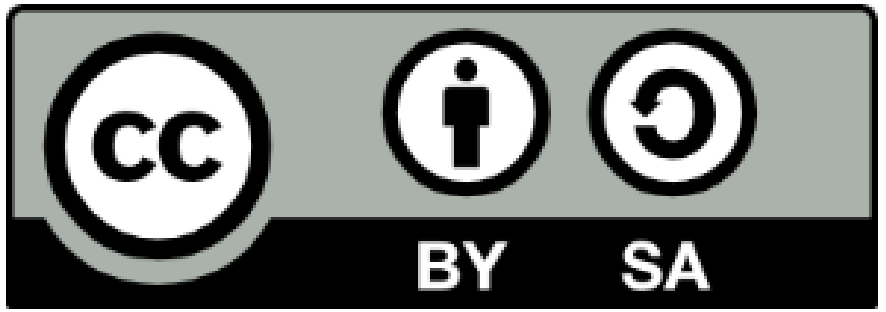

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eFMI® Tutorial – Agenda

Part 1: eFMI® motivation and overview (40 min)

Part 2: Running use-case introduction (10 min)

Part 3: Hands-on demonstration in Dymola and CATIA ESP (25 min)

Coffee break (30 min)

Part 3: Hands-on demonstration in Dymola and CATIA ESP (35 min)

Part 4: Live demonstration in TargetLink (30 min)

Part 5: Short presentation of further tooling (5 min)

Part 6: Conclusion (5 min)

Tutorial leader:
Christoff Bürger

DASSAULT SYSTEMES

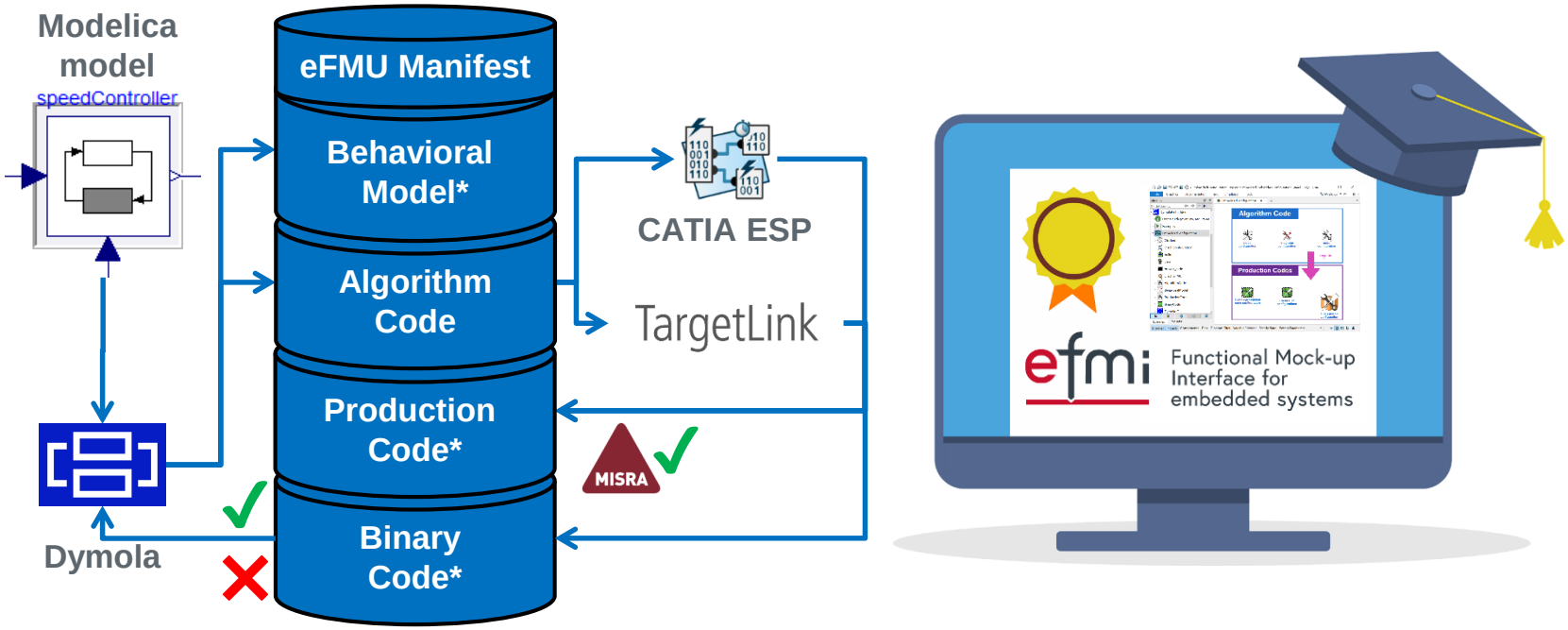
Presenter:
Oliver Lenord

BOSCH
Invented for life

Presenter:
Jörg Niere

dSPACE

efmi Functional Mock-up Interface for embedded systems



Part 1: eFMI® motivation and overview

eFMI® Tutorial – 15th International Modelica Conference – 9th of October 2023

Christoff Bürger
Dassault Systèmes
Christoff.Buerger@3ds.com

Oliver Lenord
BOSCH
Oliver.Lenord@de.bosch.com

Modelica Association Project eFMI (MAP eFMI)

Modelon
ALTAIR
efmi
Functional Mock-up Interface for embedded systems
iVH
Institute of Vehicle Engineering
MITSUBISHI ELECTRIC
Changes for the Better
DLR
esi
DASSAULT SYSTEMES
dSPACE
BOSCH
Invented for life
SIEMENS
Ingenuity for life
EFS
ELEKTRONISCHE FAHRWERKSYSTEME
OpenModelica
ETAS
DRIVING EMBEDDED EXCELLENCE
PIKETEC
software engineering
Mercedes-Benz

Project leader:
Christoff Bürger

DASSAULT SYSTEMES

Deputy project leader:
Hubertus Tummescheit

Modelon

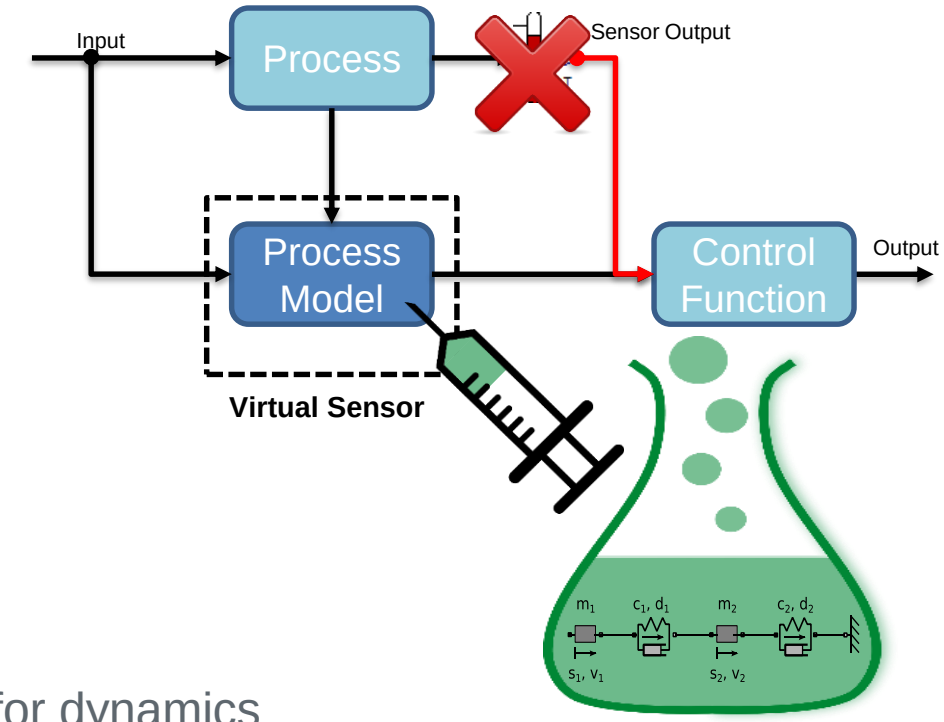
https://efmi-standard.org/

What is it all about?

eFMI motivation: Advanced control is challenging

Online physics models key technology for advanced (engine) control software:

- Virtual sensors, i.e., observers,
- Model-based diagnosis
- Inverse physical models as feed forward part of control structures
- Model predictive control



Physics model

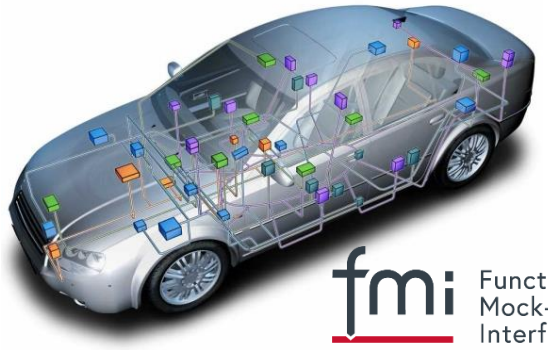
Physics models:

