Advances in Railway Control Systems Architectures and Related Challenges for Verification and Validation

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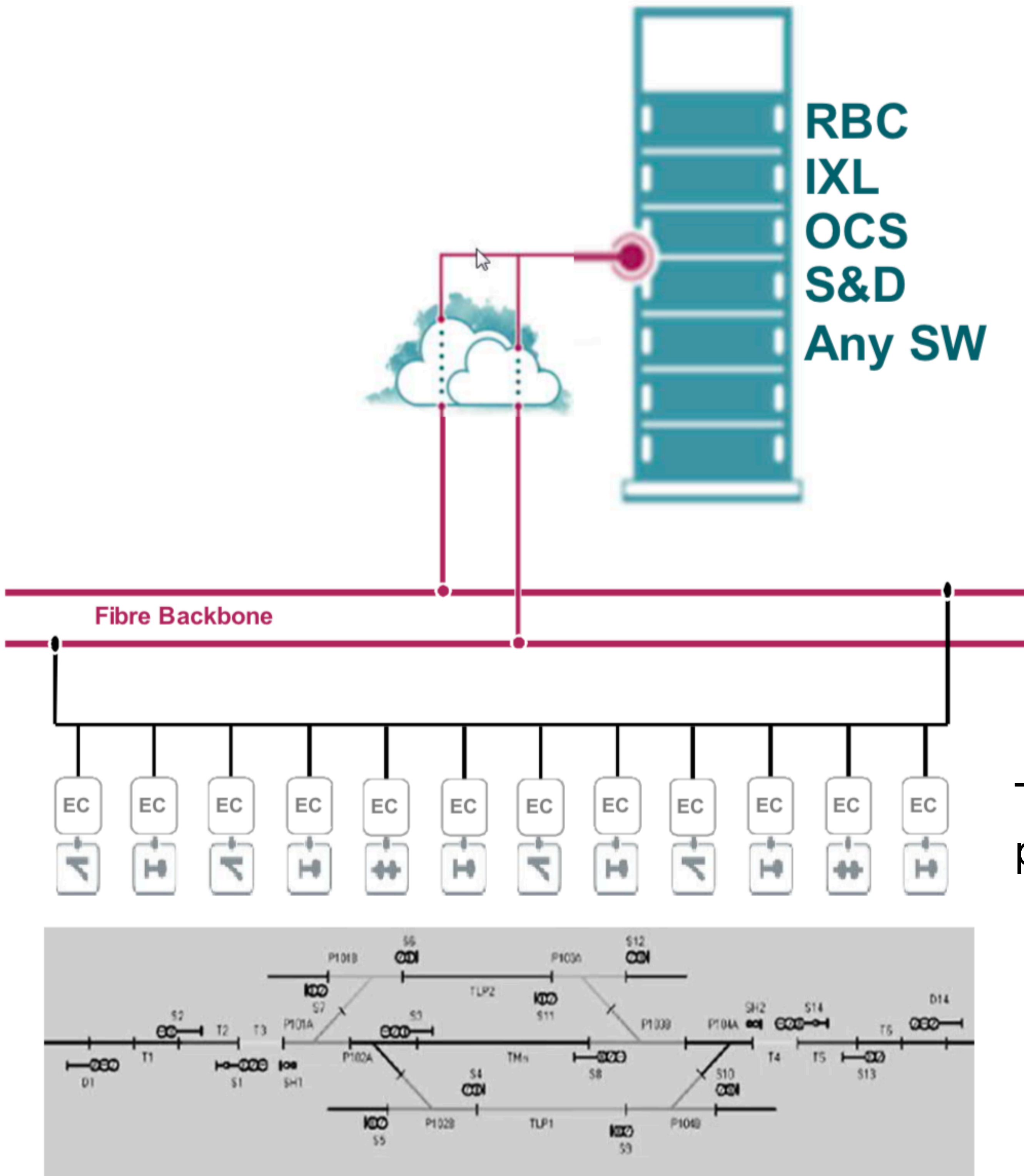
A Novel Distribution Paradigm.
Cloud-based Railway Control

Cloud-based Railway Control

- Siemens Mobility **DS³ – Distributed Smart Safe System**
  - IXL, RBC and related functionality are moved into the cloud
  - Functions run safely on standard HW, standard OS (Windows, Linux), and standard VMs
  - Cloud severs communicate with track element controllers via high-speed back bone and Ethernet
  - see Siemens Mobility publication [1]

Safety @ COTS multicore



(Radio Block Centre)
(Interlocking System)
(Occupation Control System)

Track element controllers for points, signals, axle counters . . .

Source: see [1]

Motivation for this Architecture

- Excellent **scalability**
- Excellent **performance** through state-of-the-art servers and networks
- Significant **availability** improvements enabled by
  - Reconfigurable software allocation on different CPU cores and servers
  - Geographic distribution

