Cyber-Physical Systems and Digitalization - trends, opportunities and challenges

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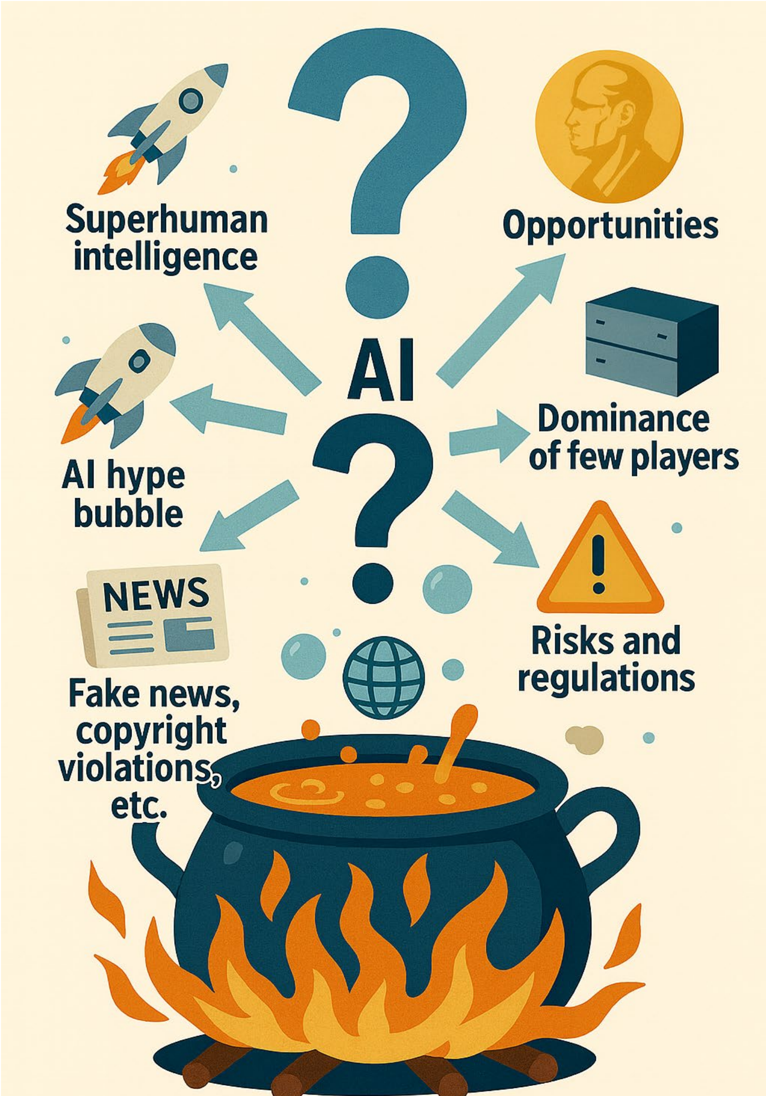
Software and AI-defined *X*
– representing a socio-technical shift

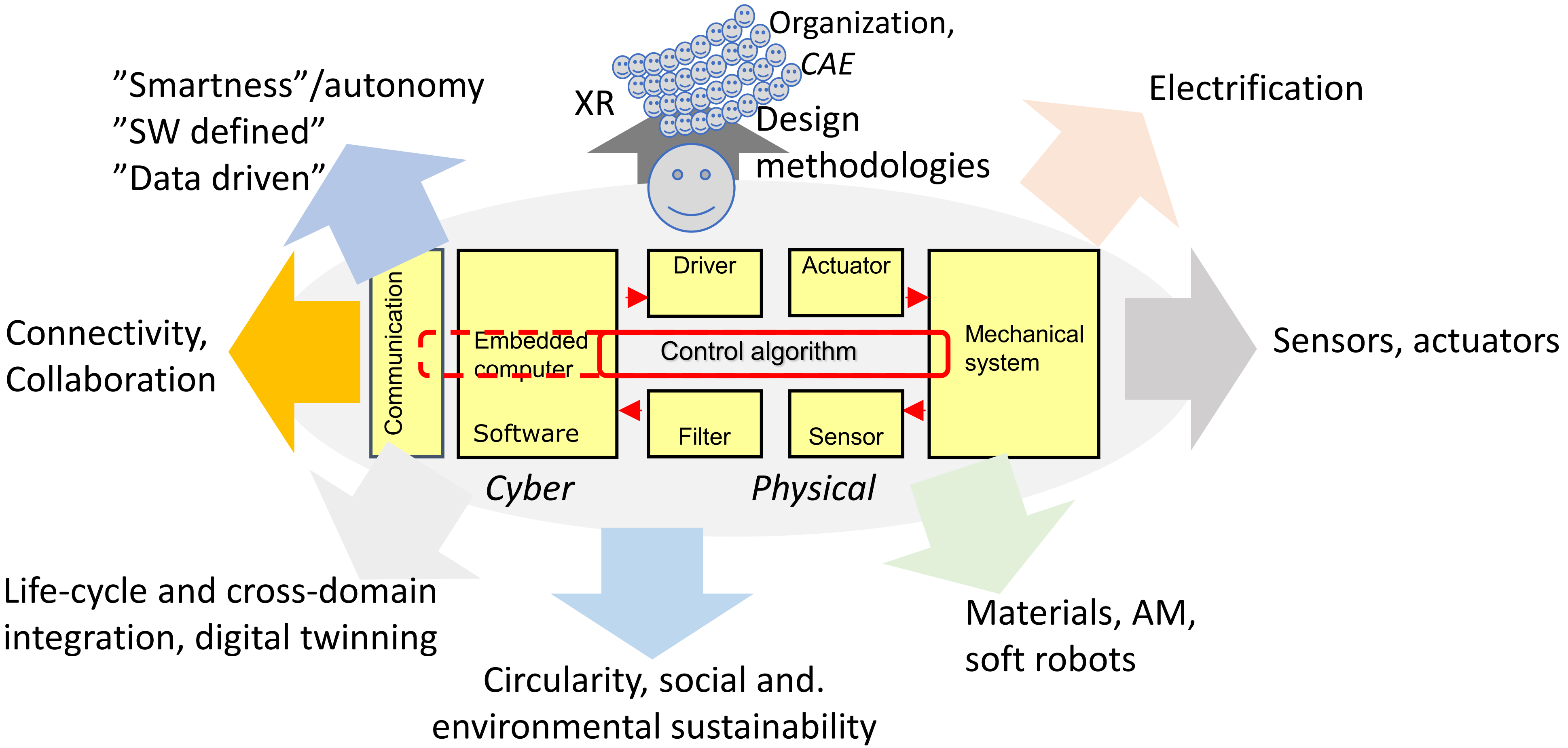


US NEWS

Billionaires Elon Musk and Sam Altman explode in ugly online fight over whose tech killed more people

