Embedded Computing Systems in the Multi-Core Era

Wolfgang Schröder-Preikschat

Background

multi/many-core systems
(since 2008)

uni-processor systems
(1981-1986)

embedded & real-time systems
(since 1995)

multi-processor systems
(1986-1995)

Background

Sparc LEON
IA-32/64

MCS6502
M6800 & M6809
PDP 11/40e
TMS9900
IBM PC

AVR
HC08
C167
MPC60x
TC1796 (AUDO)
TC277T (AURIX)

320 node M68020- &
16 node (dual CPU)
i860-based machines

Leitmotif

- embedded $\triangleq$ parallel: corresponds to
  - embedded system as epitome of concurrent operation

- parallel $\sim$ embedded: similar to
  - parallel system as epitome of power guzzler
  - and being sensitive to jitter

Outline

✔ prologue

- stock taking
  - embedded computing system
- multi-core as reference point
  - embedded ≘ parallel
  - ~~parallel ⊇ embedded~~
- epilogue

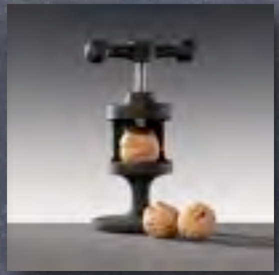
Embedded Computing System

Embedded system

- a microprocessor-based system
- that is built to control a function or range of functions and
- is not designed to be programmed by the end user in the same way that a PC is

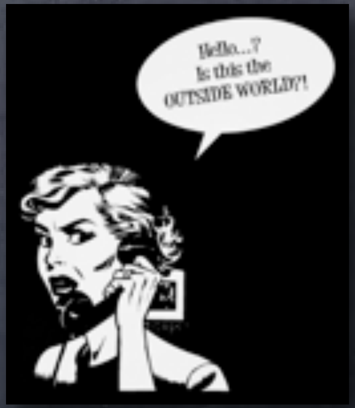
(Heath, Embedded Systems Design, 1997)

Embedded system



- is designed to perform one particular task
- albeit with choices and different options
- has to communicate with the outside world
  - done by [a zoo of] peripherals

(Heath, Embedded Systems Design, 1997)

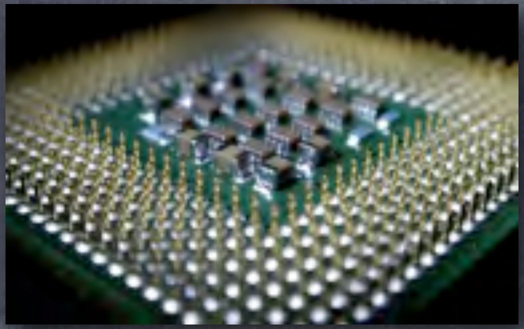


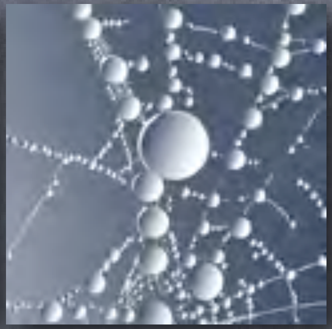
Embedded system

- any computer system hidden inside a product
- other than a computer

(Simon, An Embedded Software Primer, 1999)

Embedded systems





- have a microprocessor and a memory
- some have a serial port and a network connection
- they usually don't have keyboards, screens, or disk drives

(Simon, An Embedded Software Primer, 1999)

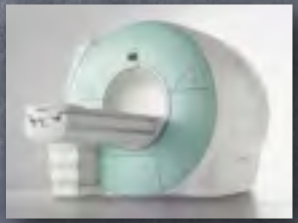
An exception that proves the rule…

Embedded system

- a computer system with a dedicated function
- within a larger mechanical or electrical system
- often with real-time computing constraints

(Wikipedia, 2013)

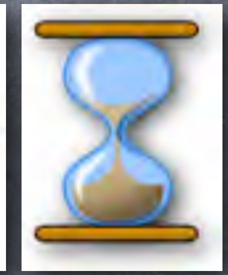
Embedded system



- range from portable devices
  - such as digital watches and MP3 players
- to large stationary installations
  - like traffic lights, factory controllers
- and large complex systems
  - e.g. hybrid vehicles, MRI, and avionics

(Wikipedia, 2013)

Embedded systems



- often have several things to do at once
  - they must respond to external events
  - their work is subject so deadlines
  - they must cope with all unusual conditions without human intervention

(Simon, An Embedded Software Primer, 1999)

An exception that proves the rule...

X

Extremes meet

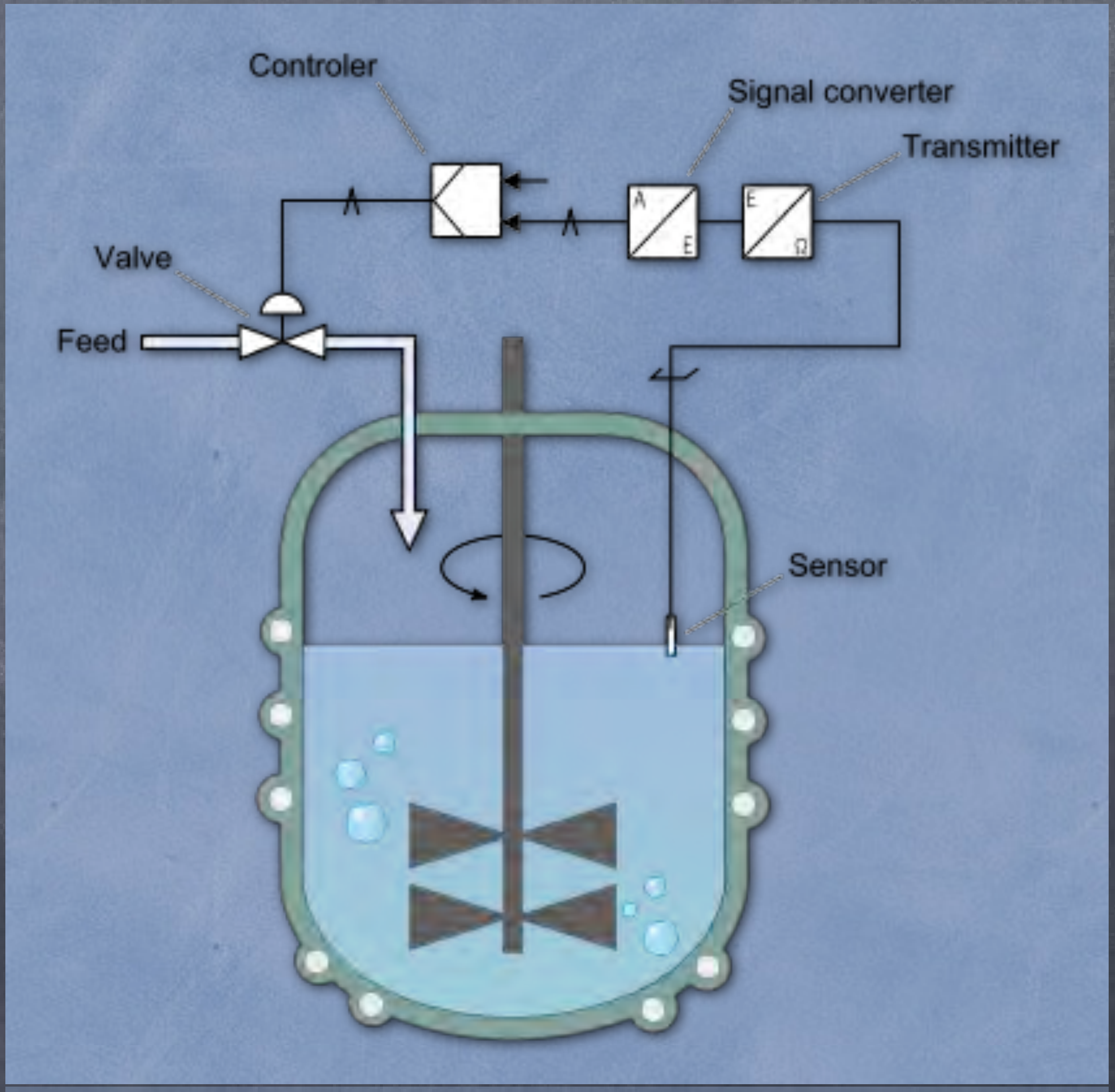
mass product	custom-built machinery
small appliance	giant equipment
resource shortage	needs-based design
best effort	dependable
non-/soft real-time	firm/hard real-time
planned obsolescence	non-stop operation

Embedded $\stackrel{\frown}{=}$ Parallel

Simultaneous operation

stirred-tank reactor

- functional units
  - sensor system
  - specific processing
  - actuating elements
- mixed mode
  - periodic
  - aperiodic/sporadic



Simultaneous operation

personal trainer

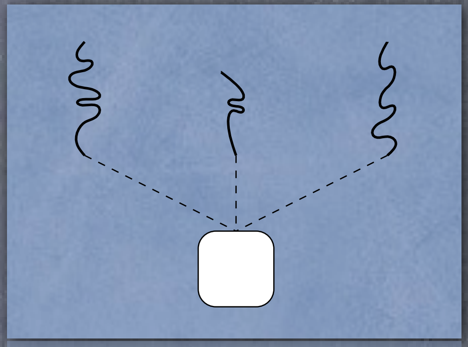
- functional units
  - sensor system
  - specific processing
  - actuating elements
- mixed mode
  - periodic
  - aperiodic~~/sporadic~~

Latent concurrency

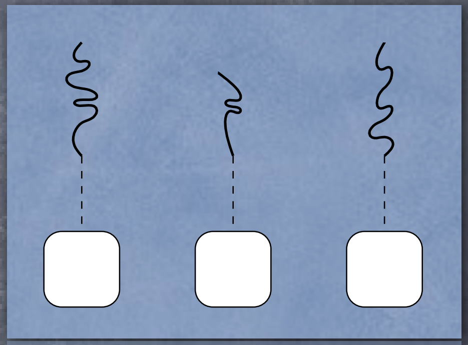
- not because of internal constraints such as to improve system utilisation but...
- induced by the characteristics of the actual object to be monitored or controlled
- positioned through hardware features used to interact with the external process and
- reflected by the logical structure of the corresponding internal process

Mix of parallelism: pseudo and real

- hardware multiplexing (CTSS, 1961)*
  - processing unit
  - address space, if applicable



- hardware multiplication (B5000, 1961)
  - processing unit, at least



- partitioning in time or space, respectively

*a.k.a. partial virtualisation

Bottom line

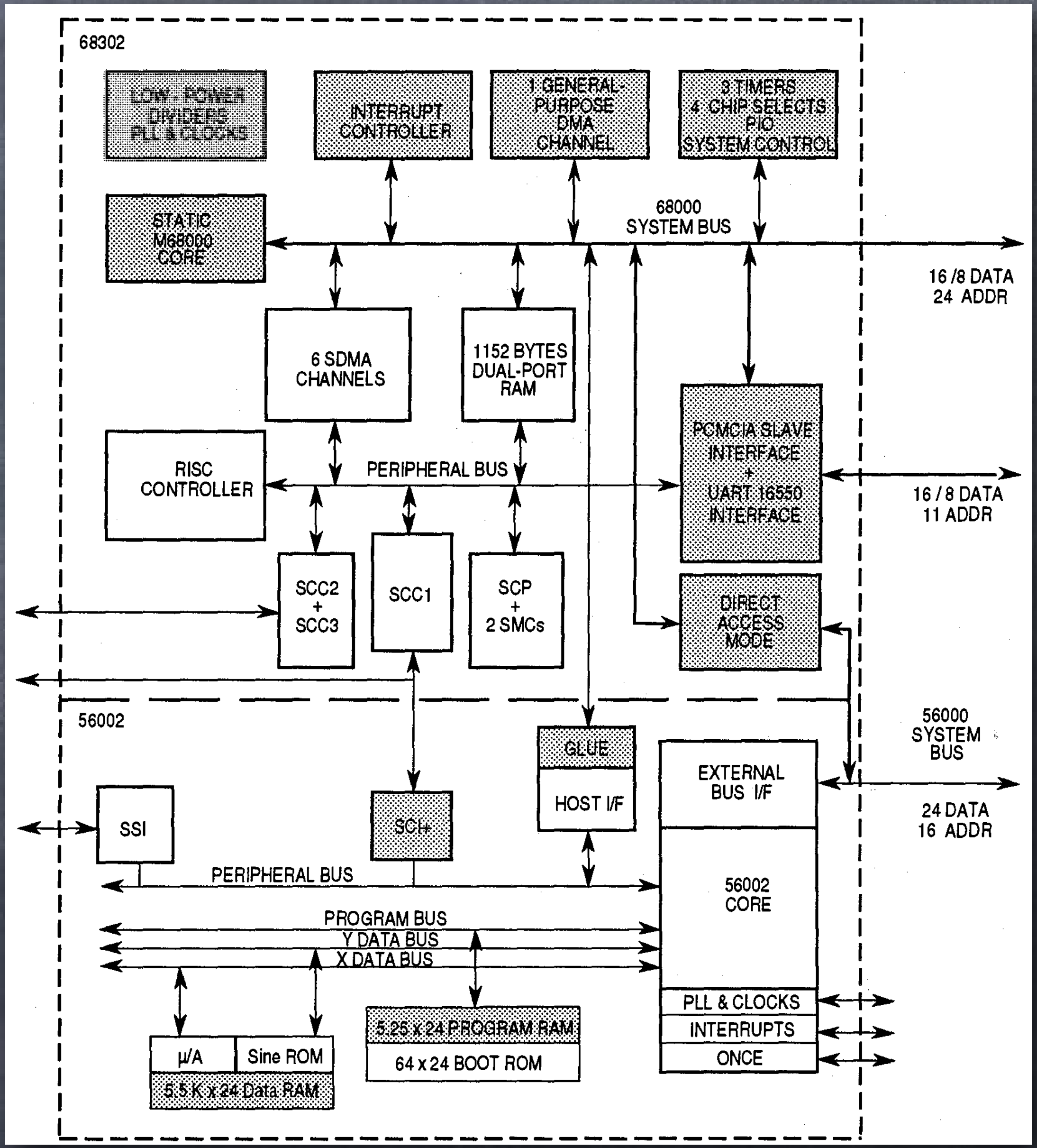
- for embedded computing systems, multi-core technology is an implication

- „free lunch" never was an option in that domain — and never will be
  - but the „menu" shows an even greater selection