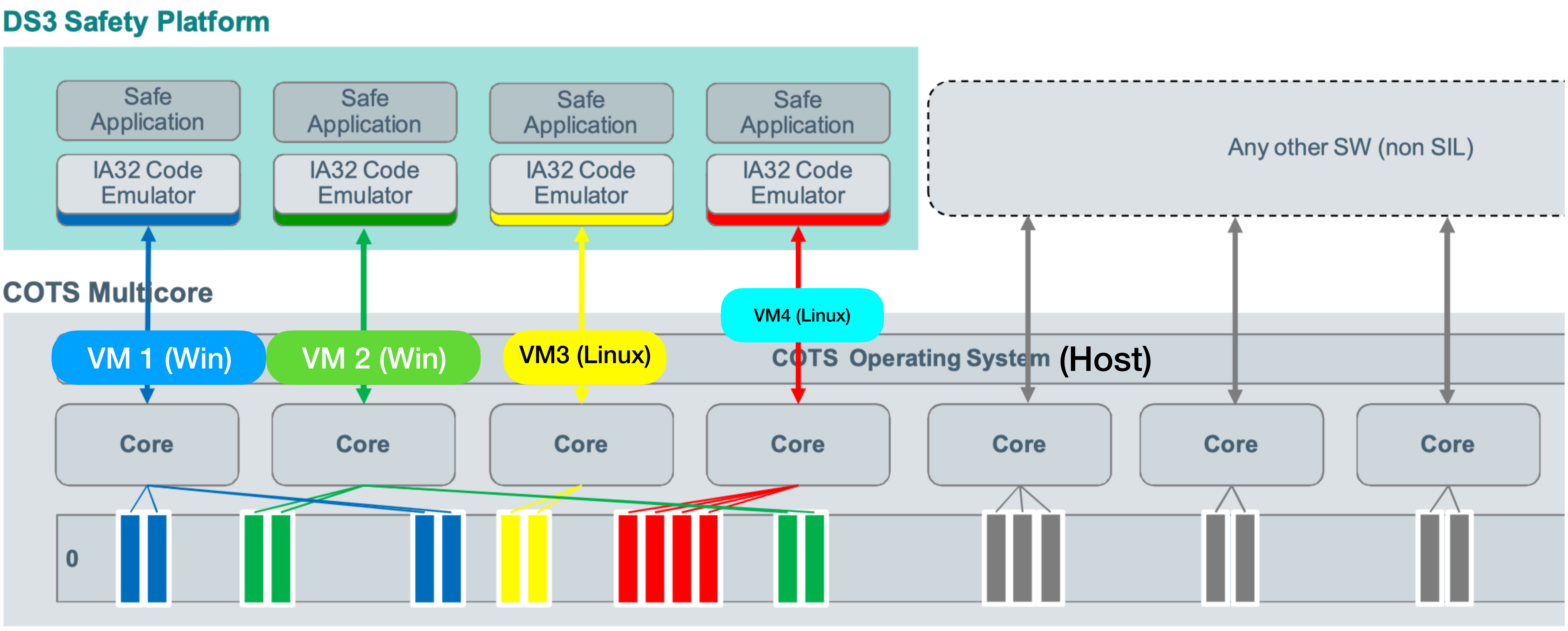
Motivation for this Architecture

- **Cost reduction** enabled by
  - COTS operating systems and virtual machines
  - COTS hardware – virtualisation removes HW dependencies
  - Mixed SIL (Safety Integrity Levels) runnable on the same HW
  - Legacy software running in emulators on high-performance COTS servers

Challenges

- Ensure **fail-safe behaviour** on unsafe HW, OS, VM
- **Safe synchronisation** between geographically distributed components
- **Safe reconfiguration** during system operation
- Complexity is so high that **no complete formal overall model** of system behaviour and system architecture can be created

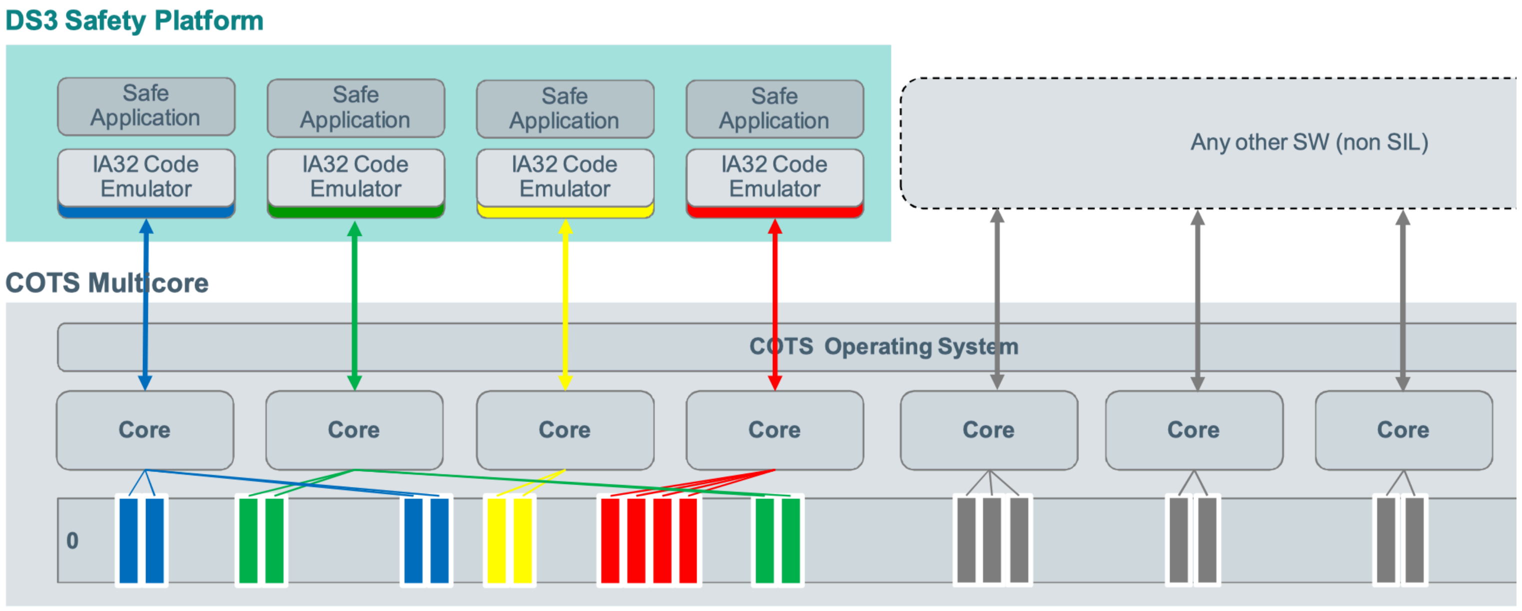
Design Characteristics



Source: see [1]