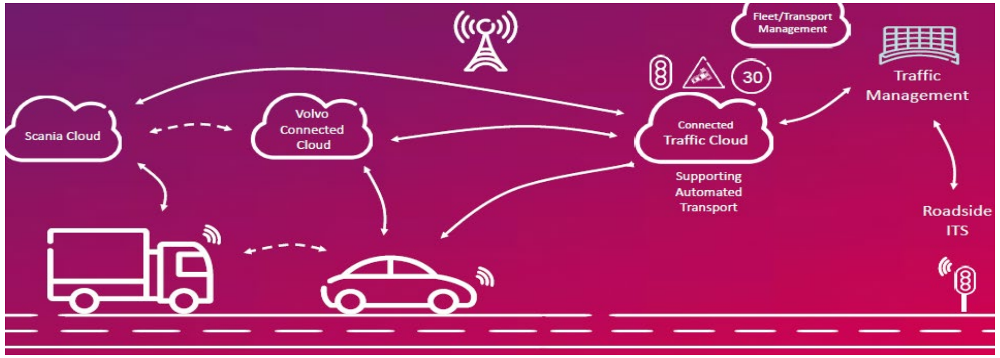
https://lnkd.in/dSaiKc57 - Published Jan. 21, 2026

Zooming in & out ➔ Mechatronics and trends



Digital infrastructure and connectivity

- Telecommunication: …3G, 4G, 5G, … and edge computing!
- Smart phones/pads
- Wireless and wired communication
- Internet and cloud
- Satelite communication and navigation
- Industrial computing
- Smart devices and embedded systems



Courtesy of Ericsson

The world as a connected and SW defined distributed system

From transistors to software and SW defined X

From electronics to SW

- Software (HLL)
- Assembly
- Binary

Digital platforms

- MicroProcessors
- CPU’s and memories
- Combinatorial circuits
- Flip-flops
- Transistors

Theories and tools

- Programming languages
- Compilers
- Abstract machines (Turing), state machines
- Instruction set architectures
- Boolean algebra
- Electrical components, electrical circuits
- Physics – laws of nature

Cyber Physical Systems (~2006)

- Integration of computation, networking and physical processes where CPS range from minuscule (pacemakers) to large-scale (e.g. national power-grid).

- Not new but with an increasing scale and new capabilities!
- It is about building systems!

More to read: "*Cyber-physical systems have far-reaching implications*."
Hipeac Vision 2021. https://doi.org/10.5281/zenodo.4710500

Physical vs. Software vs. Data systems and …

Humans

+ Deliberate reasoning

~ Biases, social complexity

- Limited memory & attention

Data / AI

+ Narrow superhuman performance
+ Function approximation
+ Big data and token prediction

~ Opaque, billions of params

- Brittle, no real understanding

Software

+ Flexibility, automation

~ Hidden state, bugs

- Decoupled from physics

Physical Systems

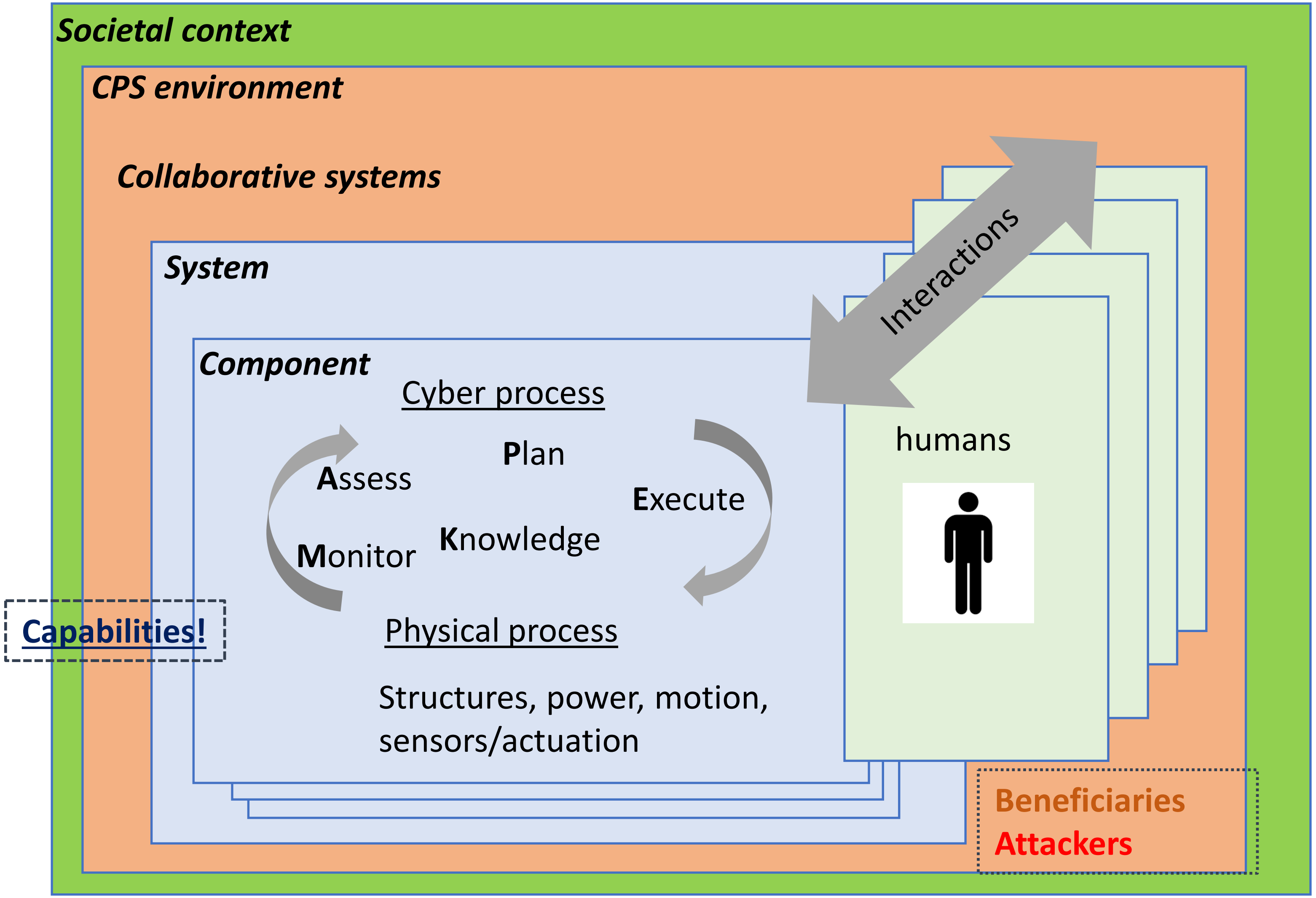
+ Structure, energy

~ Nonlinear phenomena

- Limited flexibility

Generated from “Cyber-physical systems have far-reaching implications.” Hipeac Vision 2021. https://doi.org/10.5281/zenodo.4710500

Cyber-physical systems: benefits, risks, and levels!