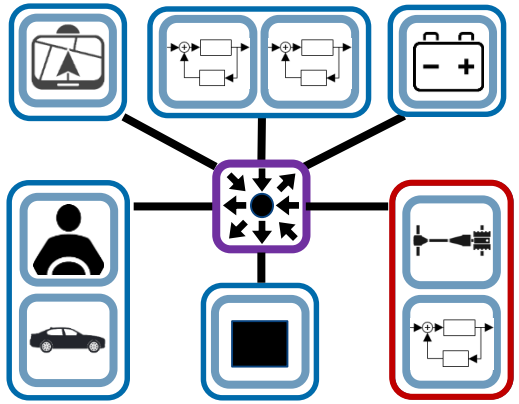
- Typically described by differential equations, best suited for dynamics
- Complementary to data-based modeling, can be combined
- Reduced calibration effort due to physical parameters

efmi Functional Mock-up Interface for embedded systems

eFMI standard: How it is different compared with FMI

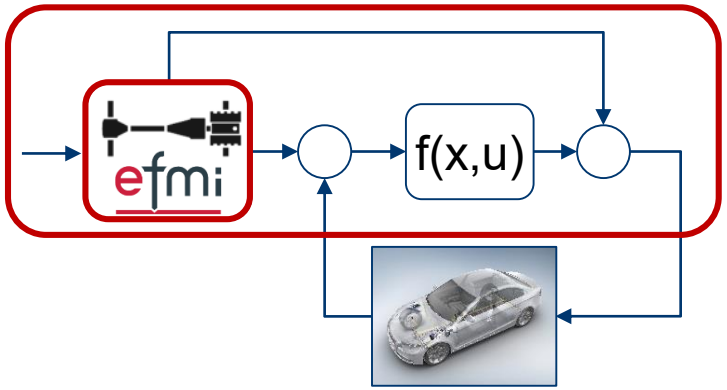
Model-based systems engineering



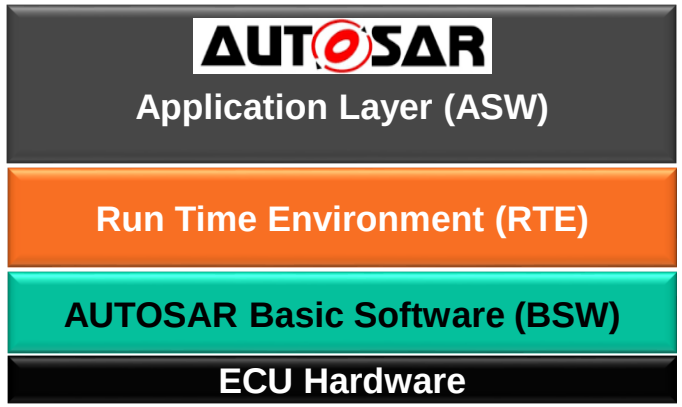


Model-based control

- Virtual sensors
- Feed-forward control
- Model-based diagnosis
- Model predictive control
- Advanced operating strategies
- …

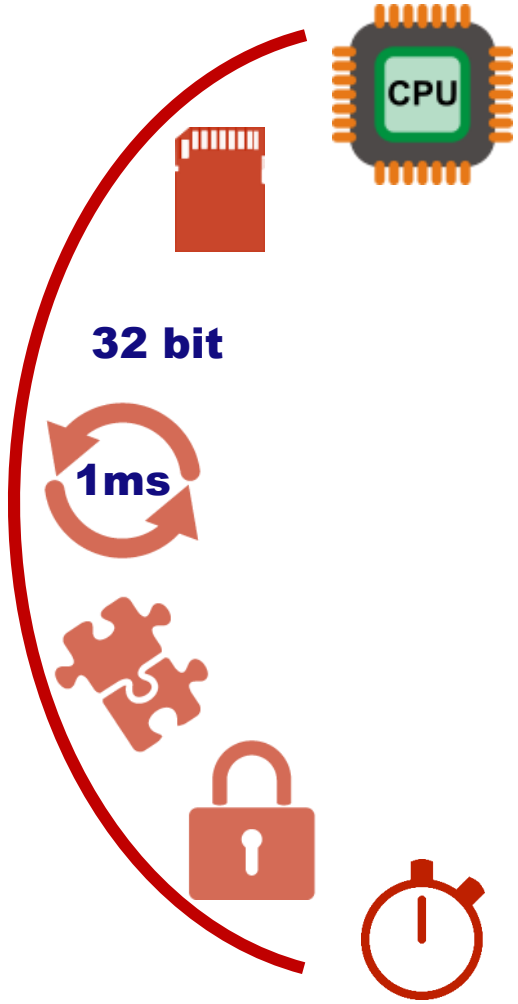


Software engineering



SW-C

eFMI motivation: Embedded systems are challenging



- Limited computation power
- Limited memory
- Limited precision
- Limited sampling rate
- Static memory allocation
- Guaranteed execution time
- Inbound guarantees
- No exceptions guarantees

- Specialized hardware

Bosch MDG1 ECU

- SW architectures

AUTOSAR

- Rules & regulations

MISRA

Motor **I**ndustry **S**oftware **R**eliability **A**ssociation

efmi Functional Mock-up Interface for embedded systems

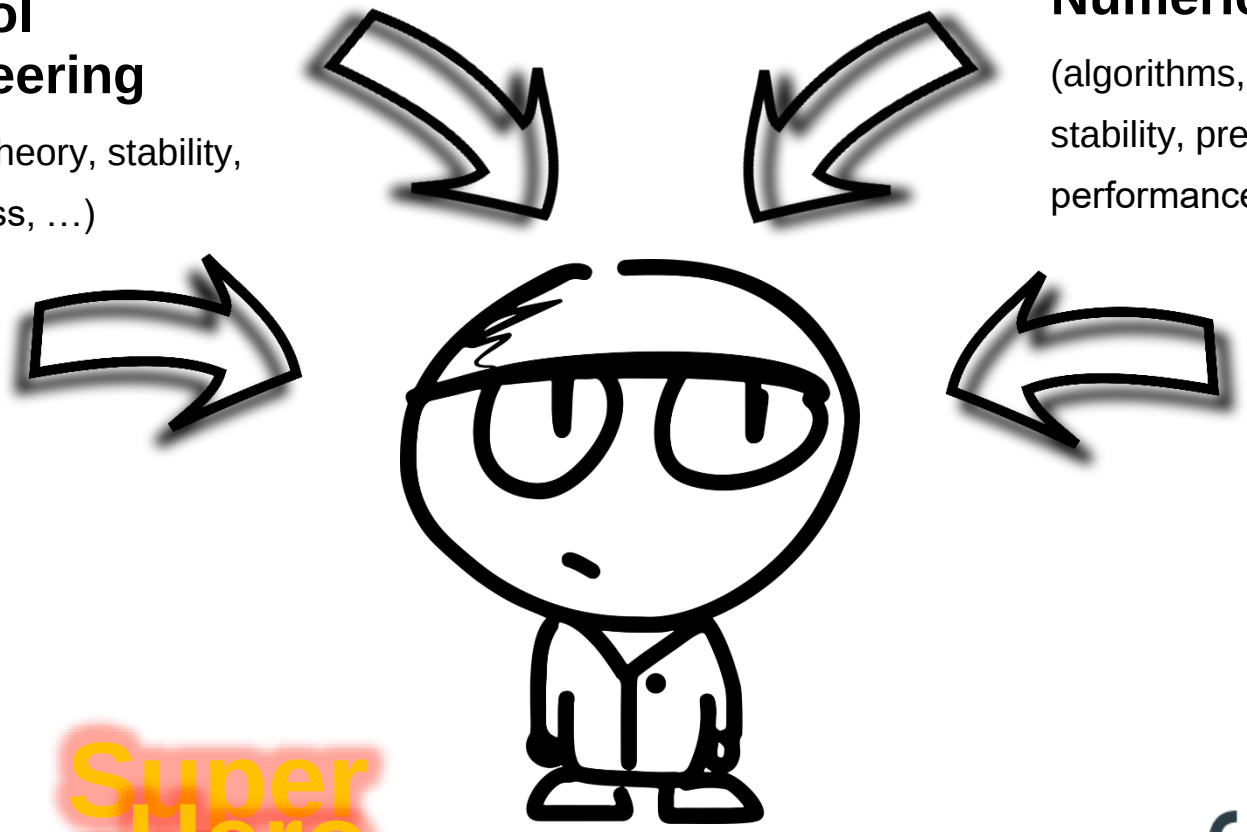
eFMI motivation: Multi-domain collaboration is challenging

Control engineering

(system theory, stability, robustness, …)

Numerics

(algorithms, complexity, stability, precision, realtime performance…)



Physics modeling

(domain knowledge, physical principles & phenomena, system dynamics, model validation, …)

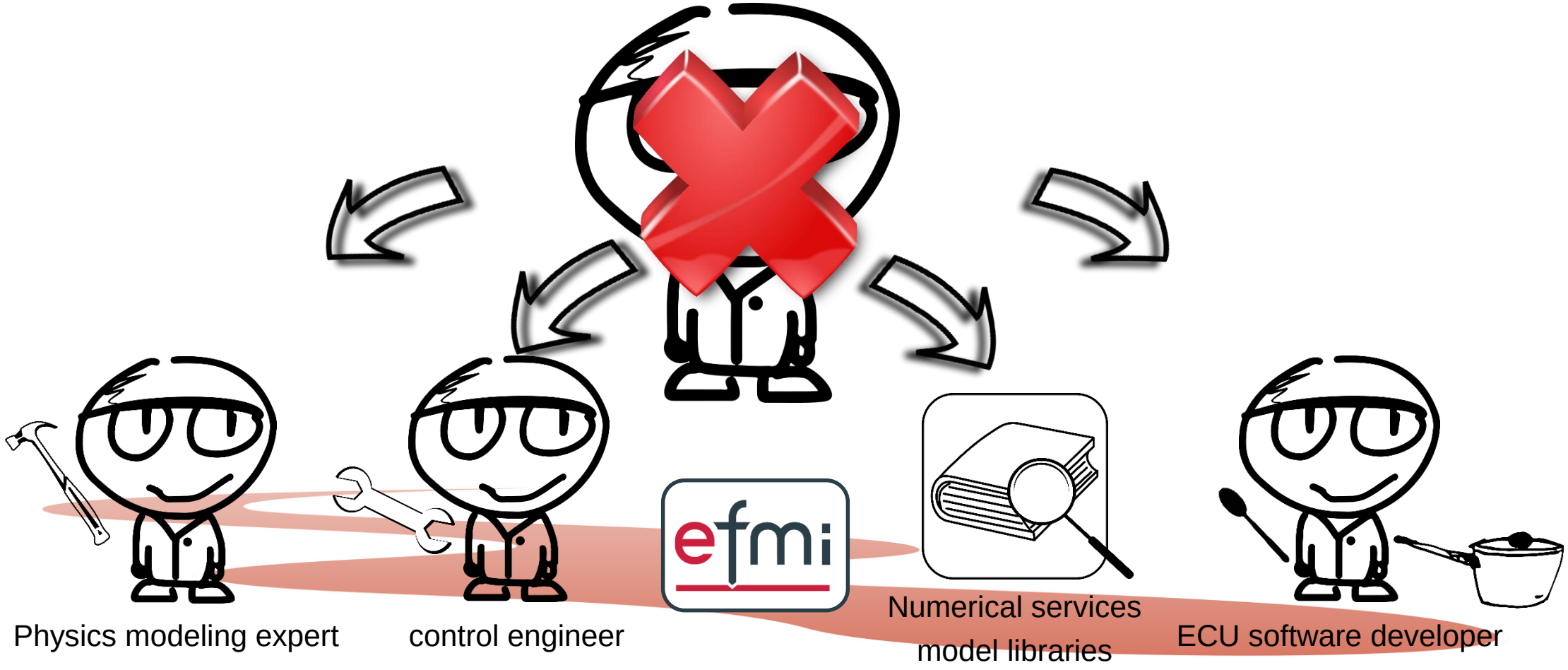
ECU software

(MISRA, ASIL, MSR, AUTOSAR, …)