Design Characteristics

Create **fail-safe behaviour** using principles of the **coded monoprocessor:** A specific approach to **software diversity**



No specialised HW required, since **cloud servers can emulate coded monoprocessor hardware** and perform **managed code execution**

Coded monoprocessor – recall.
Use of coded data

$$x \mapsto (x_f, x_c)$$

$$x_c = A \cdot x_f + B_x + D_t$$

A : transformation factor
B : static signature
D : dynamic signature

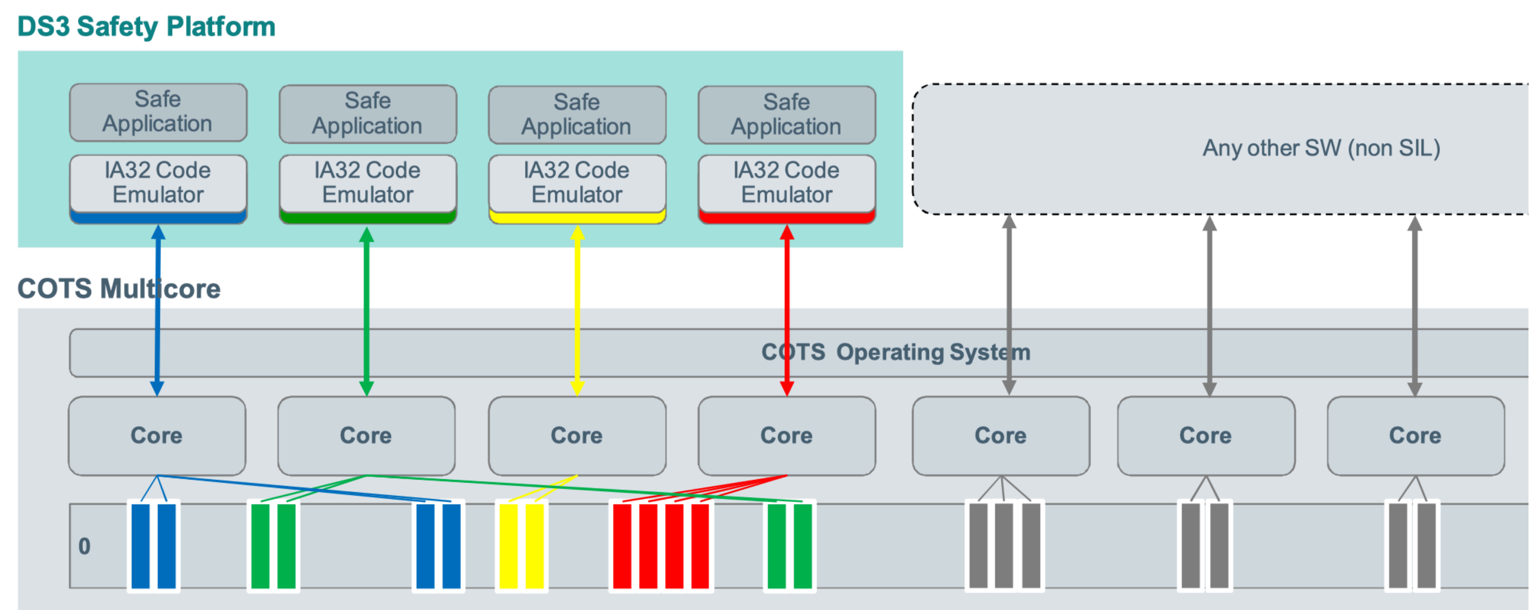
Verification of redundant channel information

