Cyber Physical Systems
a perspective

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Agenda

- CPS definition
- What's new and what's special, with examples
- Research directions from literature

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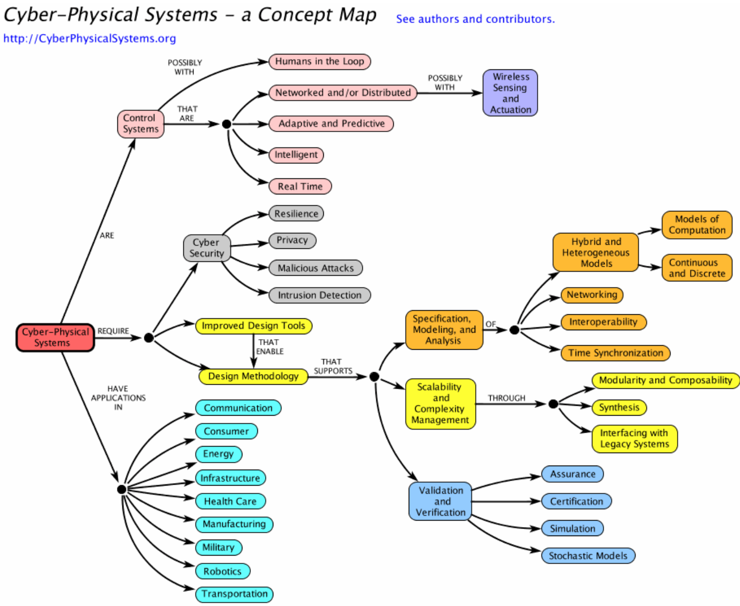
CPS: Definitions @ April 2013

- UC Berkeley (april 2013). *"Cyber-Physical Systems (CPS) are integrations of computation, networking, and physical processes."*
- *"Cyber-physical systems (CPS) are next-generation embedded systems featuring a tight integration of computational and physical elements."*



Annotated concept map from http://cyberphysicalsystems.org/

CPSNA 2013
The 1st International Conference on Cyber-Physical Systems, Networks, and Applications
Taipei, Taiwan August 19 - 20, 2013

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ICCPS @ April 2013

- *"Cyber-physical systems (CPS) are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core.*
- *This intimate coupling between the cyber and physical will be manifested from the nano-world to large-scale wide-area systems of systems.*
- *And at multiple time-scales."*

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Two more definitions

- *“A cyber-physical application is a computer system that processes and reacts to data from external stimuli from the physical world and make decisions that also impact the physical world”*
  - J. Sztipanovits. Composition of Cyber-Physical Systems. In: Engineering of Computer-Based Systems, 2007. ECBS’07
    (cited from White et.al;, R&D challenges and solutions for mobile cyber-physical applications and supporting Internet services, Journal of Internet Services and Applications, May 2010, Volume 1, Issue 1, pp 45-56)

- *“A cyber-physical system (CPS) is a system featuring a tight combination of, and coordination between, the system’s computational and physical elements.”*
  - Wikipedia, May 2013

So, CPS is…

- something that's more than just control through embedded electronics
- a CPS impacts on the world
- we don't have them yet
- it will come and be very important
- hm

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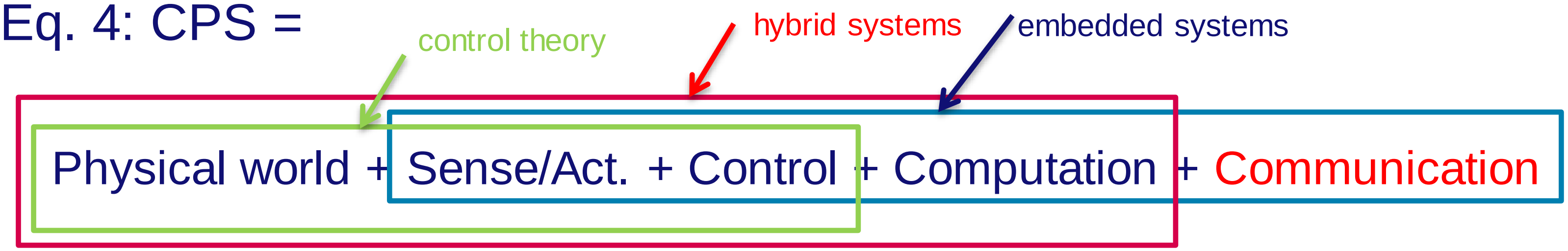
So, what is CPS?

- Eq. 1: CPS = Computing + Control
  - (“Embedded 2.0”)
- Eq. 2: CPS = Embedded Systems + Internet of Things
  - (“Embedded meets Ubiquitous Sensing and Communication”)
- Eq. 3: CPS = Embedded Systems + Internet Services
  - (“Embedded meets Big Data”, “Virtual embedding”)

- Eq. 4: CPS =



- *The novelty is to consider them all together*
  - a theory of CPS, in which 5 aspects influence each other
    - (perhaps 6, if you include data)

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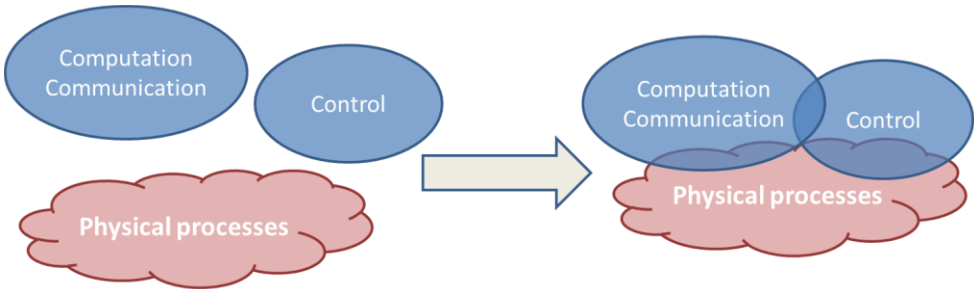
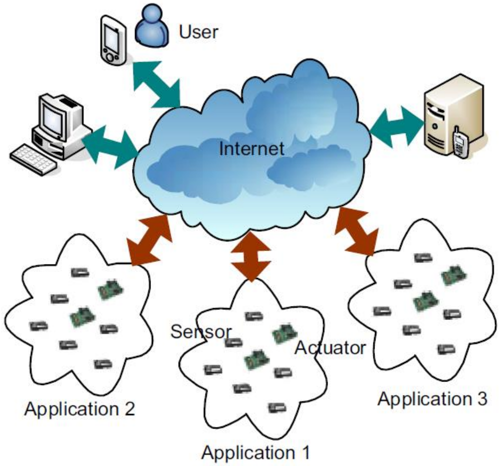
Two directions

1. High-performance control systems



2. Deep penetration of sensing and actuation into the physical world
   - Internet of Things
     - unified protocol and addressing scheme between any pair of (electronically enriched) objects
     - service discovery, (resource) management
     - large-scale heterogeneous data processing



From: *Network QoS Management in Cyber-Physical Systems,* Feng Xia et. al

- (CPS) challenges of both:
  - *robustness* under *uncertainty* and *complexity*
  - much *tighter* integration

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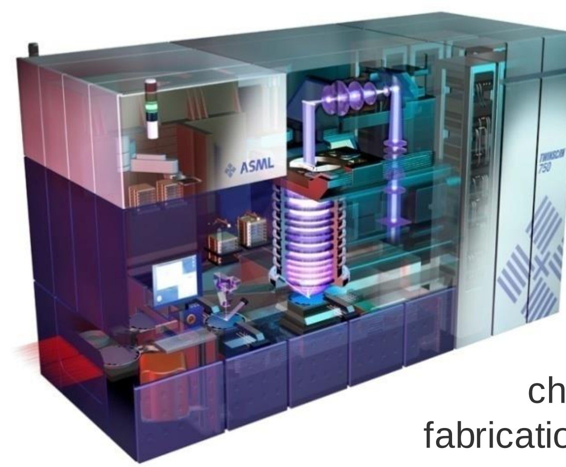
Examples (from STW RobustCPS)