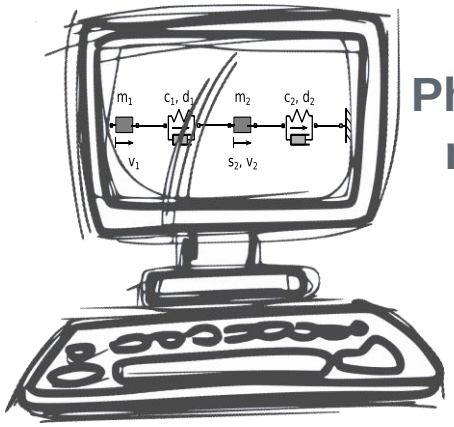
Function developer

efmi Functional Mock-up Interface for embedded systems

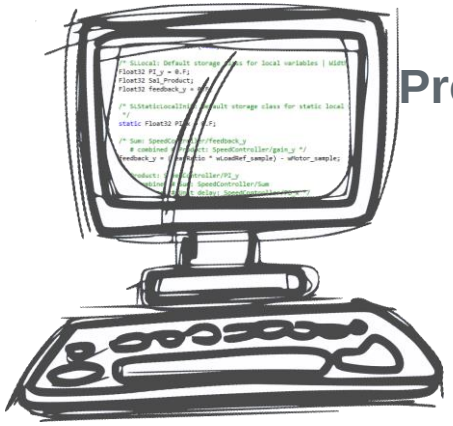
eFMI solution: Domain experts with dedicated tools…



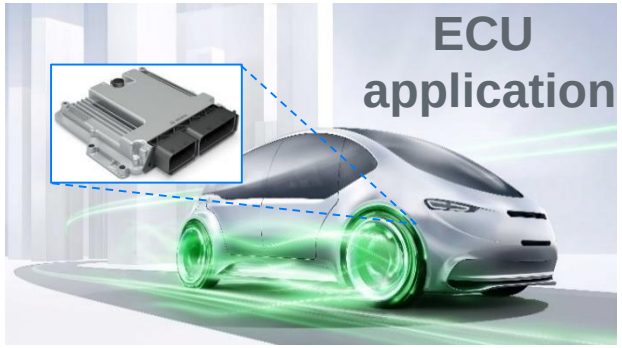
eFMI solution: …automatizing a distinct development process…



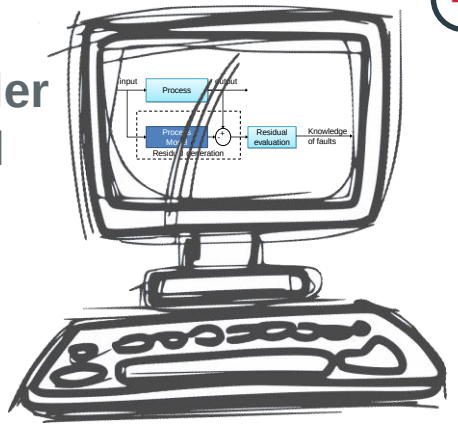
Physical model



Production code

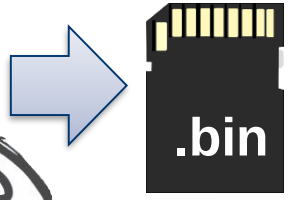


efmi



Controller model

ECU software

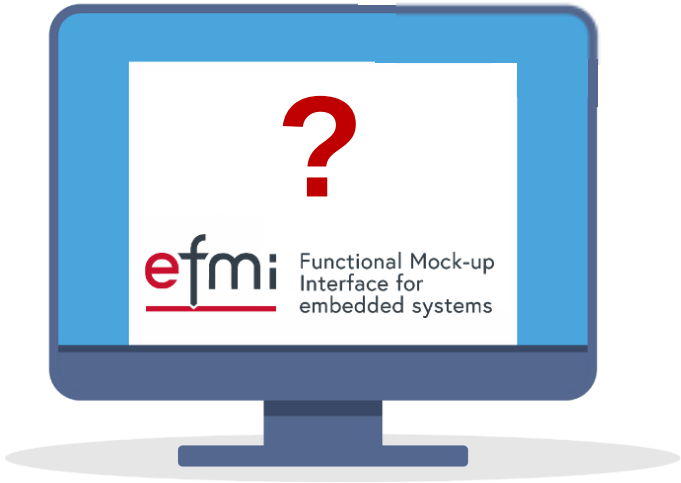


eFMI solution: …defined by a common standard

efmi Functional Mock-up Interface for embedded systems

Open standard for model-driven development of advanced control functions for safety-critical and real-time targets.

Ok, eFMI is about bringing physics simulations to safety-critical real-time targets!



But what *is* the eFMI Standard?

efmi Functional Mock-up Interface for embedded systems

eFMI Standard: Mission

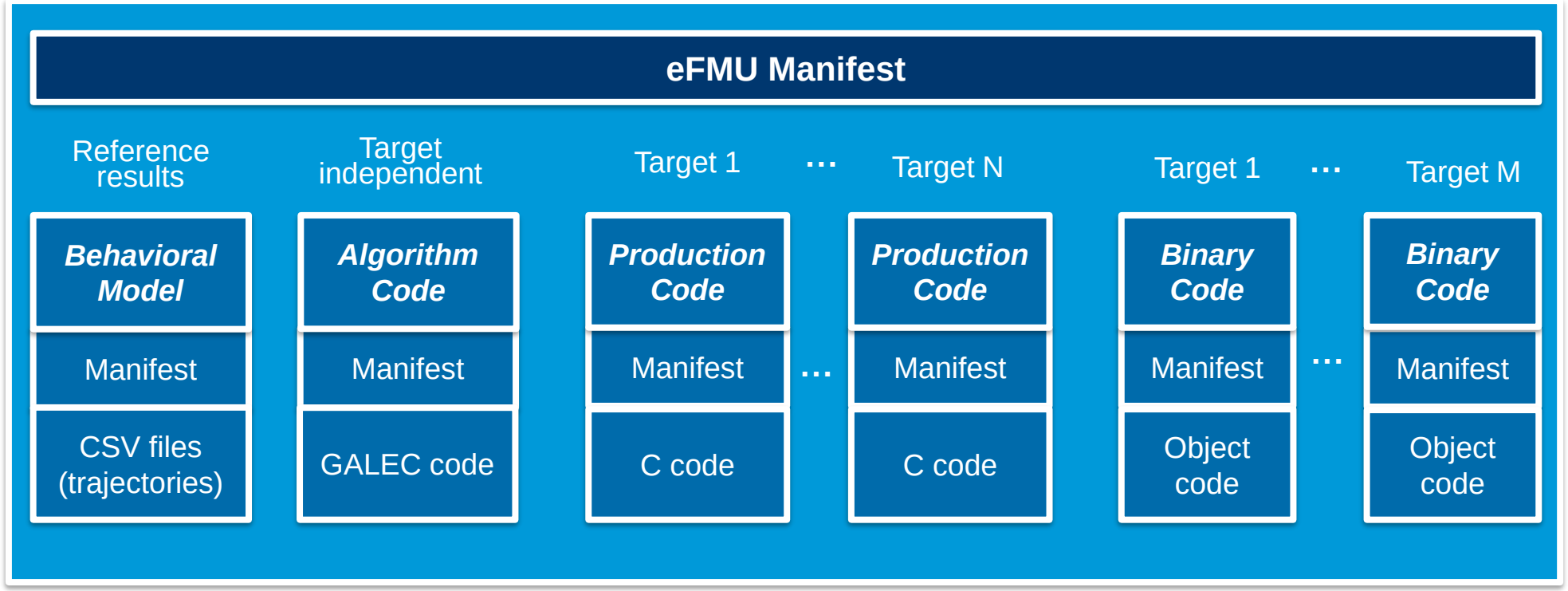
New standard enabling the application of (physics) models in embedded software:

- Workspace for step-wise development and refinement
  (from first high-level algorithmic solution to an embedded implementation on a dedicated target environment)
- Cover the development concerns of implementation, testing, and integration

eFMUs model representations support:

- *Behavioral Model* container: Behavior / reference results for testing.
- *Algorithm Code* container: Target-independent bounded algorithmic solution based on *GALEC*
  (new programming language for safety-critical, real-time suited, fix-rate sampled algorithms)
- *Production Code* container: C implementations, tailored and optimized for target environment requirements
- *Binary Code* container: Binary distributions and their „build-recipes“, ready for embedded system integration