$$z_c = A \cdot z_f + B_z + D_t ?$$

$$(z_c - B_z - D_t) \mod A = 0 ?$$

Design Characteristics

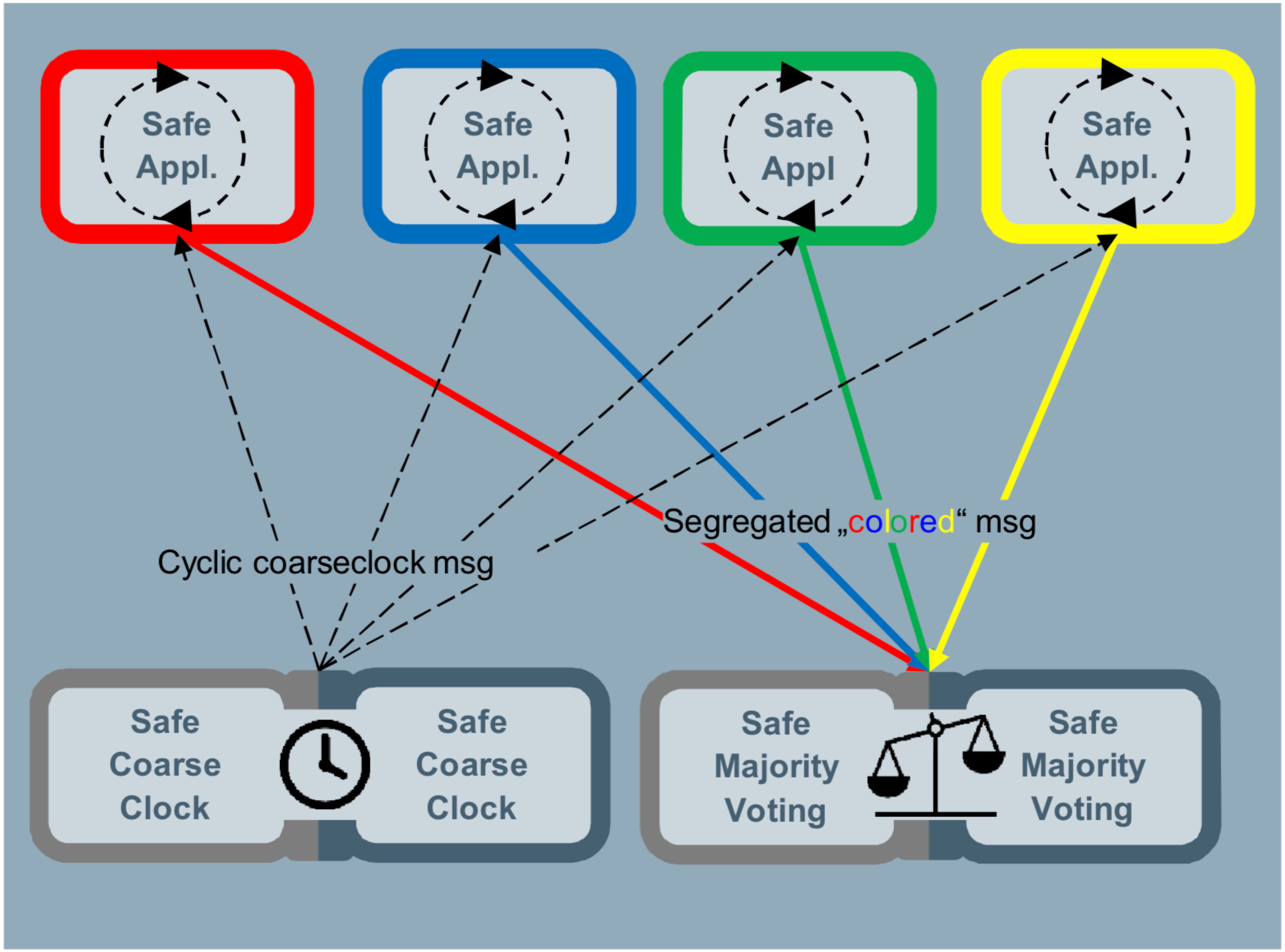
Coded monoprocessor



- Strict **cyclic processing**
- **Synchronisation** of redundant software components by logical clock
- **Memory scattering**
- **Coded data** and associated diverse transformation operations
- Calculation of **work flow digest** values
- **Dynamic data signatures** ensure use of the data at correct point in time
- Encryption with **complementary keys** ensures that data can only be used if all redundant components have calculated the equivalent result.

