# Embedded Computing Systems in the Multi-Core Era

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# Background

multi/many-core systems

(since 2008)

embedded & real-time systems

(since 1995)


uni-processor systems

(1981-1986)

multi-processor systems

(1986-1995)

# Background

Sparc LEON
IA-32/64

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

Operating Systems

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

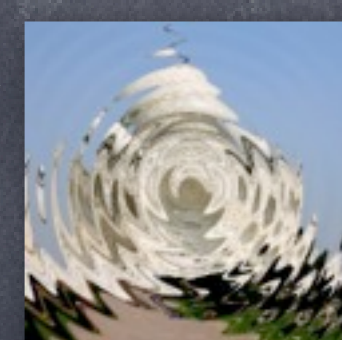
320 node M68020- &
16 node (dual CPU)
i860-based machines

# Leitmotif

- embedded $\widehat{=}$ 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

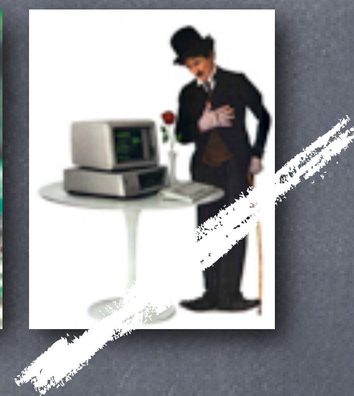


# Outline

- ✔ prologue
- stock taking
  - embedded computing system
- multi-core as reference point
  - embedded ≘ parallel
  - parallel ∼ embedded
- epilogue

# Embedded Computing System

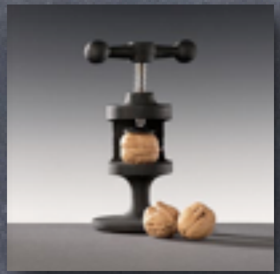
# Embedded system

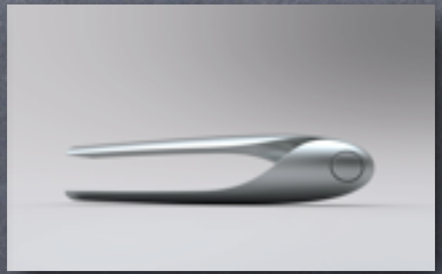
    

- a microprocessor-based system
- that is built to control a function or range of functions and
- is not designed to be programmed by the end user in the same way that a PC is

(Heath, Embedded Systems Design, 1997)

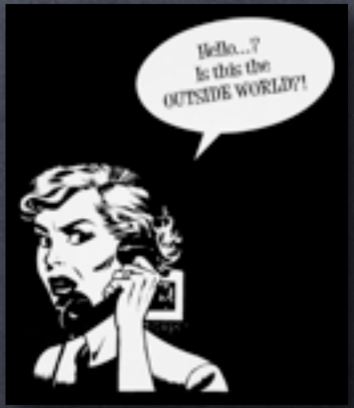
# Embedded system



- 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)

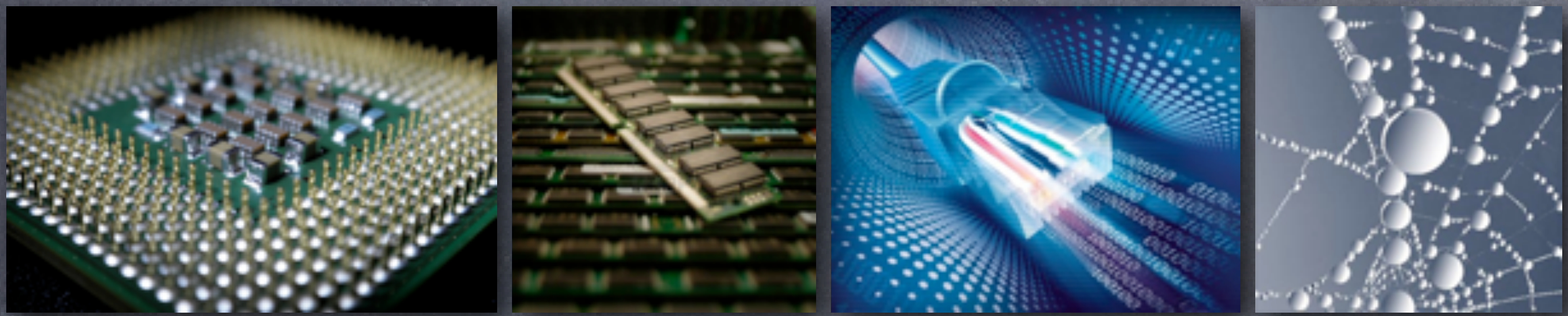


# Embedded system


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

(Simon, An Embedded Software Primer, 1999)

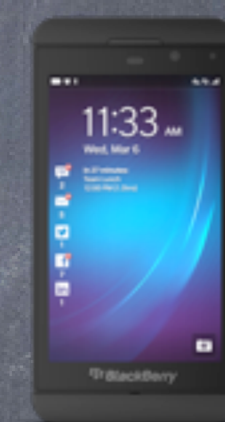
# Embedded systems



- 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...

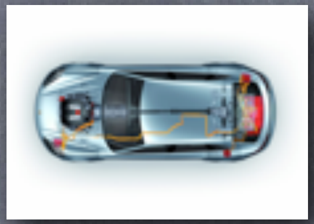


# Embedded system


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

(Wikipedia, 2013)

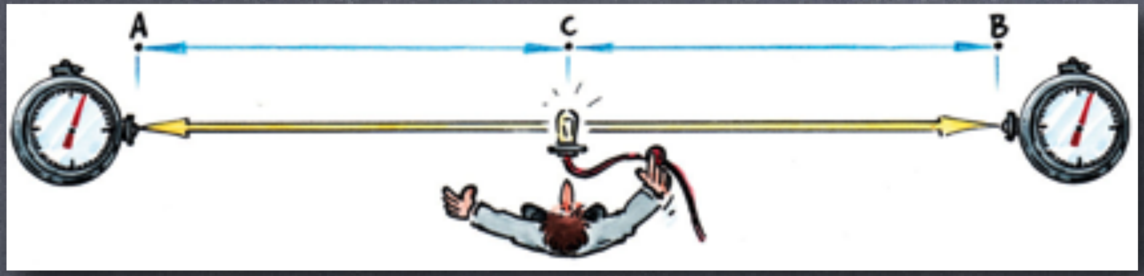
# Embedded system

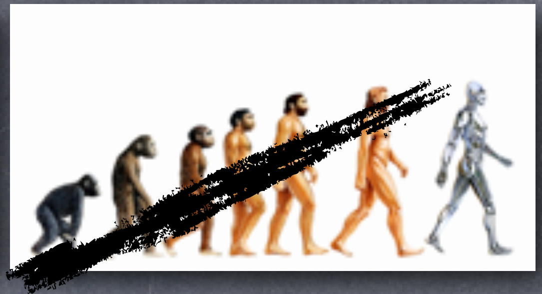
- range from portable devices
  - such as digital watches and MP3 players
- to large stationary installations
  - like traffic lights, factory controllers
- and large complex systems
  - like hybrid vehicles, MRI, and avionics

(Wikipedia, 2013)

# Embedded systems



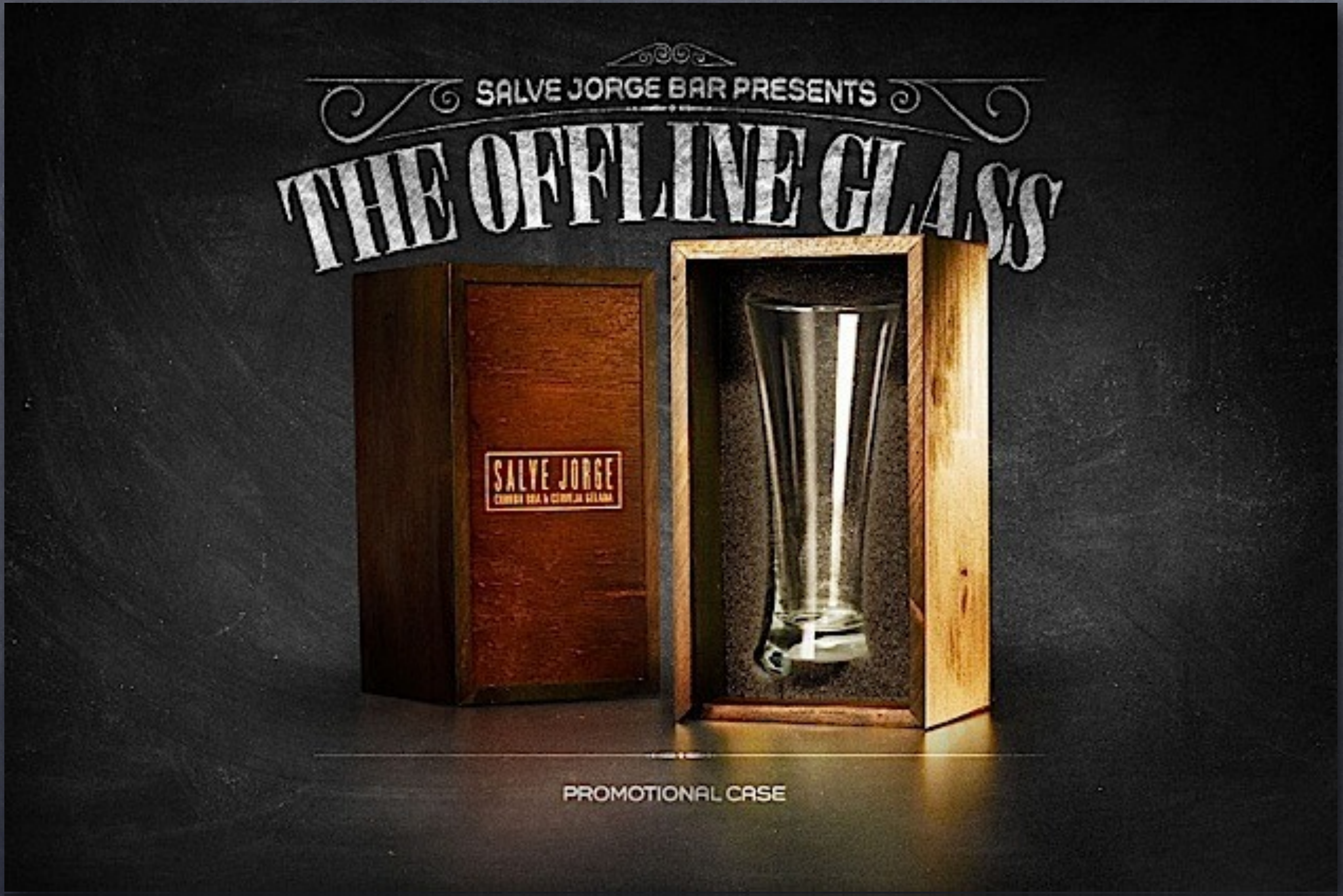




- often have several things to do at once
  - they must respond to external events
  - their work is subject so deadlines
  - they must cope with all unusual conditions without human intervention

(Simon, An Embedded Software Primer, 1999)

# An exception that proves the rule…




# Extremes meet

- mass product
- small appliance
- resource shortage
- best effort
- non-/soft real-time
- planned obsolescence