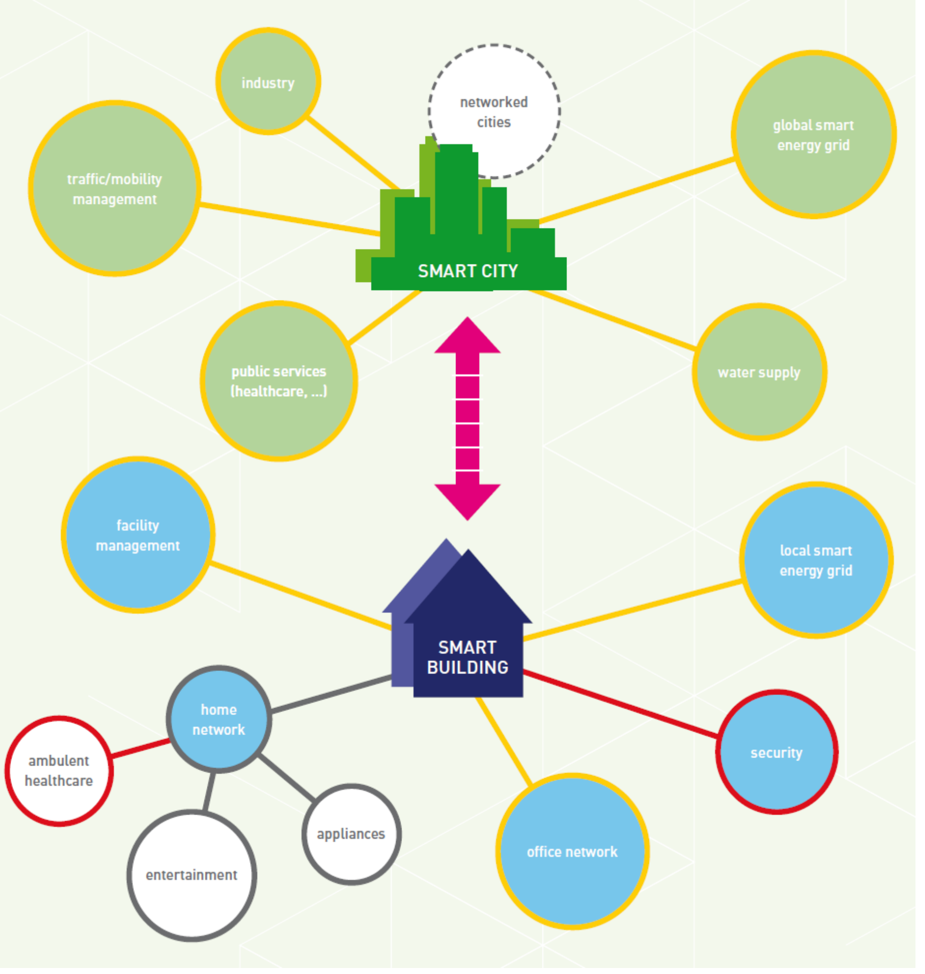


Example (from the ACCUS project)

- Integration of independent urban subsystems

- New applications…
  - …operating *across* different subsystems
  - …using services of different subsystems

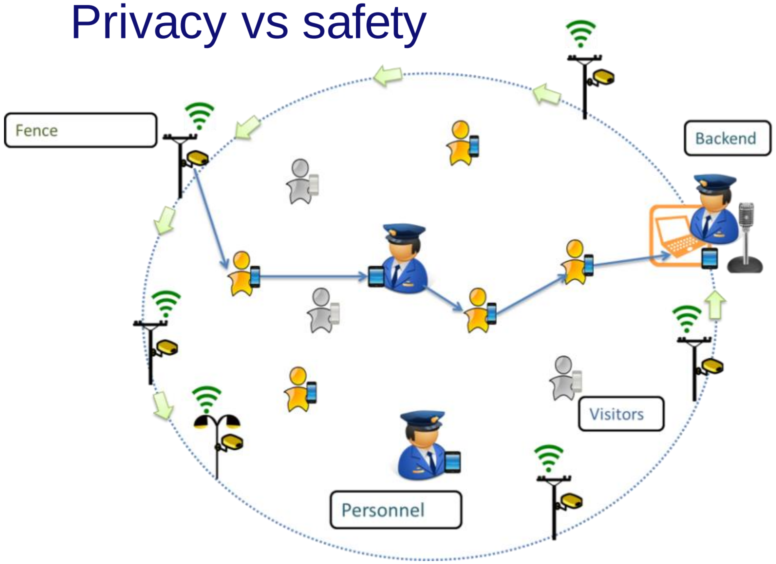
- Examples:
  - *emergency response*:
    - use traffic lights, street lighting and vehicle guidance
  - *energy optimization*



Example (from the SENSAFETY project)

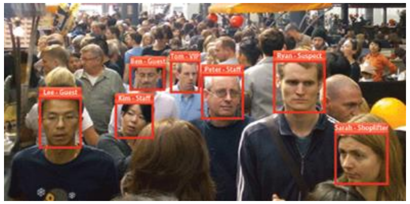
Twitter and facebook are sensors…
Smartphones are sensors..
Fences have sensors…
Camera's everywhere…

- In-network processing to reduce traffic
- Latency vs bandwidth vs storage
- Privacy vs safety



Backend combines information from different networks (ad-hoc, dedicated, internet)

SENSAFETY Festival App



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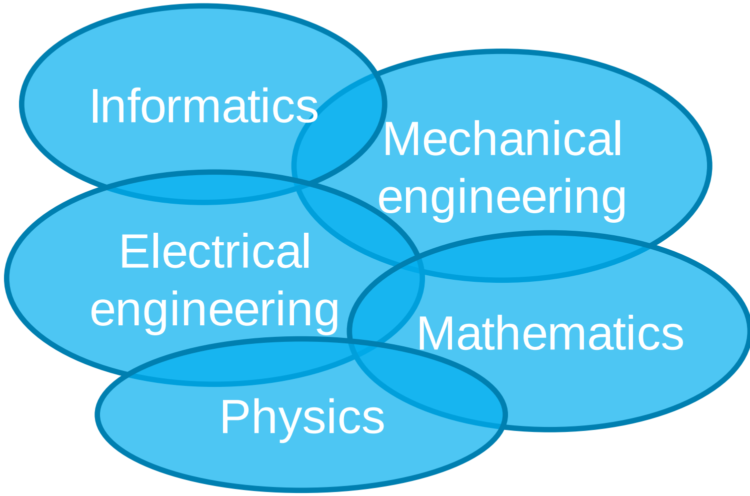
So, CPS is newish (since ~2008)