Public perception
Regulations, standards
Societal effects

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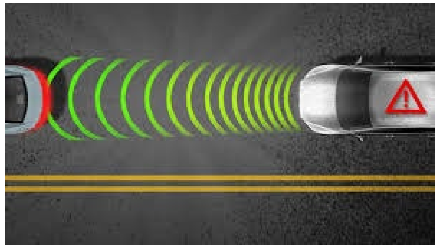
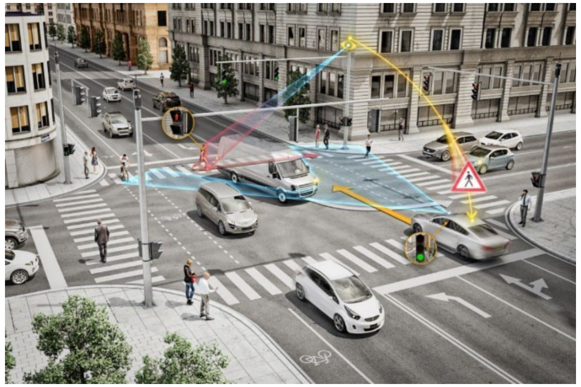
Enhancing traffic safety Towards vision zero!





Passive safety | Active safety | Tactical safety | Tactical and collaborative safety

Physical infrastructure ➔ Vehicle capabilities ➔ Collaborative ITS capabilities

Wardzinski, A.: Safety assurance strategies for autonomous vehicles. Safecomp (2008)
R. de Campos, et al. Precautionary safety for autonomous driving systems: … ITSC, (2021)
Schöner and Antona-Makoshi. Tactical Safety for Autonomous Vehicles on Highways. Handbook Assisted and Automated Driving. (2024)

Clashes on the path towards software- and AI-defined systems

Lessons learnt

- Autonomous CPS
  - *Levels of automation and pitfalls*
  - Automated Vehicles (AV's)
    - Safe enough, how to get there, continuous assurance?
    - New AV / road vehicle safety standards;
      - ISO 21448:2022 - Safety of the Intended Functionality
      - ISO/PAS 8800:2024 —Safety and artificial intelligence
      - ISO/TS 5083:2025 —Safety for automated driving systems — Design, verification and validation
    - Describing and reasoning about the environment – "ODD", scenario abstractions, …
- *Legacy and technical transitions*
  - Architecting, data, interoperability, exploiting patterns, graceful degradation
- Socio-technical transition
  - Organizational capabilities; competence/reskilling, responsibilities
  - Beyond wild west towards responsible innovation and societal scaling
    - Testbeds, regulatory sandboxes

Levels of automation vs. simplified models

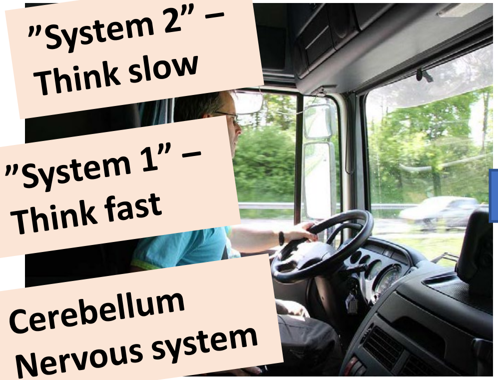
ADI – ”Autonomous Driving Intelligence”

Knowledge

Skill/Rule based

Basic capabilities
(mechatronics platform)

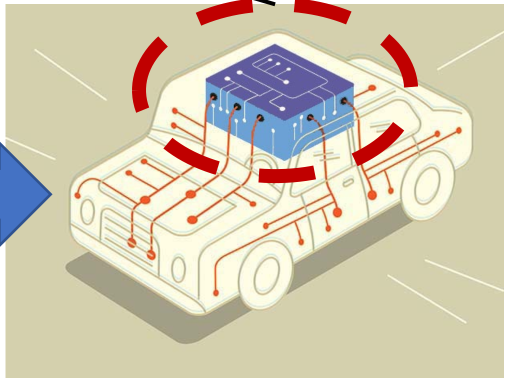
S-R-K model, Rasmussen 1983

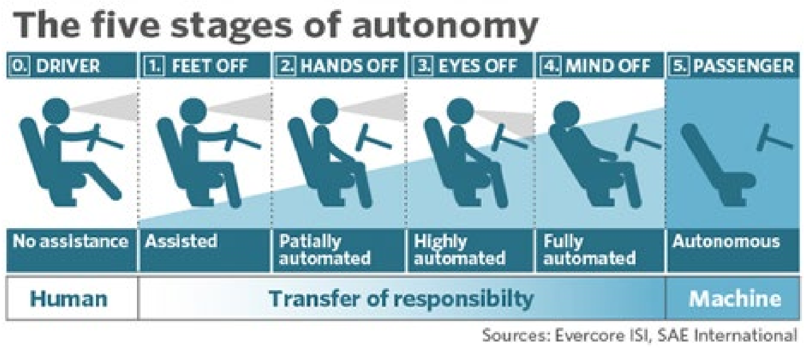


”System 2” –
Think slow

”System 1” –
Think fast

Cerebellum
Nervous system





Automation levels:

Parasuraman, Sheridan & Wickens 2000)

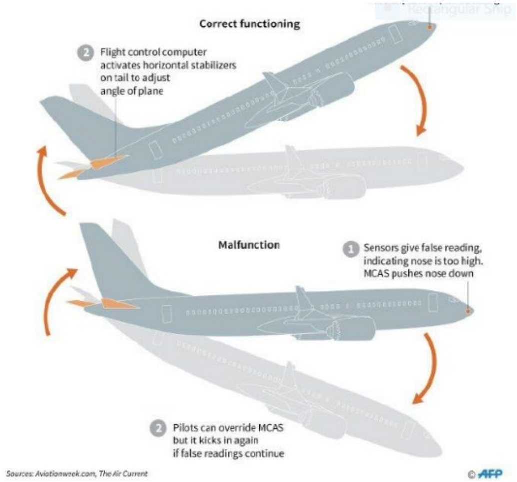
(1) What is automated (core, auxiliary functions, levels incl. tactical and strategic)
(2) To what degree,
(3) Where and when (the ”ODD”)
(4) Dependence on external systems (communications, GPS, …)
(5) Collaboration dimension – levels of collaboration (CPS and humans)