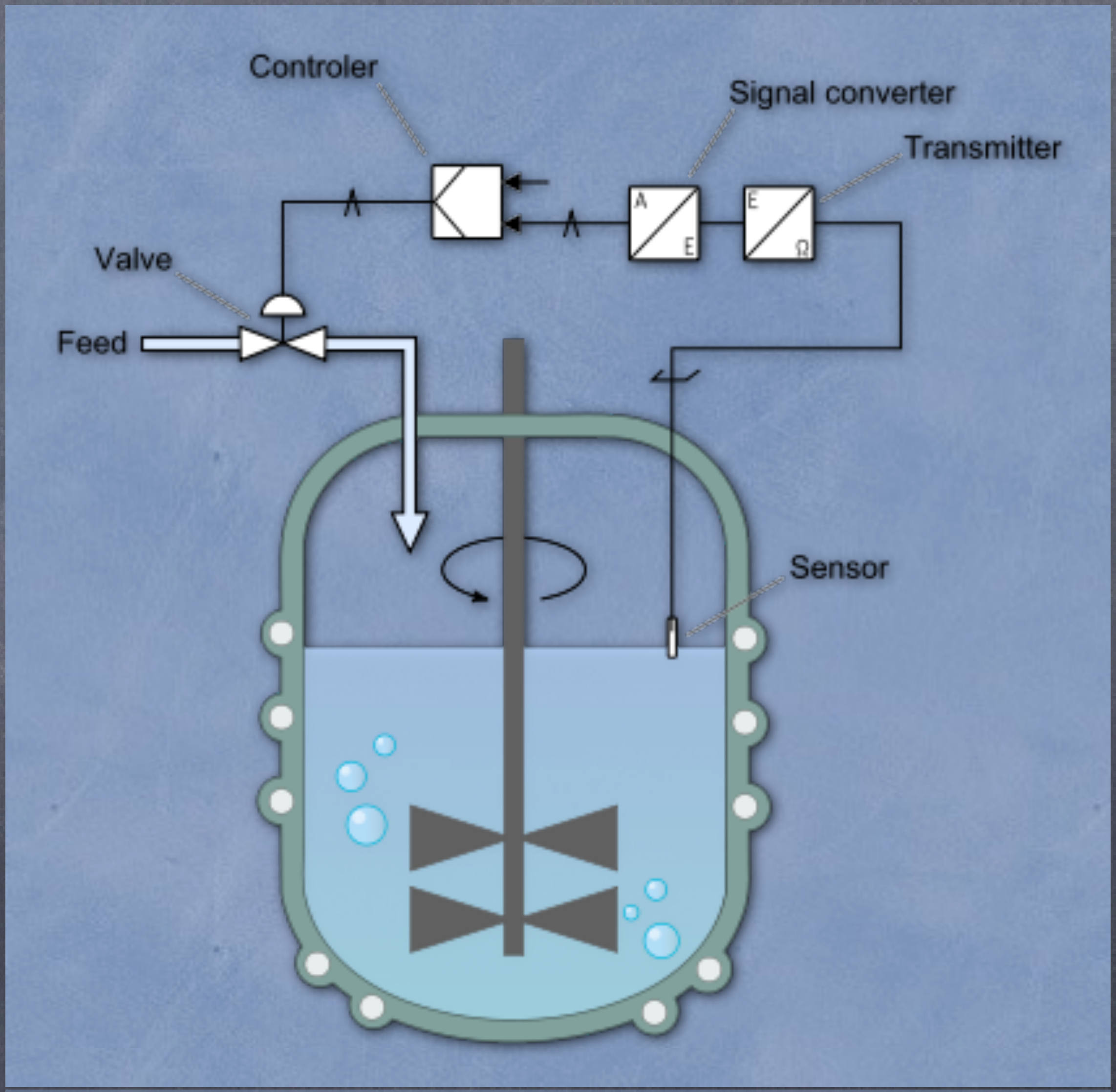
- custom-built machinery
- giant equipment
- needs-based design
- dependable
- firm/hard real-time
- non-stop operation

# 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**

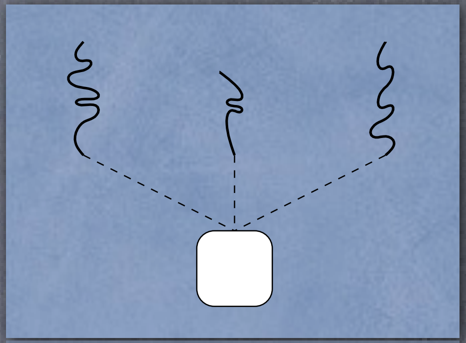
- functional units
  - sensor system
  - specific processing
  - actuating elements
- mixed mode
  - periodic
  - aperiodic~~/sporadic~~

# Latent concurrency

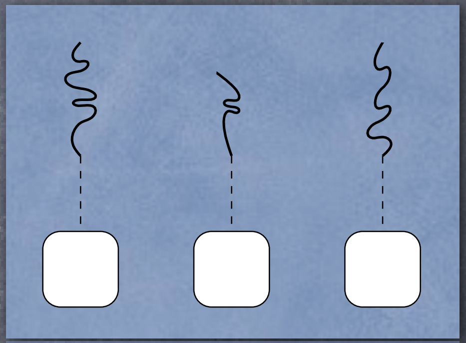
- not because of internal constraints such as to improve system utilisation but…
- induced by the characteristics of the actual object to be monitored or controlled
- positioned through hardware features used to interact with the external process and
- reflected by the logical structure of the corresponding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

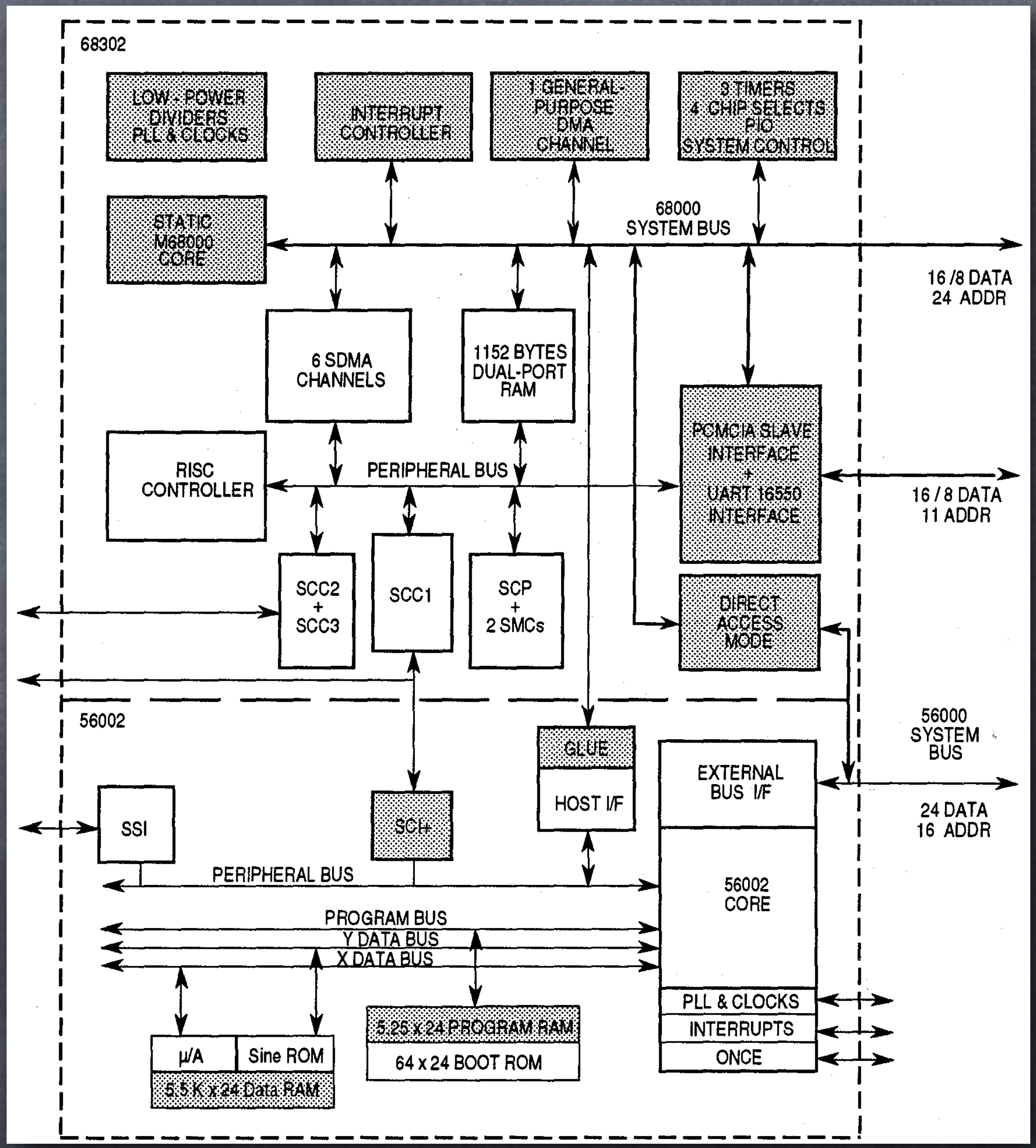
- for embedded computing systems, multi-core technology is an implication