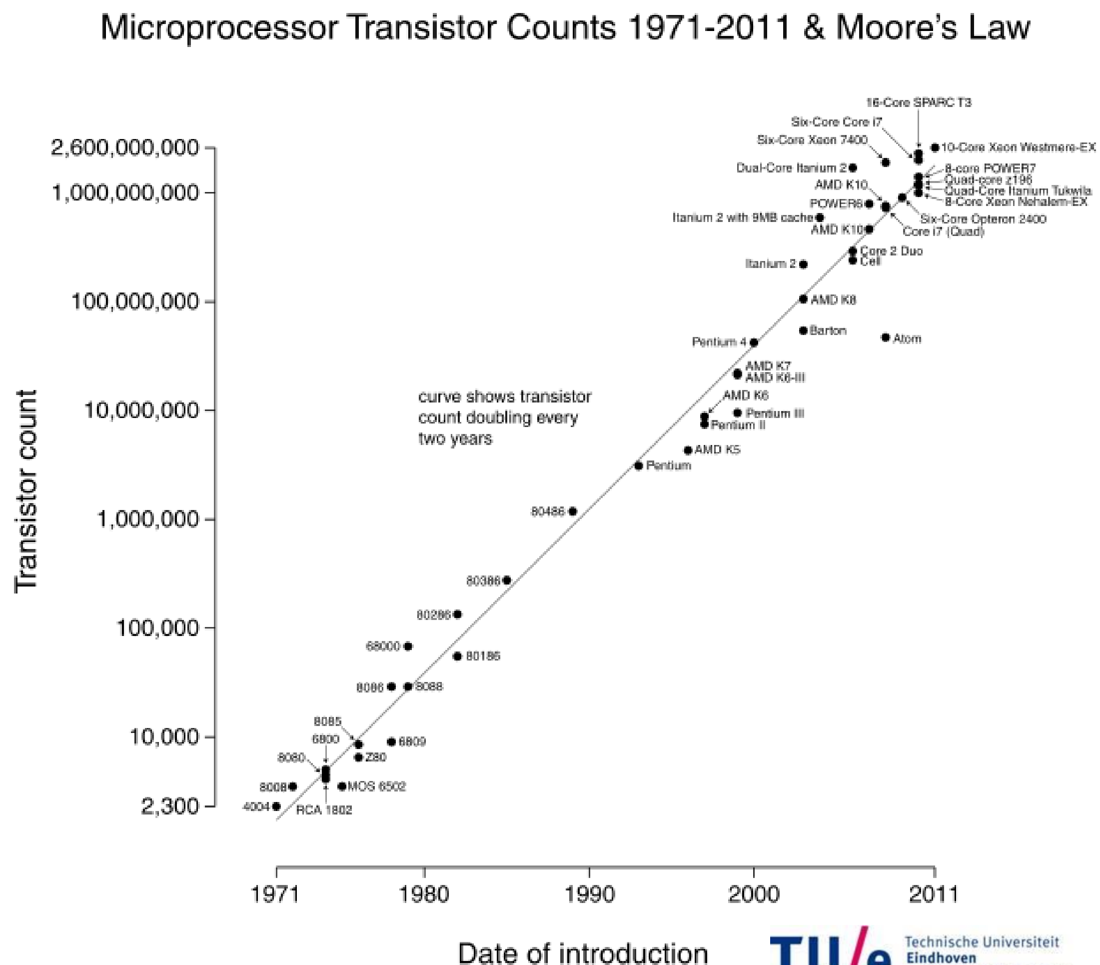
- What makes it interesting to lift the strict separation of domains (separation of concerns!) ?



1. the business of exponential growth
2. higher efficiency, lower cost
3. integration of *systems* rather than *components*
4. networked control, in multiple layers
5. ubiquitous systems and wireless technology

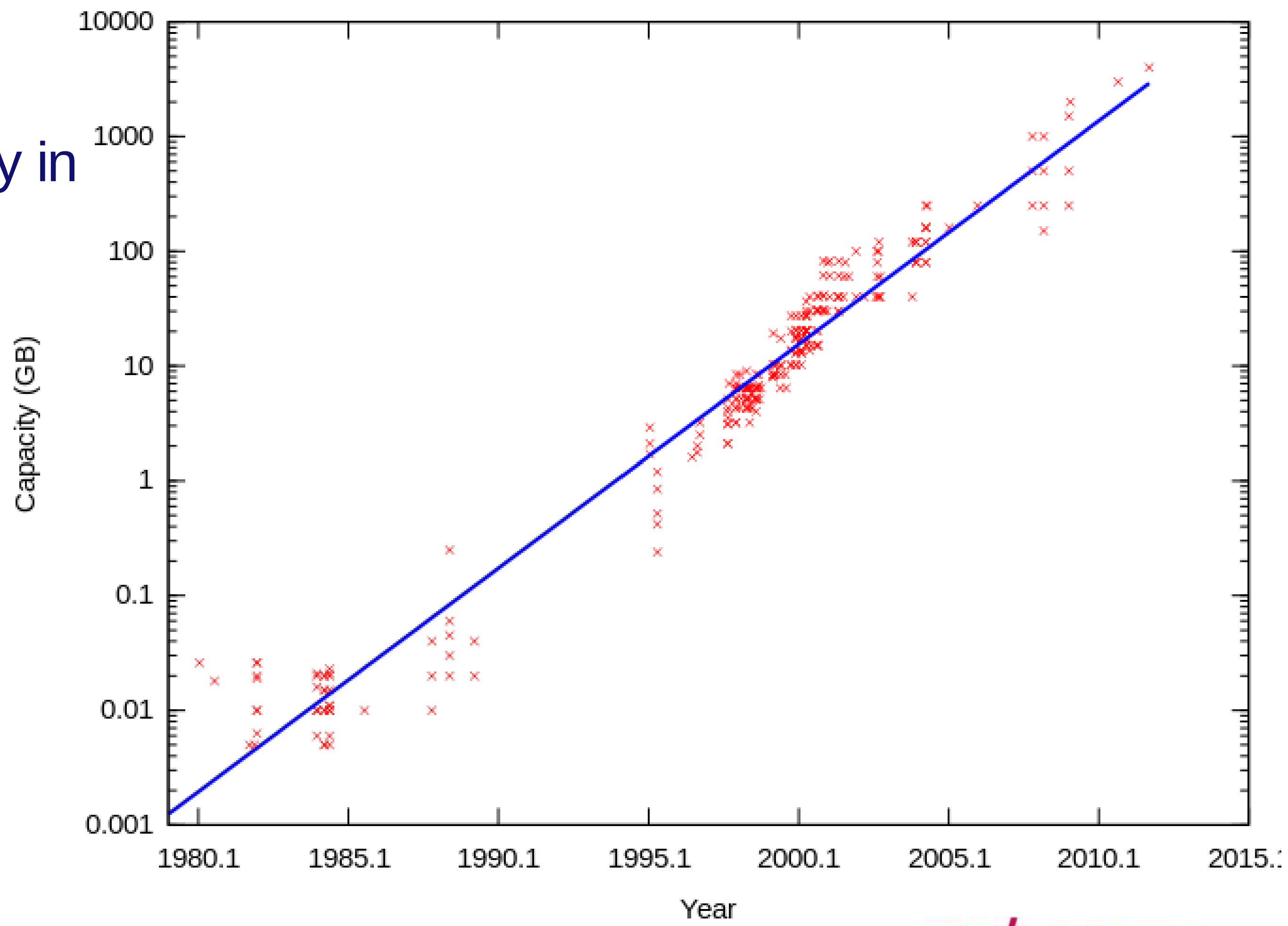
The business of exponential growth

- Moore's law
  - # transistors / area doubles every two years
  - (… at the same price)



The business of exponential growth

- Kryder's law
  - storage capacity in # bits / surface doubles every 18 months
  - 14TB @ $40 in 2020