Automation insights and pitfalls

- Safety management systems, monitoring and continuous safety assurance
- Automation pitfalls:
  - Higher automation level may make it more difficult when the automation fails!
  - Trust! Overtrust, undertrust
- Open world complexity ➔ multiple concerns: FuSA, SOTIF, AI, system, cybersecurity, …

Lisanne Bainbridge, 1983: ”Ironies of automation”
Jens Rasmussen, S-R-K model, 1983
James Reason - Human error theory, Swiss Cheese model

Boeing 737 Max



Legacy and technical transitions – lessons and directions

- Platform shifts and levels (mechanics, electrical, electronics, software)
  - Synchronization challenges; modularity will be important
- EE/SW shifts towards centralization (high-performance compute)
  - Virtualization/containerization, OTA updates, Ethernet backbone
  - Key aspects: Middleware, complexity management, data monitoring, real-time
- Expanding legacy?
  - Edge computing (separate HPC compute), an opportunity to add features incrementally
  - Exploiting automation patterns: monitoring→ analysis→ shadow modes→ loop closure
  - Key aspects: Design and retain graceful degradation; consider architectural assumptions
- Towards DevOps
  - (Forward looking) data gathering as key – access, quality, business model
- Systems thinking and architectural frameworks

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Martin Törngren, KTH

Reading

- *Cyber-physical systems have far-reaching implications*. Hipeac Vision 2021; https://doi.org/10.5281/zenodo.4710500
- *Complexity Challenges in Development of Cyber-Physical Systems*; Principles of Modeling; Lohstroh, M. et al. Eds.; Springer, 2018; Lecture Notes in Computer Science, 2018
- *Mechatronics Design Methodologies: New Frontiers in Design and Technology*. In Hehenberger, P. et al. Eds, Mechatronic Futures. Springer, Cham.

Smart Cyber-Physical Systems (CPS) for Sustainability (MF2141)
- 6.0 credits - www.kth.se/student/kurser/kurs/MF2141?l=en

Contact: martint@kth.se

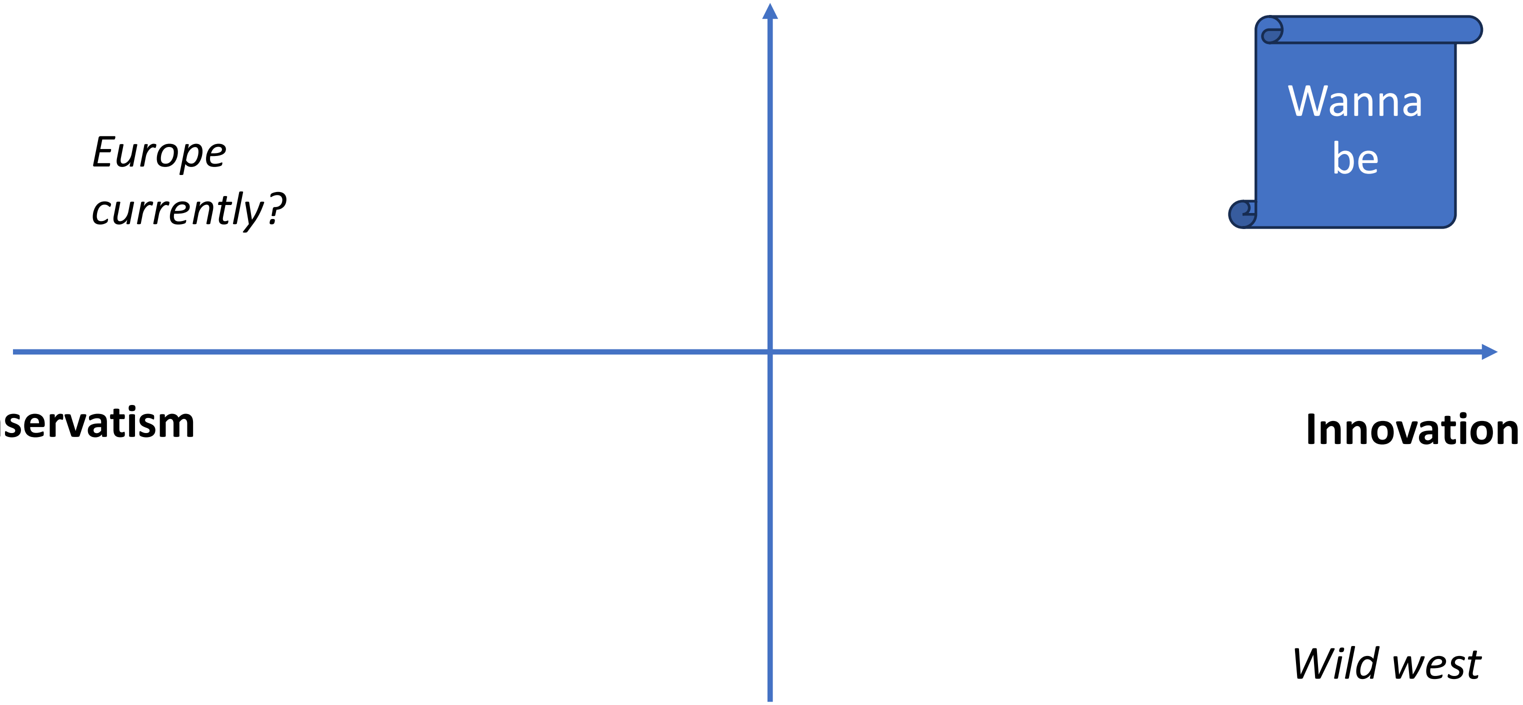
Acknowledgements:
Vinnova through the TECoSA center, and TADDO2 and Versace projects!
Collaborators including project partners!

Striving for the sweetspot

Human-centered
AI-based autonomous
cyber-physical systems

Controlled and informed testing and deployment

Europe currently?



