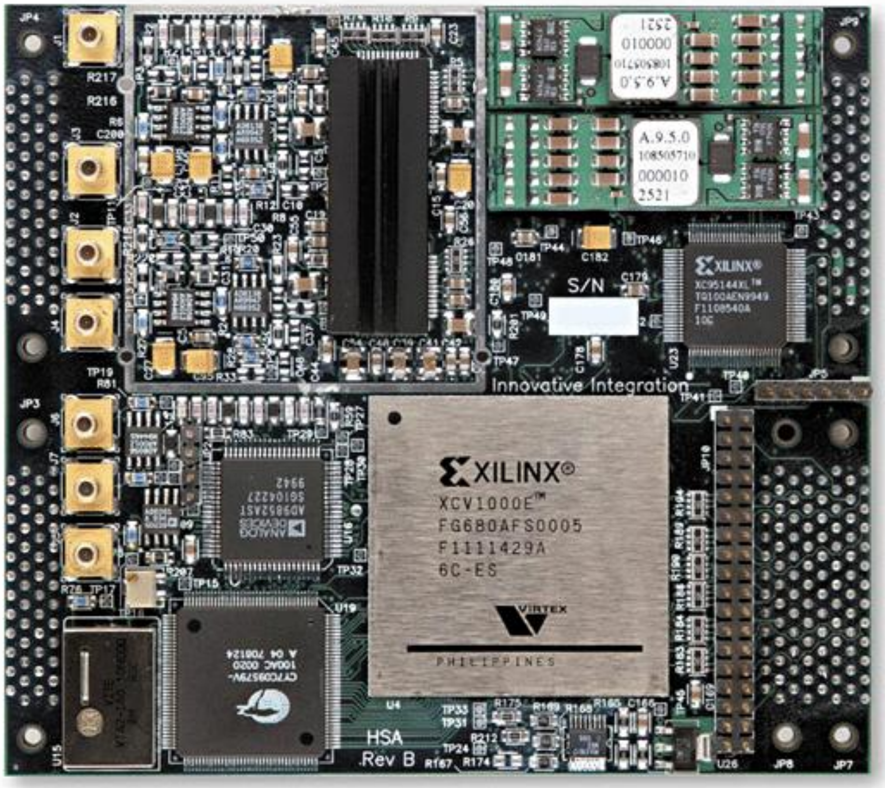
System on a Chip (SoC)



Variable (re-) configurable function!

Hardware becomes soft!

FPGA-Board


XILINX
XCV1000E
FG680AFS0005
F1111429A
6C-ES
VIRTEX
PHILIPPINES
Innovative Integration
S/N
HSA
Rev B

Reconfigurable Systems

- Instead of „solid“ logic circuits programmable (via memory cells) configurable logic units are used. The cost is larger hardware (up to a factor of 10) and lower speed (again a factor of 10) plus extra power.

- Many FPGAs of today contain „embedded“ processors fabricated in „solid“ logic. But FPGAs can also implement „soft“ processors.

- Software may be modified *at run time* depending on changing parameters & requirements. *That is often forbidden in ral life* !

- Hardware can be changed „in system“ and „at run time“ upon demand!

Software and hardware that is self-modifying upon demand is not science fiction, but reality !

Curse or Blessing??

- Systems that can perform tasks of self-reconfiguration come close to the properties of living biological systems. This is self repair or self healing, but it can also be cancer !!
- Hardware is configured by Software. But software cannot be verified formally.

→ Adventure Playground! No FPGAs e. g. in automotive control !

- Not only Software, but also Hardware becomes vulnerable against a „Computer-Virus“!
- With strict restrictions on how to modify systems, self-repair and self-healing may become an attractive property!

6. Summary

There are always tendencies and opportunities in technology,
which are prone to end in crashes ...

likely to or liable to suffer from, do, or experience something, typically something regrettable or unwelcome.

Complexity Drivers

drives

Smart phone

Computer games

Navigation systems

Audio / video

Auto (Info-Tainment)