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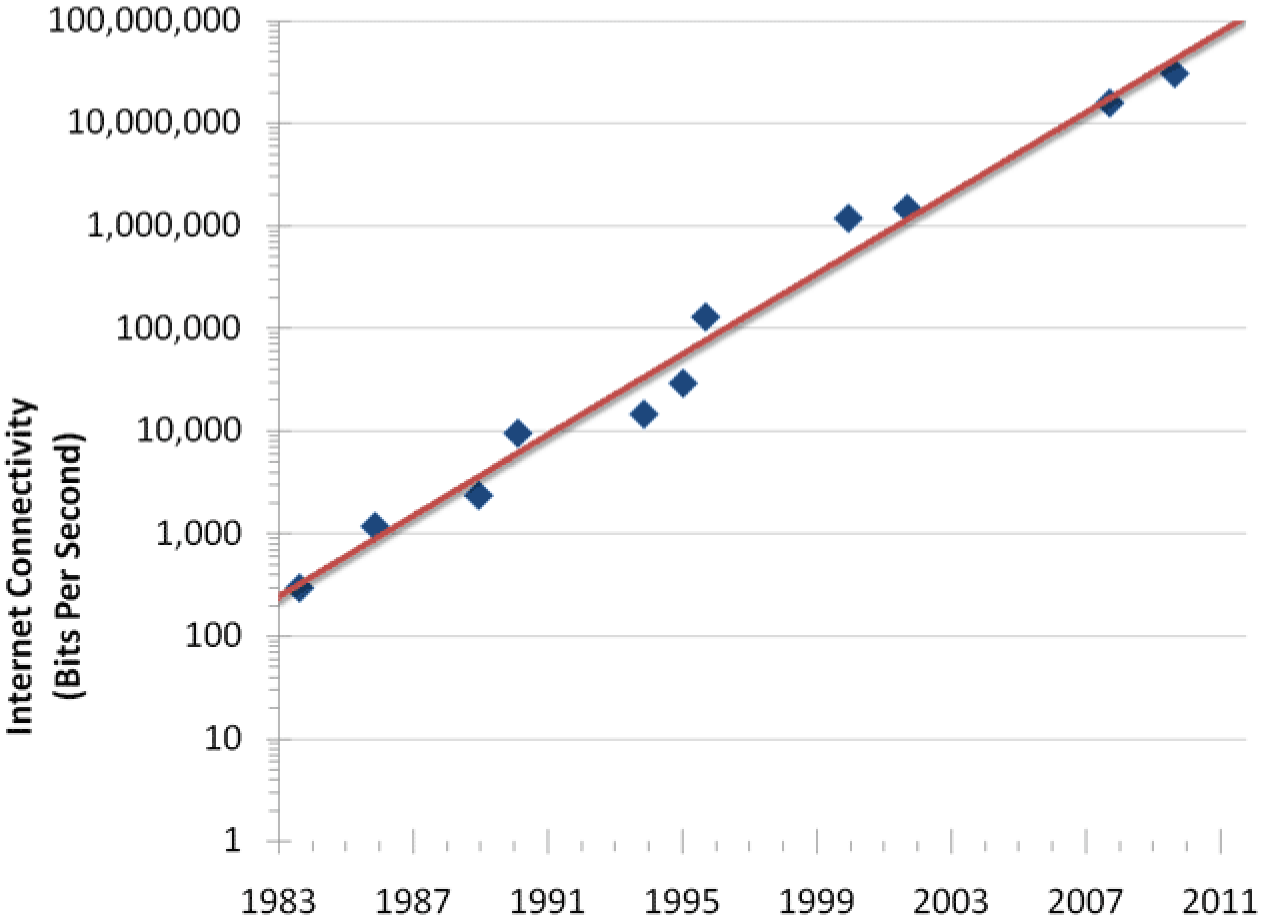
The business of exponential growth

- Nielsen's law
  - a high-end-user's connection speed grows by 50% annually



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The business of exponential growth

- Gilder's 'law': the total bandwidth of the Internet triples every year
- Metcalfe's 'law': the value of a (telecommunication) network is proportional to the square of connected users

TED talk Peter Diamandis: Abundance is our future

Progress over the past 100 years:

Average human lifespan:	↑	2x
Avg. per-capita Income:	↑	3x
Childhood Mortality:	↓	10x
Cost of Food:	↓	10x
Cost of Electricity:	↓	20x
Cost of Transportation:	↓	100x
Cost of Communications:	↓	1000x

Technologies riding Moore's Law

1. Infinite Computing
2. Sensor & Networks
3. Robotics
4. 3D Printing
5. Synthetic Biology
6. Digital Medicine
7. Nanomaterials
8. Artificial Intelligence

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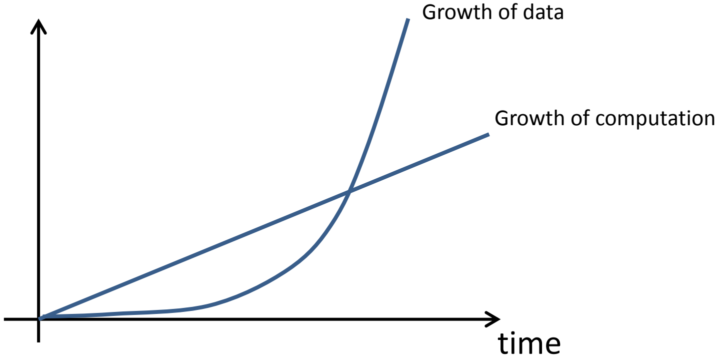
Consequences to the embedded domain

- Enormous processing capacity in control loops
  - good! we want higher sampling rates and more control loops
- Enormous amounts of data to act upon
  - coming from extensive sensing, high-resolution images, higher rates



- Latency requirements and storage restrictions lead to complex challenges
  - *distributed* processing, reducing data volume and response latency
    - using knowledge of physical processes and application requirements
      - e.g. to determine order, and quality of processing
  - network as part of the control system