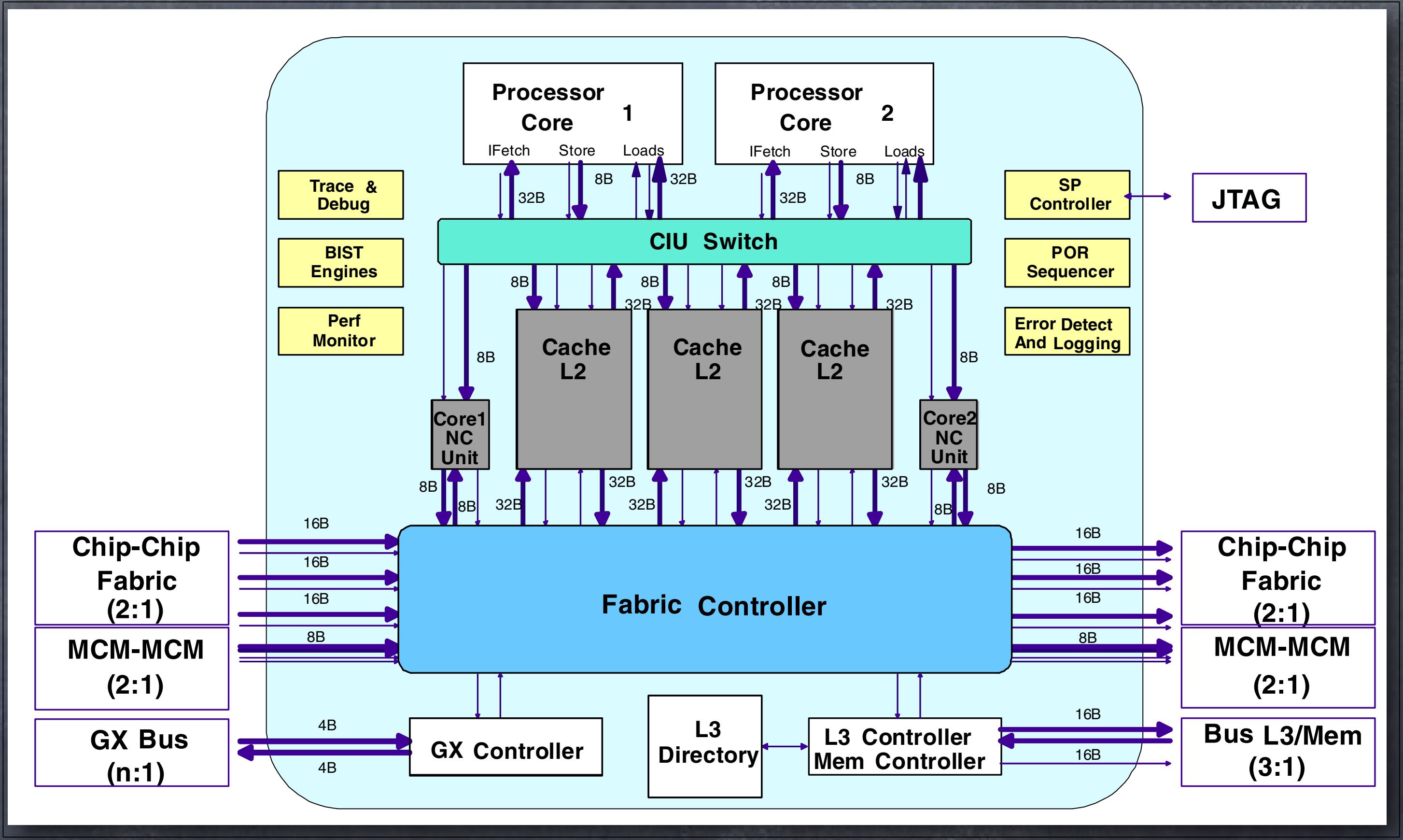
Multi-core roots

MC68356, 1994

- first embedded triple-core
  - CISC (MC68302)
  - RISC (CP, 16550)
  - DSP (MC56002)
- heterogeneous



Multi-core roots



POWER4, 2001

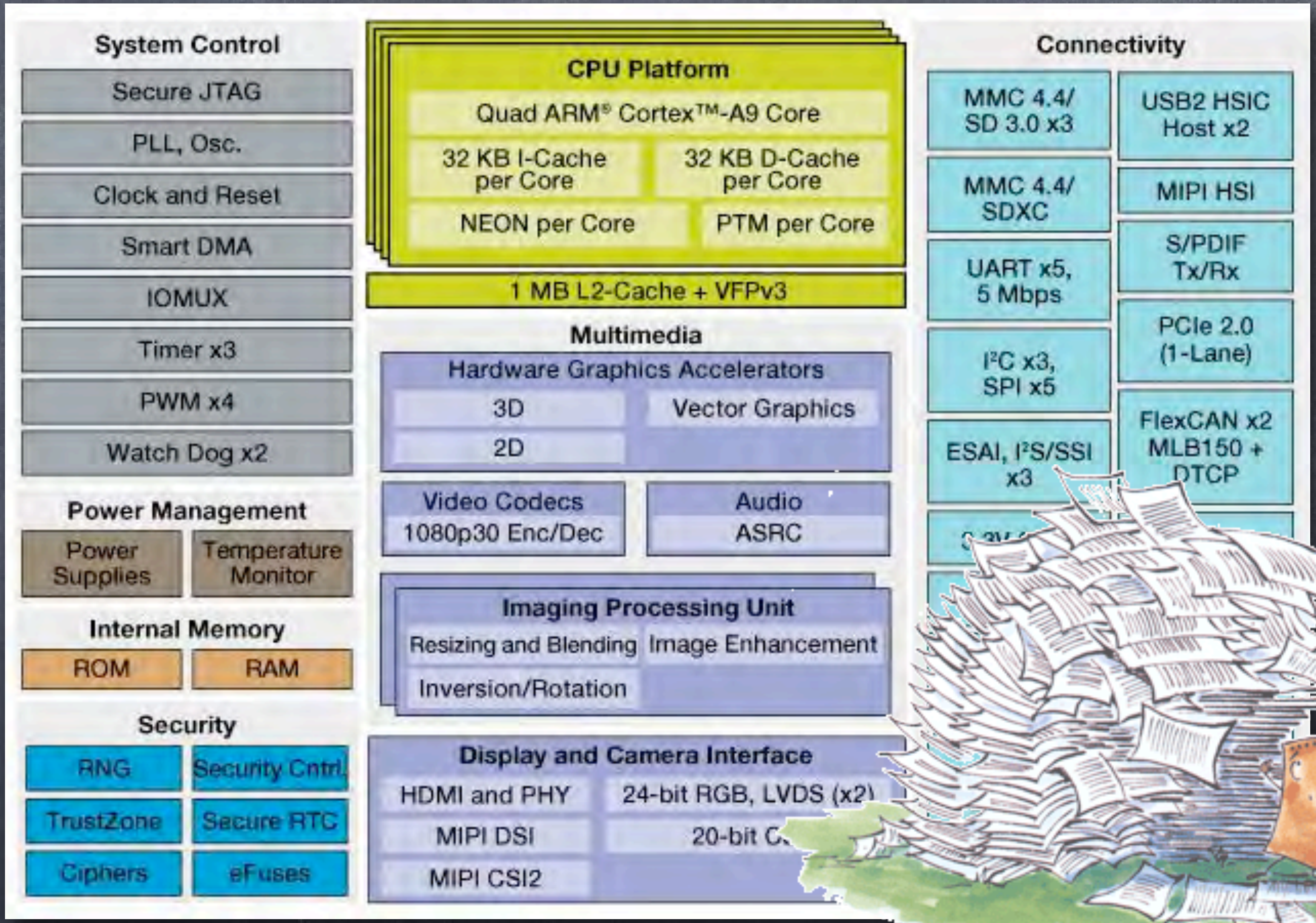
- first non-embedded dual-core, homogeneous

Being brought back down to earth…

- parallelism is challenging, but not the real problem in embedded systems
  - and so is multi-core
- much more challenging is the handling of the multitude of different functional units
  - system control, power management
  - security, multimedia, connectivity, …

Concrete example

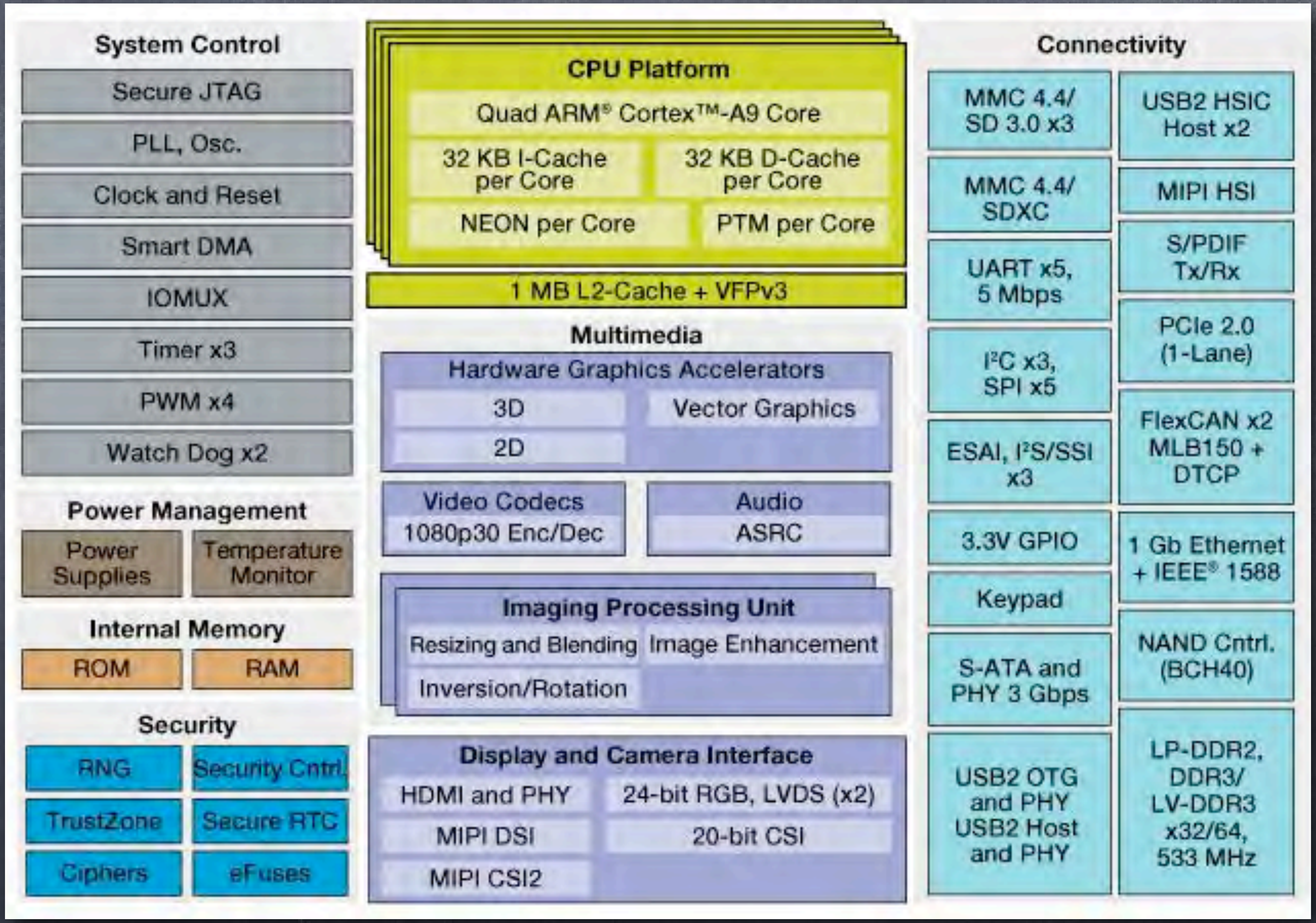
– thousands of manual pages, excl. CPU –



Multi-core/processor

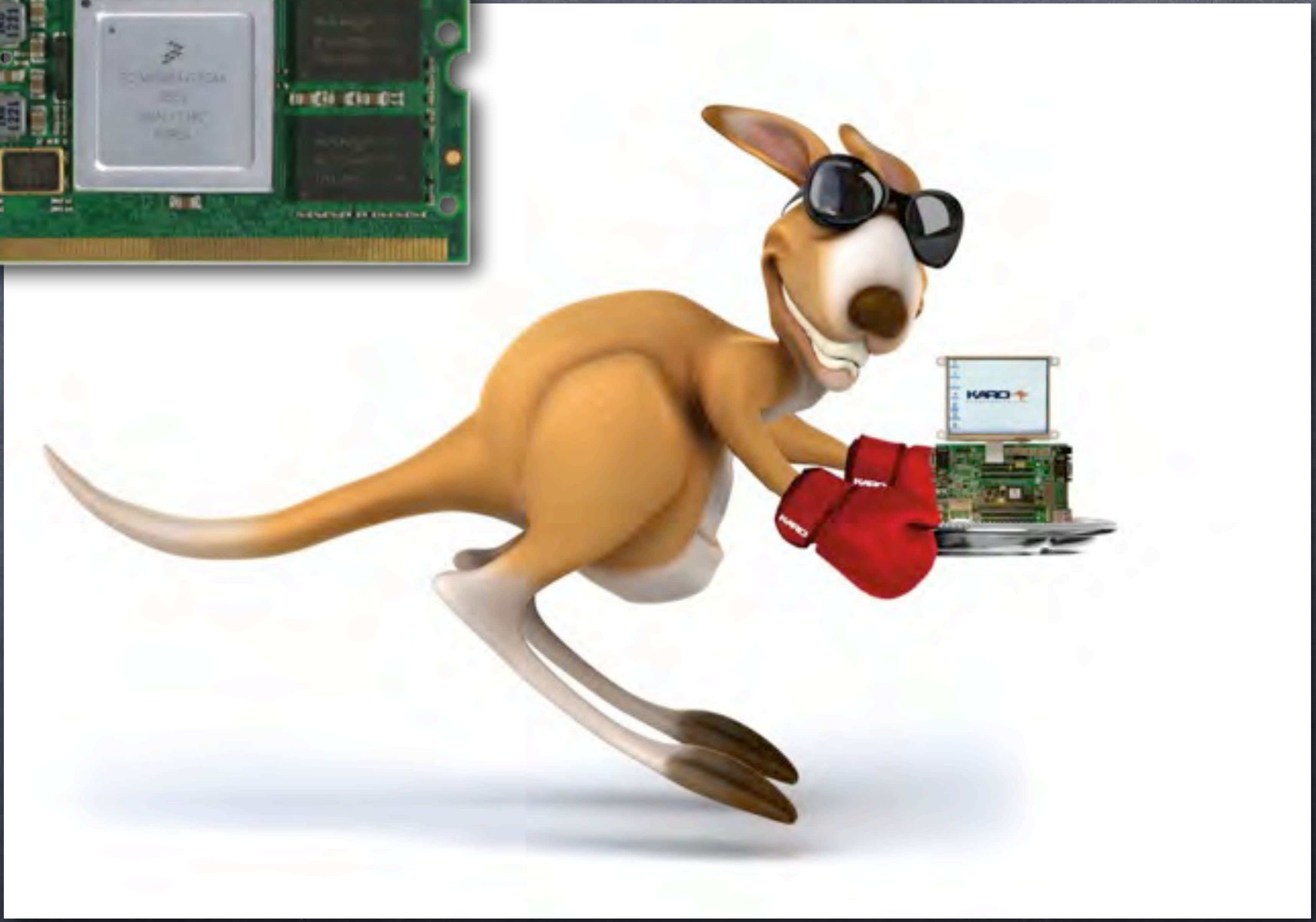
System on chip

(MPSoC)