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

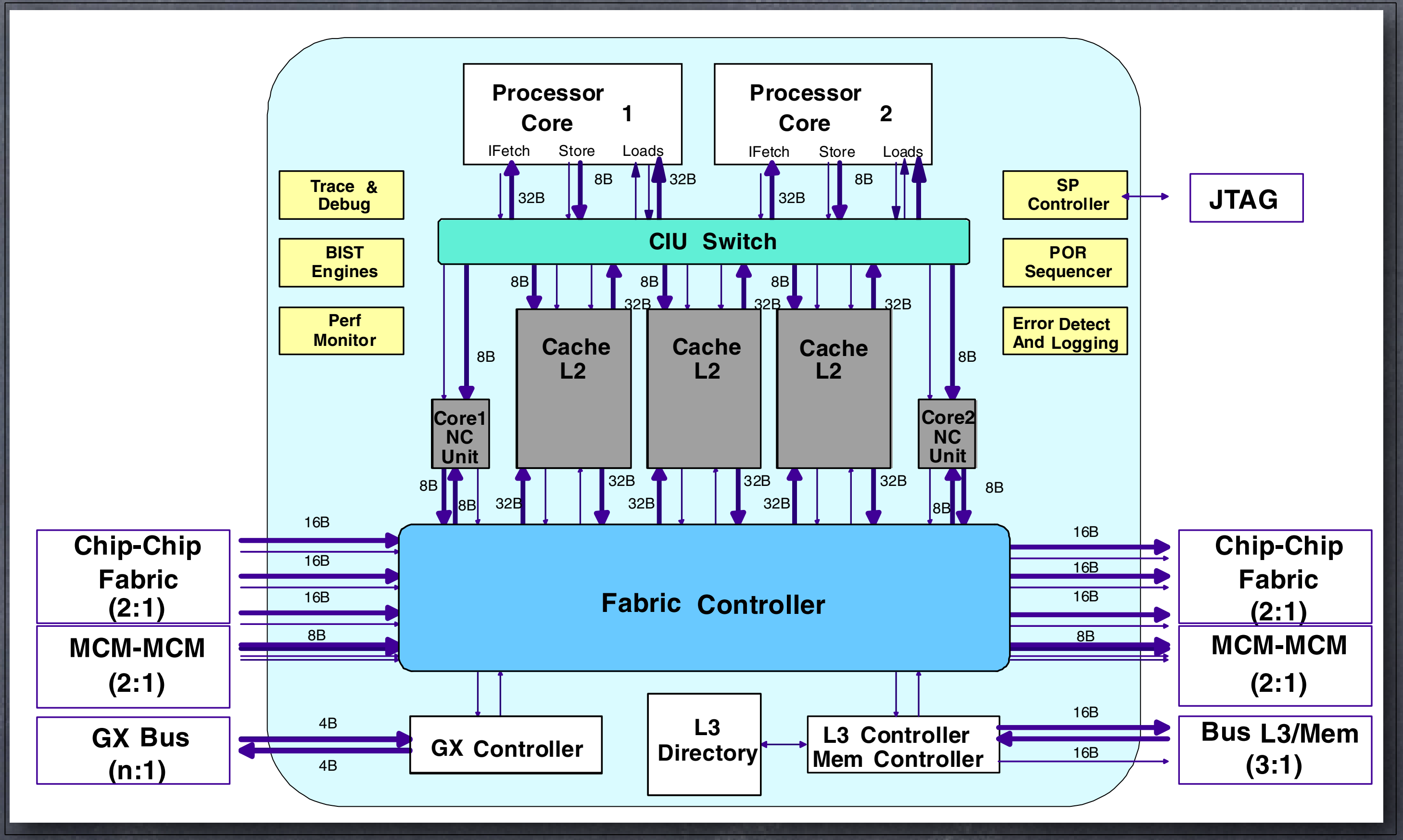
# Multi-core roots

MC68356, 1994

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



# Multi-core roots




POWER4, 2001

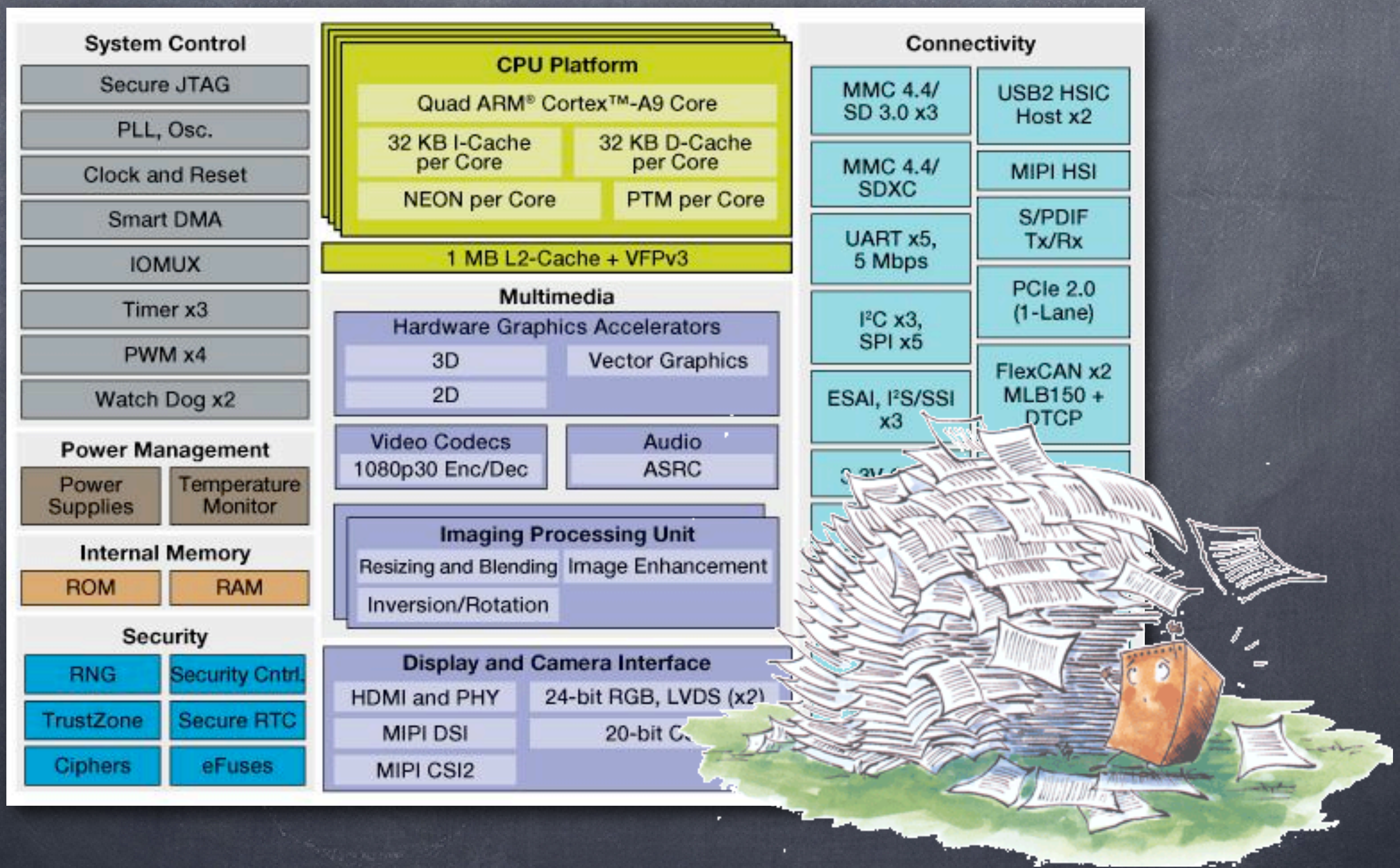
- first non-embedded dual-core, homogeneous

# 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

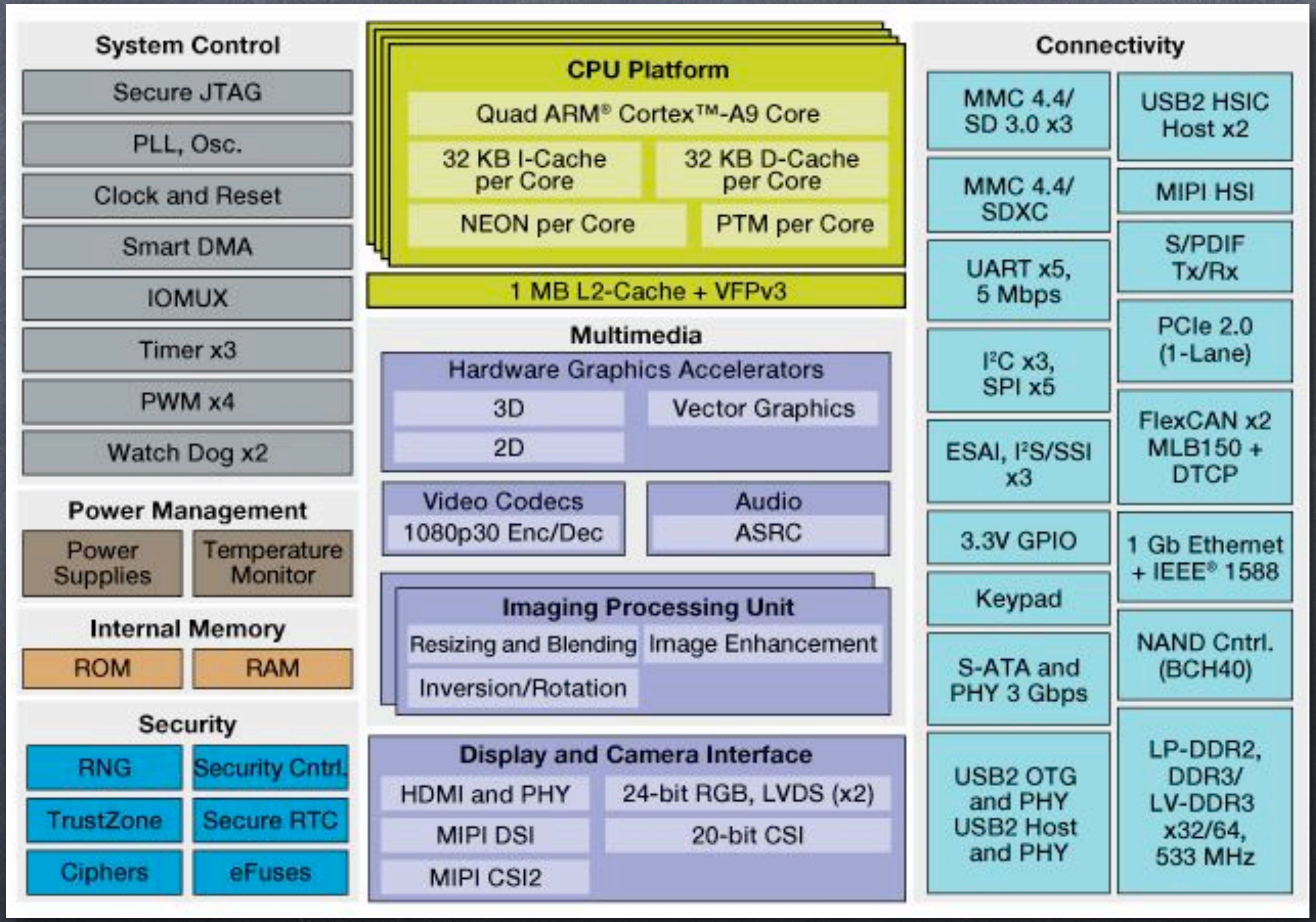
## – thousands of manual pages, excl. CPU –



Multi-core/processor

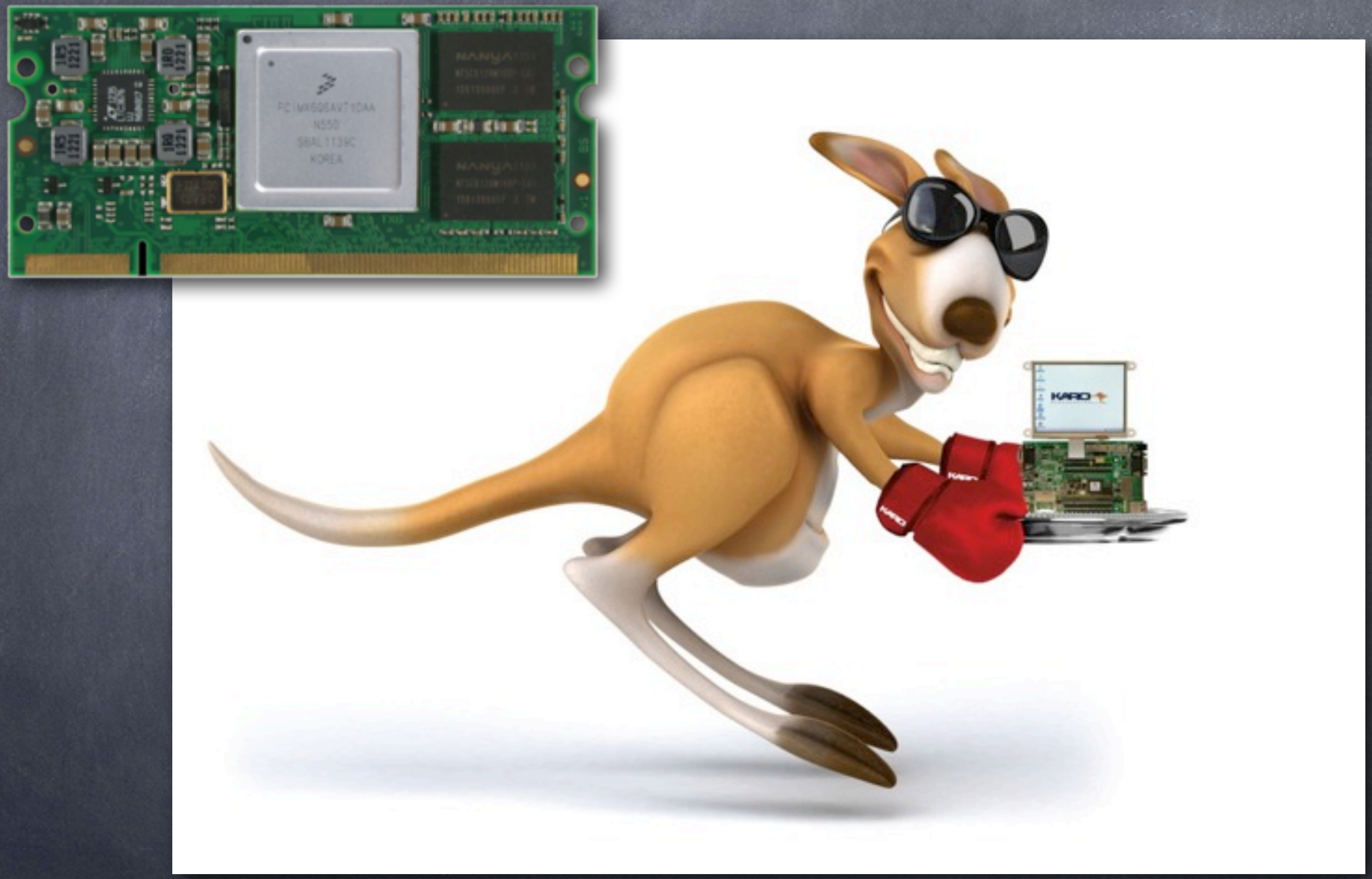
# System on chip

(MPSoC)