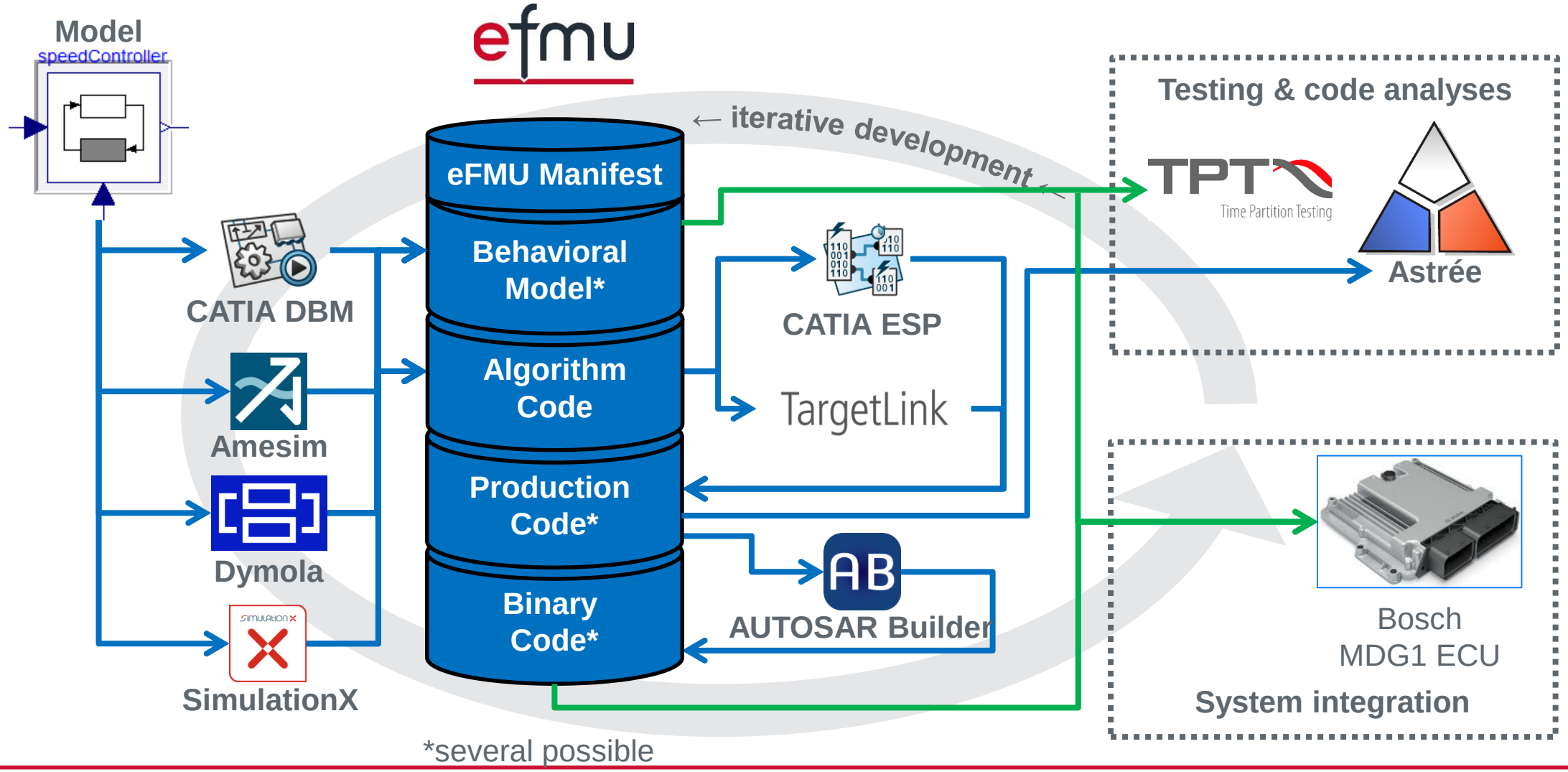
eFMI Standard: Container architecture



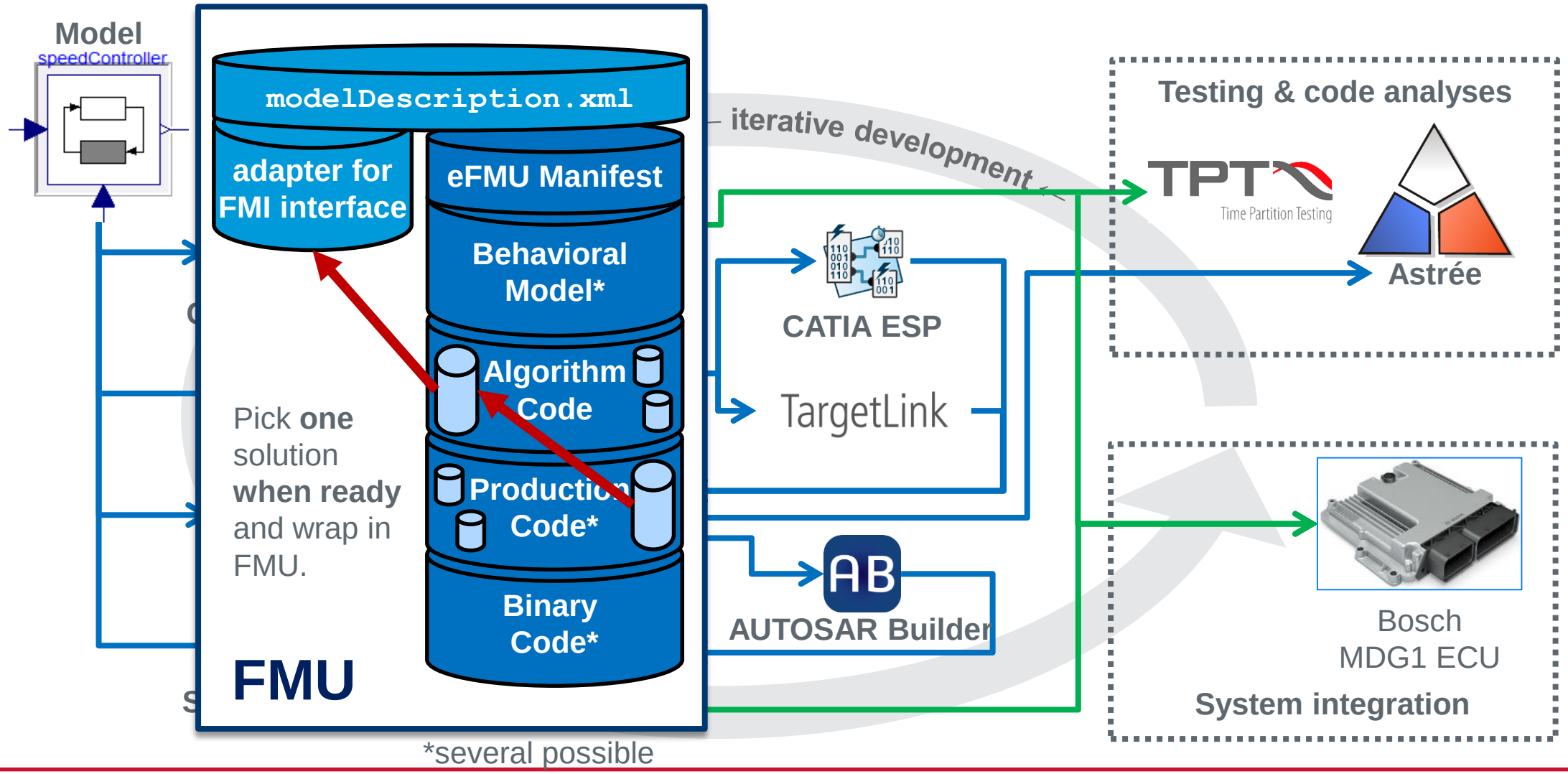
efmu

efmi Functional Mock-up Interface for embedded systems

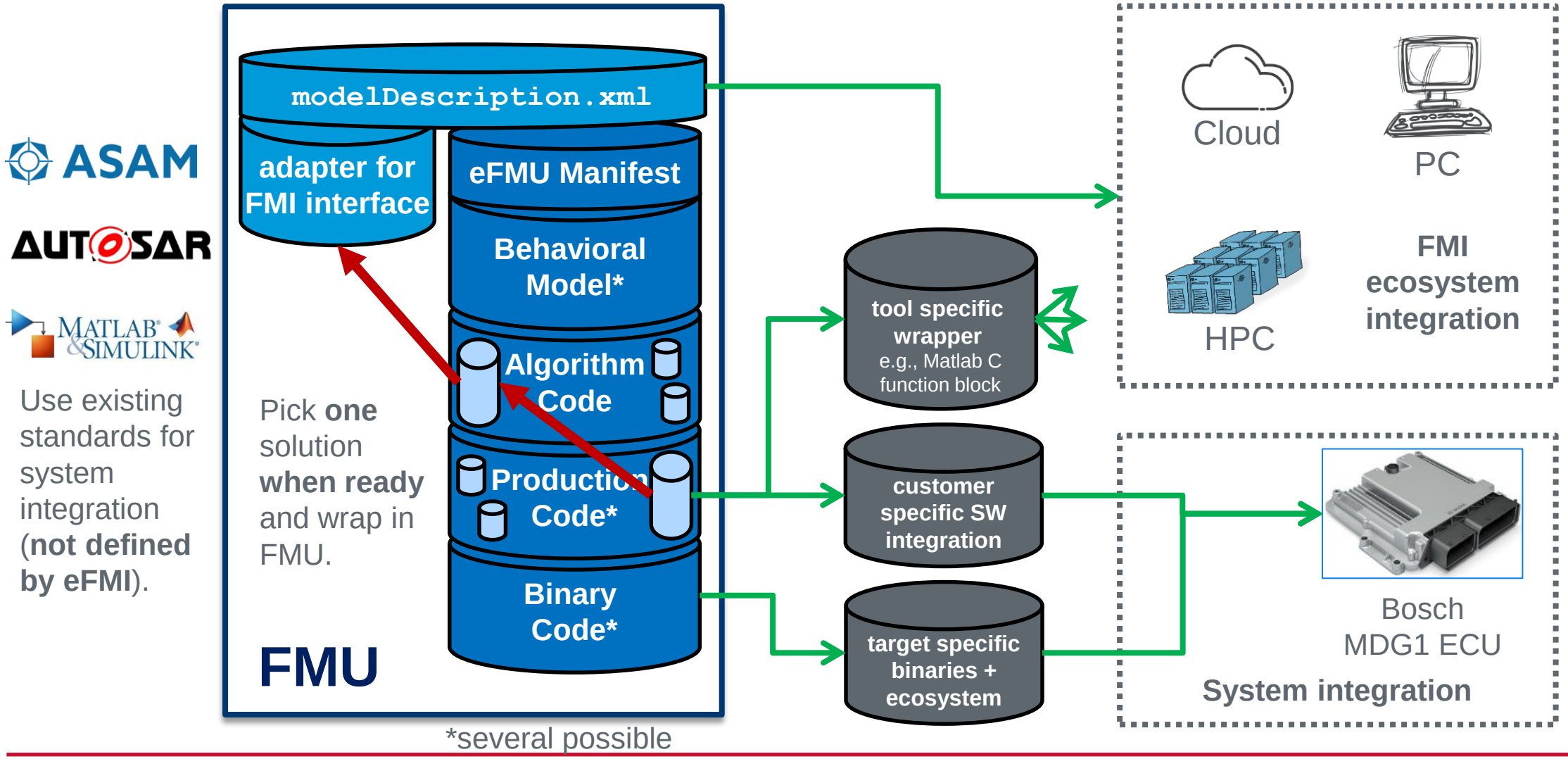
eFMI Standard: Toolchain & workflow



eFMI Standard: Deployment scenarios



eFMI Standard: Deployment scenarios



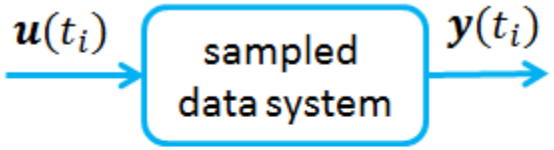
Ok, the eFMI Standard defines model representations capturing embedded software development stages, leaving finding solutions to expert tools!