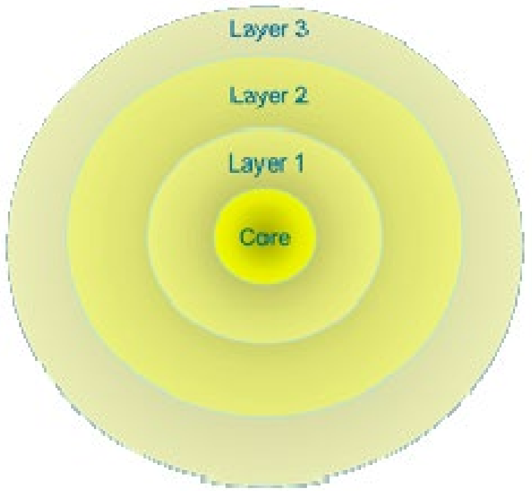
Conservatism

Innovation

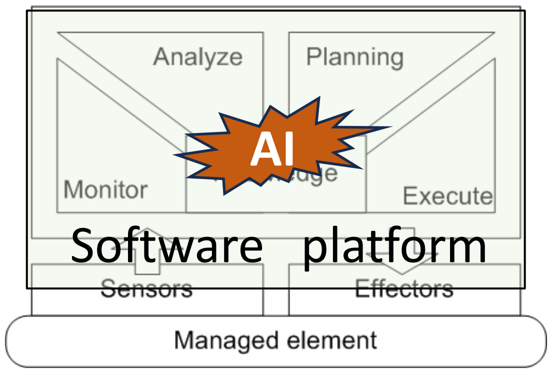
Wild west

Unregulated deployment

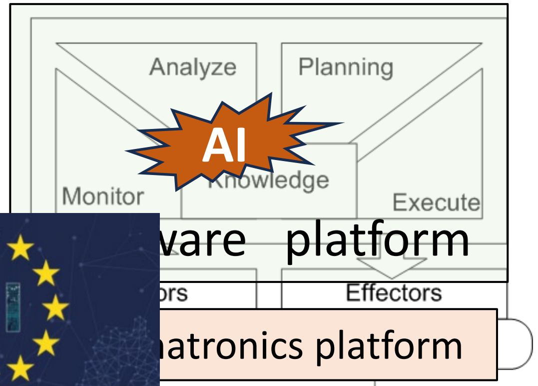
Multiple loops and DevOps



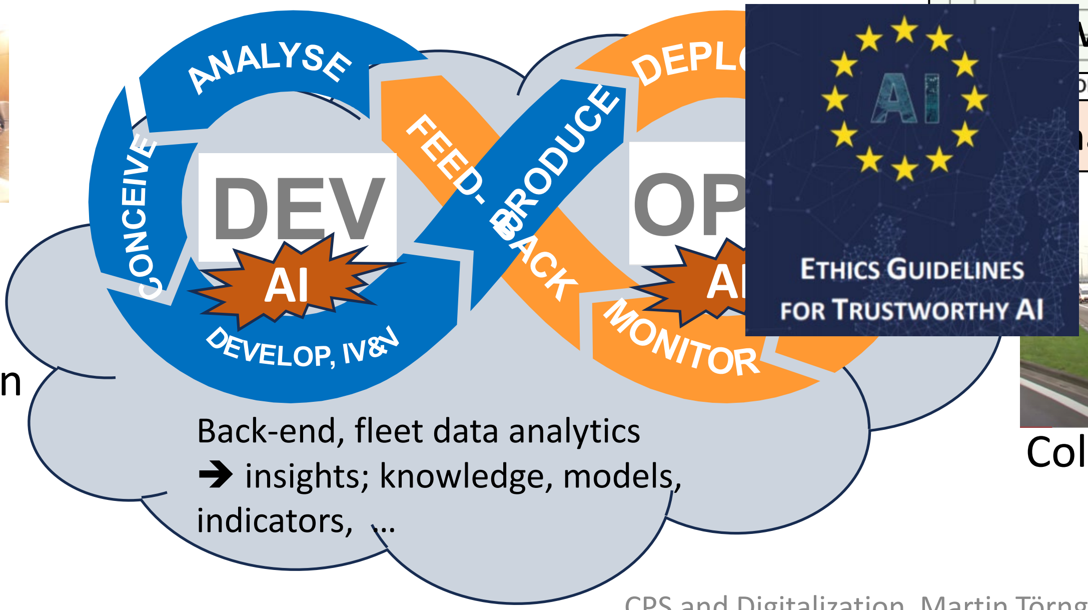
J. Birch et al. **A Layered Model for Structuring … Safety Arguments**, 2014, 10th EDCC