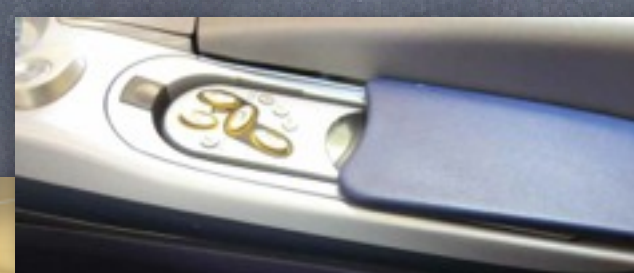



i.MX6

# System on module



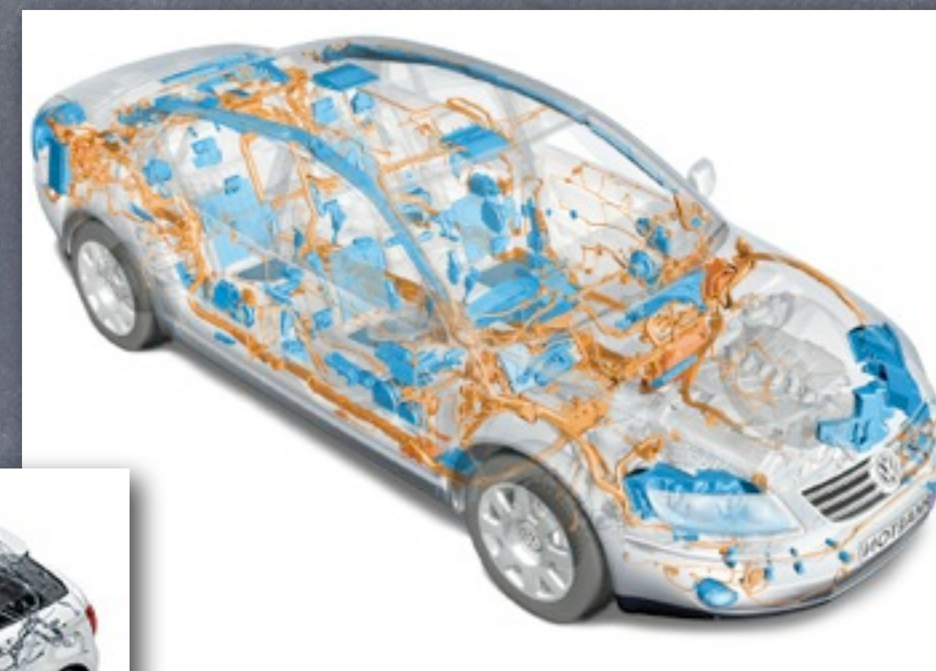
# System in field

# System in field

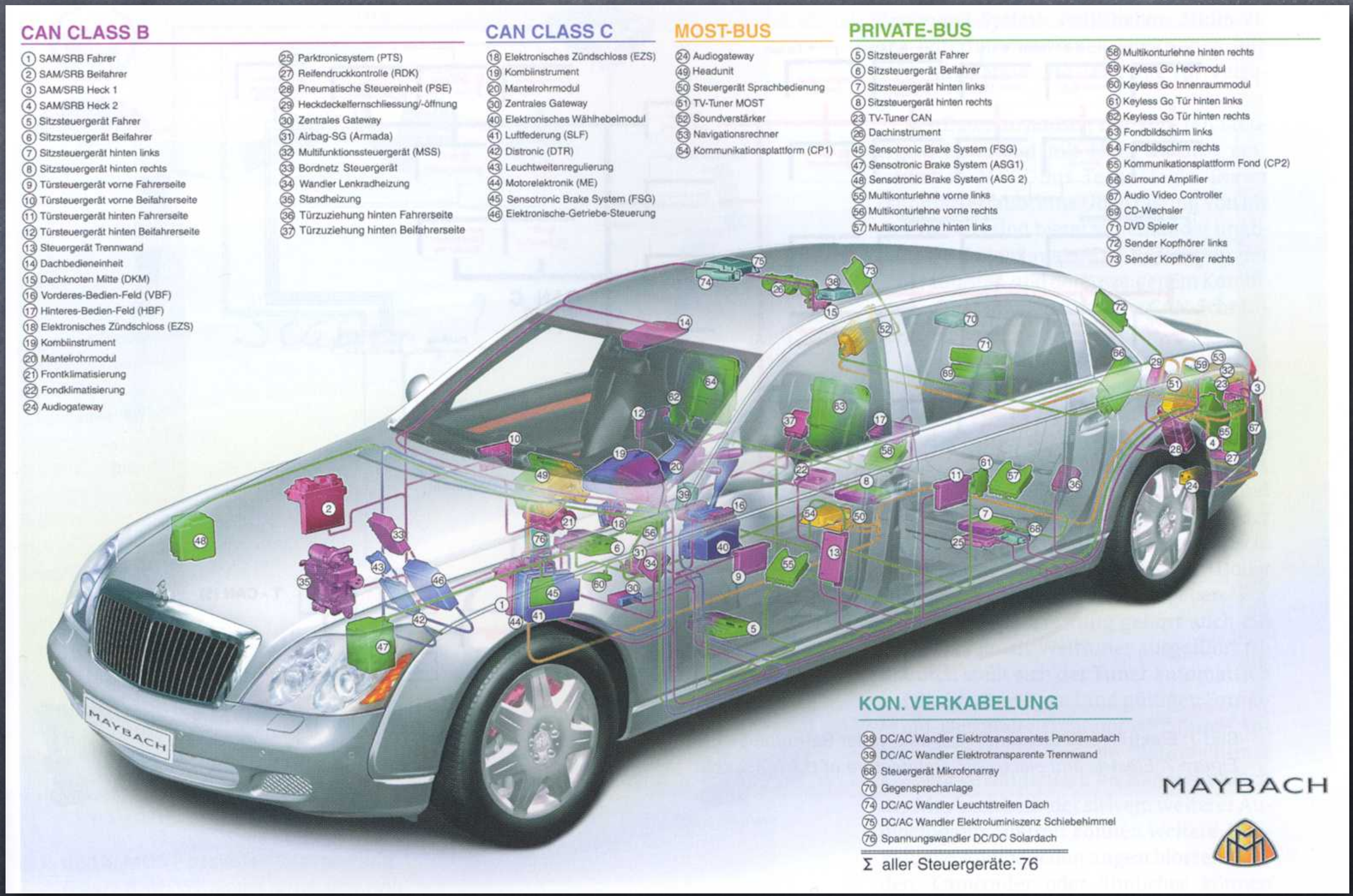
# Favourite plaything

# Rolling embedded system

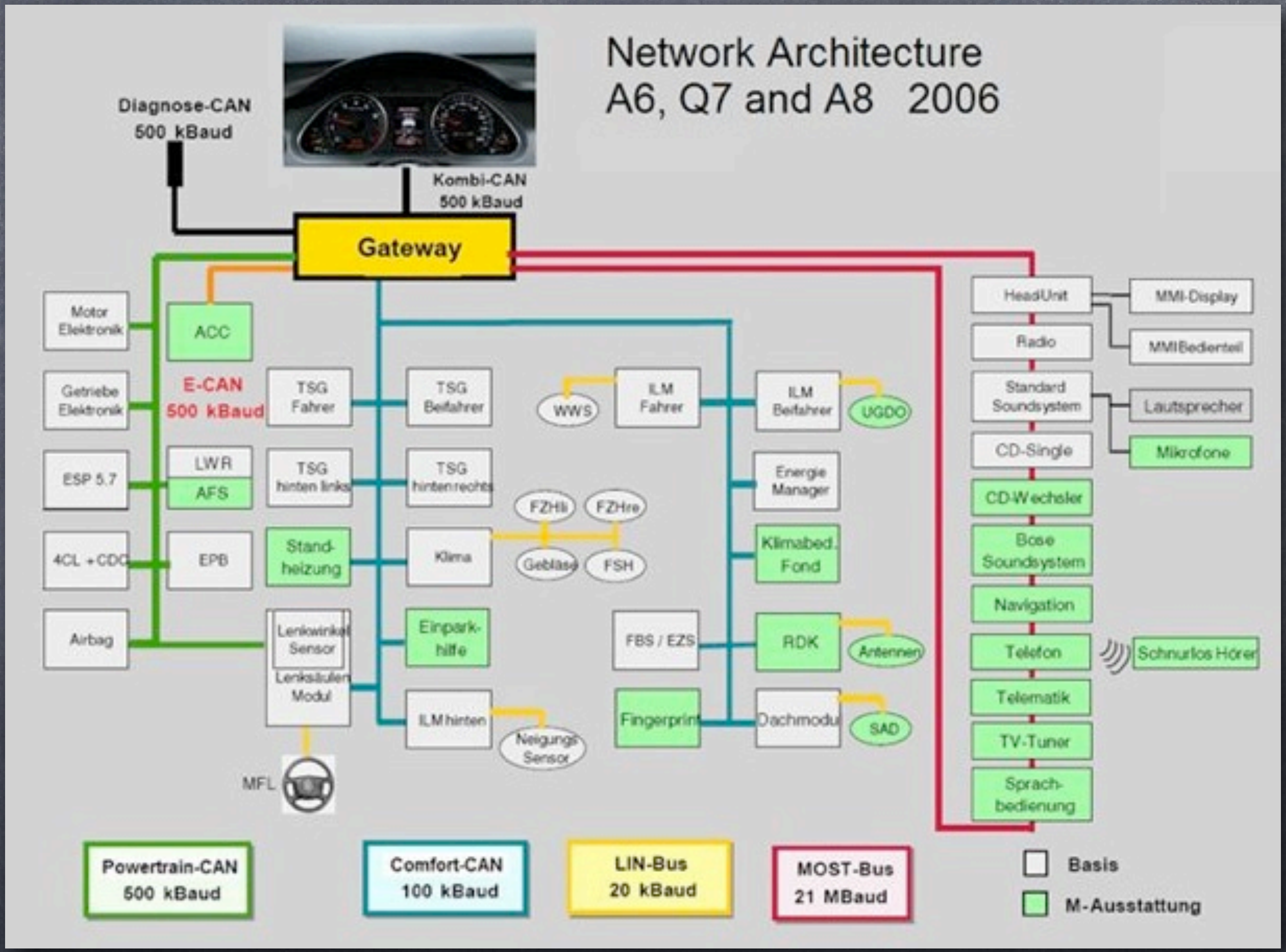


# Intranet on wheels

## – but not for much longer –



# Hybrid network



# Electronic control unit

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



# Breadboarding of a motor vehicle

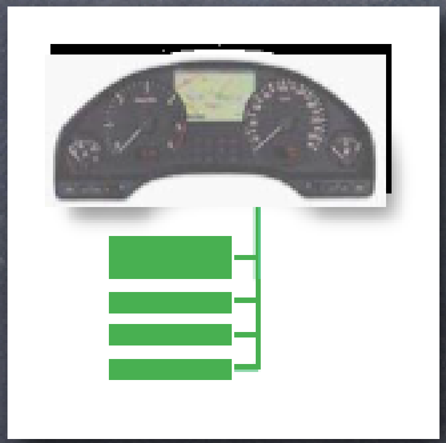
source: Audi AG

- Audi A6 (C6), detail

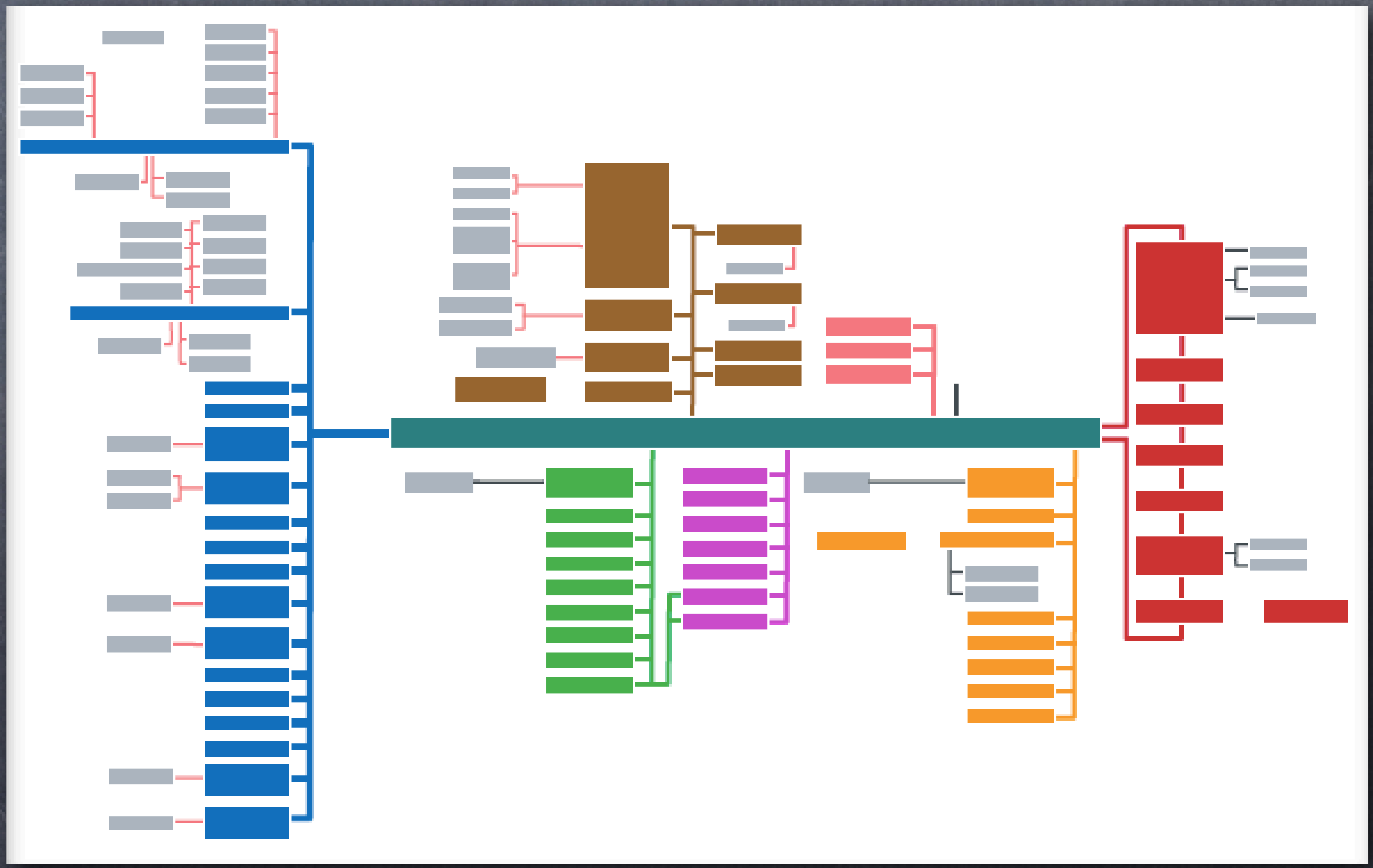
# Network complexity

- number of ECUs: Audi A8

D4, 2010

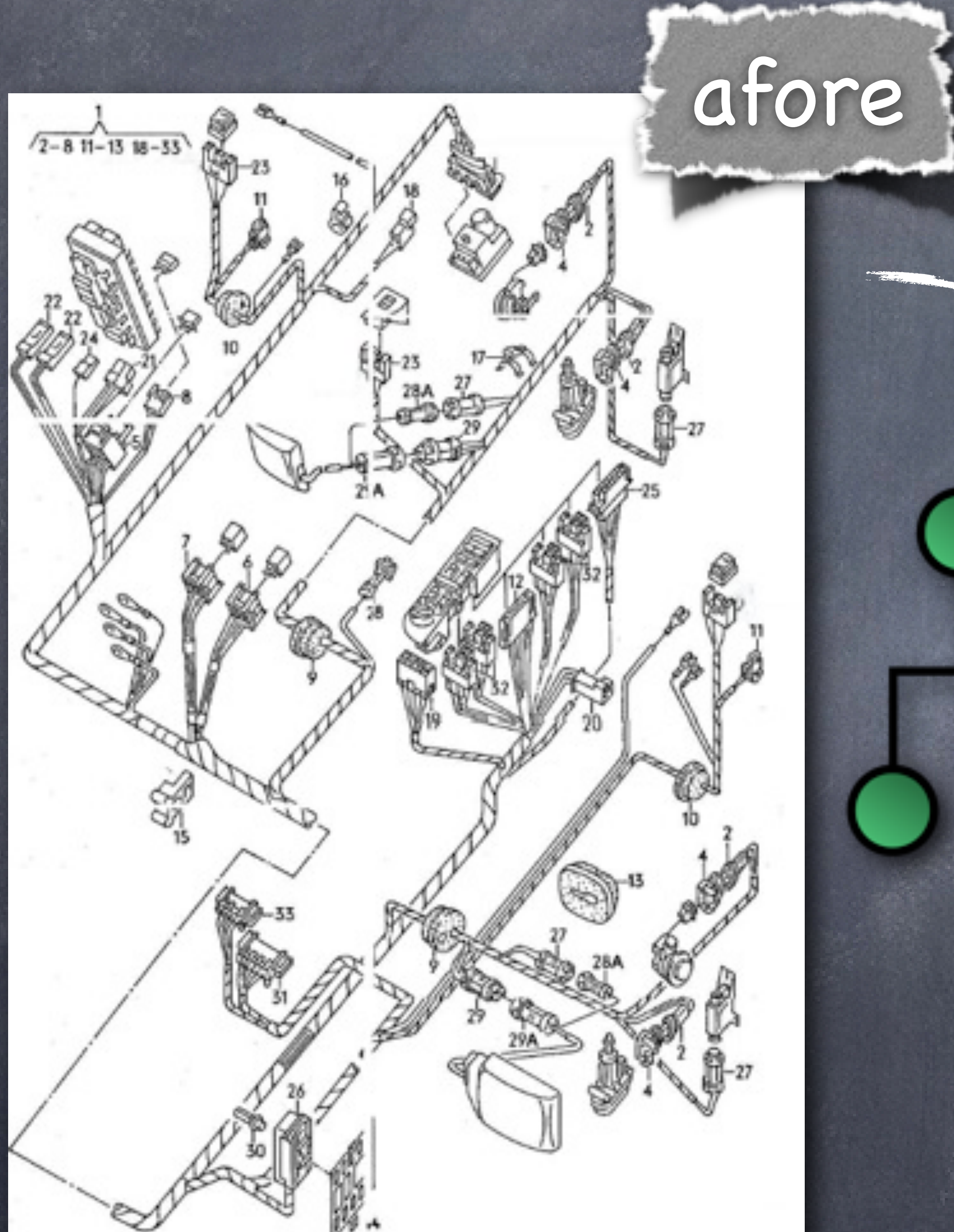


D2, 1993