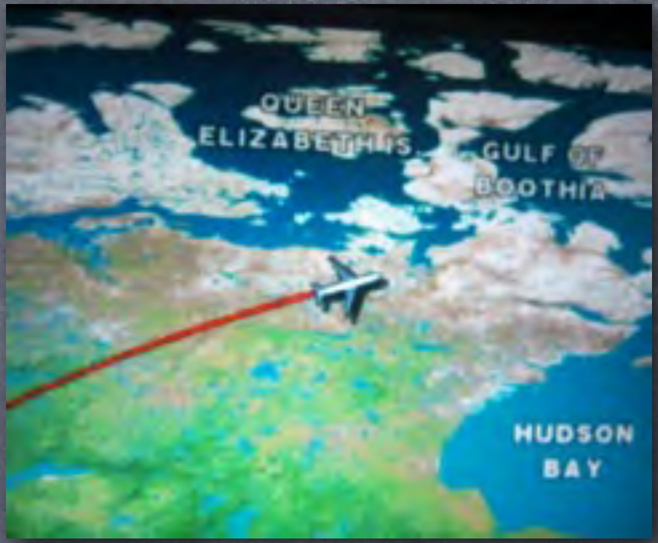


i.MX6

System on module



System in field



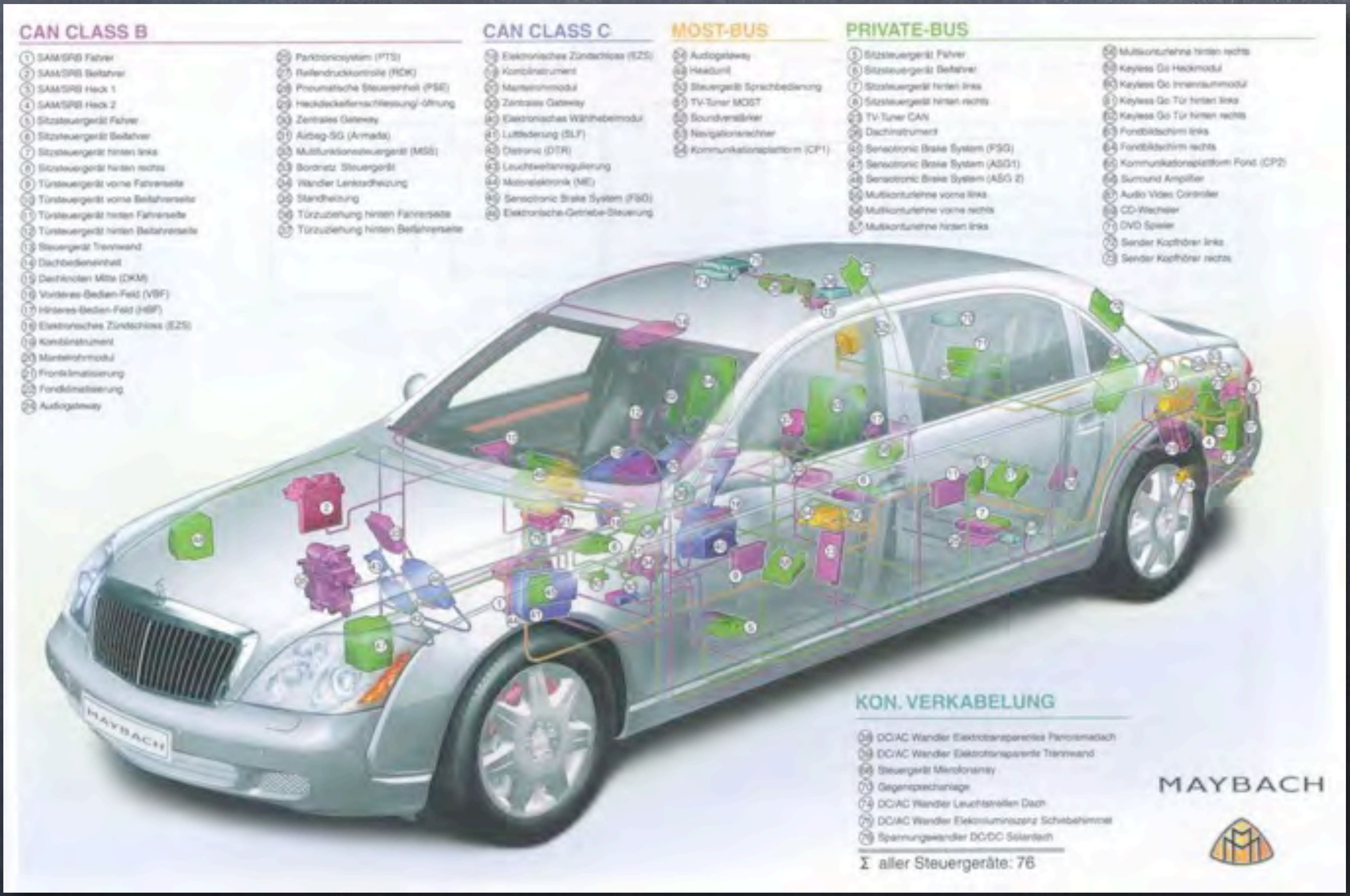
System in field

Favourite plaything

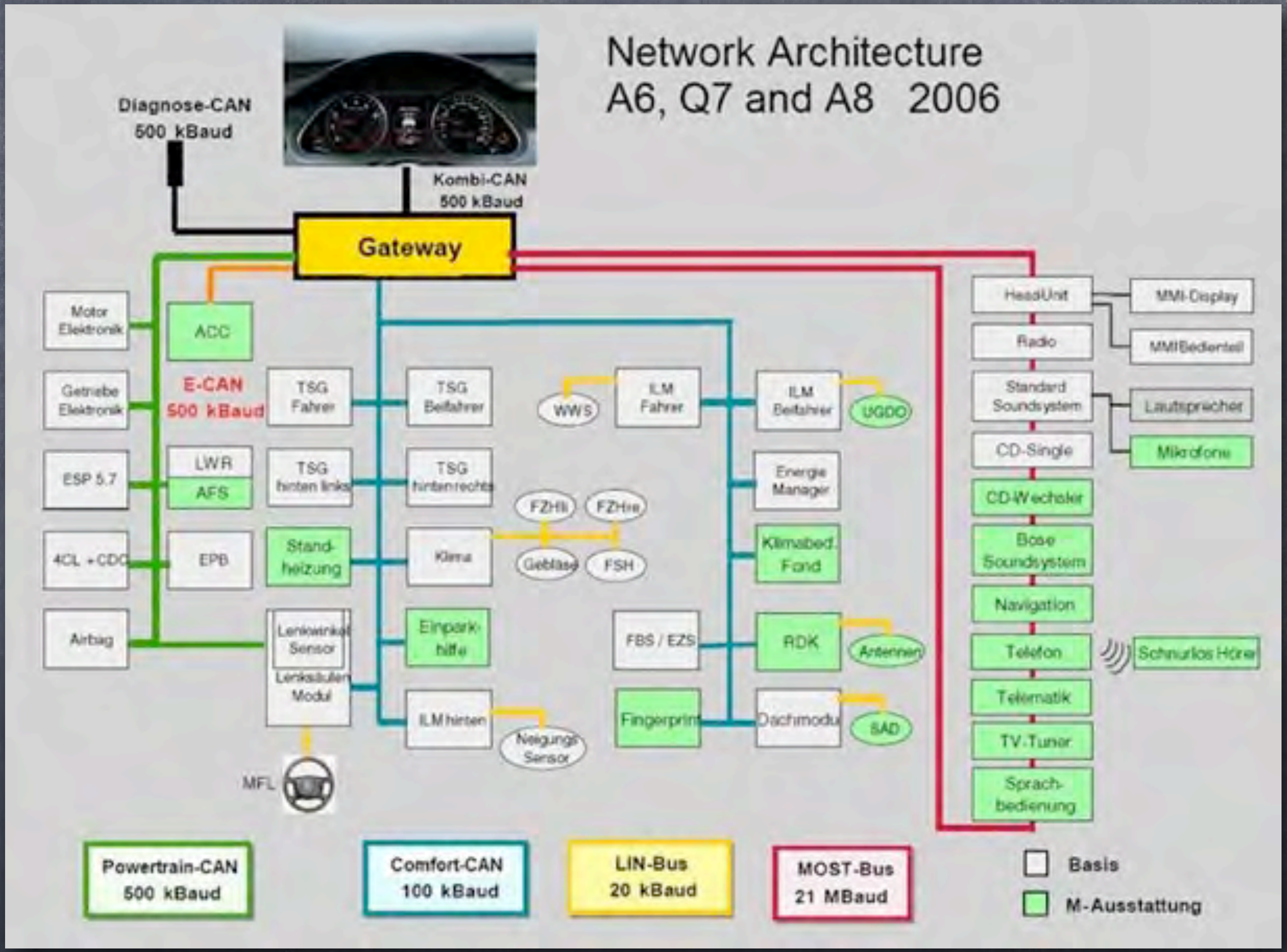
Rolling embedded system

Intranet on wheels

– but not for much longer –


CAN CLASS B
1 SAM/SRB Fahrer
2 SAM/SRB Beifahrer
3 SAM/SRB Heck 1
4 SAM/SRB Heck 2
5 Sitzsteuergerät Fahrer
6 Sitzsteuergerät Beifahrer
7 Sitzsteuergerät hinten links
8 Sitzsteuergerät hinten rechts
9 Türsteuergerät vorne Fahrerseite
10 Türsteuergerät vorne Beifahrerseite
11 Türsteuergerät hinten Fahrerseite
12 Türsteuergerät hinten Beifahrerseite
13 Steuergerät Trennwand
14 Dachbedieneinheit
15 Dachknoten Mitte (DKM)
16 Vorderes-Bedien-Feld (VBF)
17 Hinteres-Bedien-Feld (HBF)
18 Elektronisches Zündschloss (EZS)
19 Kombiinstrument
20 Mantelrohrmodul
21 Frontklimatisierung
22 Fondklimatisierung
24 Audiogateway
26 Parktronicsystem (PTS)
27 Reifendruckkontrolle (RDK)
28 Pneumatische Steuereinheit (PSE)
29 Heckdeckelfernschliessung/-öffnung
30 Zentrales Gateway
31 Airbag-SG (Armada)
32 Multifunktionssteuergerät (MSS)
33 Bordnetz Steuergerät
34 Wandler Lenkradheizung
35 Standheizung
36 Türzuziehung hinten Fahrerseite
37 Türzuziehung hinten Beifahrerseite
CAN CLASS C
18 Elektronisches Zündschloss (EZS)
19 Kombiinstrument
20 Mantelrohrmodul
30 Zentrales Gateway
40 Elektronisches Wählhebelmodul
41 Luftfederung (SLF)
42 Distronic (DTR)
43 Leuchtweitenregulierung
44 Motorelektronik (ME)
45 Sensotronic Brake System (FSG)
46 Elektronische-Getriebe-Steuerung
MOST-BUS
24 Audiogateway
49 Headunit
50 Steuergerät Sprachbedienung
51 TV-Tuner MOST
52 Soundverstärker
53 Navigationsrechner
54 Kommunikationsplattform (CP1)
PRIVATE-BUS
5 Sitzsteuergerät Fahrer
6 Sitzsteuergerät Beifahrer
7 Sitzsteuergerät hinten links
8 Sitzsteuergerät hinten rechts
23 TV-Tuner CAN
25 Dachinstrument
45 Sensotronic Brake System (FSG)
47 Sensotronic Brake System (ASG1)
48 Sensotronic Brake System (ASG 2)
55 Multikonturlehne vorne links
56 Multikonturlehne vorne rechts
57 Multikonturlehne hinten links
58 Multikonturlehne hinten rechts
59 Keyless Go Heckmodul
60 Keyless Go Innenraummodul
61 Keyless Go Tür hinten links
62 Keyless Go Tür hinten rechts
63 Fondbildschirm links
64 Fondbildschirm rechts
65 Kommunikationsplattform Fond (CP2)
66 Surround Amplifier
67 Audio Video Controller
68 CD-Wechsler
71 DVD Spieler
72 Sender Kopfhörer links
73 Sender Kopfhörer rechts
KON. VERKABELUNG
38 DC/AC Wandler Elektrotransparentes Panoramadach
39 DC/AC Wandler Elektrotransparente Trennwand
69 Steuergerät Mikrofonarray
70 Gegensprechanlage
74 DC/AC Wandler Leuchtstellen Dach
75 DC/AC Wandler Elektrolumineszenz Schiebehimmel
76 Spannungswandler DC/DC Solardach
Σ aller Steuergeräte: 76
MAYBACH