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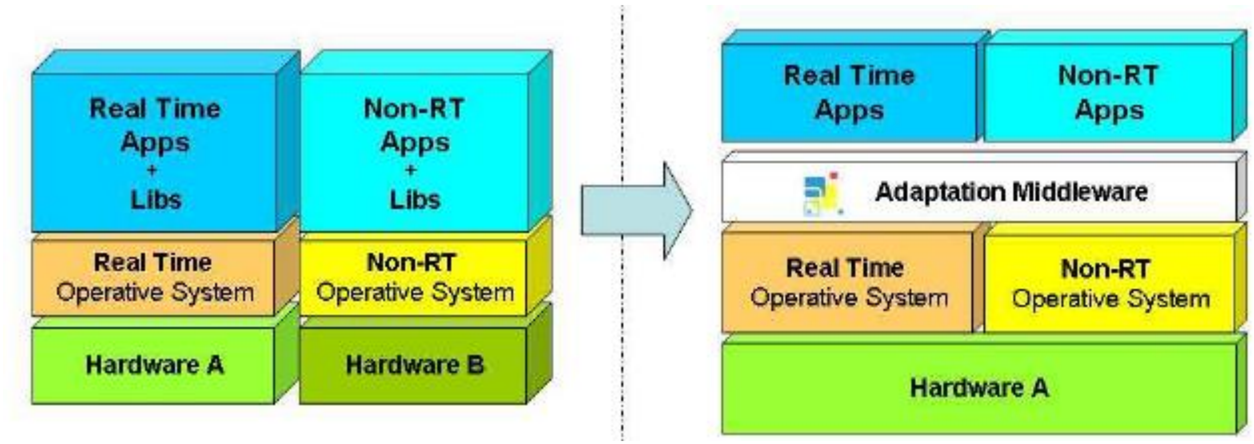
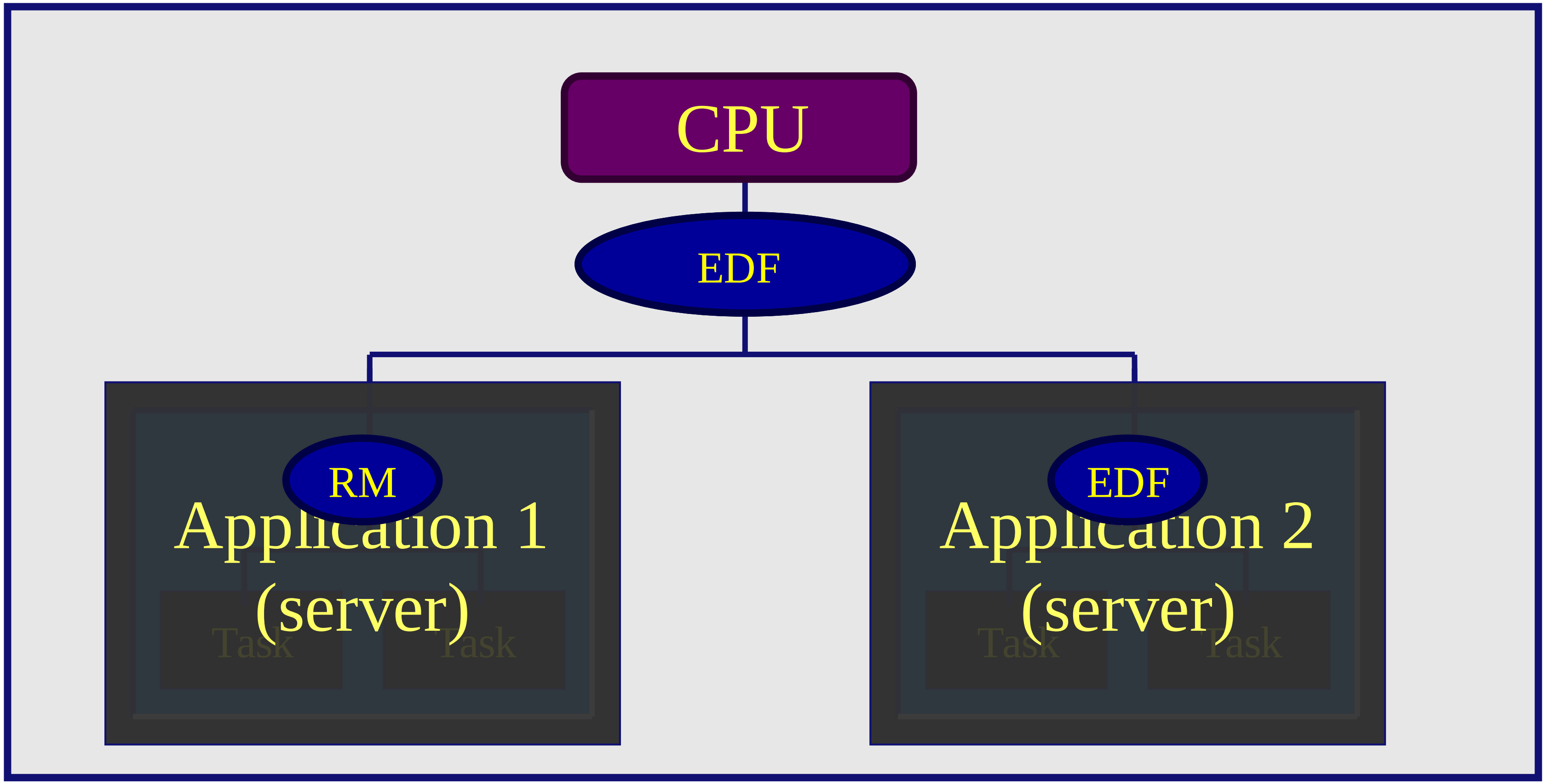
Higher efficiency, lower cost

- Integrate different applications on the same hardware
  - must still guarantee spatial and temporal protection
  - mixed-criticality systems



Federated Integrated

Sharing by multiple critical applications



Tasks, located in arbitrary applications, may share resources

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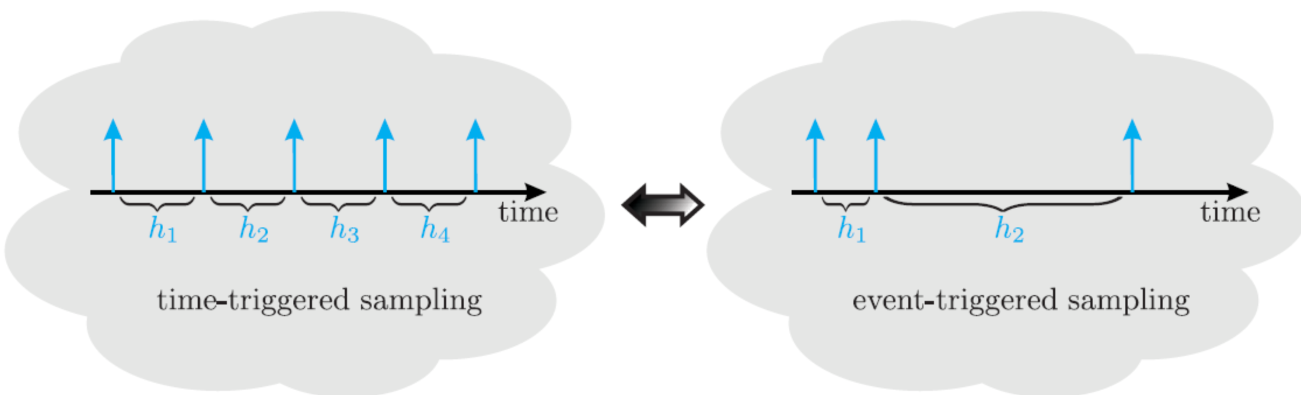
Higher efficiency, lower cost

- "Control on demand" saves resources and energy
  - corrective action based on state or output of system
    - event-based control, stability-dependent deadlines:
      - determine interval in which action must be taken
      - determine consequences of delayed action
    - self-triggered control



picture by Maurice Heemels

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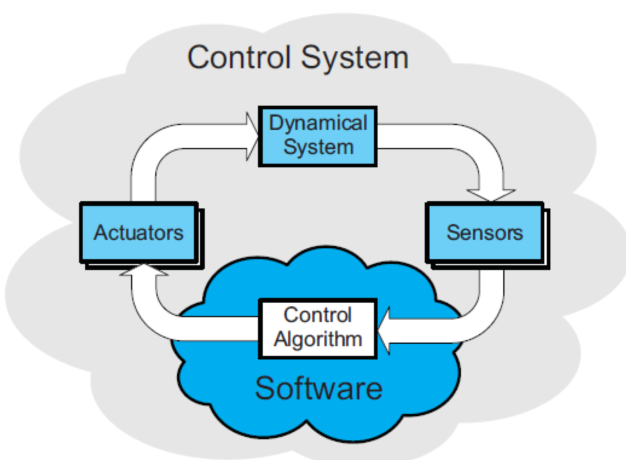
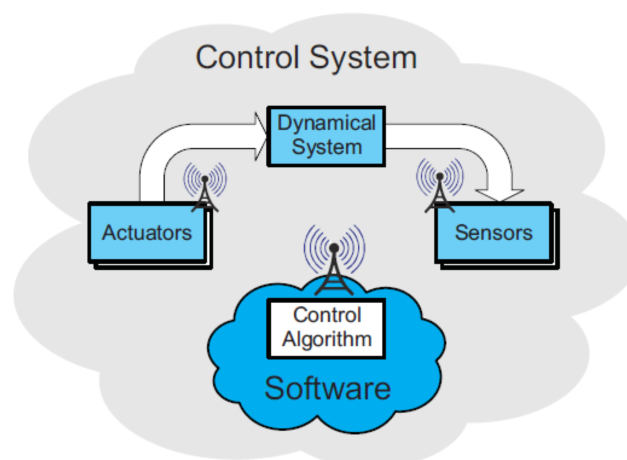
Higher efficiency, lower cost

- Technology is not perfect
  - 'perfect' can be extremely costly, or impossible
    - e.g. wireless communication, with inherent limitations, is nevertheless used in control systems
  - analyze impact of relaxed assumptions on physicical system
    - packet loss, delay
  - *Trade quality of service versus quality of control*