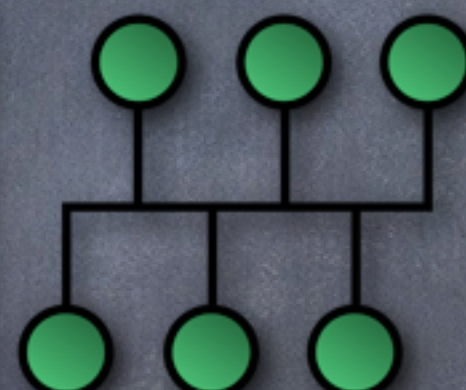


5 vs. > 100

# Through the ages

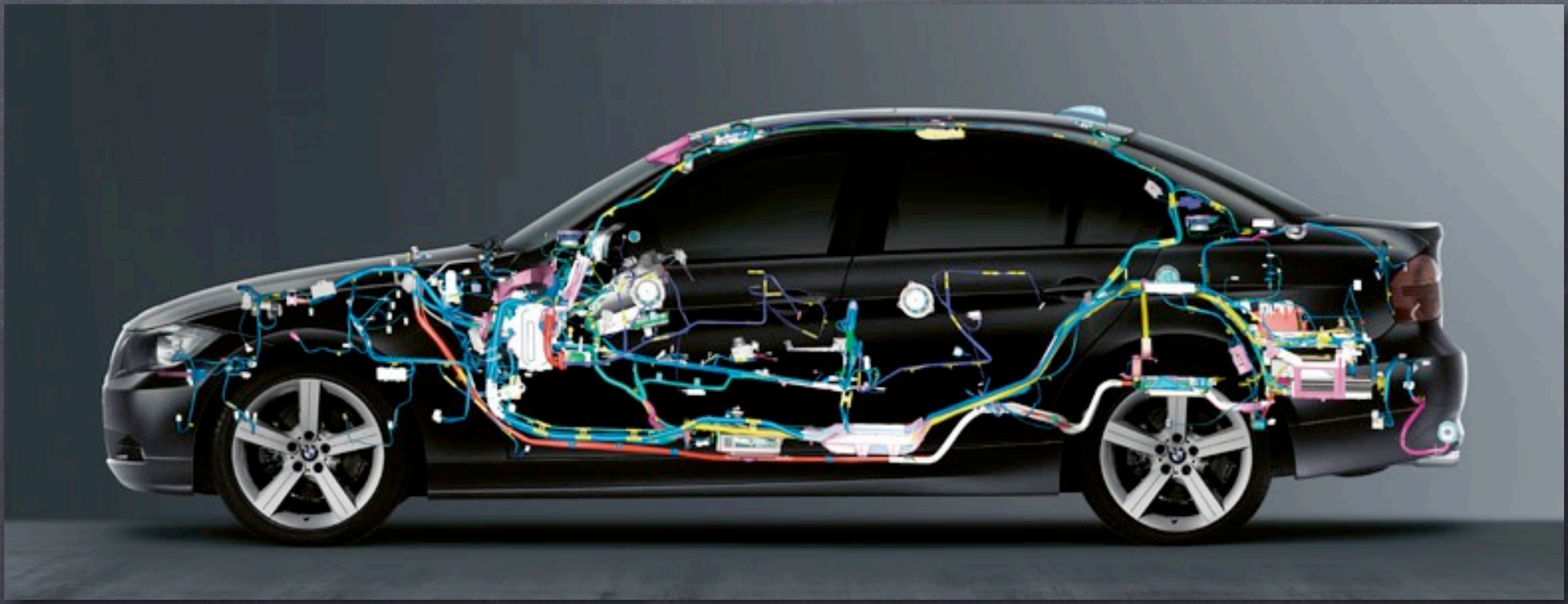



Audi V8, 1991




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

# Application consolidation

combines multiple applications

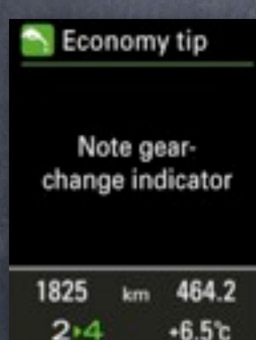
- of different types

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

# Constraint: Two-tier system

## soft real-time







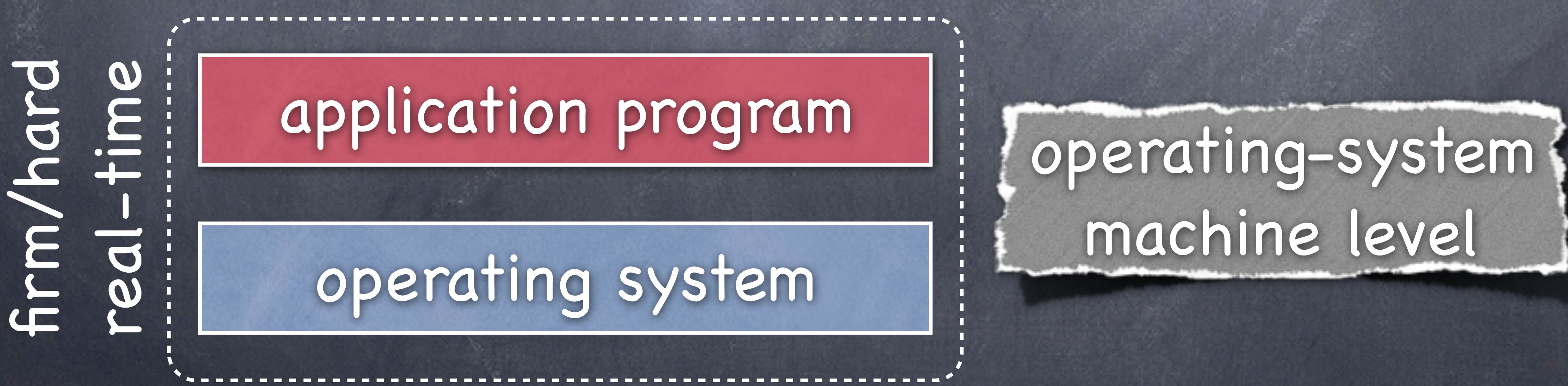
- QNX, CE, Linux

## firm/hard real-time

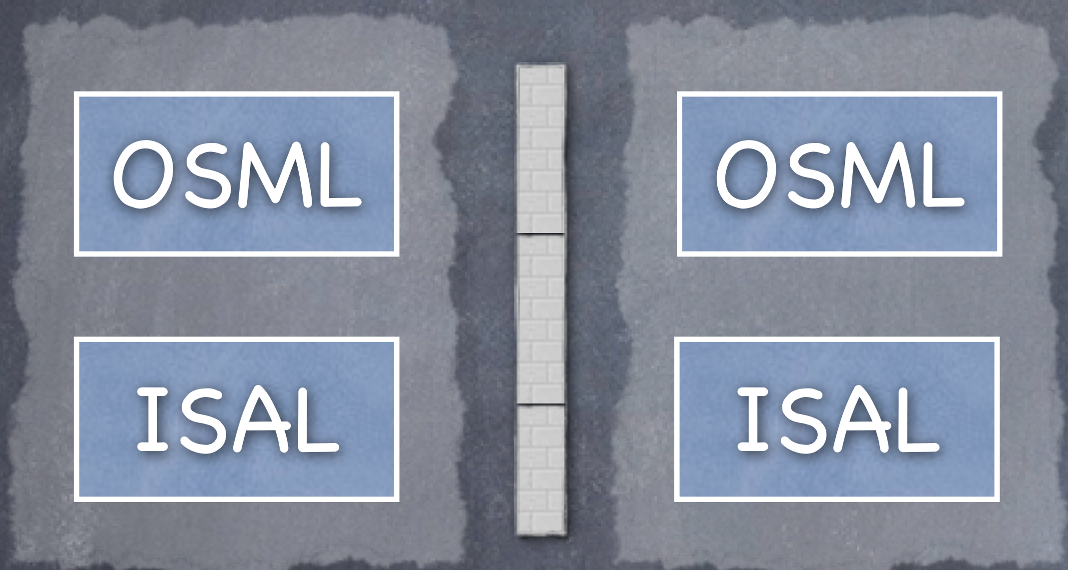
- ITRON, AUTOSAR

# 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

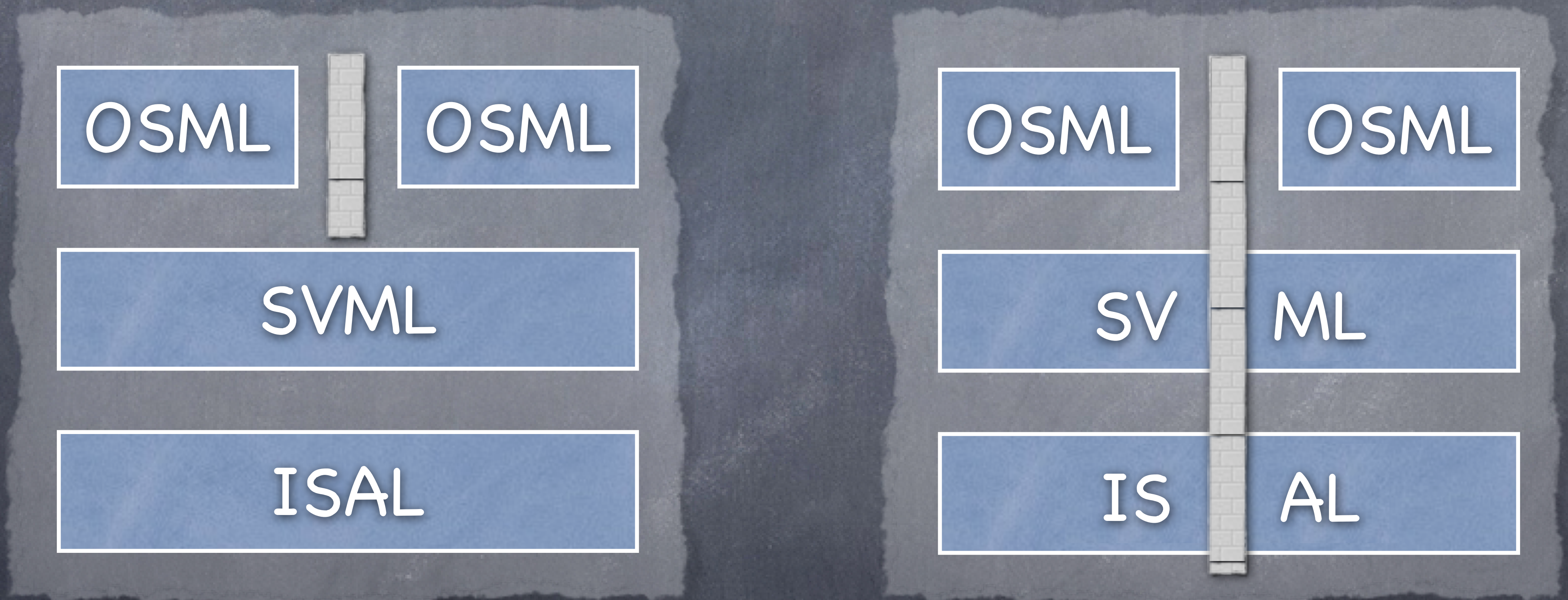



- one application per ECU
- co-location of multiple ECUs
- single site: motor vehicle