But how does the eFMI Standard enable an automatized toolchain satisfying functional, safety-critical and real-time objectives?

efmi Functional Mock-up Interface for embedded systems

eFMI Standard: Container architecture & traceability

GALEC program:

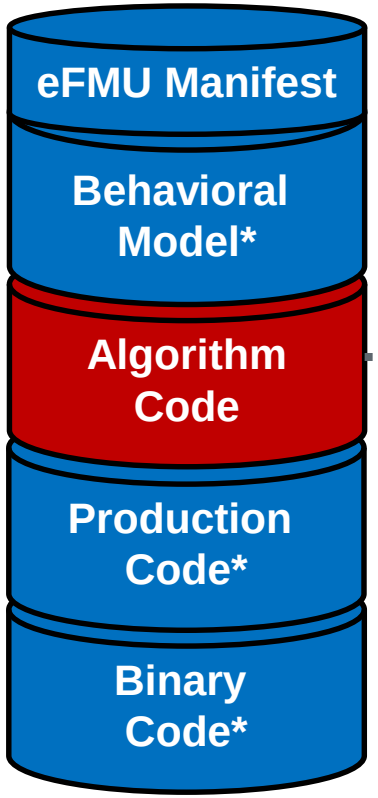


$$x_{i+1} = f_x(x_i, u_i)$$
$$y_i = f_y(x_i, u_i)$$

GALEC language features:

- Imperative, target independent with high math-abstraction level
- Well-defined, decidable semantics and safe numerics
- Guaranteed error handling
- Simple; high potential for target code tailoring & optimization

⇒ Nice intermediate representation for code generation (modelling target & embedded source)



*several possible

GALEC program

```
block Controller
  // Block interface variables:
  input Real u (min = -1.5, max = 1.5);
  output Real y[20] (min = -1.0, max = 1.0);
  parameter Real tP; // tunable parameter
  parameter Real tV[20];// tunable parameter
protected
  // Internal block variables and functions:
  parameter Real dP; // dependent parameter
  Real M1[20,10] // state
    (min = -1.0, max = 1.0);
  Real M2[10,20] // state
    (min = -1.0, max = 1.0);
  function checked_transpose
    signals UNDERFLOW, NAN [[...]];
  function sum [[...]];
public
  // Block interface functions:
  method Recalibrate
    signals INVALID_ARGUMENT [[...]];
  method Startup [[...]];
  method DoStep
    signals NO_SOLUTION_FOUND [[...]];
end Controller;
```

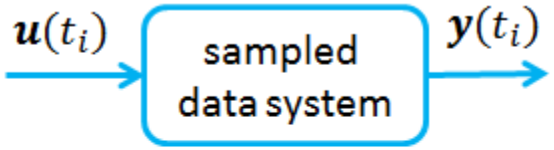
GALEC program
(algorithmic solution)
+
Meta information
(interface, checksums, documentation, ids for referencing content)

XML manifest

```
<?xml version="1.0" encoding="UTF-8"?>
<Manifest
  xsi:noNamespaceSchemaLocation="../[[…]]“
  efmiVersion="1.0.0"
  xsdVersion="0.13.0“
  id="{b928ee7f-ddfc-4955-a8d3-c4386df5ce8f}“
  kind="AlgorithmCode“
  name=[[…]]
  generationDateAndTime="2023-09-18T12:20:06Z“
  generationTool=[[…]] description=[[…]] version=[[…]]>

<Files>
  <File
    role="Code“ id=[[…]]
    name=[[…]] path="./“
    needsChecksum="true“ checksum=[[…]]/>
</Files>

[[…]]

<Units>
  <Unit id=[[…]] name="Hz"><BaseUnit s="-1"/></Unit>
  [[…]]
</Units>

<Variables>
  <RealVariable
    id=[[…]]
    name=“u“
    blockCausality="input“
    unitRefId=[[…]]
    min="-1.5“ max="1.5“ start="0.0">
  </RealVariable>
  [[…]]
```

eFMI Standard: Container architecture & traceability

GALEC program:



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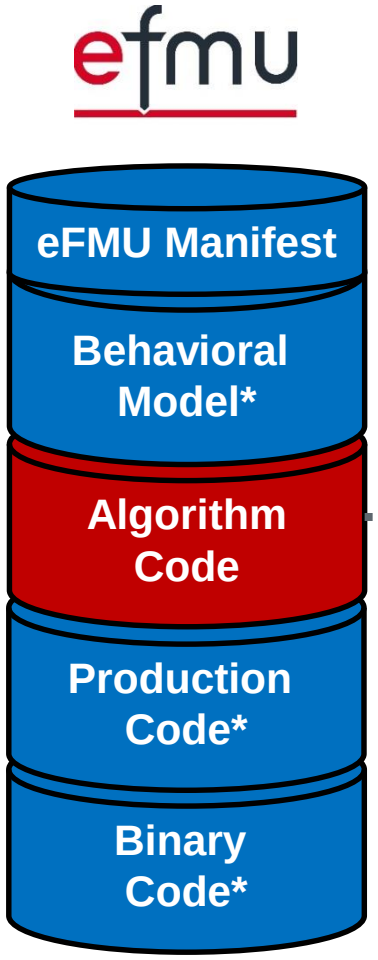

*several possible

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protected
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    (min = -1.0, max = 1.0);
  Real M2[10,20] // state
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  function sum [[...]];
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  // Block interface functions:
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  method DoStep
    signals NO_SOLUTION_FOUND [[...]];
end Controller;
```

GALEC program
(algorithmic solution)
+
Meta information
(interface, checksums, documentation, ids for referencing content)

XML manifest