Fashion, advertisement

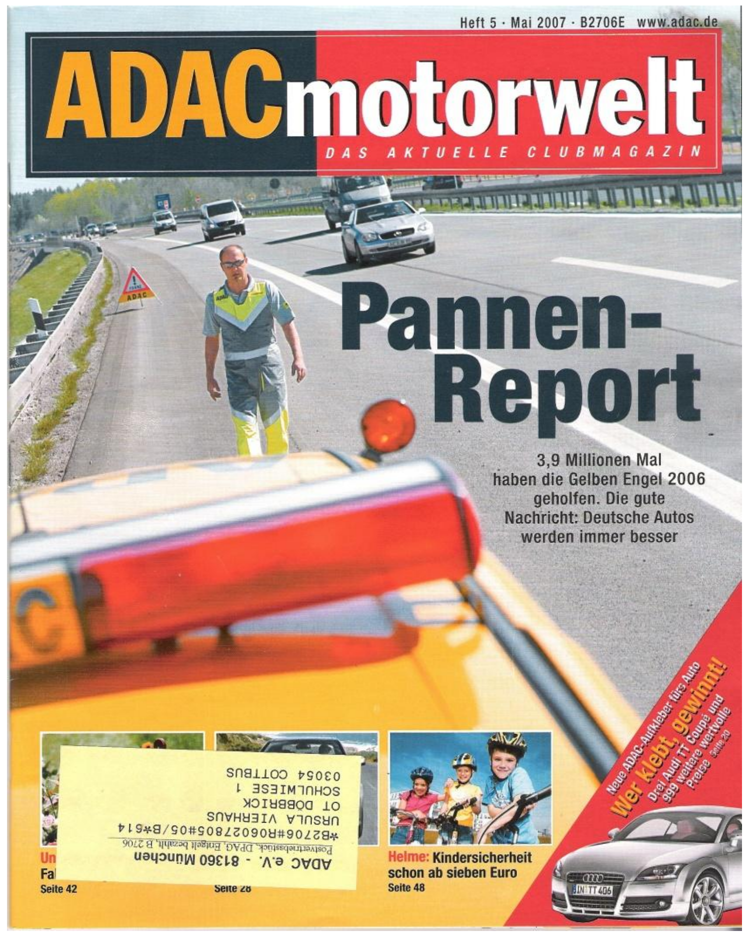
brakes

Auto-Electronics („hard“ funktions)

Control Medium ??

ADAC-Pannenreport !

The Most Powerful Medium !



ADAC Pannenhäufigkeit 2006: 87 Modellreihen im Vergleich

Unsere Tabelle zeigt, wie oft die Autos mit Erstzulassung 2001 bis 2006 im vergangenen Jahr (wegen technischer Pannen) liegen blieben. Die Zahlen geben an, wie viele Pannen auf jeweils 1000 Autos des gleichen Typs und Jahrgangs entfielen. Ausgewertet wurden Modellreihen, die mindestens drei aufeinanderfolgende Jahre prinzipiell unverändert gebaut wurden und zumindest in einem Jahr 10 000 Neuzulassungen erreichten. Fällt die Zulassungszahl in einem Jahr unter 7500, wird dieses Jahr nicht bewertet. Je niedriger der Durchschnitt der Platzziffern in den jeweiligen Jahren ist, um so weiter vorne liegt das Fahrzeugmodell im Gesamtergebnis. Die farbige Bewertung von Grün (= zuverlässig) bis Rot (= unzuverlässig) ergibt sich aus der Spanne der Pannenzahlen des jeweiligen Jahres in der Fahrzeugklasse, für jedes Zulassungsjahr wird also eine individuelle Rangfolge erstellt. Die unterschiedlichen durchschnittlichen Laufleistungen der einzelnen Modellreihen innerhalb der Fahrzeugklassen werden durch einen entsprechenden Bonus-/Malusfaktor ausgeglichen, wobei einkalkuliert ist, dass nur ein Teil der Pannen durch die Laufleistung beeinflusst wird.

Platz/Modell Erstzulassung:	2001	2002	2003	2004	2005	2006
Kleine Klasse						
1 Audi A2	12,2	12,3	8,3	5,1	2,2	
2 BMW Mini		12,3	7,7	4,9	2,6	2,0
3 Renault Modus				5,8	3,1	3,2
4 VW Lupo	23,4	17,4	13,3	8,6		
5 VW Polo	22,0	23,8	13,6	8,3	5,1	3,0
6 Toyota Yaris, Yaris Verso	15,1	11,6	11,2	6,9	6,1	7,5
7 Honda Jazz			9,3	7,8	5,5	3,4
8 Opel Corsa	27,8	24,6	13,8	8,8	5,7	2,2
8 Renault Twingo	37,7	26,7	16,8	6,7	4,3	2,6
10 Smart Forfour				9,6	6,3	0,9
11 Fiat Panda (neu)				8,4	4,1	5,6
12 Seat Ibiza/Cordoba	27,6	27,7	15,9	7,3	5,4	12,6
13 Ford Fiesta	16,4	16,3	15,9	10,7	9,0	6,0
13 Renault Clio	55,9	39,1	22,9	10,0	4,3	2,1
15 Skoda Fabia	26,6	24,9	16,0	9,8	7,4	3,7
16 Peugeot 206	37,2	25,7	19,9	10,0	6,6	2,9
17 Nissan Micra	25,8	20,2	26,1	18,0	9,9	1,5
18 Citroën C3			21,3	13,4	5,7	2,4
19 Citroën C2				13,8	5,7	2,6
20 Smart Fortwo	41,3	35,9	30,6	13,5	6,0	1,7
21 Fiat Punto	52,5	51,3	25,1	12,0	7,1	1,6
22 Ford Ka/Streetka	11,5	10,9	20,0	22,0	14,6	8,8
23 Mazda 2			15,4	12,6	8,0	3,4
24 Hyundai Getz			18,7	14,4	10,7	8,0
25 Kia Picanto				11,3	11,5	9,1
Untere Mittelklasse						
1 BMW 1er				4,5	3,0	1,6
2 Mazda 3				5,6	3,8	1,9
3 Audi A3	23,6	19,0	12,7	5,2	3,0	1,6
4 VW Golf/Bora	23,2	17,6	11,8	7,2	4,9	4,0
5 VW New Beetle			13,1	7,2	5,3	
6 Toyota Corolla, Corolla Verso	28,6	11,2	9,8	7,8	6,2	8,0
7 Mercedes A-Klasse	37,0	21,5	14,7	8,6	3,9	2,5
8 Seat Leon/Toledo	23,2	22,1	11,7	9,4	5,2	8,0
9 Honda Civic	18,3	17,8	15,9	8,9	8,5	8,1
10 Ford Focus	18,7	16,9	15,1	11,9	12,2	4,8
11 Citroën Xsara/Xsara Picasso	36,6	24,3	16,2	10,3	5,2	8,1
11 Opel Astra	32,5	29,9	17,7	13,3	5,4	3,7
13 Nissan Almera/Almera Tino	22,4	21,2	20,1	16,2	11,4	
14 Peugeot 307	52,2	34,5	23,9	9,9	7,7	3,0
15 Renault Mégane	53,6	60,1	41,6	11,1	5,1	4,4
16 Fiat Stilo		47,3	38,5	22,2		
Mittelklasse						
1 Audi A4	20,4	12,0	7,7	5,2	4,0	2,8
2 Mercedes C-Klasse	23,2	13,6	8,1	4,0	1,9	2,8
3 BMW 3er	18,9	17,1	12,1	6,5	3,1	2,6
4 VW Passat	19,9	14,7	10,6	7,9	5,4	4,3