- 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


* 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

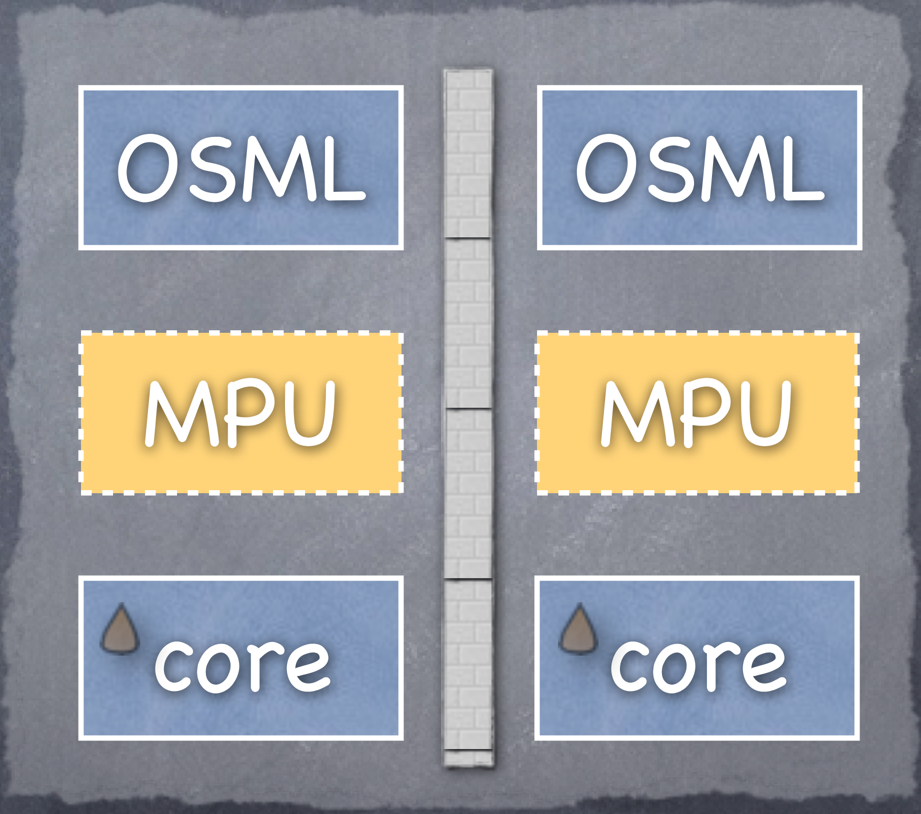
efficiency

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

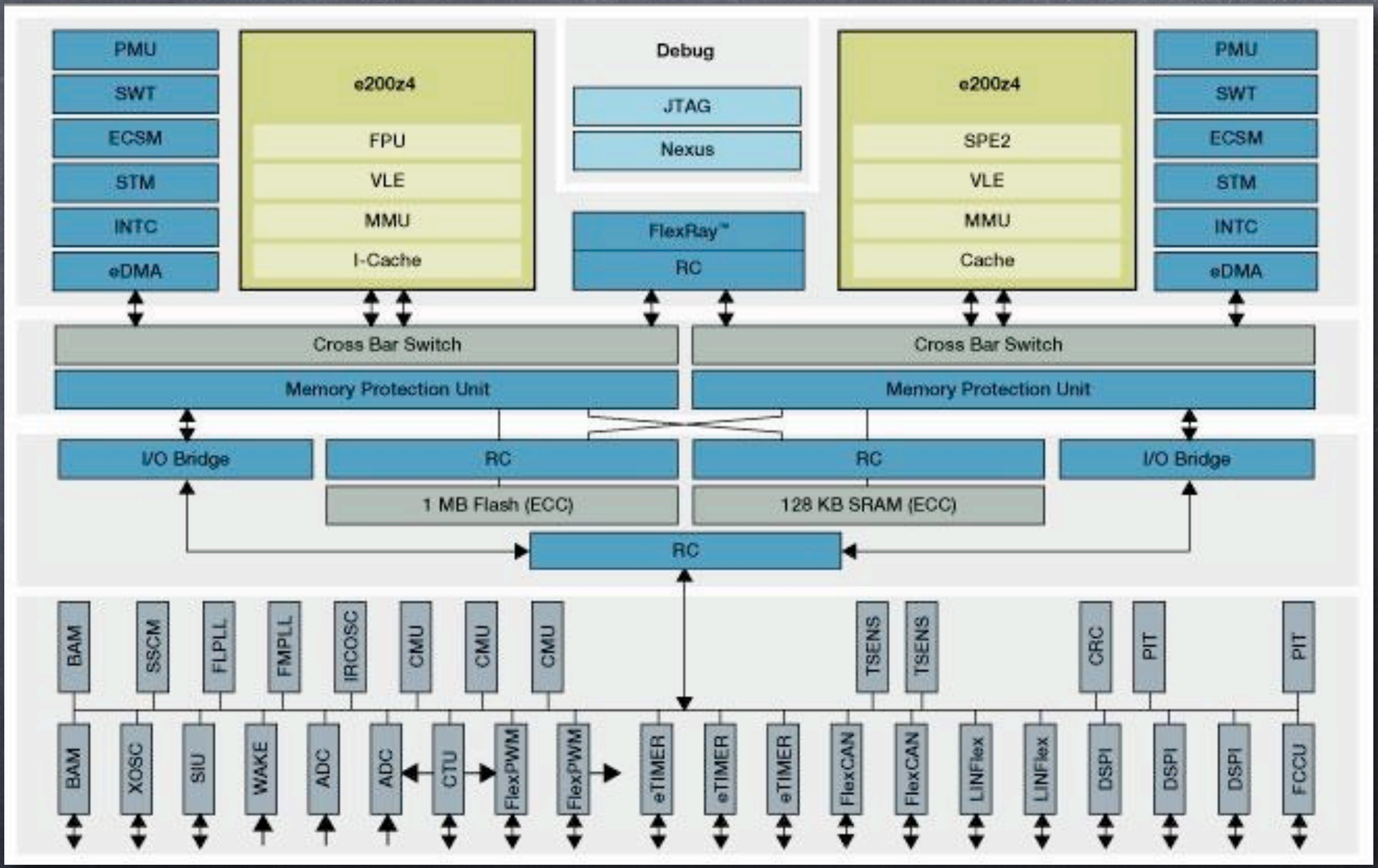
flexibility

# Partial virtualisation

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

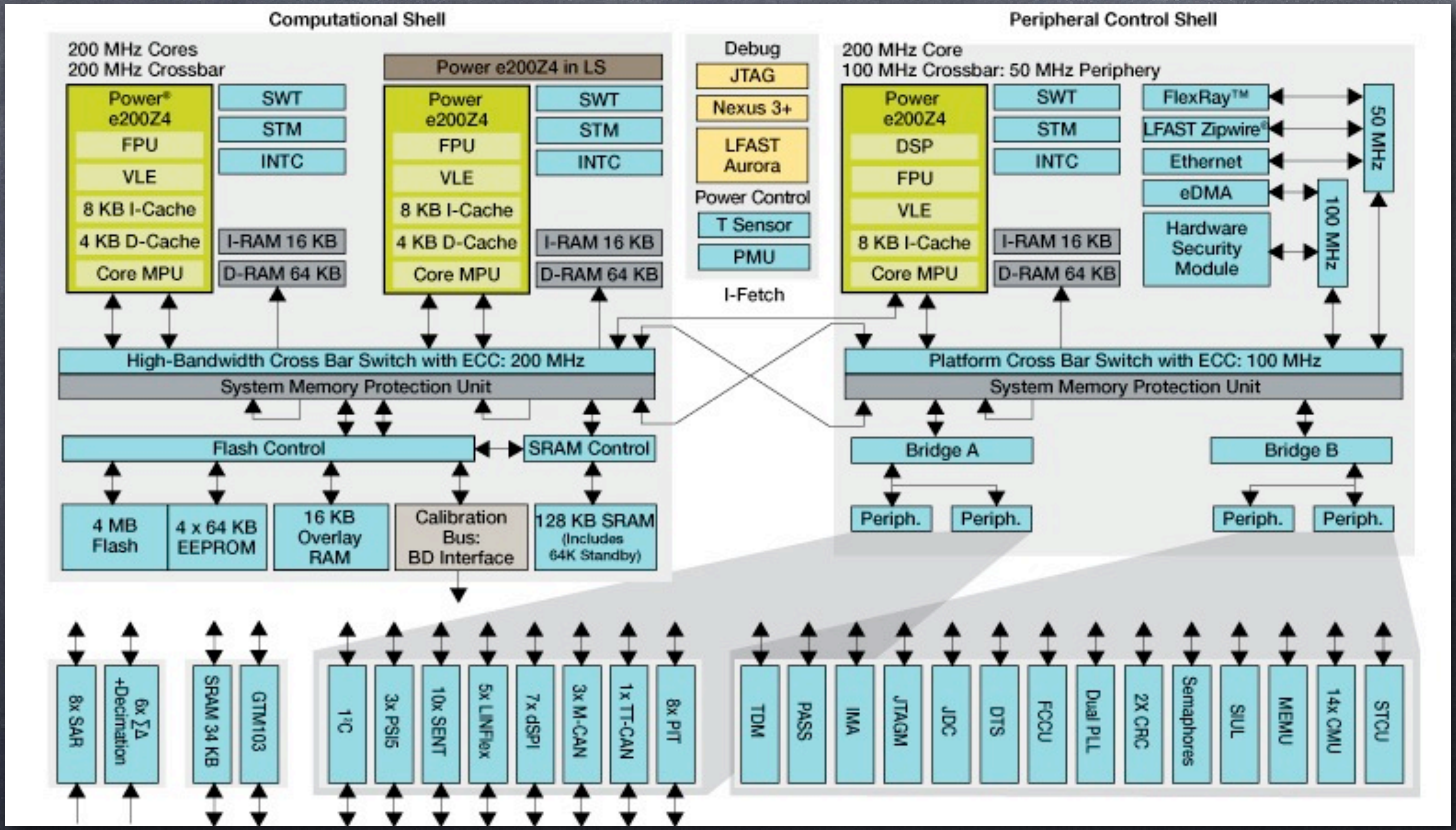


# Safety applications




MPC564xL

# Power-train applications



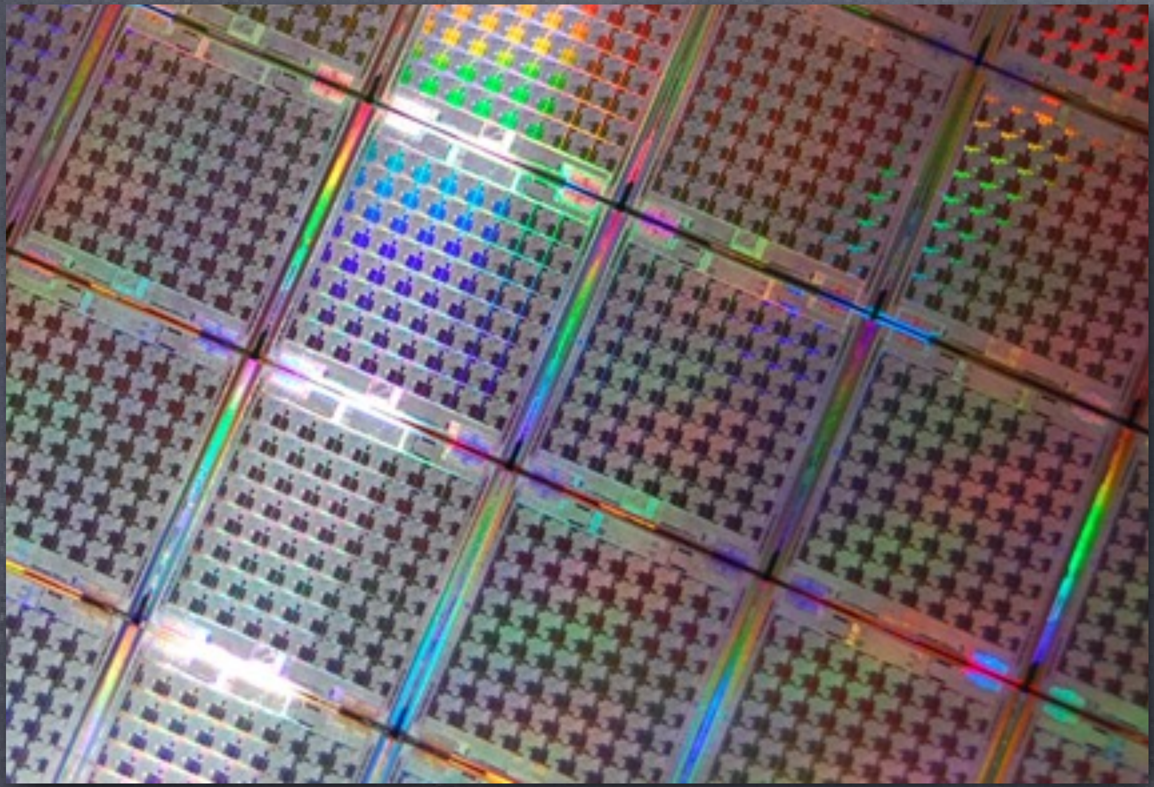

MPC5746M