```
<?xml version="1.0" encoding="UTF-8"?>
<Manifest
  [[…]]
</Units>

<Variables>
  <RealVariable
    id=[[…]]
    name="u"
    blockCausality="input"
    unitRefId=[[…]]
    min="-1.5" max="1.5" start="0.0">
  </RealVariable>
  [[…]]
```

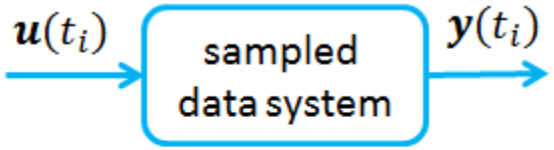
Common interface, with well-defined life-cycle semantic:

- (default) initialization
- sampling
- recalibration
- reinitialization

⇒ Defines valid system integration scenarios.

eFMI Standard: Container architecture & traceability

GALEC program:



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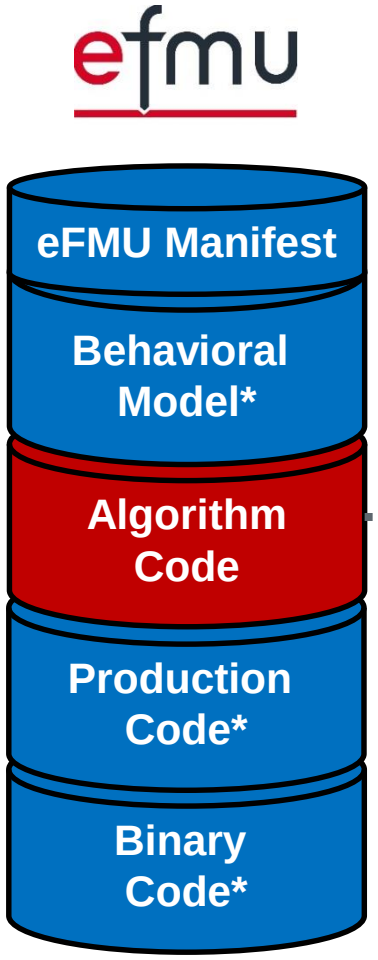
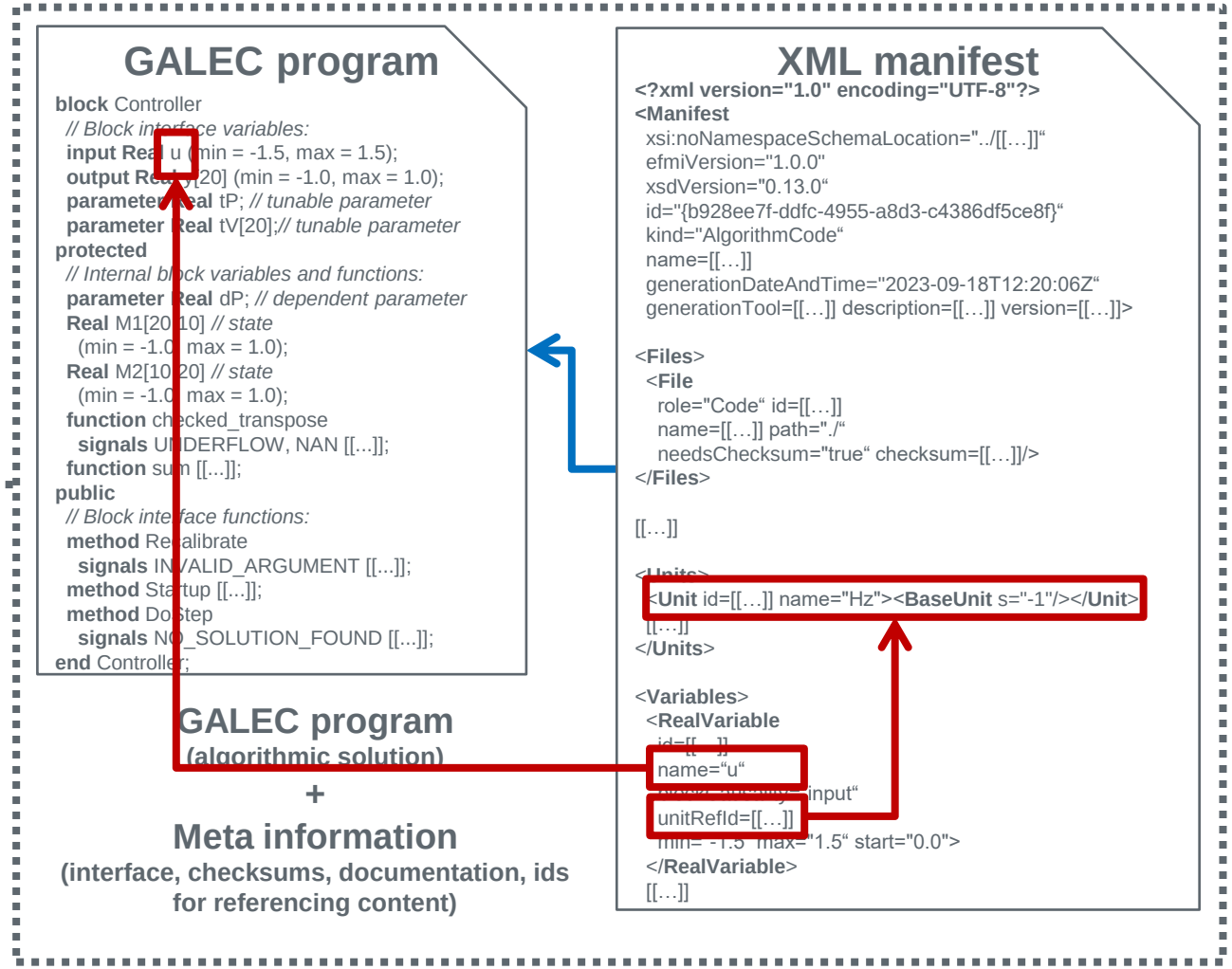
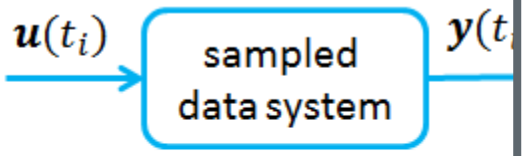


*several possible



eFMI Standard: Container architecture & traceability

GALEC program:



$$x_{i+1} = f_x(x_i, u_i)$$
$$y_i = f_y(x_i, u_i)$$

Starting point of further code generation: *GALEC* program generated by modeling tool.

GALEC language features:

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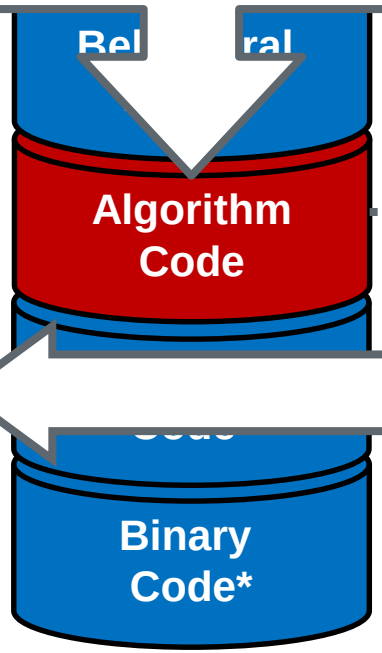
- Well-defined, decidable semantics and safe numerics
- Guaranteed error handling
- Simple; high potential for target code tailoring & optimization

⇒ Nice intermediate representation for code generation (modelling target & embedded source)



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  parameter Real tV[20];// tunable parameter
protected
  // Internal block variables and functions:
  parameter Real dP; // dependent parameter
  Real M1[20,10] // state
    (min = -1.0, max = 1.0);
  Real M2[10,20] // state
    (min = -1.0, max = 1.0);
  function checked_transpose
    signals UNDERFLOW, NAN [[...]];
  function sum [[...]];
public
  // Block interface functions:
  method Recalibrate
```

Implicit language guarantees guard further eFMI tooling.

(algorithmic solution)

+

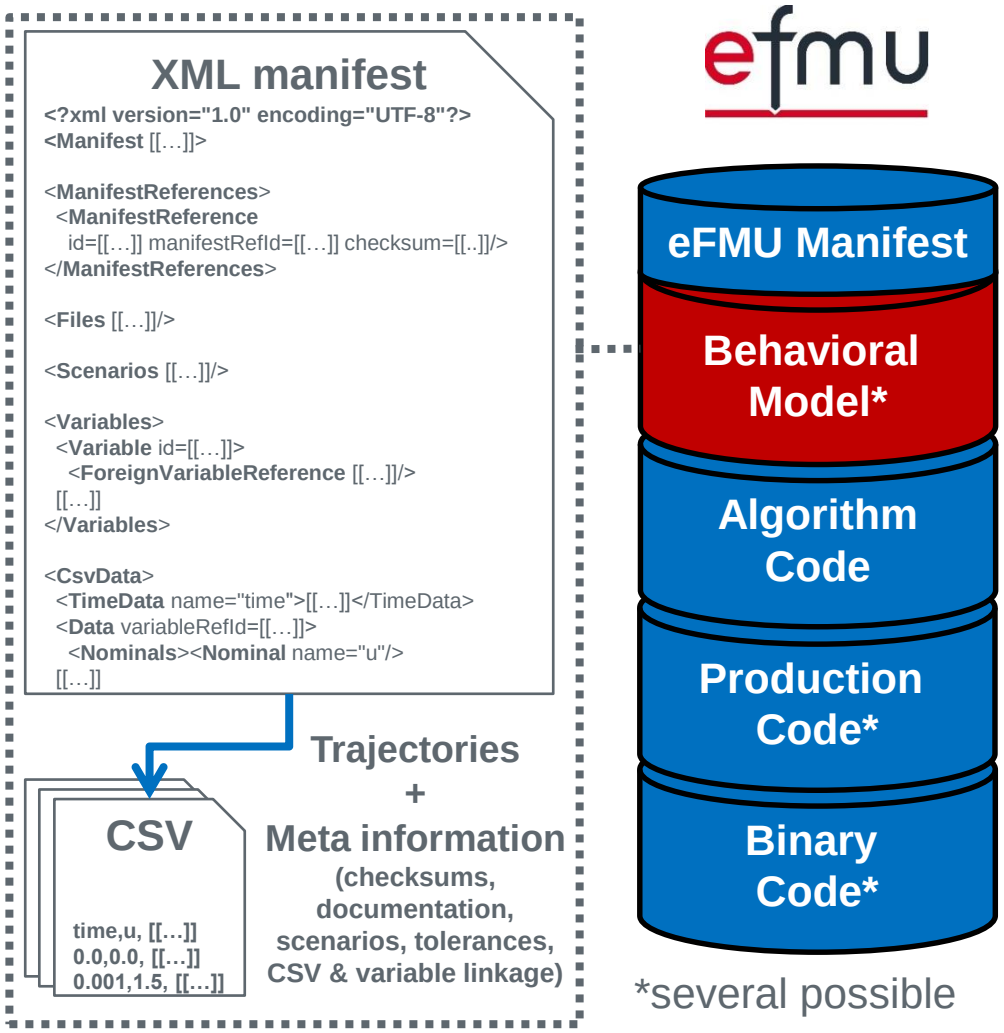
Meta information

(interface, checksums, documentation, ids for referencing content)

XML manifest

```
<?xml version="1.0" encoding="UTF-8"?>
<Manifest
  xsi:noNamespaceSchemaLocation="../[[…]]"
  efmiVersion="1.0.0"
  xsdVersion="0.13.0"
  id="{b928ee7f-ddfc-4955-a8d3-c4386df5ce8f}"
  kind="AlgorithmCode"
  name=[[…]]
  generationDateAndTime="2023-09-18T12:20:06Z"
  generationTool=[[…]] description=[[…]] version=[[…]]>

<Files>
  <File
    role="Code" id=[[…]]
    name=[[…]] path="./"
    needsChecksum="true" checksum=[[…]]/>
</Files>

[[…]]

<Units>
  <Unit id=[[…]] name="Hz"><BaseUnit s="-1"/></Unit>
  [[…]]
</Units>

<Variables>
  <RealVariable
    id=[[…]]
    name="u"
    causality="input"
    unitRefId=[[…]]
    min="-1.5" max="1.5" start="0.0">
  </RealVariable>
  [[…]]
```