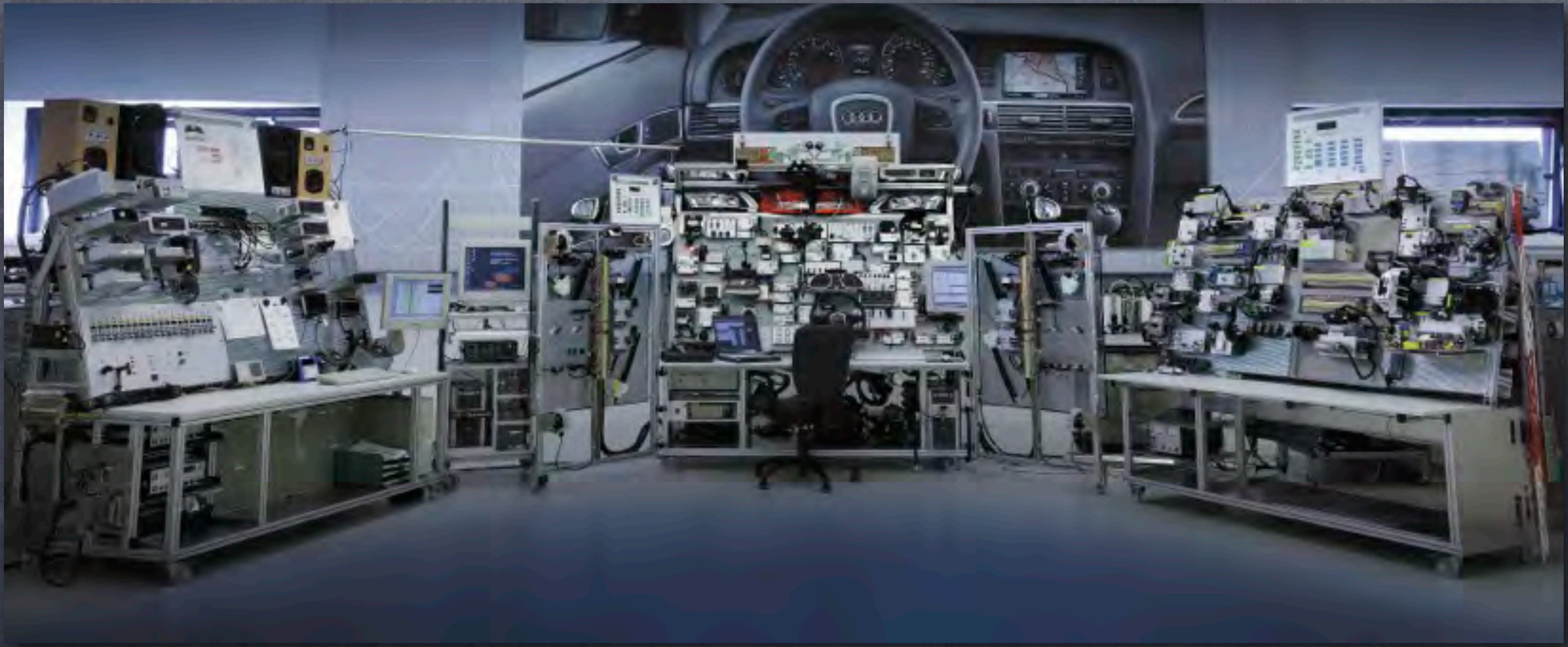
Hybrid network



Electronic control unit

- engine management
- chassis applications
- body control module
- driver information system
- safety functions
- gateway operations