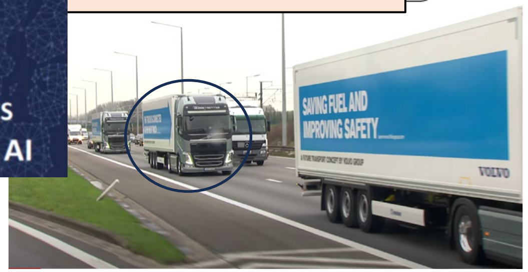


Strategic
Tactical
Operational

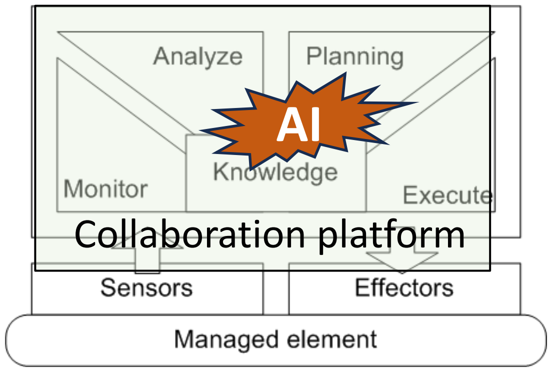


Organization and processes

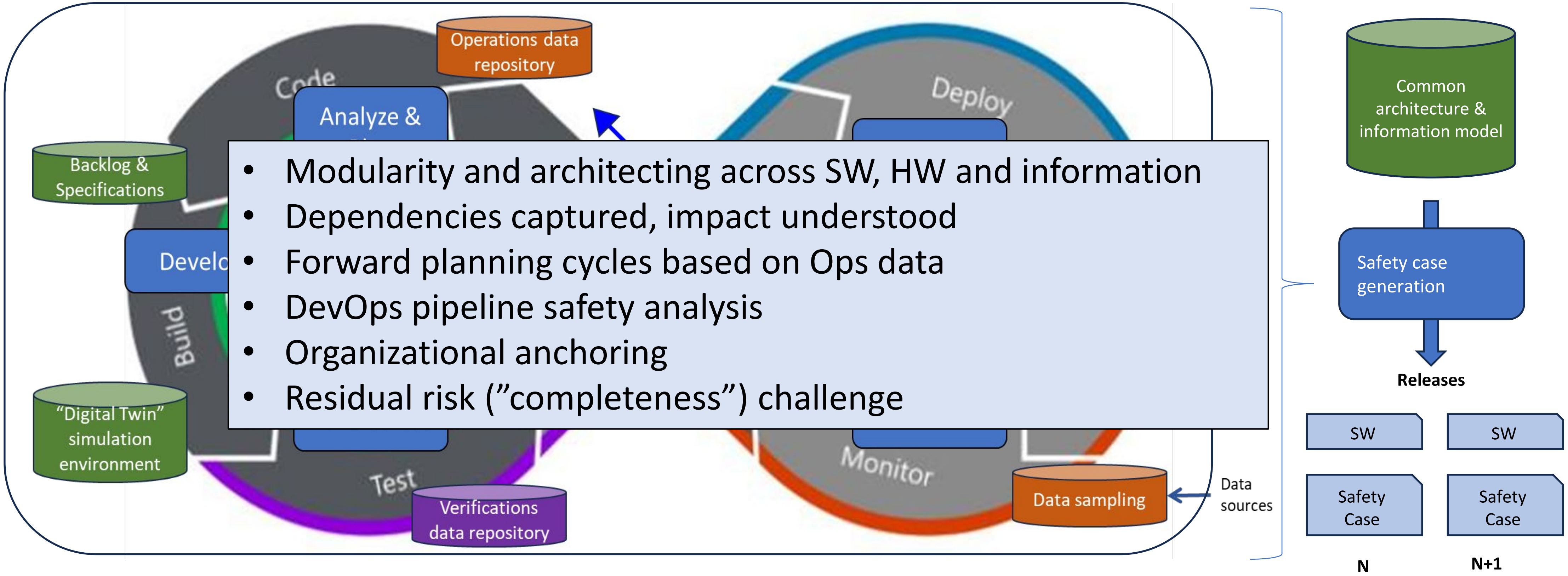




Collaborative behavior



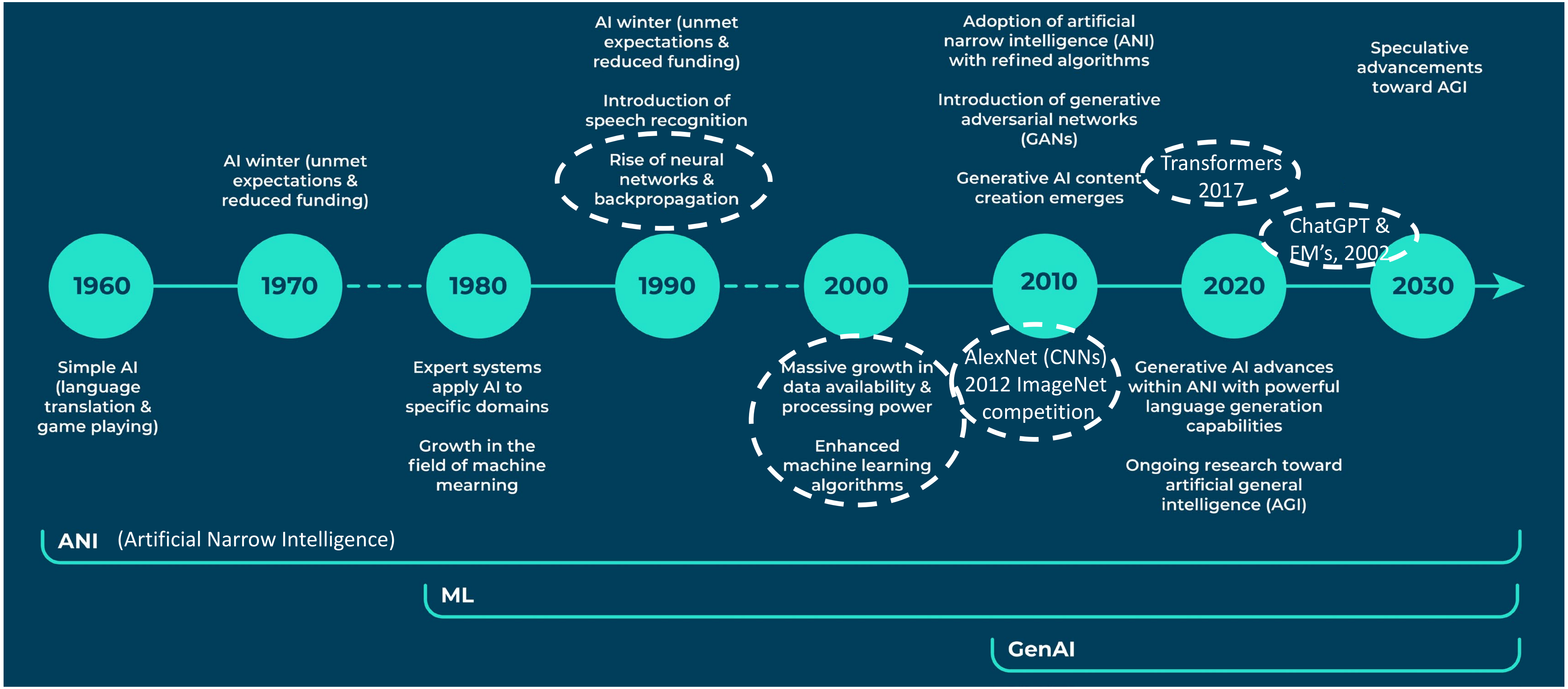
DevOps adapted to safety



- Modularity and architecting across SW, HW and information
- Dependencies captured, impact understood
- Forward planning cycles based on Ops data
- DevOps pipeline safety analysis
- Organizational anchoring
- Residual risk (”completeness”) challenge