Design Characteristics

Increase **reliability** by means of n-modular redundancy and m-out-of-n voters

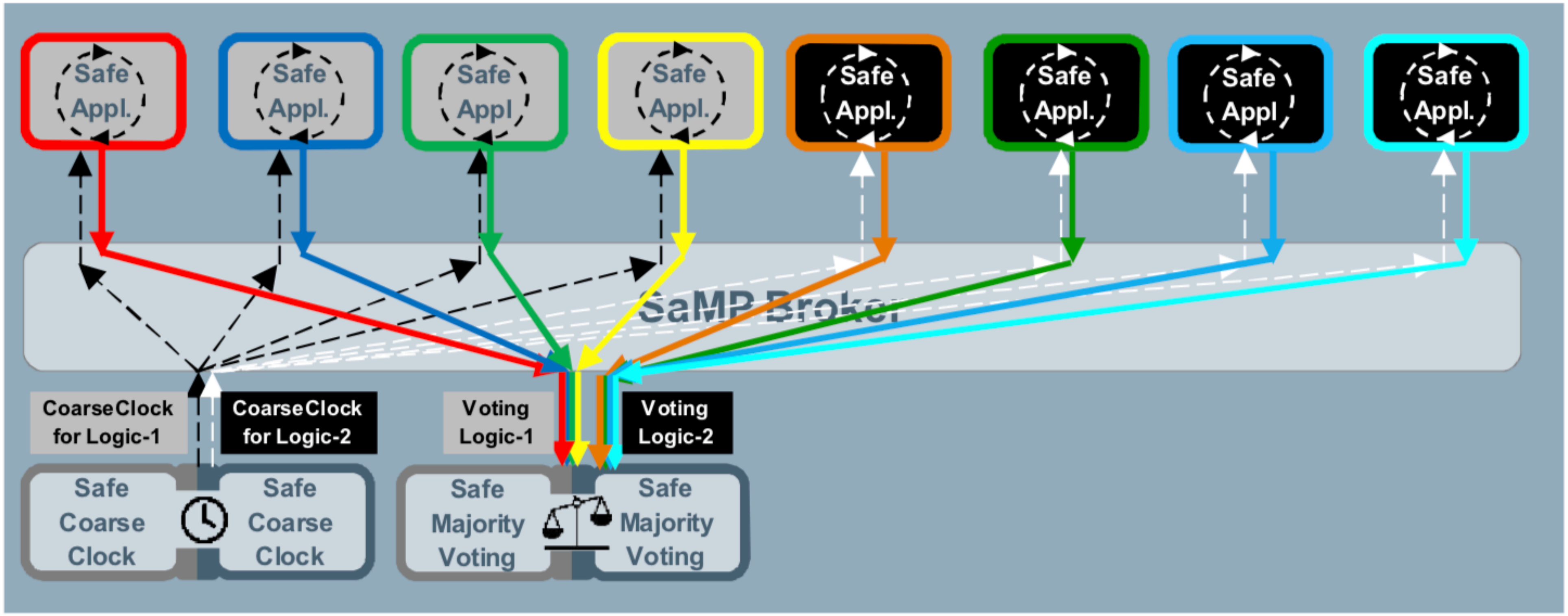


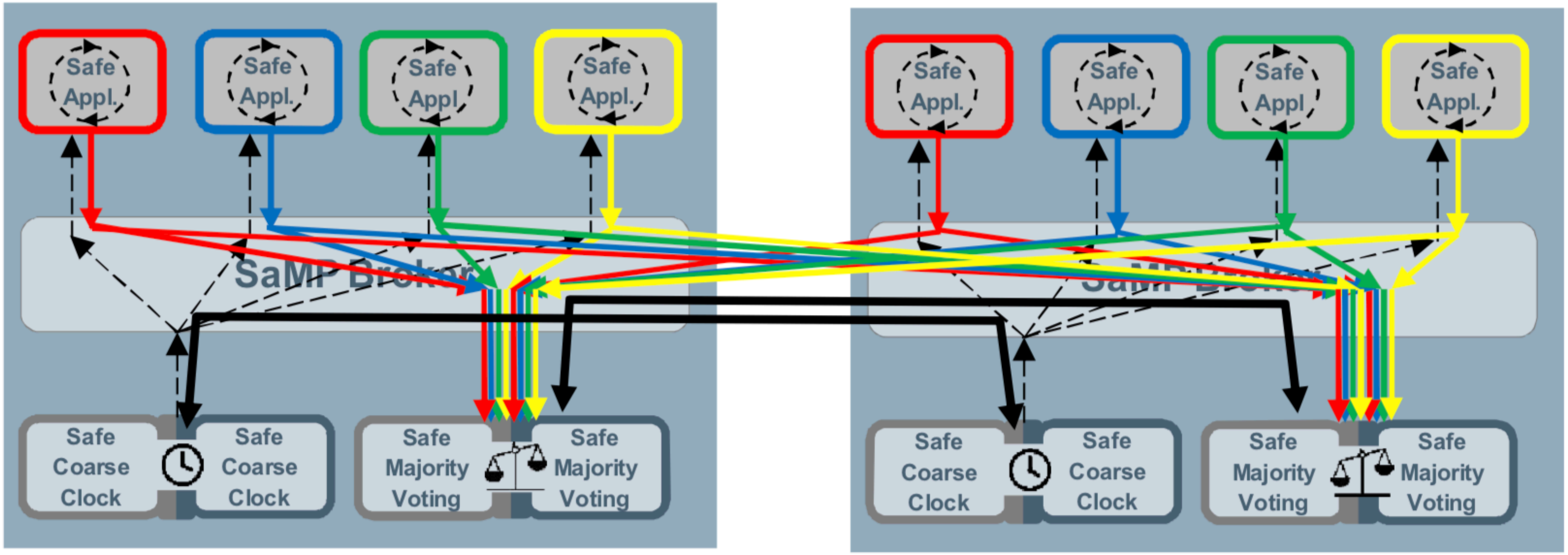
Source: see [1]

Design Characteristics

Dynamic reconfiguration …

… even across geographically distributed server farms





Source: see [1]

Cloud-based Railway Control – V&V Challenges

V&V Challenges: many different SW and system paradigms to be integrated

Coded Monoprocessor

Hard Real-Time Guarantees

Legacy Software Execution

Distributed Deployment

SAFE PROTOCOLS

Publish-Subscribe Pattern

n-Modular Redundancy

Distributed Clock Synchronisation

MESSAGE BROKER

HW Emulation

Fail-safe Behaviour

Security Mechanisms

Generics

Dynamic Reconfiguration

Safety Software Patterns

Virtual Machines

MULTICORE PROCESSING

V&V Solutions

Side Remark – why Models are so Important

- Formal models/specifications are highly recommended according to standard EN 50128
- We need them for
  - specification validation by model checking and simulation
  - automated code generation
  - automated model-based testing
  - enabling traceability between requirements, code, tests, and other V&V artefacts

Scenario Models

- **Coping with model complexity** – an approach adopted from the field of autonomous vehicles, see [2]
  - Identify scenarios
  - Develop **collection of per-scenario models**
    - Parameterised models specifying the required behaviour **for a specific operational situation**

Automated Model-based Testing

- **Coping with large amount of test cases**
  - Test case/test data generation and test procedure **generation from models can be fully automated**
  - **Test suite execution may be parallelised** by using cloud services

Complete Test Suites

- **Coping with high test strength requirements**
  - A black-box test suite is **complete** with respect to a given fault model if and only if
    - Every conforming SUT passes all test cases
    - Every non-conforming SUT inside the fault domain fails at least one test case

Complete Test Suites

- How can we cope with the size of complete test suites?
  - Take generic parameters into account by using symbolic methods [3], [4]
  - Reduce test suites size by building equivalence classes [5]
  - Reduce test suite size further by enforcing completeness only for safety-related or mission-critical requirements [6]

Remaining Challenge. Completeness&Consistency of Scenario Models

- Even if all scenarios have been tested by means of complete test suites:
  - **How do we ensure that the collection of scenario models is consistent and describes all relevant system behaviours?**
- New research field, involves
  - **Machine learning**

Autonomous Trains (Rolling Stock)