Breadboarding of a motor vehicle

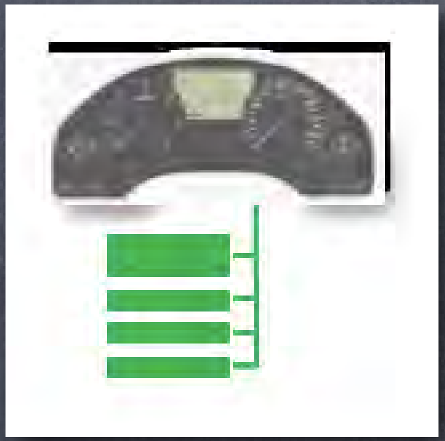


source: Audi AG

- Audi A6 (C6), detail

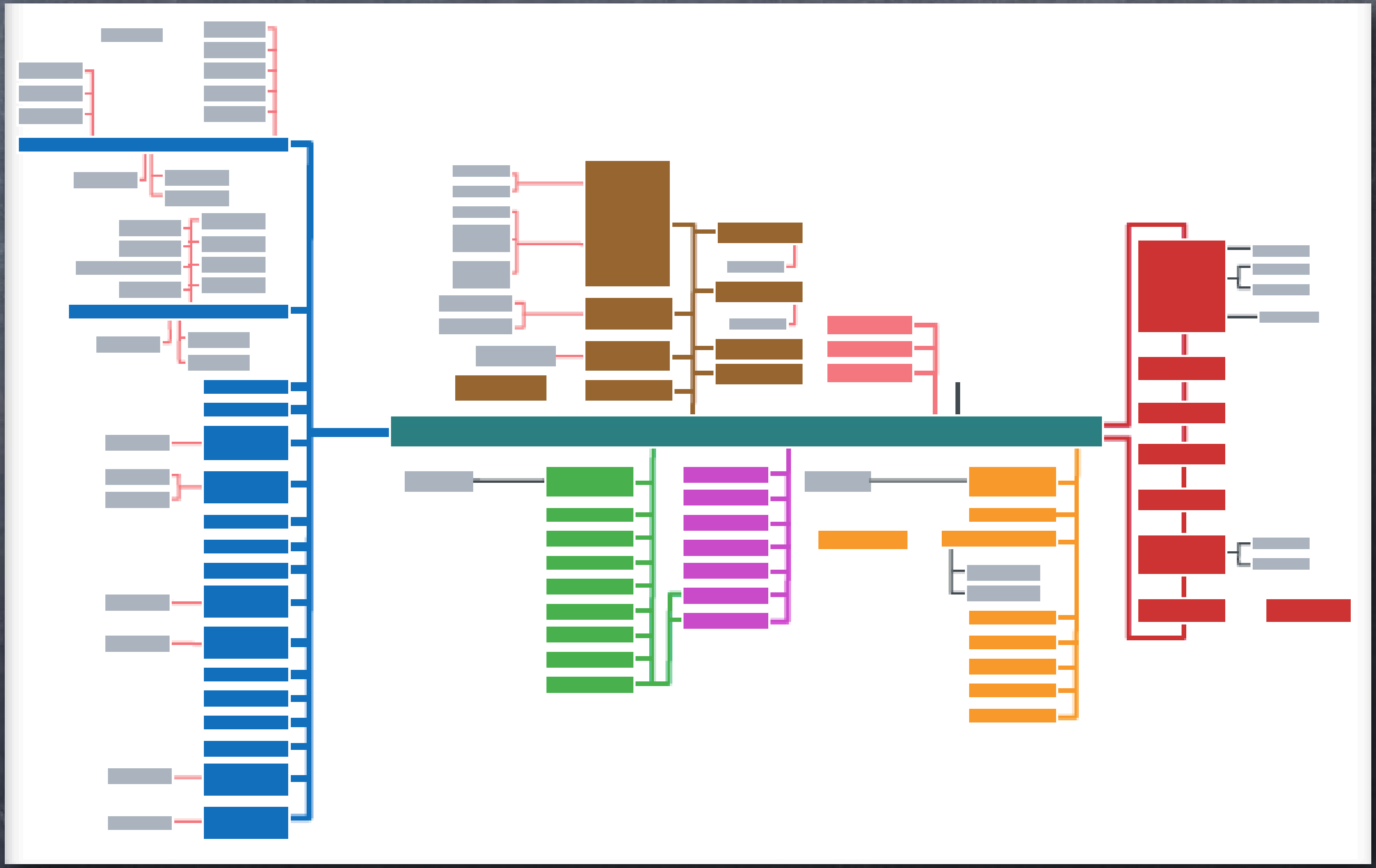
Network complexity

- number of ECUs: Audi A8



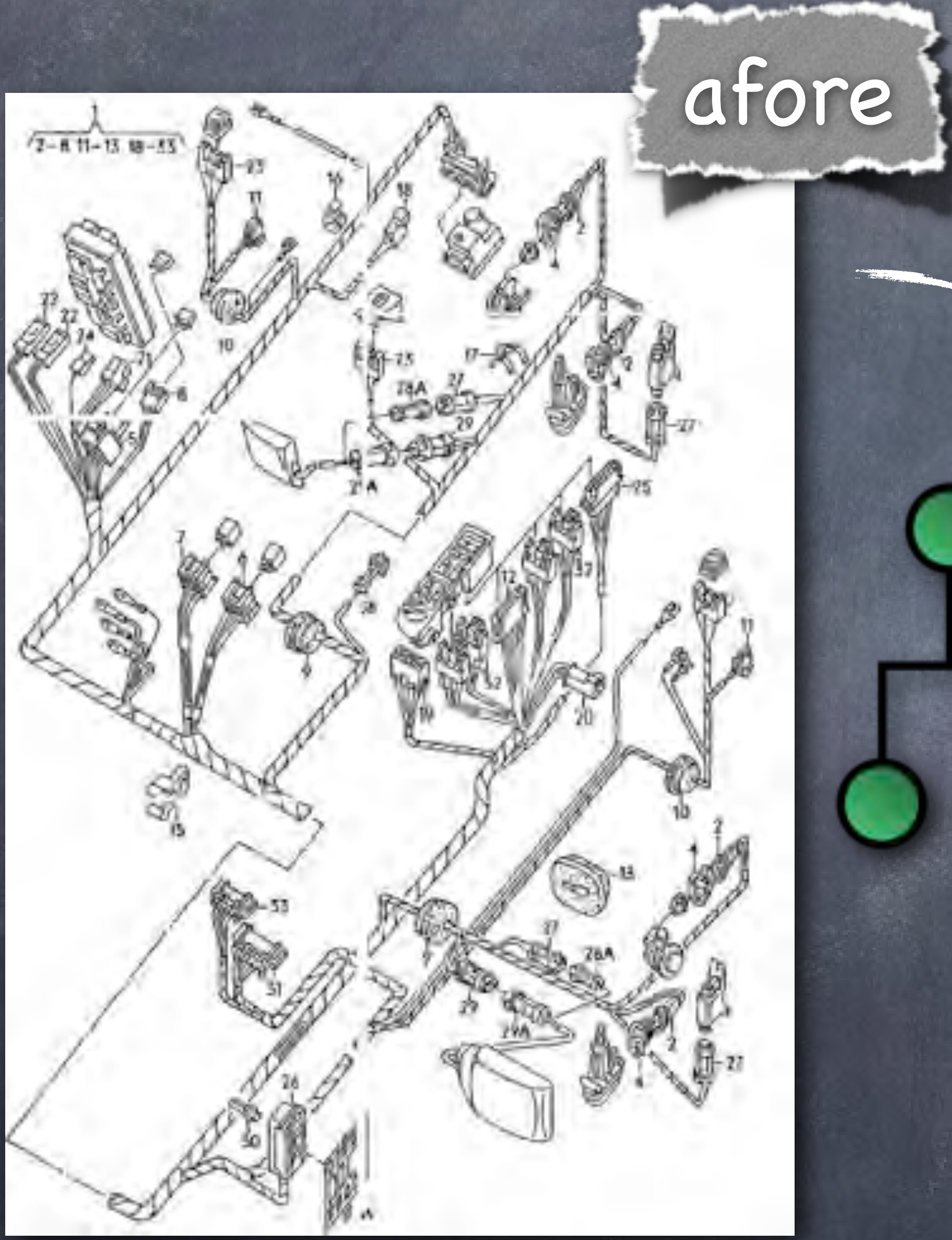
D2, 1993

D4, 2010

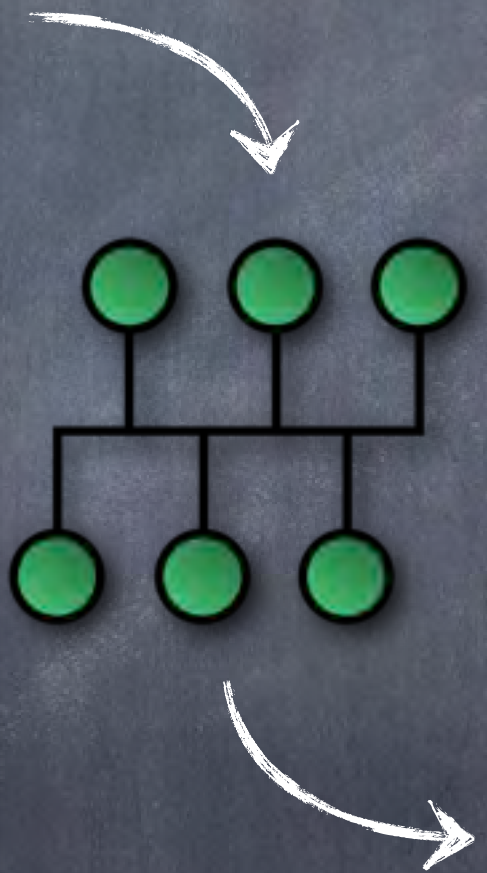


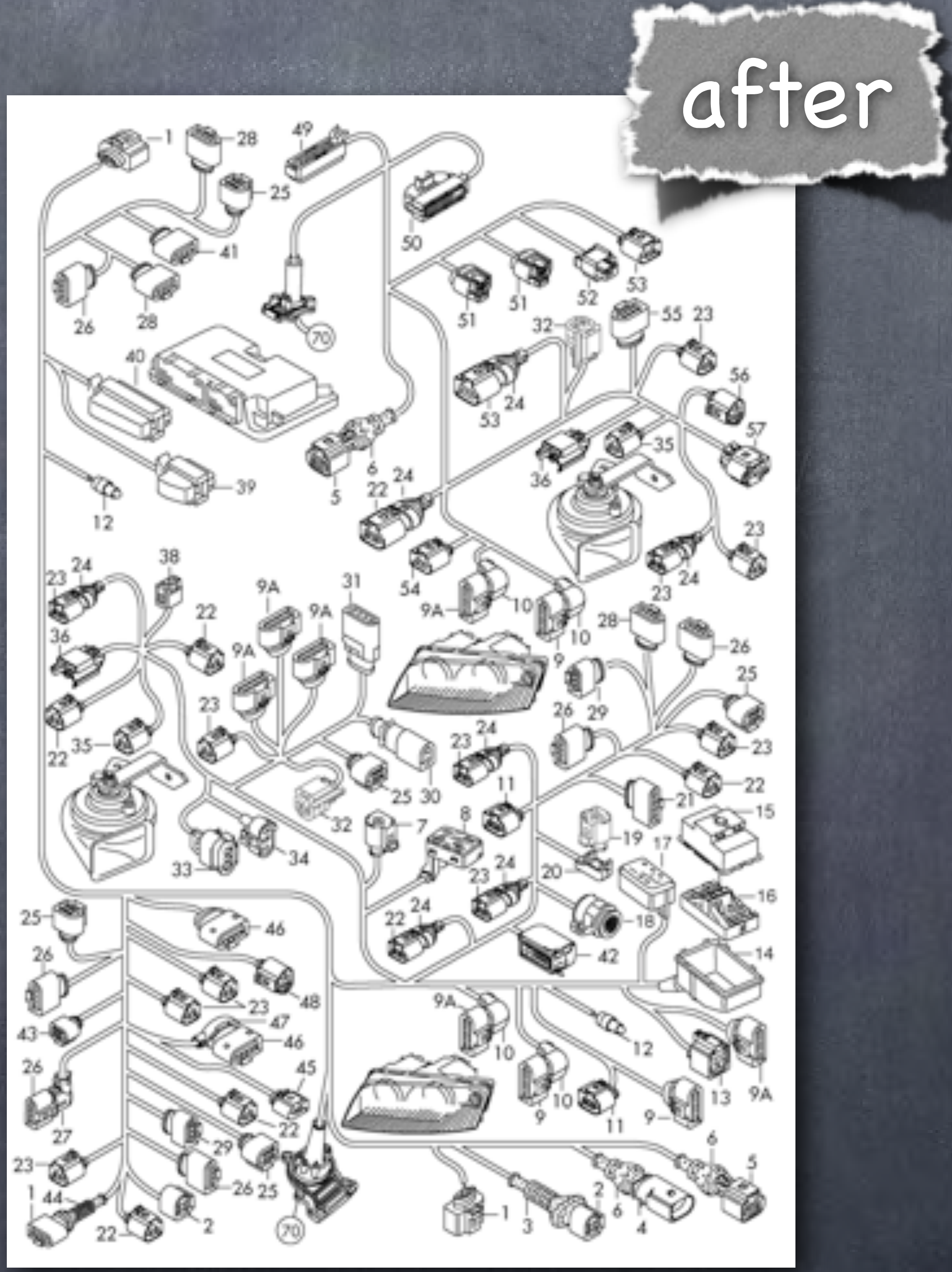
5 vs. > 100

Through the ages



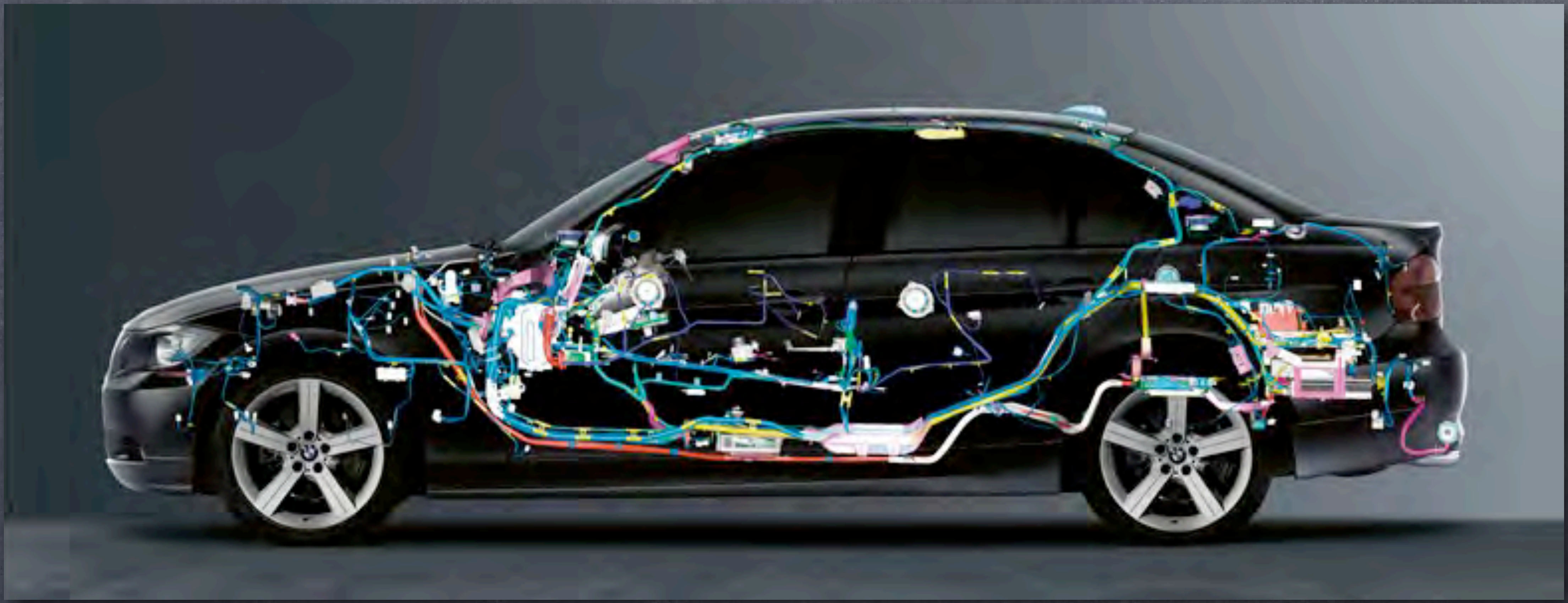
Audi V8, 1991





Audi A3 (8P), 2012

Consumption factor



- length of 3km, weight of 60kg: not unusual...
- including ECUs ≈ 1l/100km or (US) 235mpg

Streamlining needed…

Consolidation

☟

Virtualisation

☟

Multi-Core

Consolidation

- logical
  - simplified operations, common processes
- physical
  - co-location of multiple platforms, fewer sites
- workload
  - more users, same application, fewer platforms
- application
  - combine mixed workloads, fewer platforms

rationalised $\left\{\right.$ workload, application

x

Application consolidation

combines multiple applications

- of different types

onto the same physical platform (i.e., ECU)

Constraint: Two-tier system

soft real-time

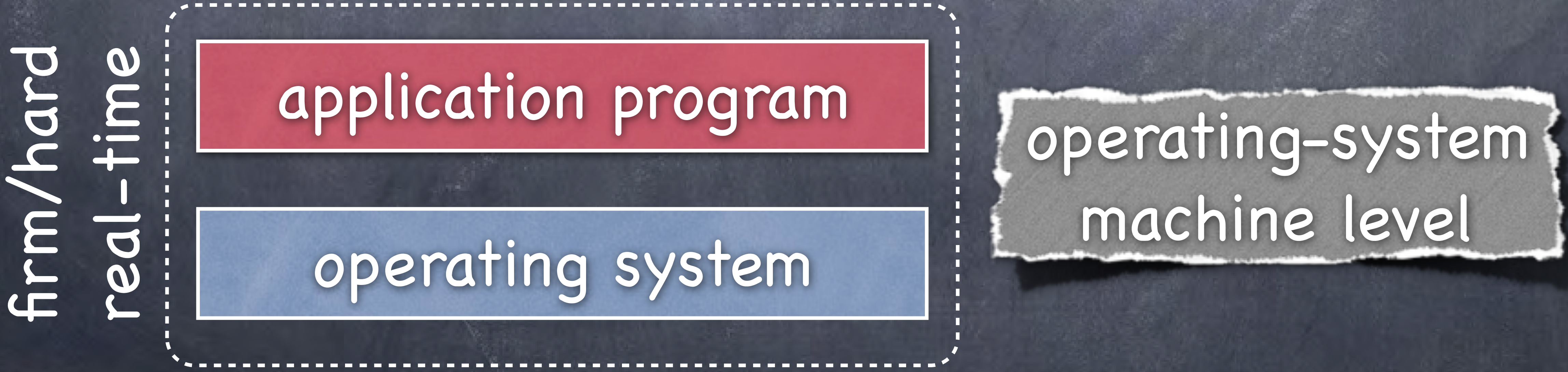
- QNX, CE, Linux

firm/hard real-time

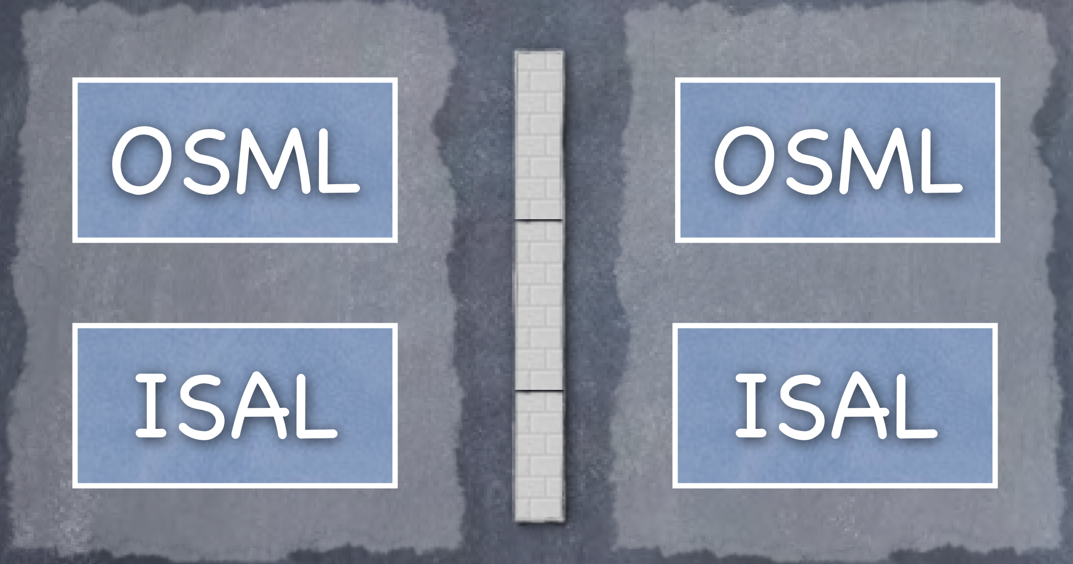
- ITRON, AUTOSAR

Constraint: Transparency

- adopt application software as it stands
  - library-like operating system (OS)
  - OS and application program as a package
- ECU ≡ casing ≡ protection domain



Physical consolidation

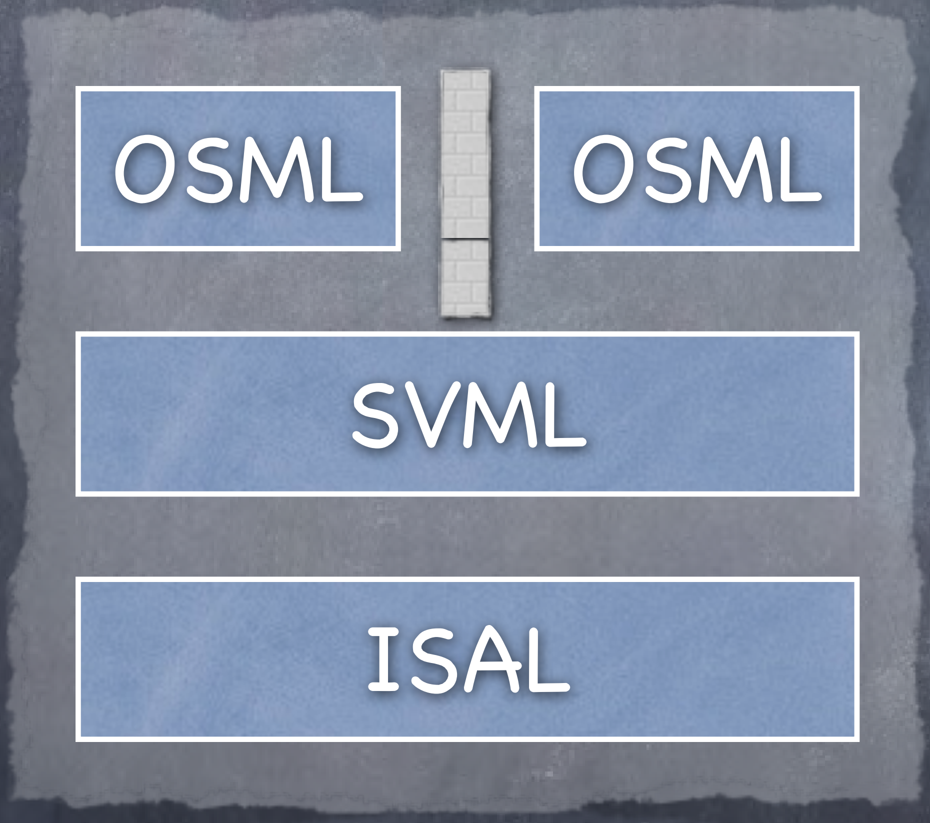


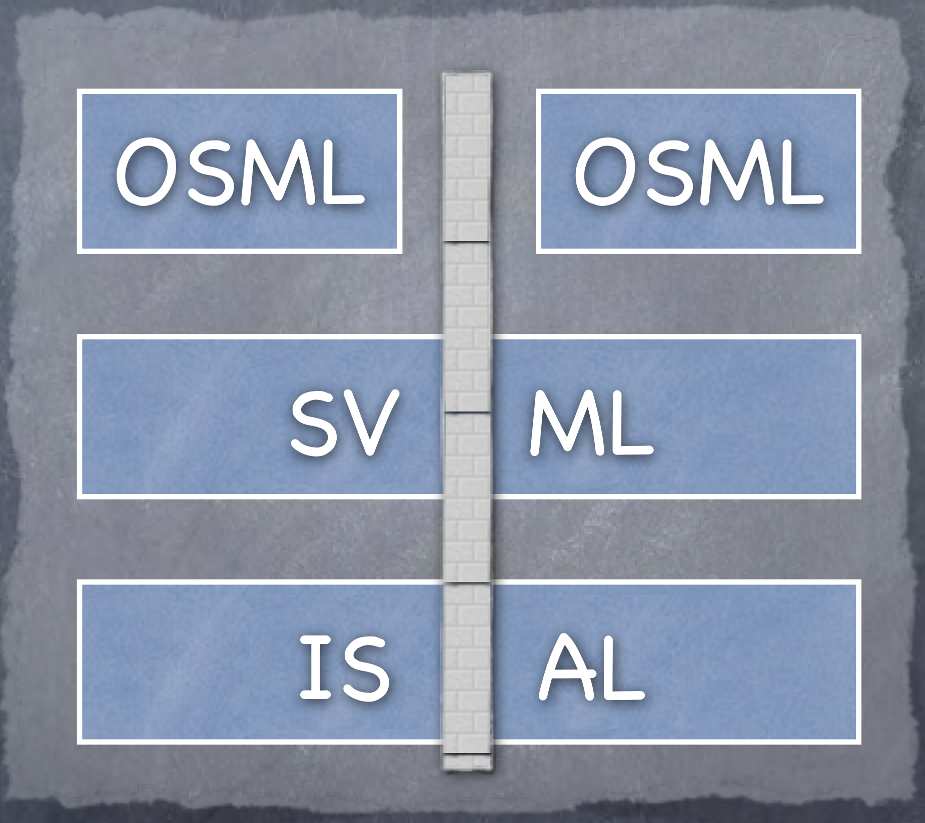
- one application per ECU
- co-location of multiple ECUs
- single site: motor vehicle

- operating-system machine level (OSML)
- instruction set architecture level (ISAL)