Platz/Modell Erstzulassung:	2001	2002	2003	2004	2005	2006
Mittelklasse						
5 Mazda 6		12,7	10,7	8,2	5,5	4,0
6 Skoda Octavia	20,2	17,4	12,5	6,8	8,0	6,1
7 Toyota Avensis, Aven.Verso	23,3	16,8	12,3	9,2	8,4	7,1
8 Peugeot 407				10,3	6,6	6,3
9 Ford Mondeo	21,9	23,5	21,6	13,6	9,3	5,1
10 Nissan Primera	21,9	26,7	32,3			
11 Opel Vectra	34,1	30,5	26,0	18,4	7,9	3,2
12 Volvo S40/V40/V50	24,2	21,7	18,3	15,4	12,3	5,2
13 Renault Laguna	58,8	61,3	41,0	19,0	7,6	4,7
Obere Mittelklasse/Oberklasse						
1 Audi A6	28,4	21,3	14,9	6,1	3,4	2,3
2 Mercedes E-Klasse	41,2	24,8	11,5	5,5	3,4	3,2
3 BMW 5er	39,7	31,9	18,0	7,6	4,4	2,7
4 Opel Signum			34,8	21,6	8,6	1,0
5 Volvo S60/S70/S80/V70	36,4	27,0	20,4	11,6	12,9	8,0
Sportwagen/Cabrios						
1 Mercedes CLK	31,6	15,3	7,3	2,8	2,3	1,8
2 BMW 3er Cabrio	13,1	8,7	8,4	5,0		
3 Mercedes SLK	22,9	18,6	12,1	3,9	2,5	1,2
4 Peugeot 206 CC	34,0	27,3	16,1	8,6	5,5	2,9
Geländewagen						
1 BMW X3				3,1	1,8	1,2
2 Mercedes ML	27,8	20,7	13,6	6,8	3,5	2,0
3 Toyota RAV4	25,4	16,9	13,5	9,4	5,9	3,1
4 BMW X5			18,7	6,8	5,6	
5 VW Touareg				7,1	4,5	3,2
6 Nissan X-TRAIL			13,2	9,7	7,8	3,6
Kleine Vans						
1 Mazda Premacy	23,0	16,3	9,02			
1 Mitsubishi Space Star	14,9	15,0	12,4	9,2		
3 VW Touran			13,7	10,2	7,2	3,3
4 VW Caddy				14,1	8,5	2,5
5 Ford Fusion			20,5	10,3	8,0	5,7
5 Seat Altea				10,7	8,5	5,0
7 Opel Agila	33,5	28,9	24,2	17,1		
7 Opel Meriva			13,9	9,7	11,0	5,7
9 Renault Scénic	53,3	50,4	43,5	17,9	6,0	2,5
10 Opel Zafira	35,1	32,8	22,7	14,9	12,0	5,6
11 Citroën Berlingo	51,1	39,0	26,0	18,1	9,3	5,8
12 Renault Kangoo	77,9	56,8	37,1	21,5	11,1	3,5
13 Ford C-Max				18,3	13,3	6,3
Große Vans						
1 VW Sharan	35,7	30,1	24,3	13,8	8,3	6,2
2 VW T4/T5	34,6	29,8	26,7	22,3	15,4	4,9
3 Fiat Ducato	35,4	35,2	32,0	21,1	13,4	3,3
3 Mercedes Vito/Viano	59,7	33,5	27,2	19,1	11,6	6,0
5 Ford Galaxy	47,8	44,5	32,0	23,3	11,4	9,6

Und what about the Future ??

Unreliable hardware / software may give a lot of fun sometimes..
.. But you depend on the rescue helicopter, and that one needs to be dependable at least !