eFMI Standard: Container architecture & traceability

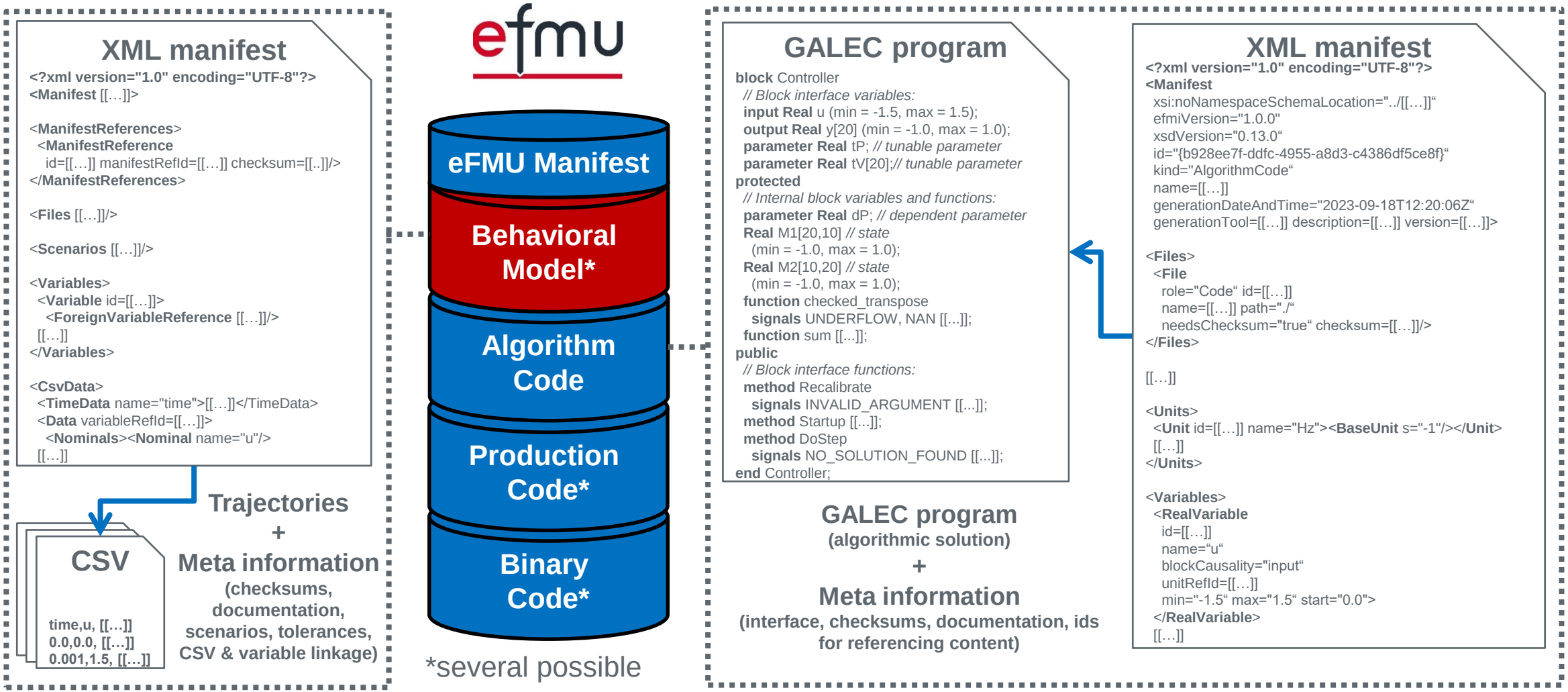


Behavioral Model features:

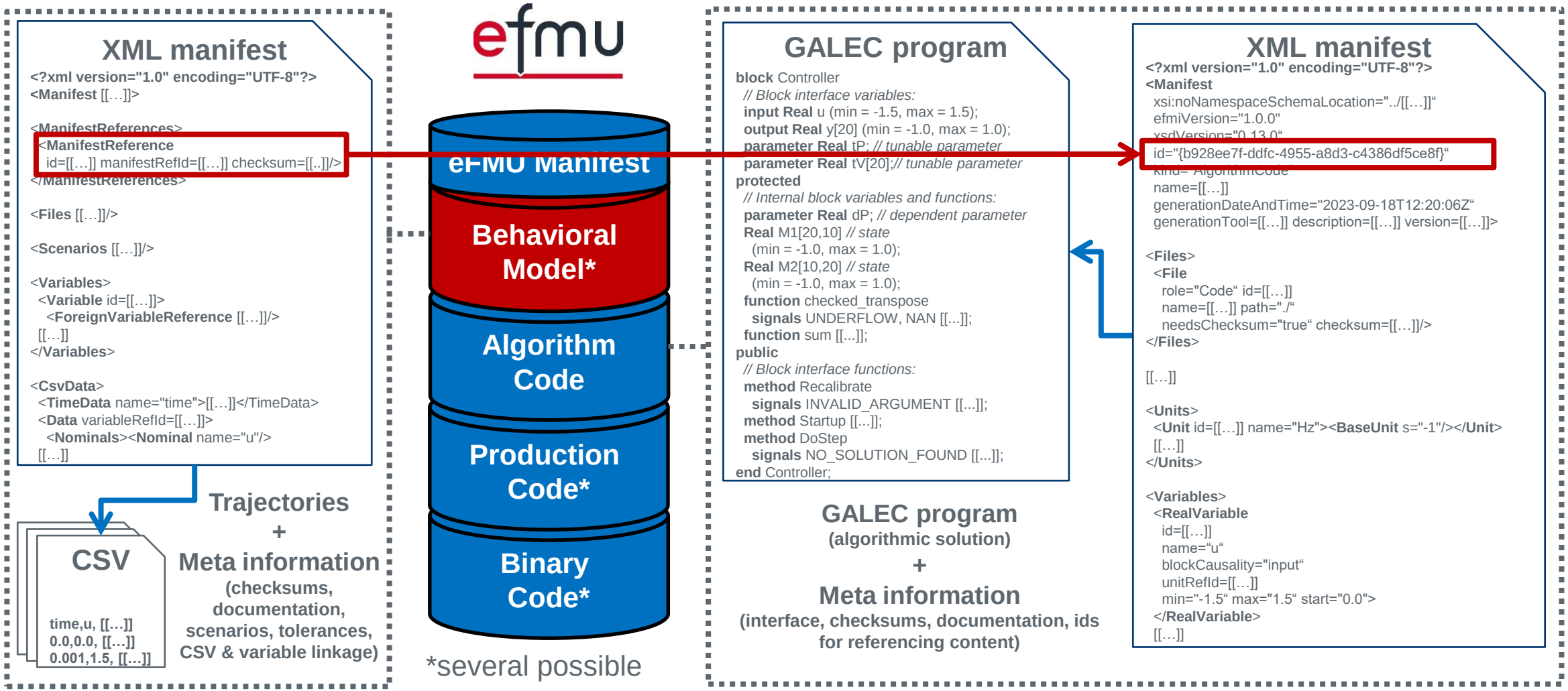
- Documentation & test scenarios in manifest
- Well-defined units and types via linking to Algorithm Code manifest
- Three types of tolerances, with well-defined interpretation:
  - absolute
  - relative
  - explicit upper and lower bound trajectories
- Two types of trajectories:
  - sampled (with well-defined restrictions on time trajectory tolerances)
  - unrestricted (with well-defined interpolation)
- CSV reference trajectories strictly follow RFC 4180 (only "," as separator, not ";"; only CRLF line-endings) with further restrictions:
  - no quoting, no additional whitespace
  - GALEC syntax for numbers
  - strictly monotone time trajectory

⇒ Unique interpretation

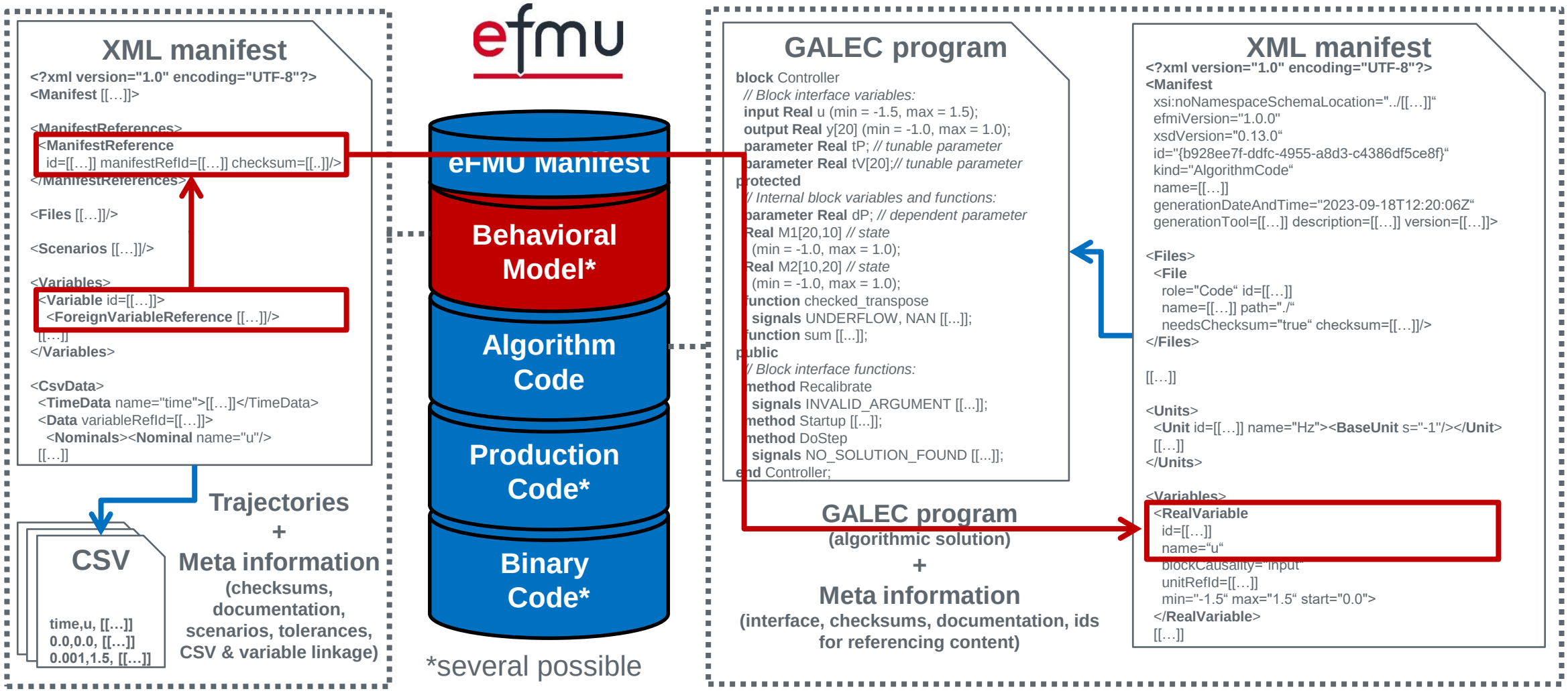
eFMI Standard: Container architecture & traceability