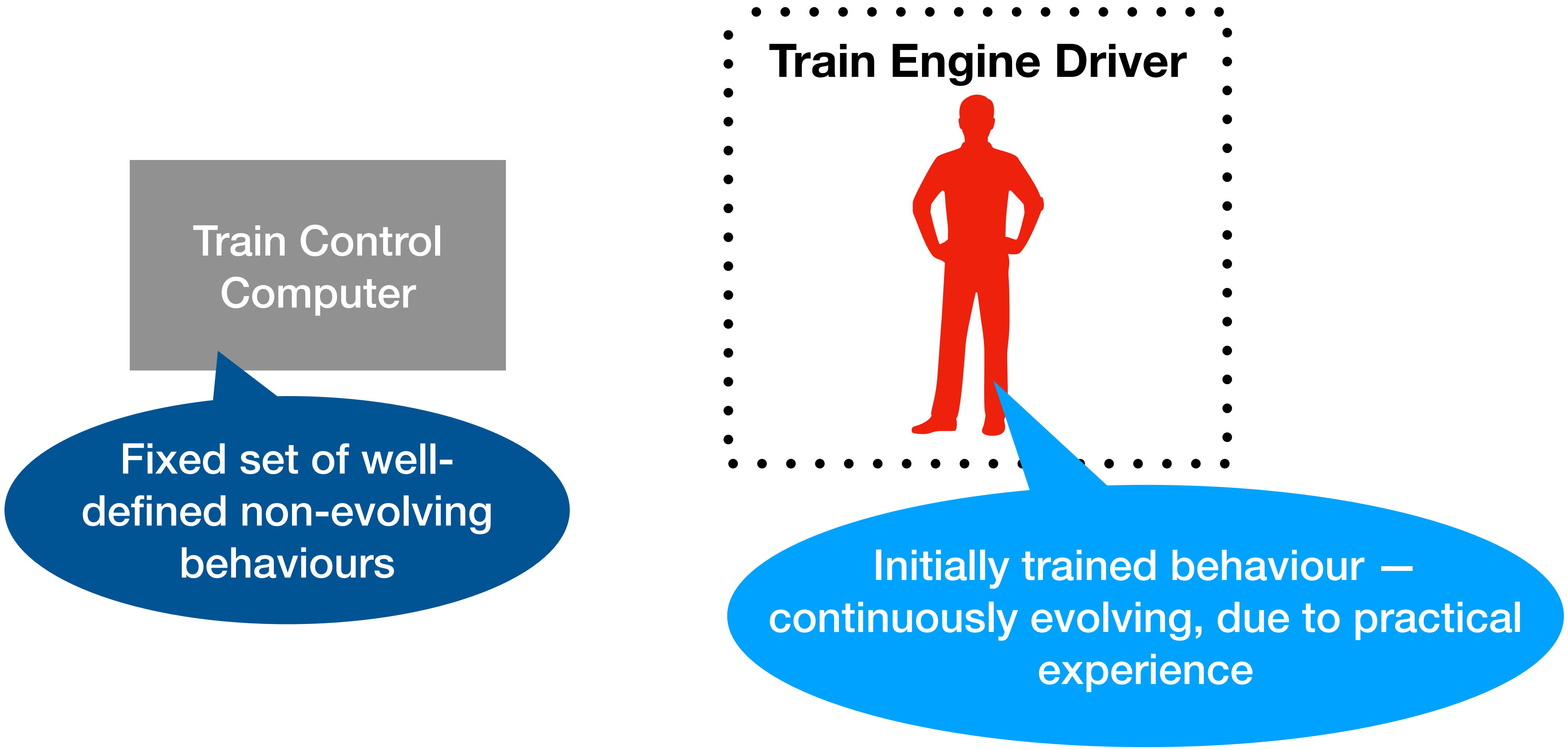
Autonomous Trains (Rolling Stock)

- Driving rolling stock trains without human train engine drivers has many advantages, in particular
  - Freight trains can be “parked” anywhere to let passenger trains bound to fixed time tables pass, without having to consider rest periods for the train engine driver