Audi Calamaro Flying Car

# Parallel $\sim$ Embedded

# Parallel processing

# Parallel processor: CPU



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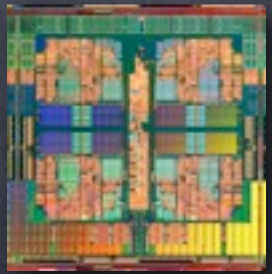

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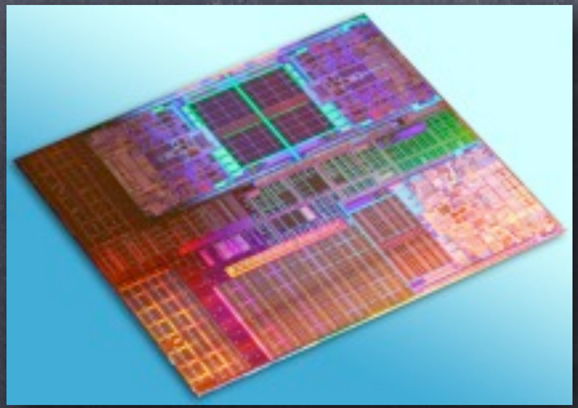

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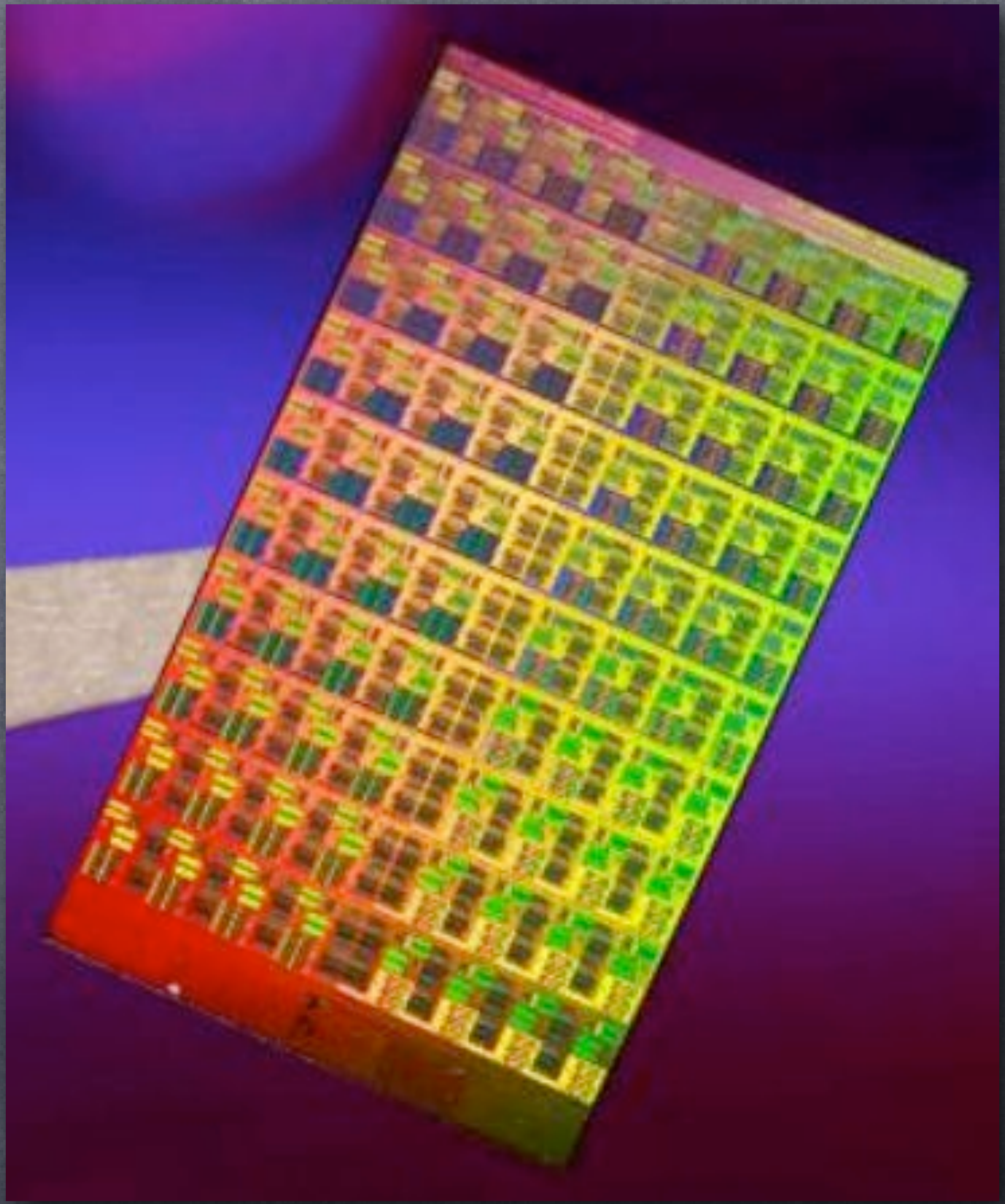

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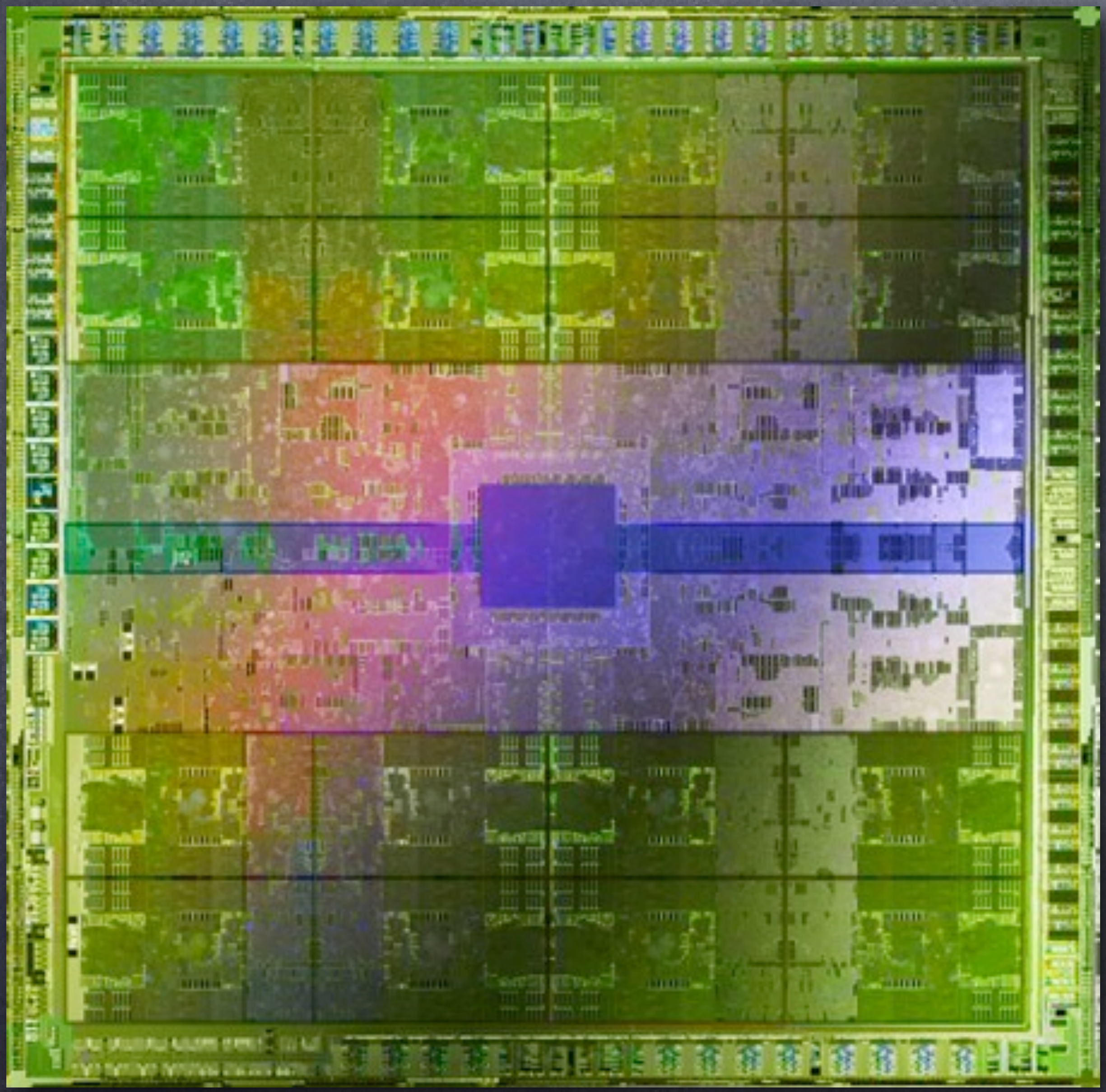
# Parallel processor: GPU