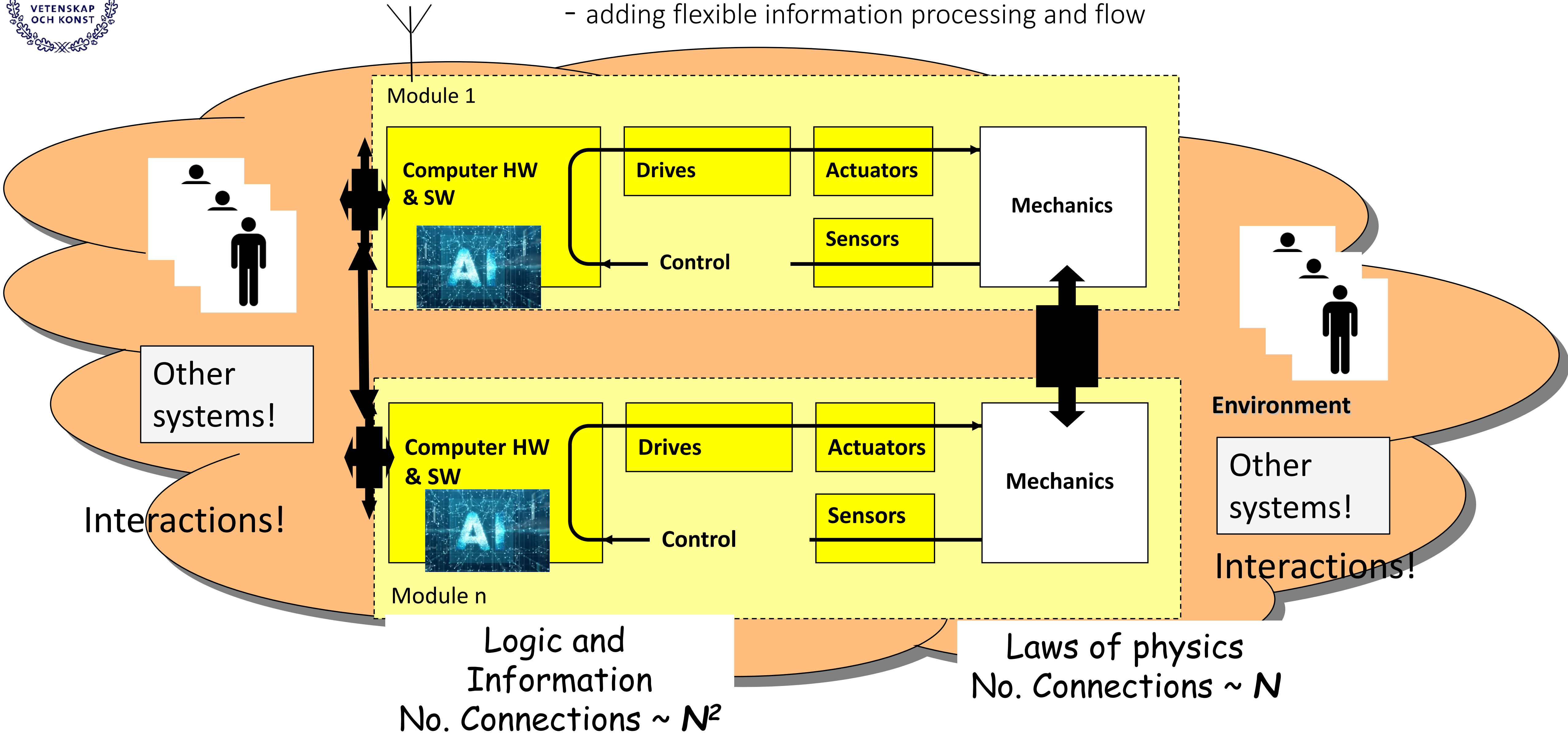
www.vinnova.se/p/palitlig-devops-for-autonoma-fordon-taddo2
www.vinnova.se/p/versace

Towards SW&AI defined *X*

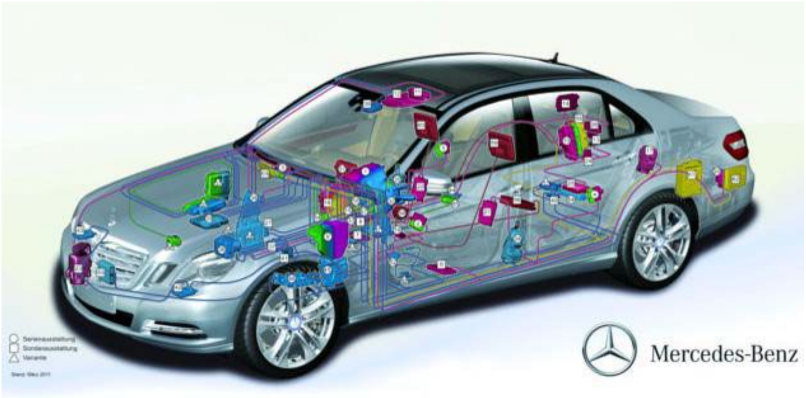


Example: From mechanics to CPS

- adding flexible information processing and flow



Mechanics ➔ Mechatronics



	Susp	Brake	Steer	Wheel	Diff	Trans	Clutch	Eng	Driver
Susp				X					X
Brake				X					X
Steer				X					X
Wheel	X	X	X		X				
Diff				X		X			
Trans					X		X		
Clutch						X		X	X
Eng							X		
Driver		X	X				X		

	Susp	Brake	Steer	Wheel	Diff	Trans	Clutch	Eng	Driver
Susp		P	P	X+P	P	P	P	P	X+P
Brake	P		P	X+P	P	P	P	P	X+P
Steer	P	P		X+P	P	P	P	P	X+P
Wheel	X	X	X+P		X				
Diff	P	P	P	X+P		X+P	P	P	
Trans	P	P	P	P	X+P		X+P	P	P
Clutch		P	P		P	X+P		X+P	P
Eng	P	P	P	P	P	P	X+P		P
Driver	P	X+P	X+P		P	P	X+P	P	

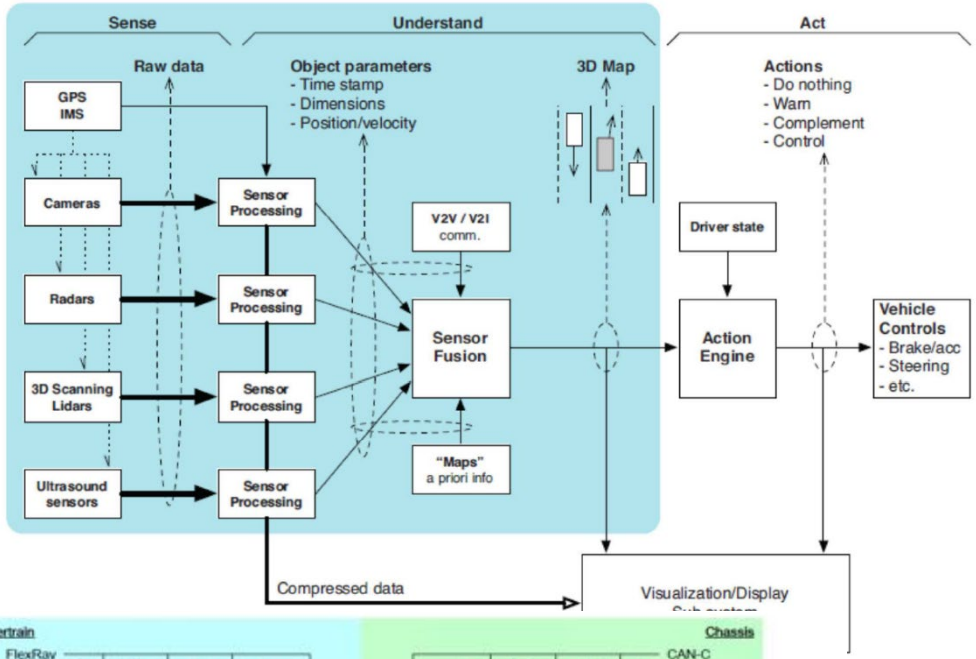
Design structure matrices illustrating vehicle components and relations: P – Programmable relations. X – Possible change