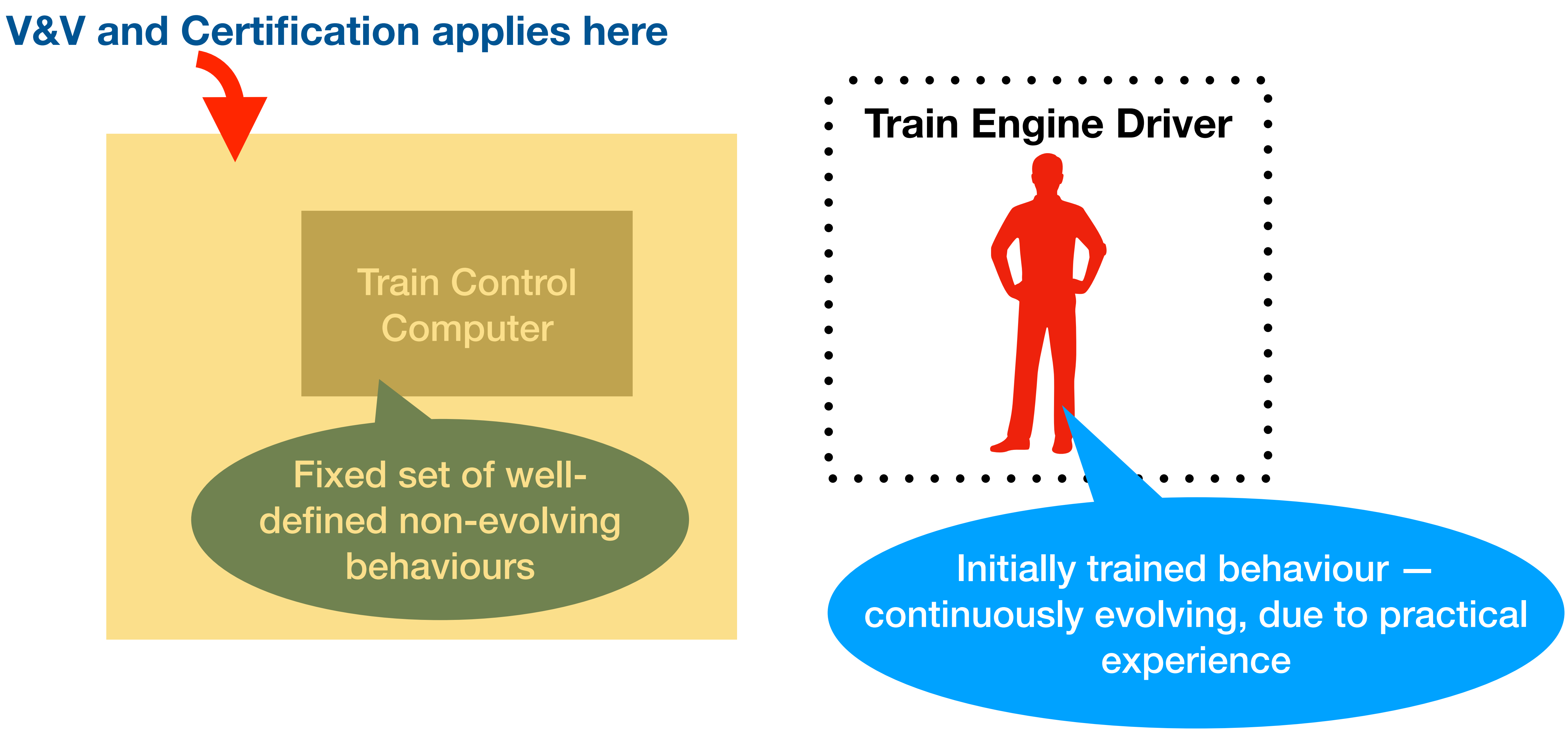
Autonomous Trains V&V

- Why does V&V for autonomous trains require more effort than V&V for manual train control ?

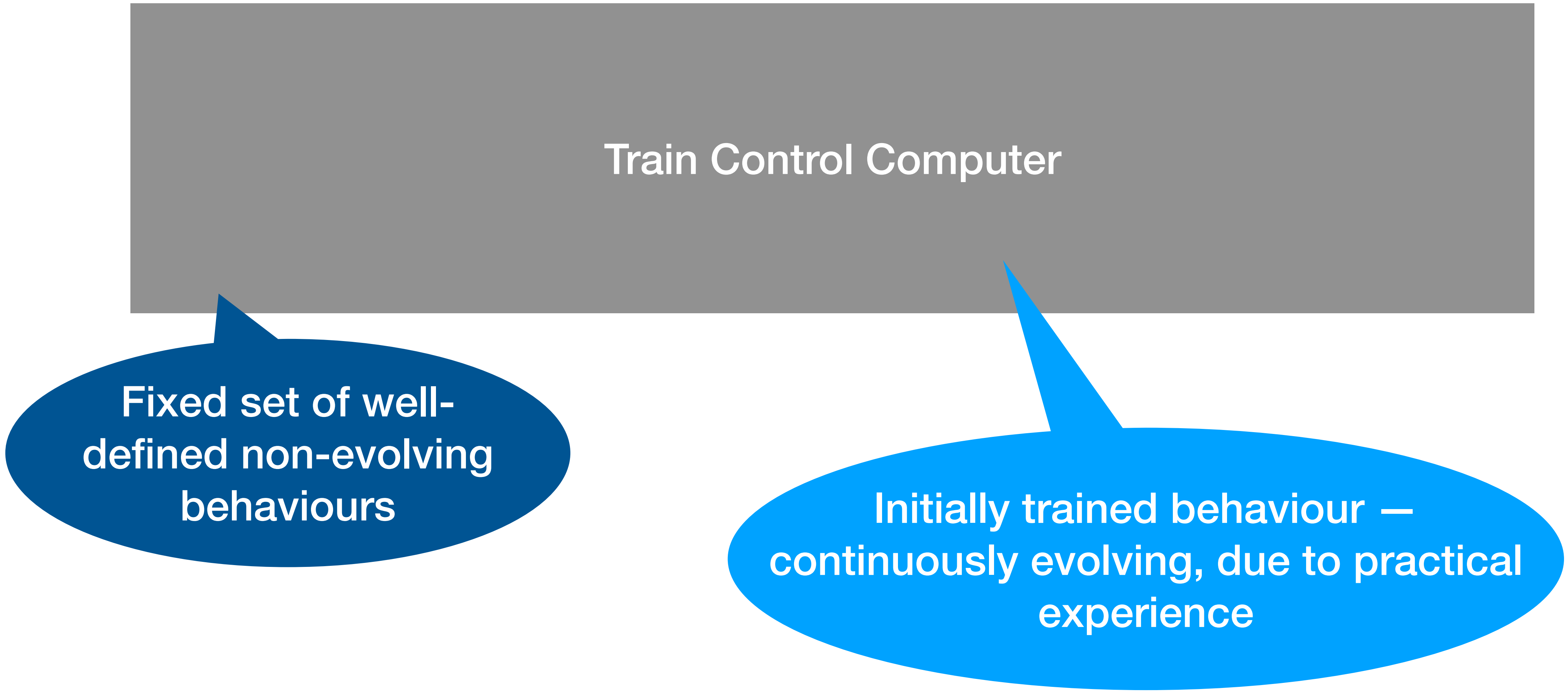
Consider First V&V for Conventional Train Control With Human Train Engine Driver