$\Rightarrow$



picture by Maurice Heemels

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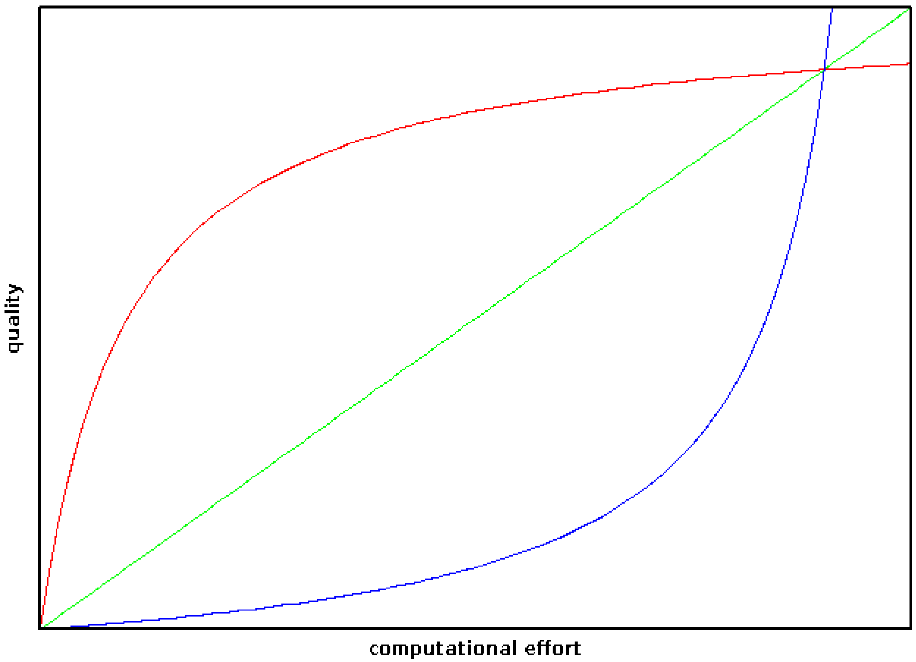
Higher efficiency, lower cost

- The highest quality outcome of subsystems is not always required
  - (response-)time versus quality trade-off

- An “any-time” algorithm
  - provides a valid solution any time when it is interrupted
  - increases quality over time

- Examples:
  - Newton-Raphson
  - Trajectory estimation
  - Video decoders



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Integrate systems instead of components

- Feedback control loops spanning multiple layers, networks and time scales
  - integration of *systems* rather than of (dedicated) *components*
    - "Systems of Systems"
  - leading to *resource sharing* within systems by applications with distinct importance
    - "mixed criticality" (see before)

- 'System perimeter' much less clear
  - systems must work with *incomplete knowledge*, and uncertainty about their context
  - "virtual embedding": use Internet services in embedded systems

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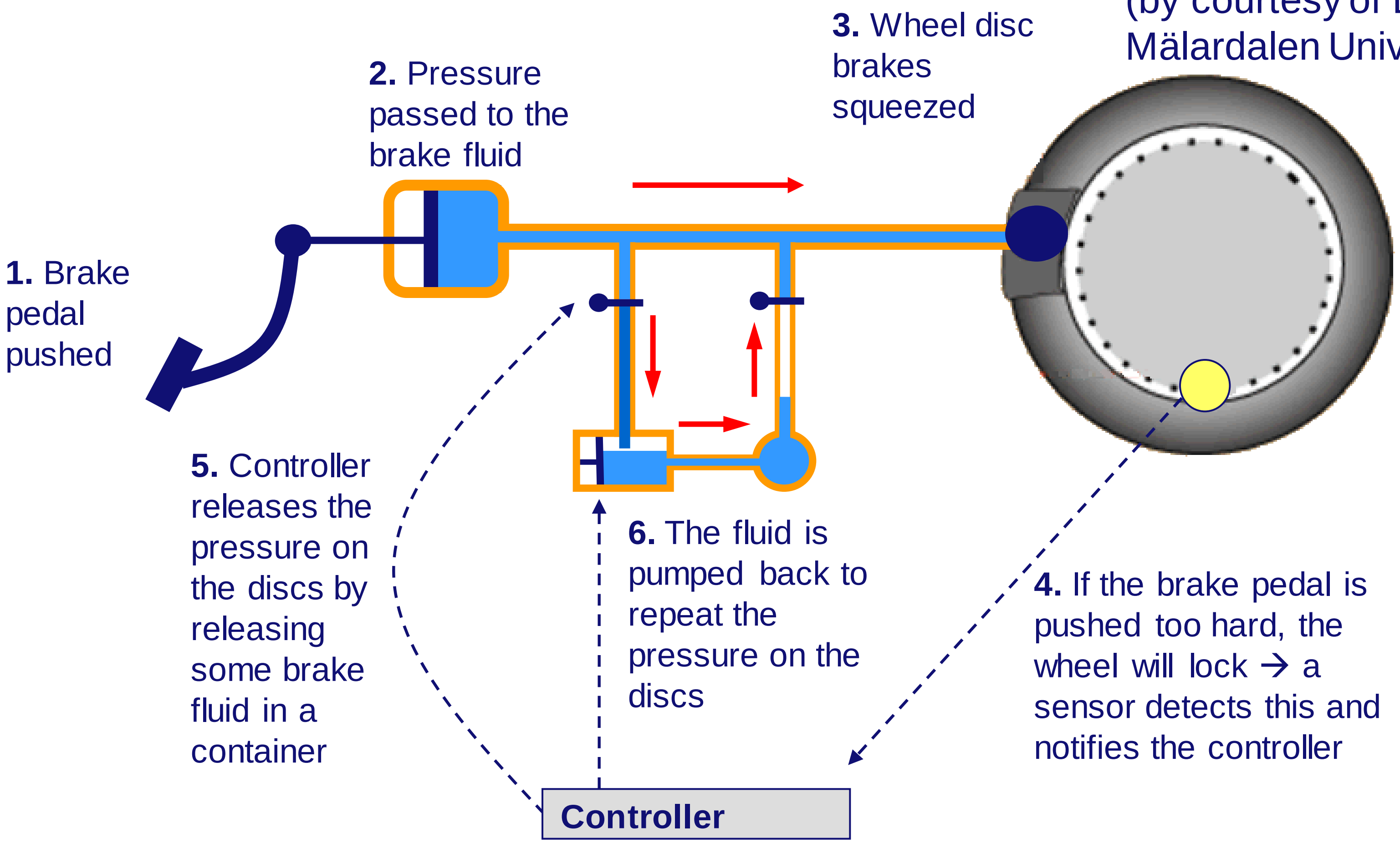
Anti-lock Braking System (ABS)

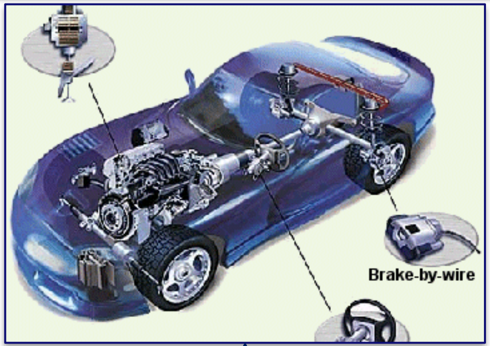
(by courtesy of Damir Isovic
Mälardalen University)