Rationalised consolidation

- multiple applications per ECU, fewer ECUs

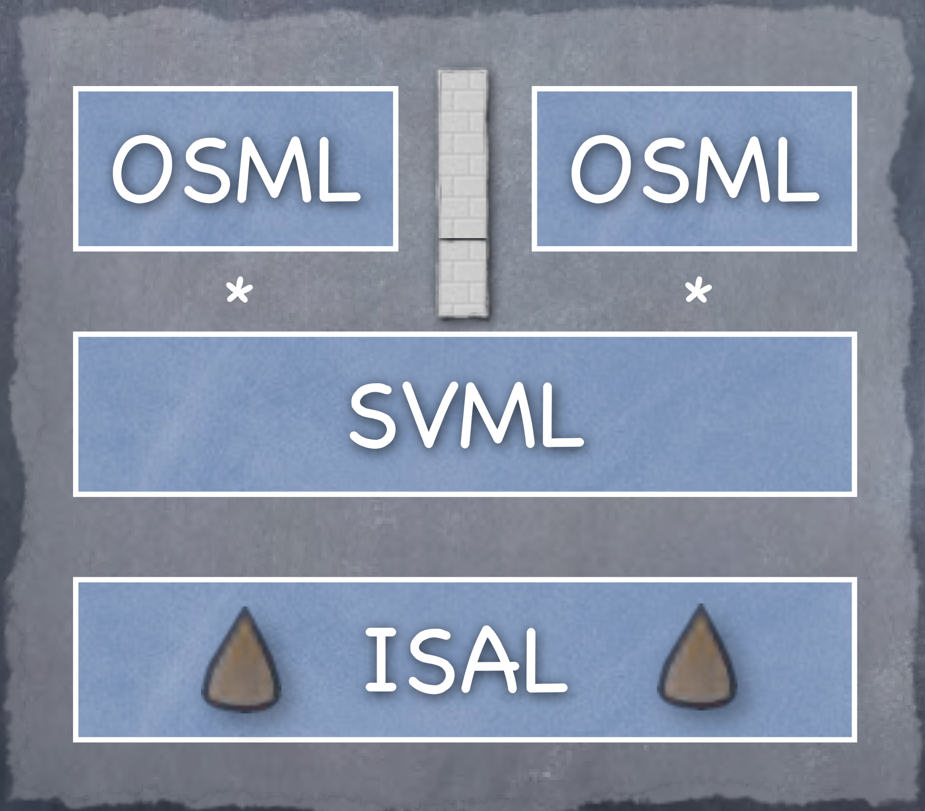




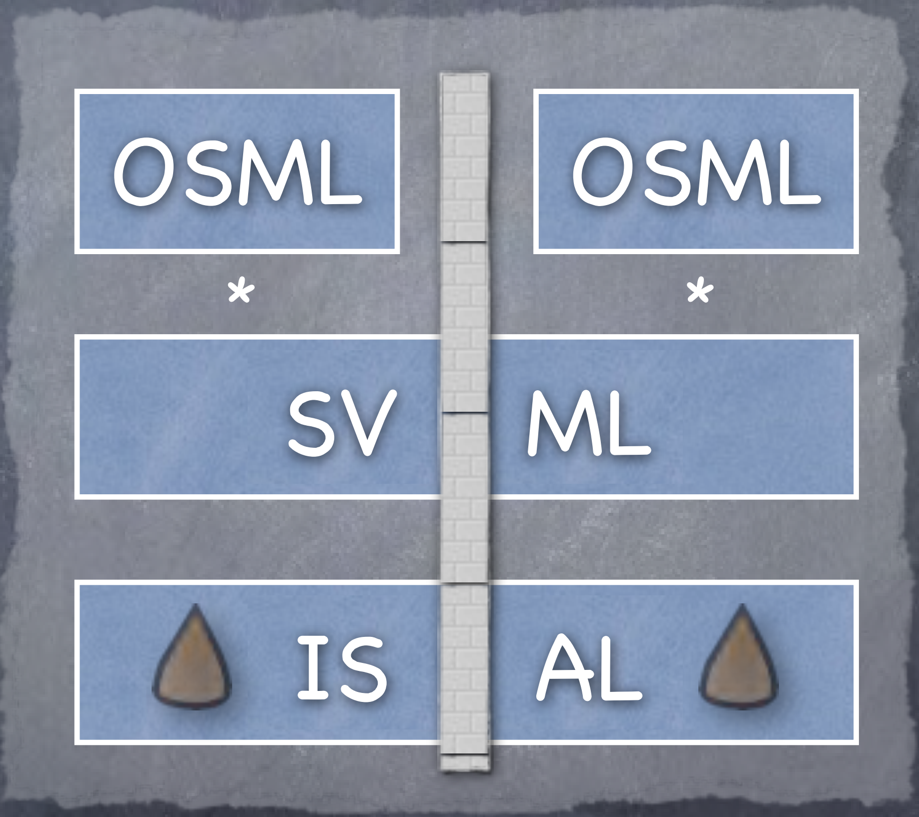
- system virtual machine level (SVML)

Rationalised consolidation

partitioning in time



partitioning in space



* interference with (guest) operating system

Performance handicaps

- partial interpretation of system requests
  - traps, interrupts
- maintenance of real-machine state
  - processor state, shadow page tables, …
- interference with guest operating system
  - scheduling, synchronisation
- interference with guest system(s) in general
  - cache-aware (machine) programs

Partitioning techniques

- with HW support
  - physical
  - logical
    - microprogramm
    - ☞ hypervisor

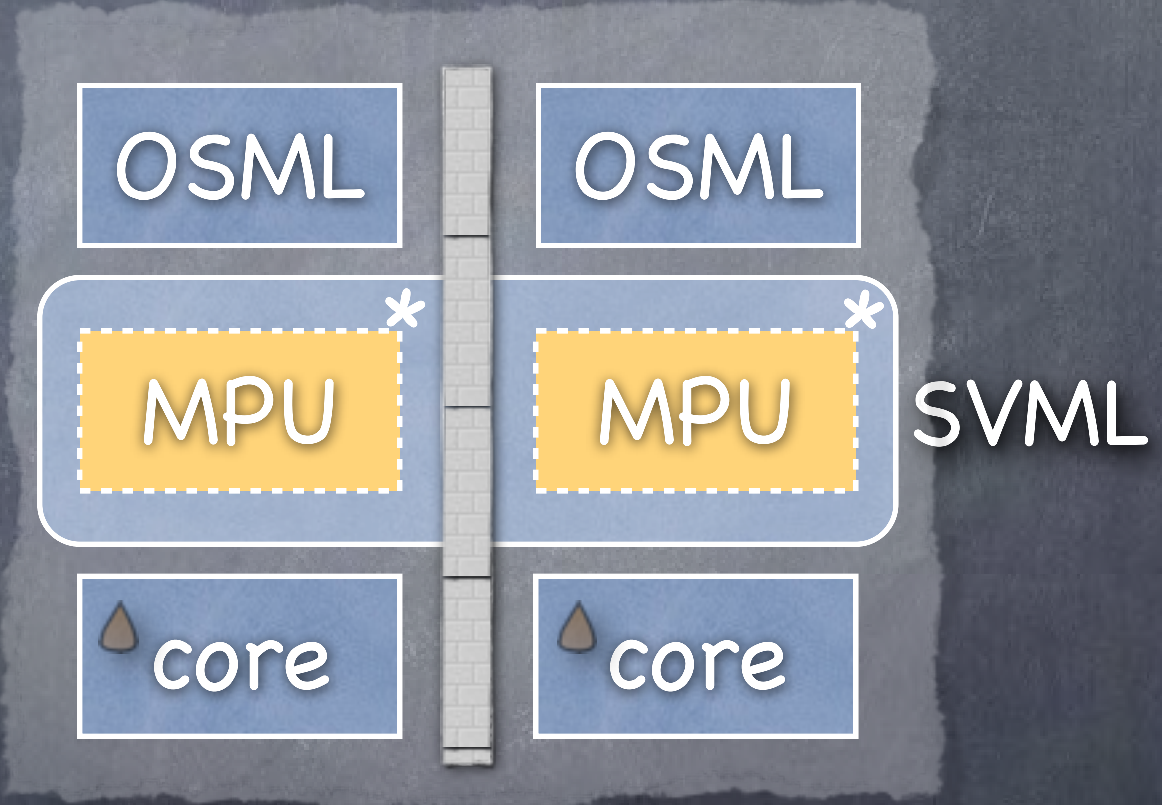
efficiency

- without HW support
  - SVM-based ☜
    - homogeneous
    - heterogeneous
  - OS-based ☜

flexibility

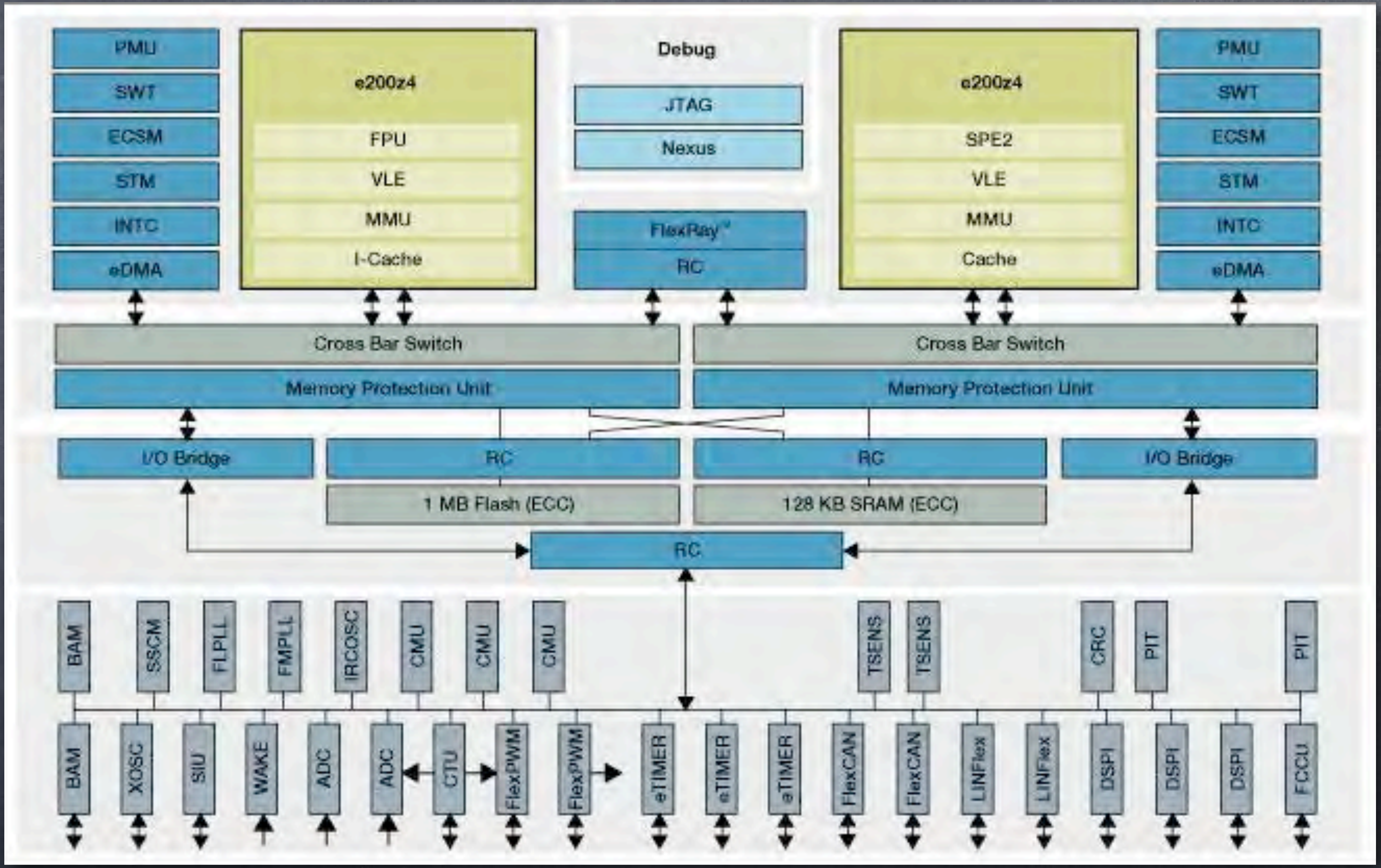
Partial virtualisation

- address-space/memory protection
- I/O-channel mapping
- static IRQ forwarding
- prevent false sharing
  - cache lines!!!
  - interference may break deadlines!!!