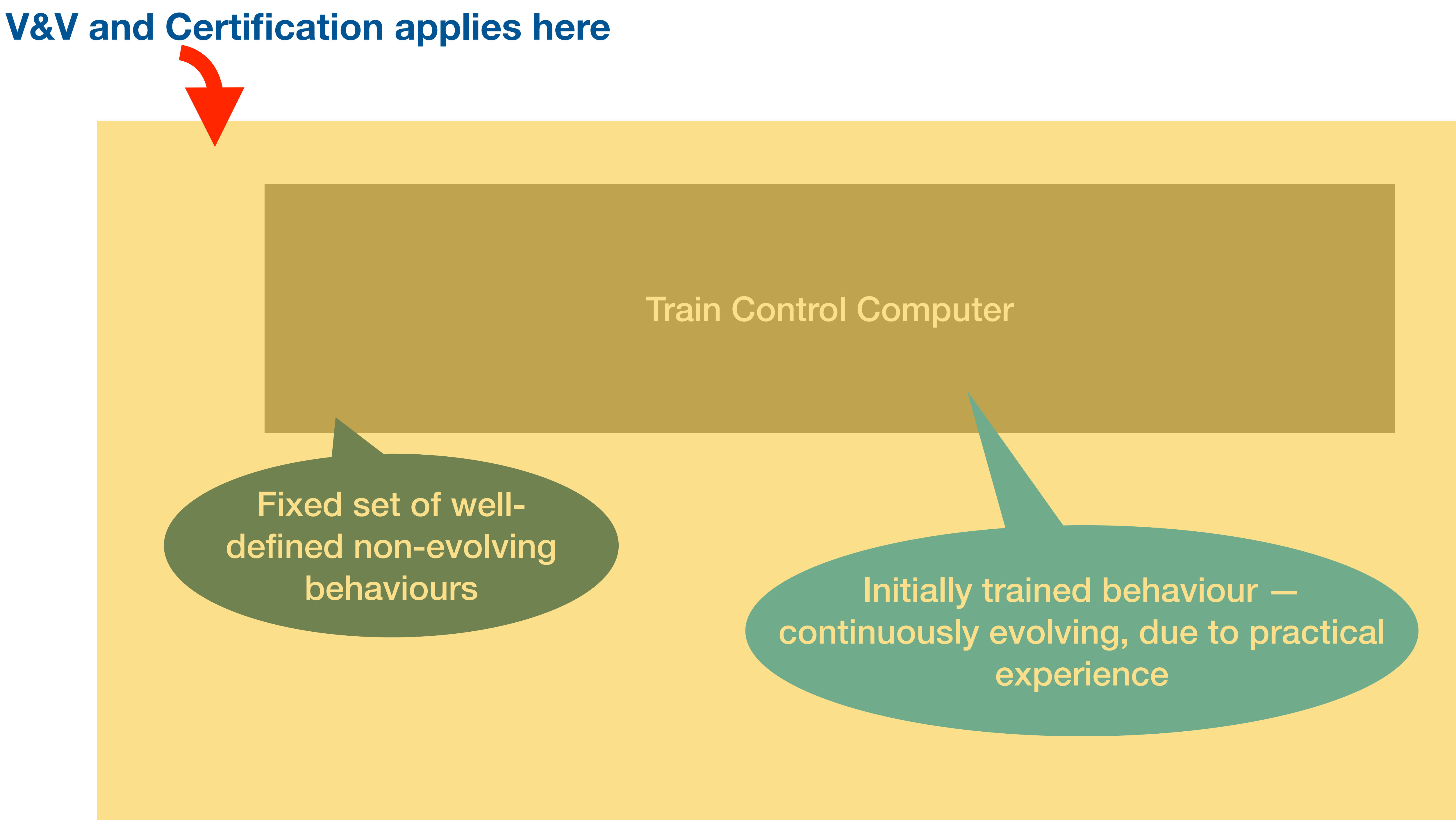
Consider First V&V for Conventional Train Control With Human Train Engine Driver



Autonomous Trains V&V



Autonomous Trains V&V



Consequences of High V&V Workload for Autonomous Trains

- A considerable portion of tests needs to be **executed in the cloud**, with very many tests running in parallel
- To obtain certification credit for tests in the cloud, these **tests need to run in an emulation environment** that reflects the true HW target platform in a trustworthy way
  - Again, we need emulators
  - The research fields related to building trustworthy emulators are
    - **HW/SW Codesign**
    - **Virtual Prototypes** [7]

Conclusion

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- Cloud-based architecture for railway control systems has been presented
  - Based on the DS^3 system by Siemens Mobility GmbH
- V&V issues have been analysed
- Feasible modelling approach can be based on scenarios
- Test strategies with full fault coverage may be used to prove correct implementation of safety-relevant requirements with acceptable effort

Main Challenges for the Future

- Invent validation methods to **check completeness and consistency of scenario collections** – based on machine learning

- **Tool qualification for trustworthy emulators** (research field Virtual Prototypes [7])
    - Needed for
        - Execution of legacy IXL software in the cloud
        - Execution of trustworthy tests in the cloud

Further Reading

1. Sonja Steffens. Safety@COTS Multicore, Distributed Smart Safe System DS³. Siemens Mobility GmbH 2018, available under https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwizhdvT-djiAhVQr6QKHU5QDQUQFjAAegQIBRAC&url=https%3A%2F%2Fsmartrail40.ch%2Fservice%2Fdownload.asp%3Fmem%3D0%26path%3D%255Cdownload%255Cdownloads%255C2018%252011%252013%2520Innovationstag%2520ETCS%2520Stellwerk_smartrail%25204.0.pdf&usg=AOvVaw23cALWR65rwvLr7jpjvt11

2. Hardi Hungar: Scenario-Based Validation of Automated Driving Systems. ISoLA (3) 2018: 449-460

3. Jan Peleska: Model-based avionic systems testing for the airbus family. ETS 2018: 1-10

4. Jan Peleska, Jörg Brauer, and Wen-ling Huang: Model-Based Testing for Avionic Systems Proven Benefits and Further Challenges. ISoLA (4) 2018: 82-103

5. Wen-ling Huang and Jan Peleska: Complete model-based equivalence class testing for nondeterministic systems. Formal Aspects of Computing 29(2), 335-364, 2017. doi=10.1007/s00165-016-0402-2

6. Wen-ling Huang, Sadik Özoguz, and Jan Peleska: Safety-complete test suites. Software Quality Journal, published online, DOI 10.1007/s11219-018-9421-y, 2018

7. Mehran Goli, Rolf Drechsler:
Scalable Simulation-Based Verification of SystemC-Based Virtual Prototypes. DSD 2019: 522-529