7. Entire process is repeated about 15 times/sec

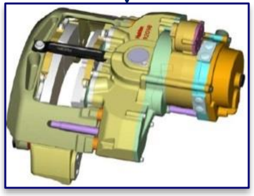
ABS is just one subsystem

Driver Control



In-car network

Local Control	Local Control	Local Control



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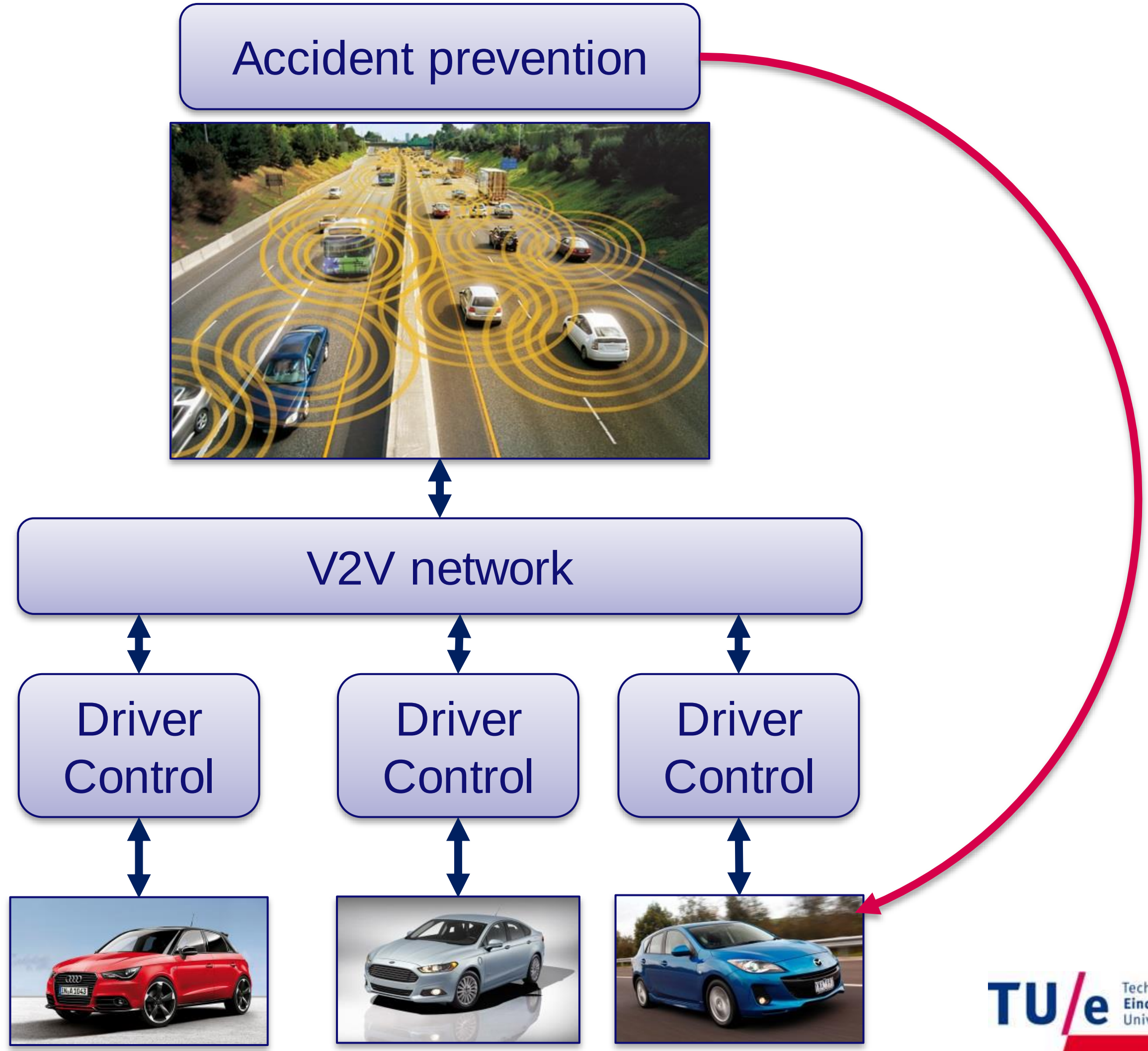
Car is part of traffic system: V2V, V2I



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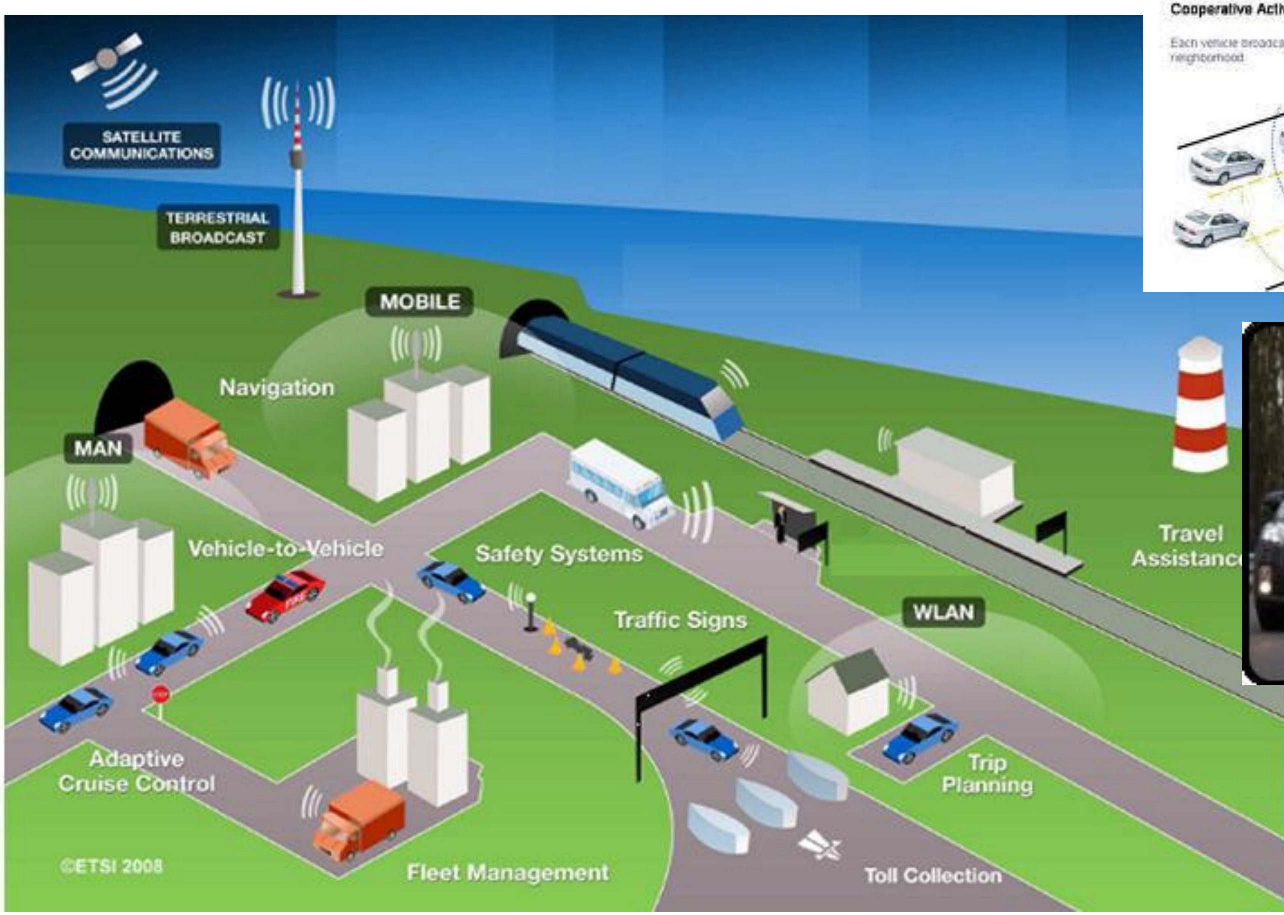