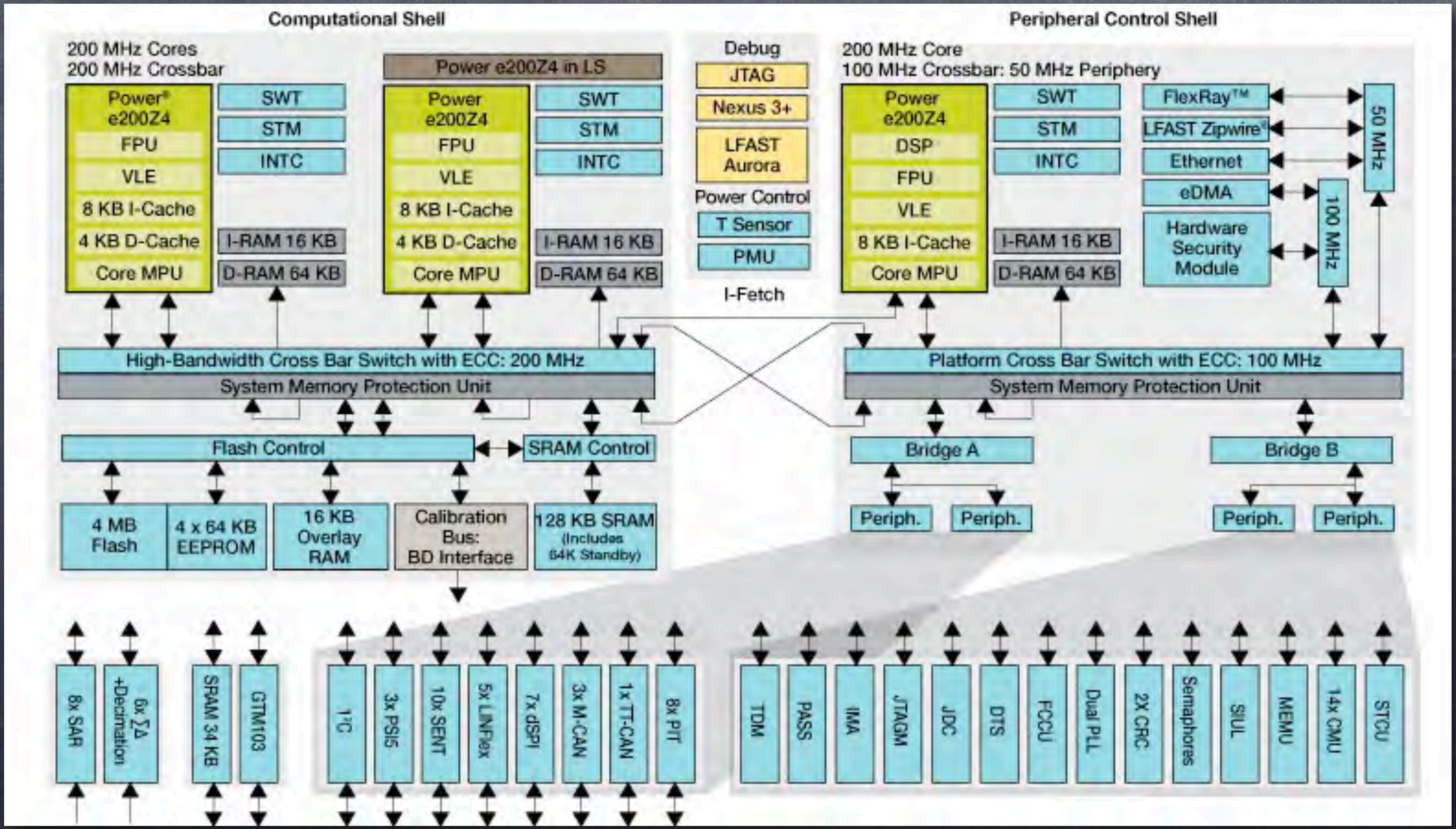
*memory protection unit

Multi-core case: Safety applications



MPC564xL

Multi-core case: Power-train applications



MPC5746M

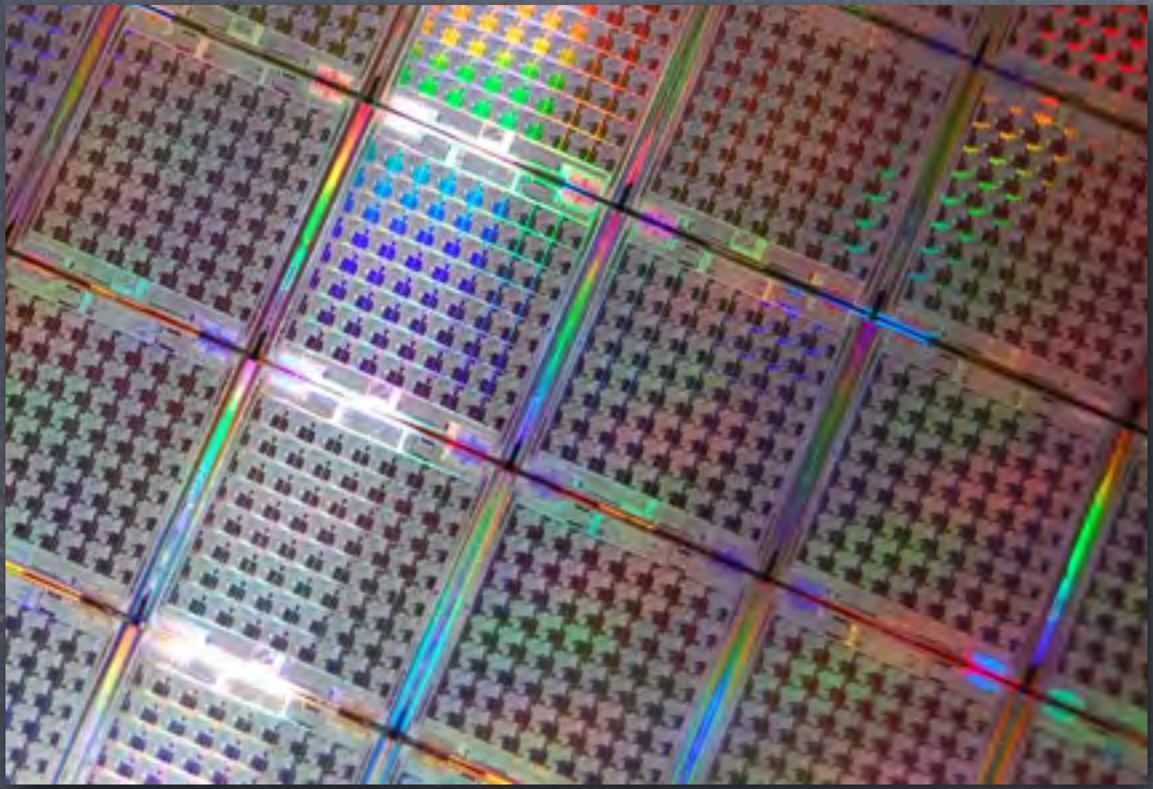
Audi Calamaro Flying Car

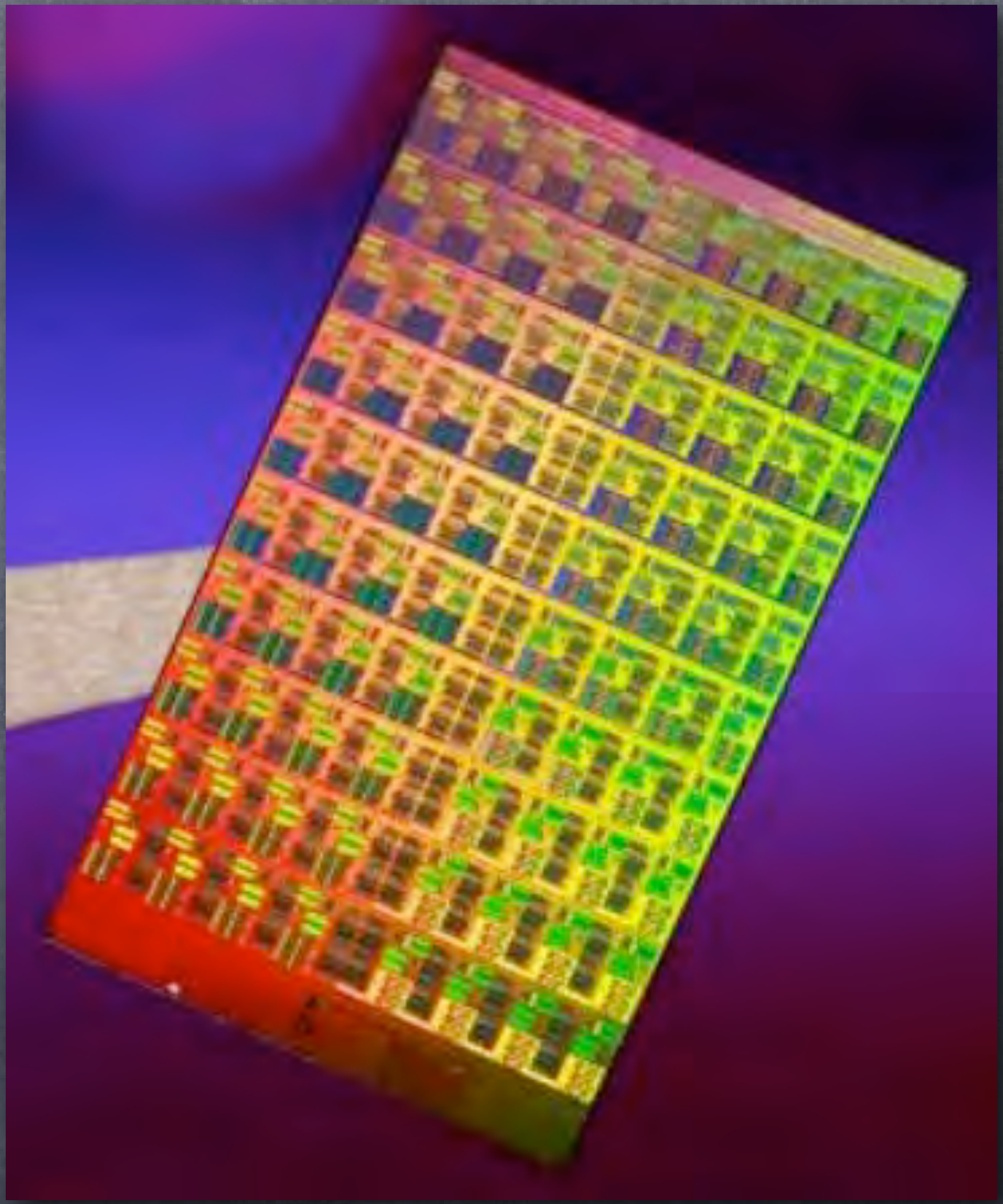
Parallel ~ Embedded

Parallel processing

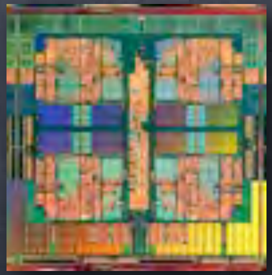
x

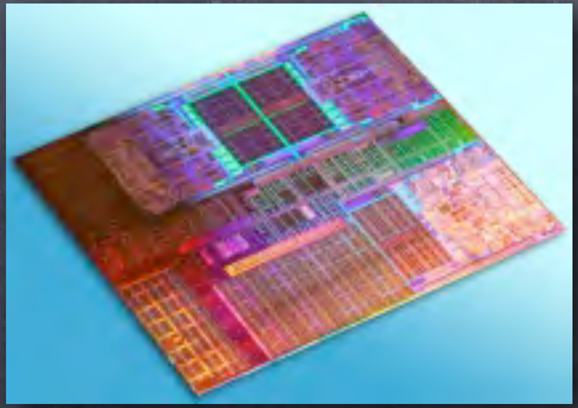
Parallel processor: CPU


100



2

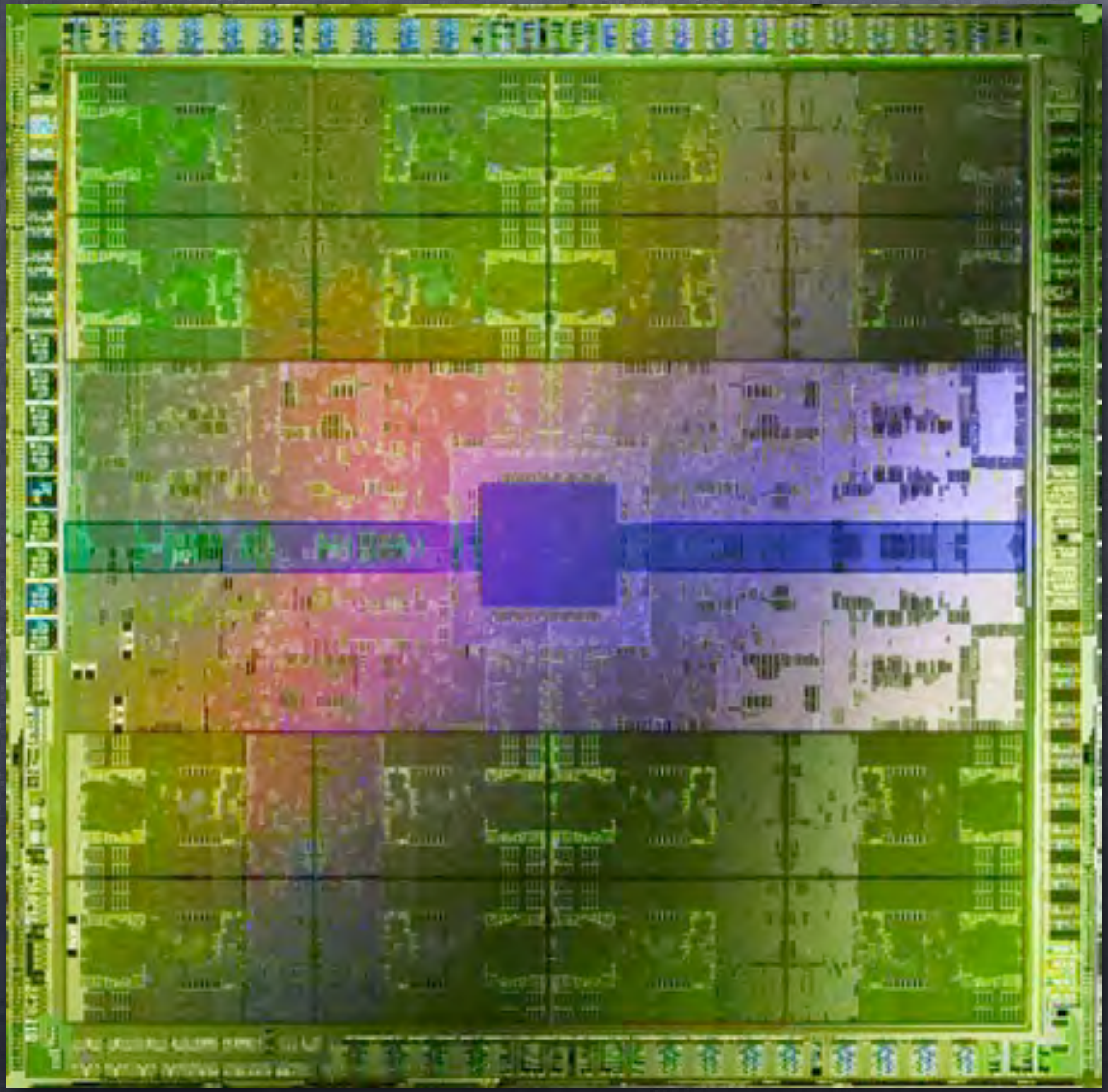

4

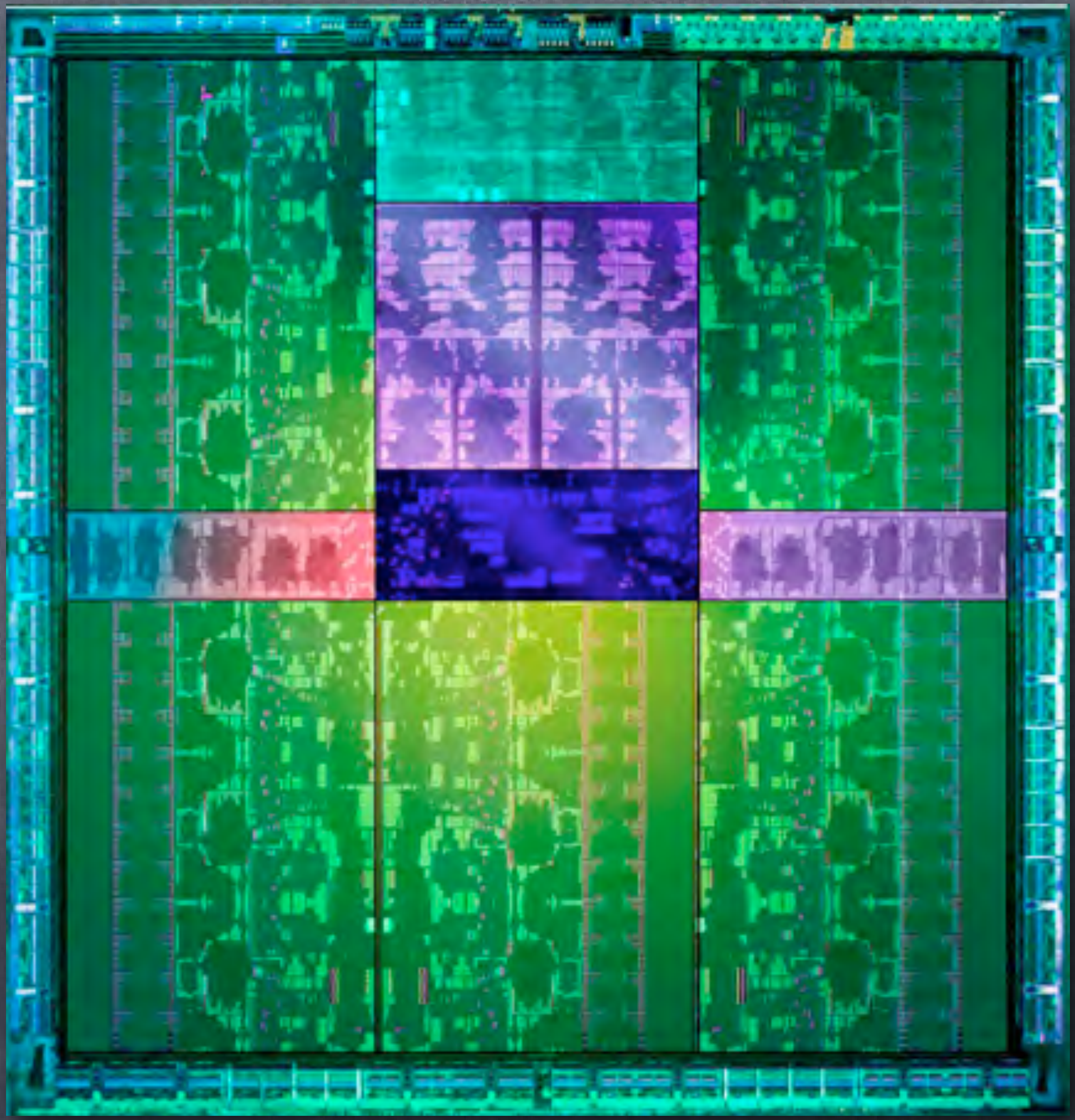

8

80

X

Parallel processor: GPU


512


1536

X

Parallel system: HPC

3120000

X

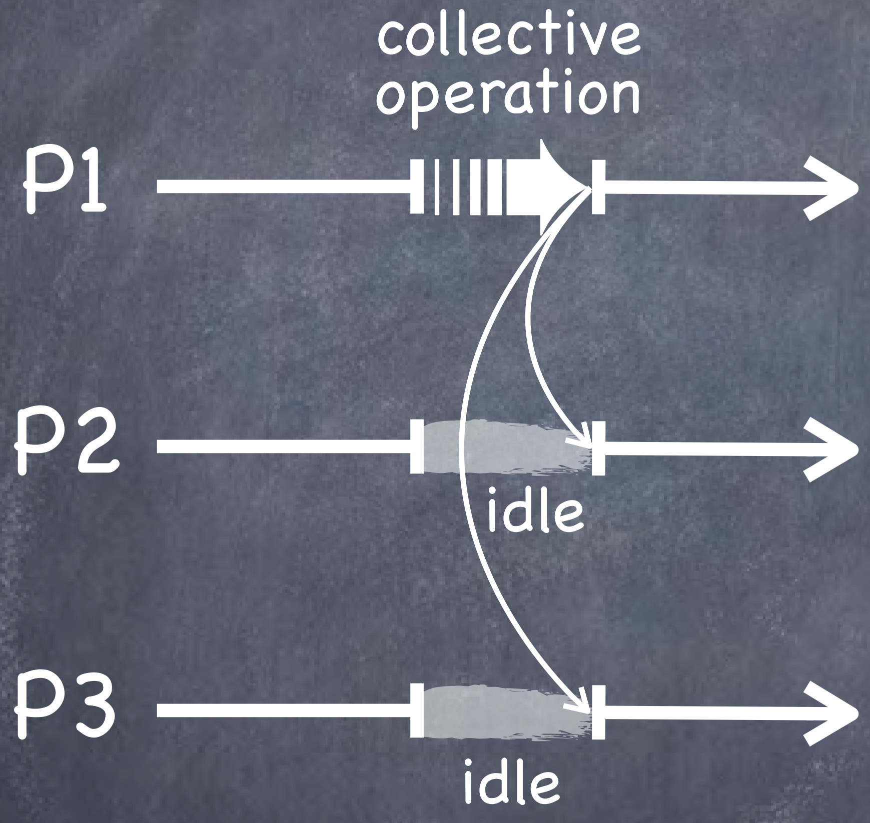
Collective operations

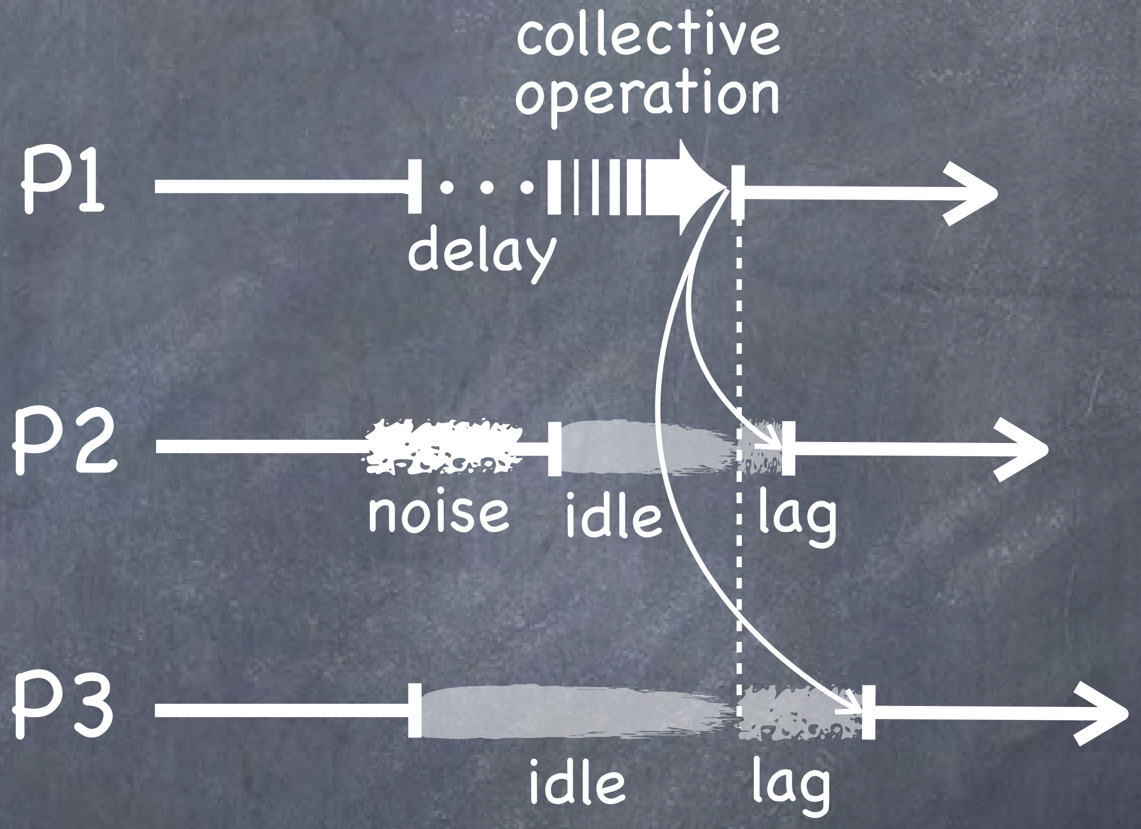
- gather
  - collect data from all nodes
- scatter
  - split a set of data into pieces
  - send a different piece to all nodes
- broadcast
  - send same data to all nodes

Collective operations

- reduce
  - collect data from all nodes
  - combine collected data in some way
  - if applicable, send result to all nodes
- barrier
  - suspend the arriving process until all of one`s peers have arrived

Outline of the problem





theory

practice

Detrimental factors

- process skew
  - parallel operations cannot start at once
  - system noise delays processes by chance
  - process lags keep other processes waiting
- data skew
  - unbalanced (distributed) data sets
  - overloaded processes thwart under- or normally loaded processes, resp.

Solution statement

unbalanced (distributed) data sets

- partitioning, static load balancing

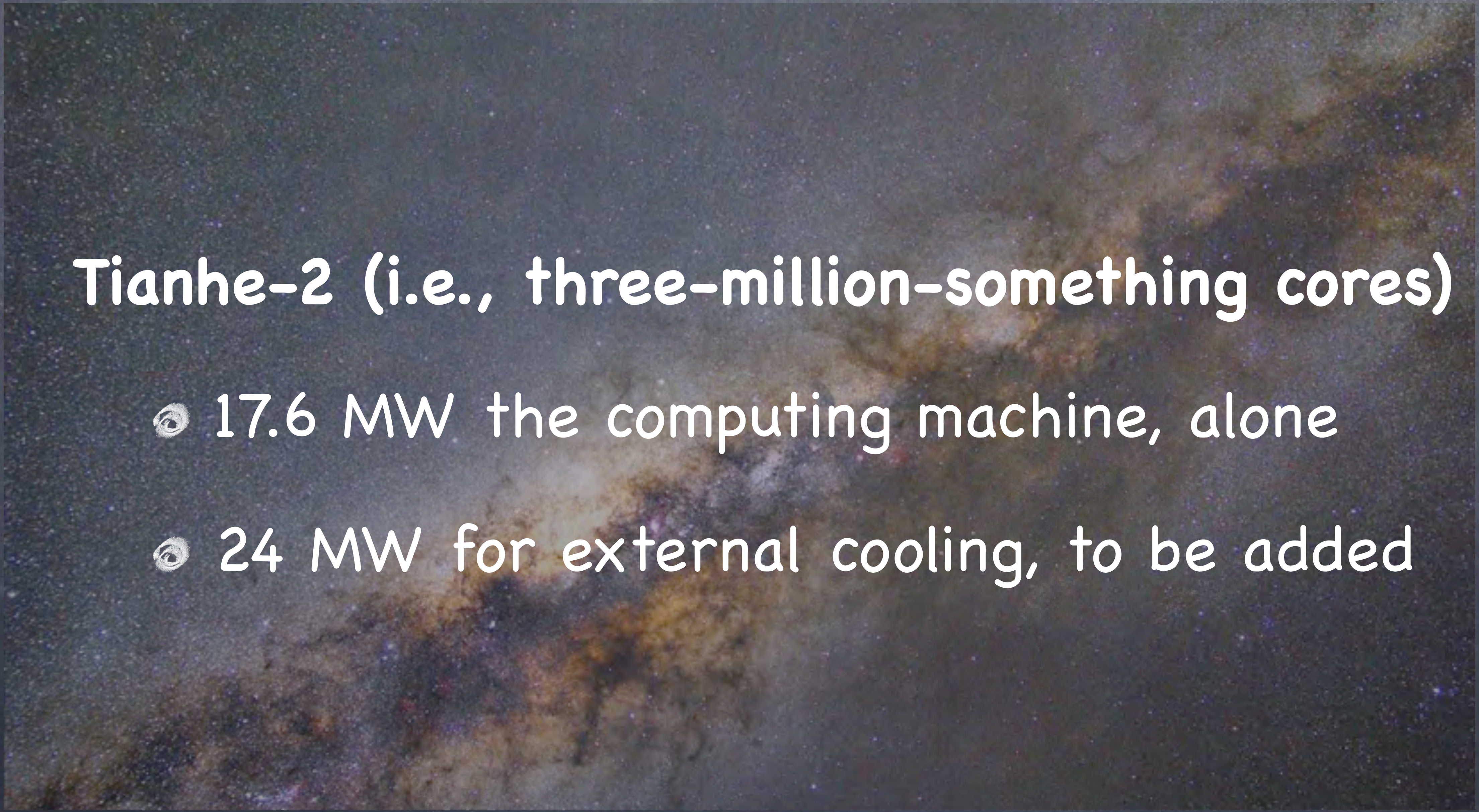
time-shifted start of parallel operations