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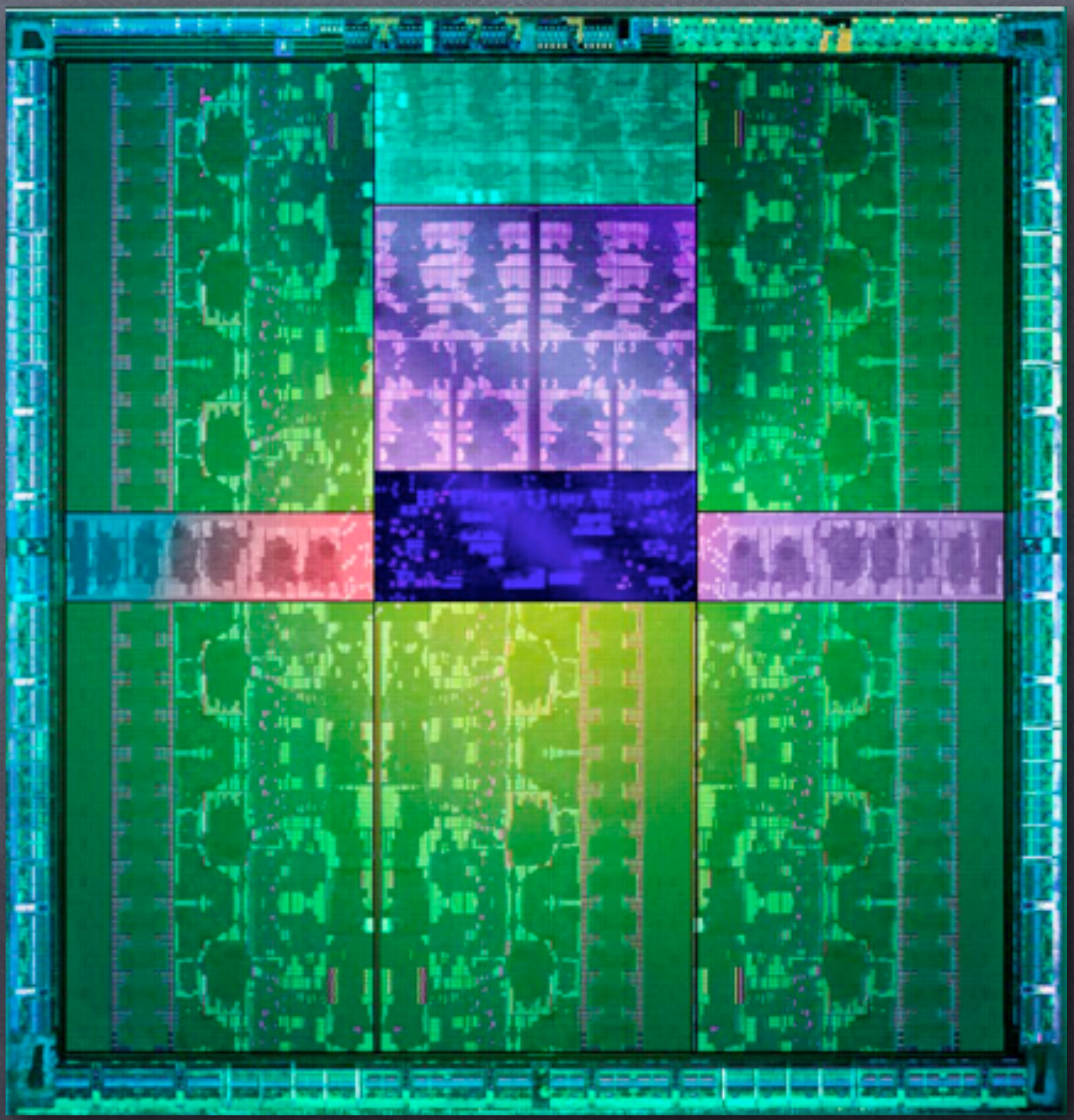

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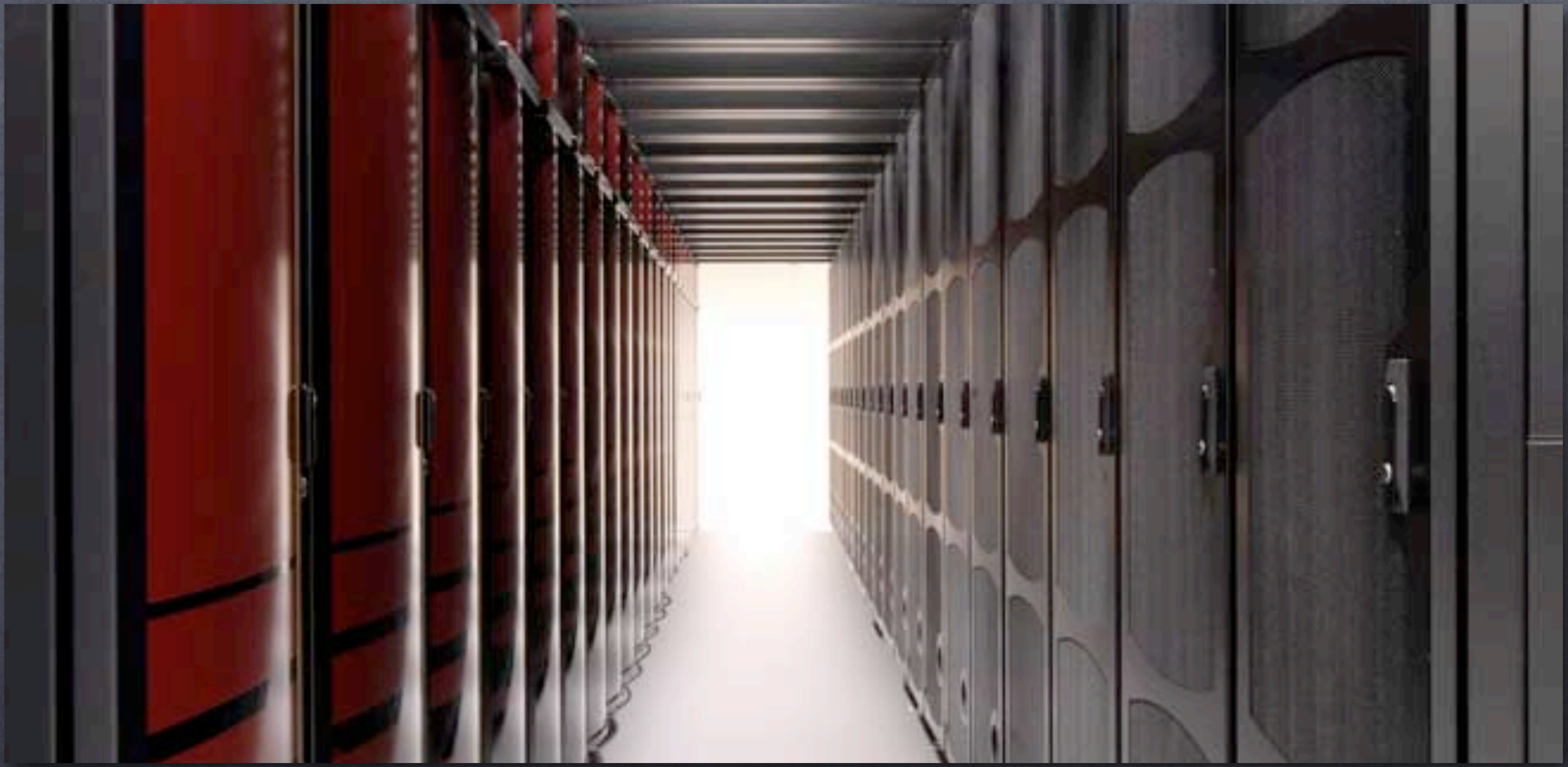
# Parallel system: HPC



3120000

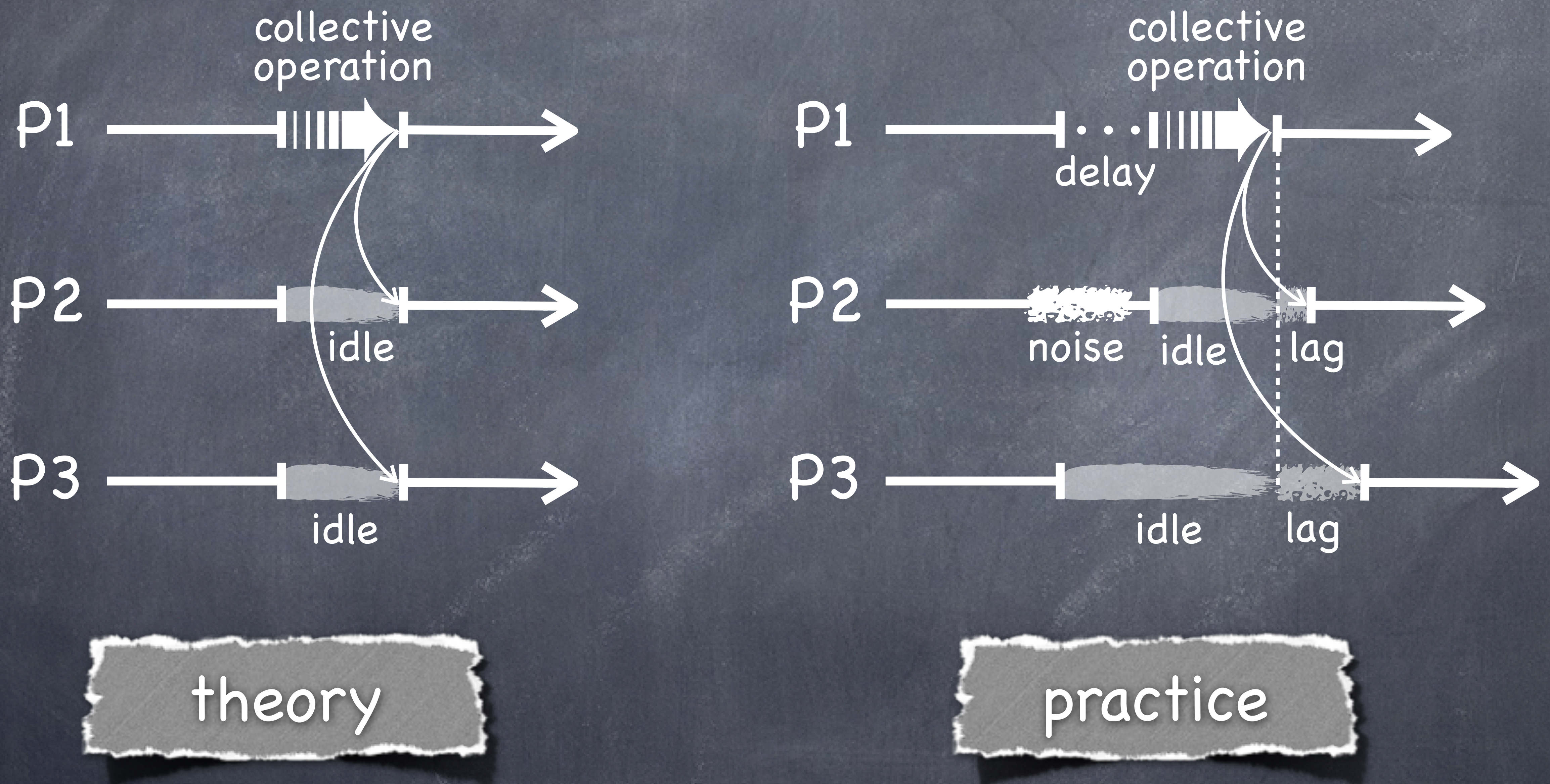
# Collective operations

- 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



# 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“

# 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"