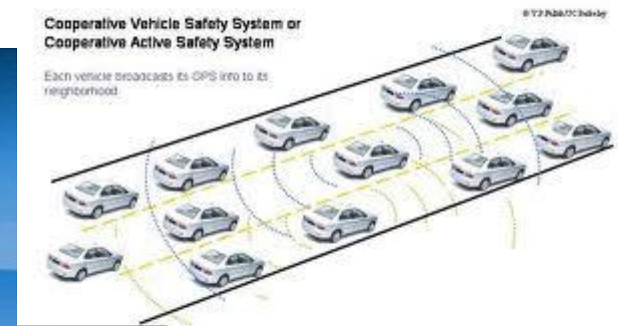

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Pattern: local-global control cycle

- Collect CAN signals and location data from individual cars

- Interpret CAN signals and location:
  - road condition
  - traffic situation
  - weather
  - accidents

- Global feedback
  - traffic routing
  - planning of maintenance

- Local feedback
  - individual guidance
  - perhaps: adaptation of in-vehicle systems, or of V2V

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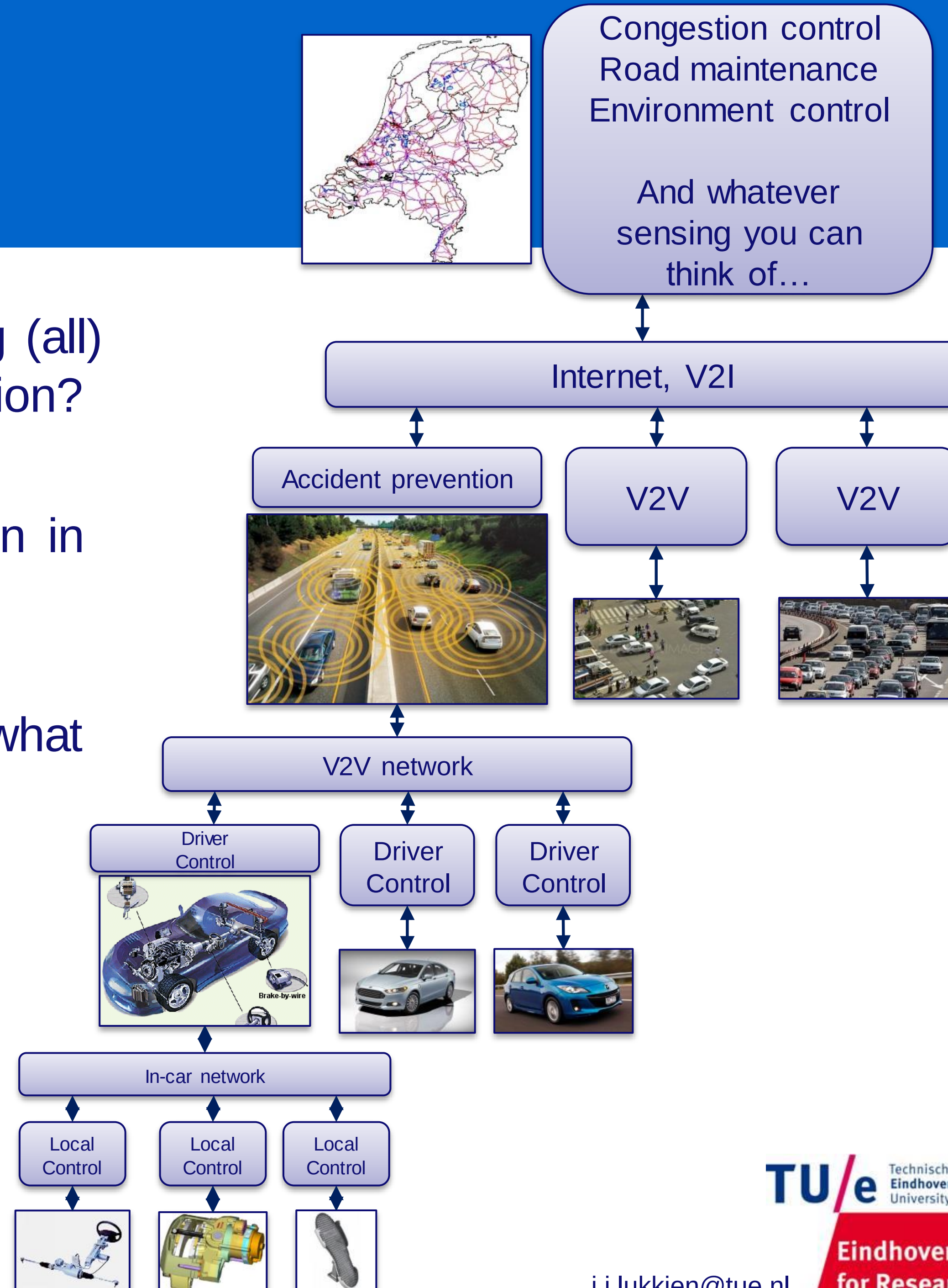
- Can we avoid sending (all) data to a central location?
  - levels of aggregation in the data?
  - can we keep local what is required locally?
  - intrusion protection, trustworthiness of data and control



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Some literature

- Cyber-Physical Systems: A New Frontier
  - *Lui Sha, Sathish Gopalakrishnan, Xue Liu, and Qixin Wang 2008 IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing*

- Cyber Physical Systems: Design Challenges
  - *Edward Lee, 2008 11th IEEE International Symposium on Object Oriented Real-Time Distributed Computing (ISORC)*

Advances: *CPS Systems Science*

- A *robust* design flow
  - … combining computational and physical aspects
  - … with multi-scale dynamics
  - … and integrated wired and wireless networking

- Management of systems' resources, including e.g. mass, energy and information

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Advances: *Ubiquitous, trustworthy computing*

- Adequate abstractions:
  - Distributed, real-time computing
  - Real-time group communication
  - Dynamic topology management in mobile systems

- Programming models
  - that include timing and deal with events in time and space
  - have real-time and concurrency abstractions
    - e.g. bands of simultaneity
  - configurable / tunable software components

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Advances: *Robustness, safety and security*

- Coherent set of metrics that capture uncertainty, faults / error / failures and security
  - …to be included in the software / system design process
  - …and in algorithms (e.g. *anytime* algorithms, *event-based* control)

- A philosophy of a small, correct kernel
  - formally specified and verified against a sound and complete environment model
  - against which guarantees for (safety-)critical services are given

- Self monitoring and feedback control within software systems

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Advances: *composition*

- Composition (of software components) includes *service quality* and *resource use*
  - Resource specification at interfaces
  - Resource aware behavior

- Derive correctness and QoS properties from:
  - architecture (logical, physical)
  - protocols, mappings
  - component properties

- Theory of composition
  - language support, model-driven (DSL)
  - integrating time-triggered and event-triggered

Advances: *trust, trustworthiness*

- (tools to) Visualize and analyze a CPS within its broader context (social, technical)
- Transparent privacy protection
  - concepts, analytical and engineering framework
- Cohesive, conceptual, predictable, transparent from user's perspective

Conclusion: techniques / domains

- Systems of systems integration
  - integration of independent subsystems with *architectural diversity*, *uncorrelated requirements*, *competition of control*
  - concerns of *interoperability* and *emergent properties*

- Mixed Criticality
  - *a mixed-critical system is an integrated suite of hardware, operating system and middleware services and application software that supports the execution of safety-critical, mission-critical, and non-critical software within a single, secure compute platform*

(from http://www.cse.wustl.edu, research agenda for Mixed-Criticality Systems)

- Real-time techniques
  - event-based control, sharing
- Anytime algorithms

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Conclusion

- CPS
  - removes the distinction between specializations
  - calls for an integrated approach, which may lead to *new methods*

- In order to retain *separation of concerns*, new approaches to interfaces between systems and components need to be investigated
  - particularly, specification of extra-functional properties
  - and policies for data sharing, control

- …. and these must be supported by proper theory

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