- latency-aware process and data structures
- predictable operating-system processing

sporadic process delays

- co- or gang scheduling, resp., of processes
- holistic operating-system design

Energy consumption



Tianhe-2 (i.e., three-million-something cores)

- 17.6 MW the computing machine, alone
- 24 MW for external cooling, to be added

Descriptively written…

ultimate consumer

- high-speed train TGV: ≈ 20 MW
- medium-sized town in Germany: ≈ 48 MW

power generator: wind engine, 2.3 MW

- Tianhe-2 uncooled needs 9 installations
- Tianhe-2 cooled, a complete wind farm…

Potential „power supply“

X

Observing of predictions

- load-dependent power allocation
  - stipulated by contract
  - minimum payment clause
  - chargeable unexpected underload
- contract-aware deployment and scheduling
  - economise: waste energy to avoid a fine...

Near embedded systems

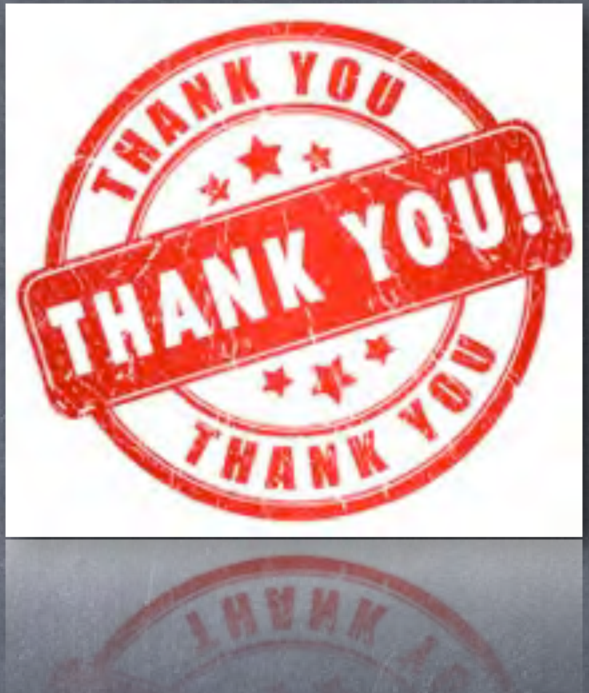
- „a priori“ knowledge is all the world
  - worst-case execution time (WCET)
  - process and data dependency
  - predictable run-time behavior
- special-purpose mode of operation
  - foreseeable and timely processes
- resource-aware programming
  - feature-oriented and holistic approach

Epilogue

Challenges

- ✔ consolidation
- interference suppressed, temporal isolaton
- mode of operation
  - asymmetric, symmetric, bound
- RAMS plus security (RAMSS)
  - reliability, availability, maintainability, safety

Conclusion



embedded computing systems

- are dedicated to handle a specific task
- life cannot possibly be imagined without it
- were forerunner of multi-core technology
- stop at nothing, neither virtualisation
- can serve as role models for „green HPC"