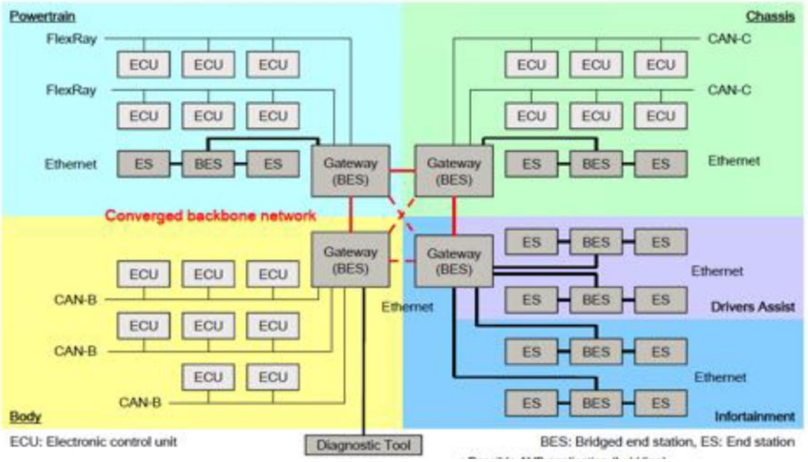
CPS example – opportunities and co-design

Hy-Wire Skateboard concept
In 2002 (GM)

Fuel-cell
Distributed control
Electrical actuators

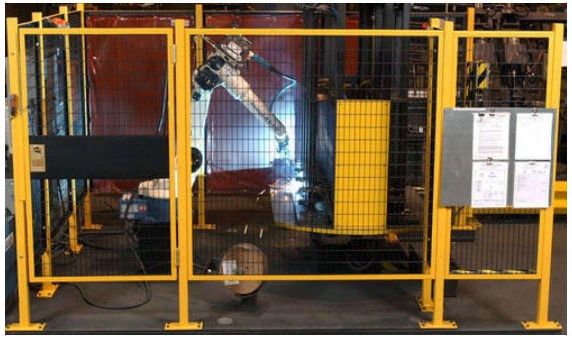
The ”environment is the mould”



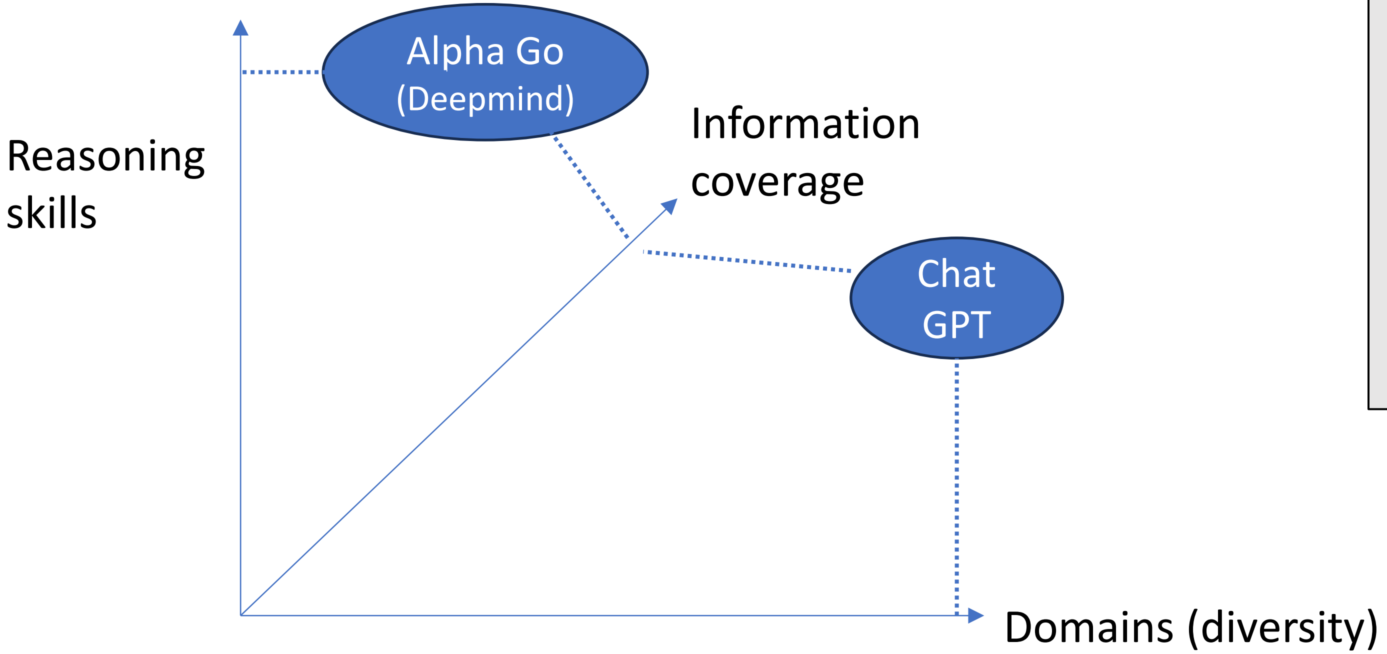


Martin Törngren and Ulf Sellgren. Complexity Challenges in Development of Cyber-Physical Systems. In Principles of Modeling; Lohstroh, M. et a. Eds.; Springer, 2018; Vol. 10760, Lecture Notes in Computer Science, July 2018

Spares



The (narrowing) AI gap



LLMs as statistical machines!
Lacking a common sense

Modern generative AI as hybrid systems!

Michael Jordan: ML methodologies still emerging