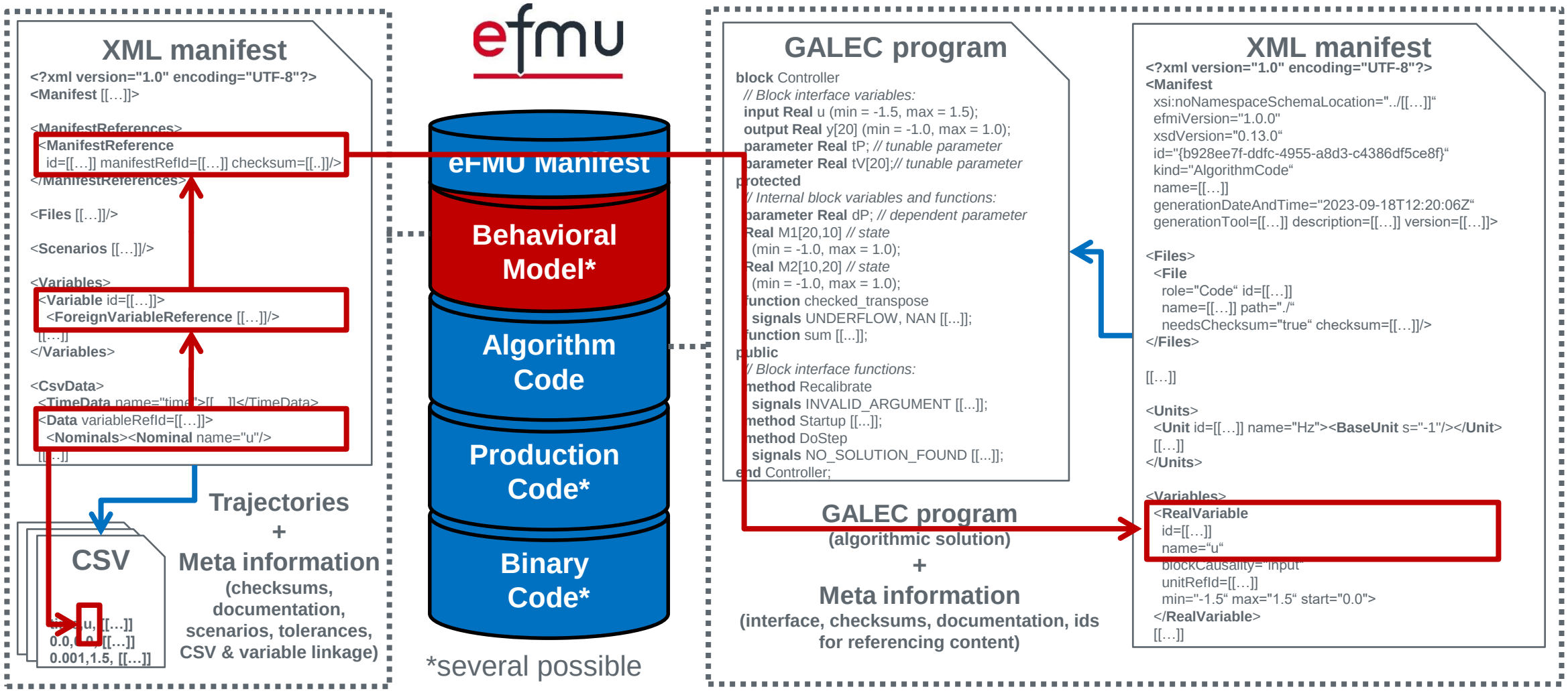
eFMI Standard: Container architecture & traceability



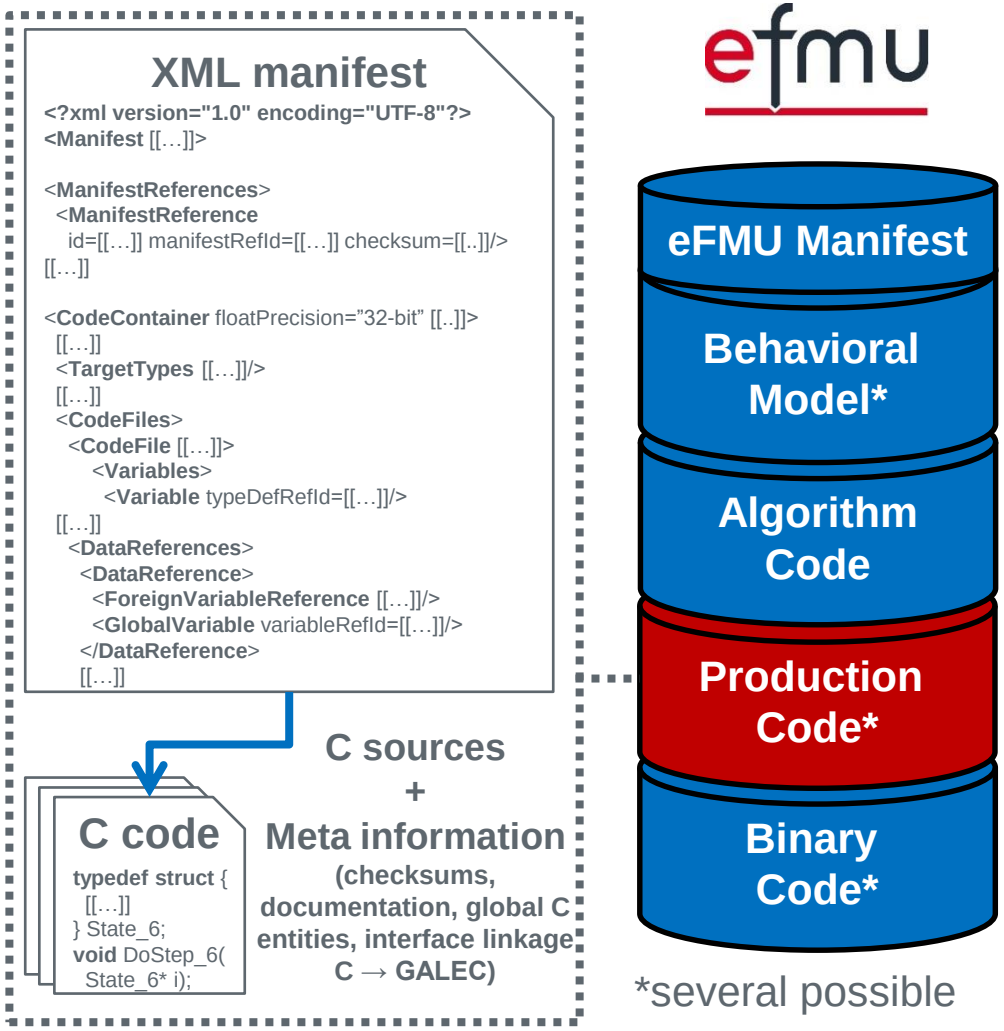
eFMI Standard: Container architecture & traceability



eFMI Standard: Container architecture & traceability



eFMI Standard: Container architecture & traceability

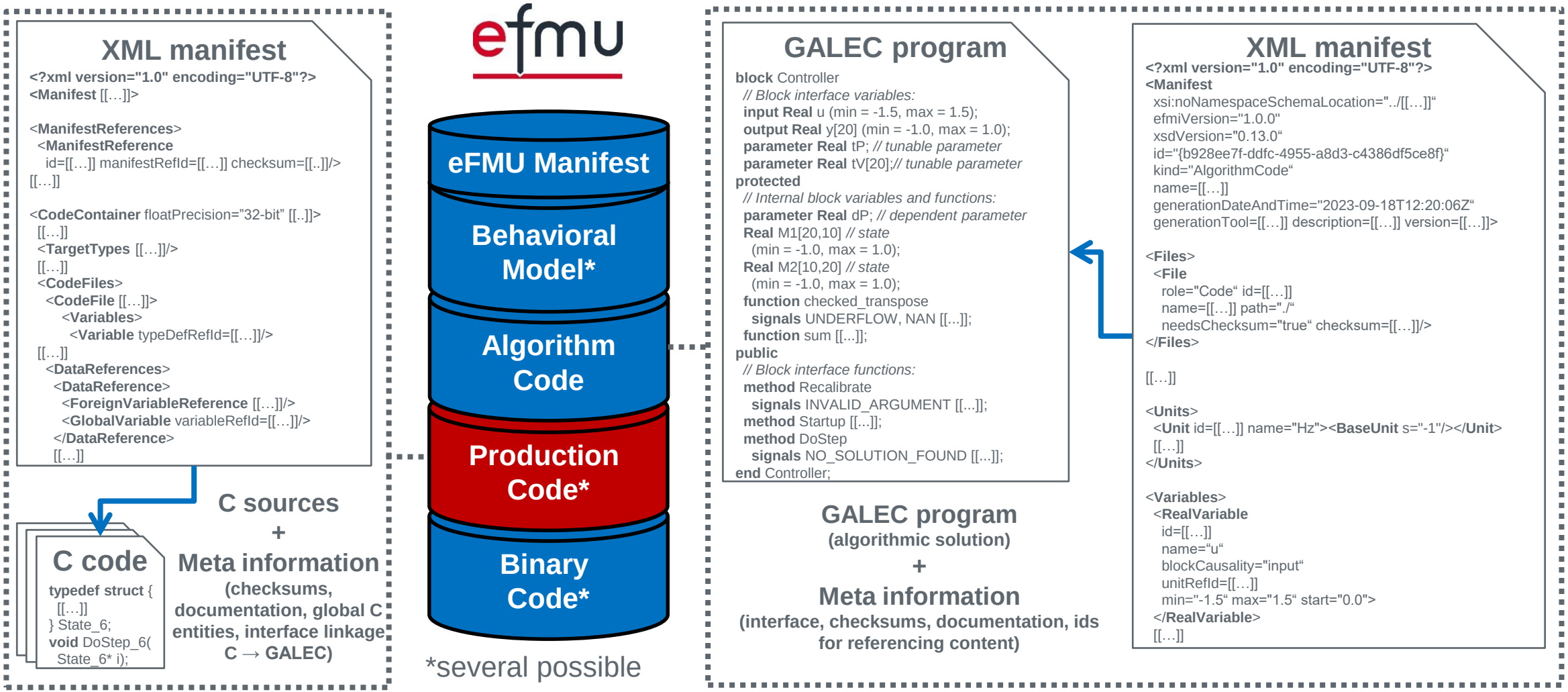


*several possible

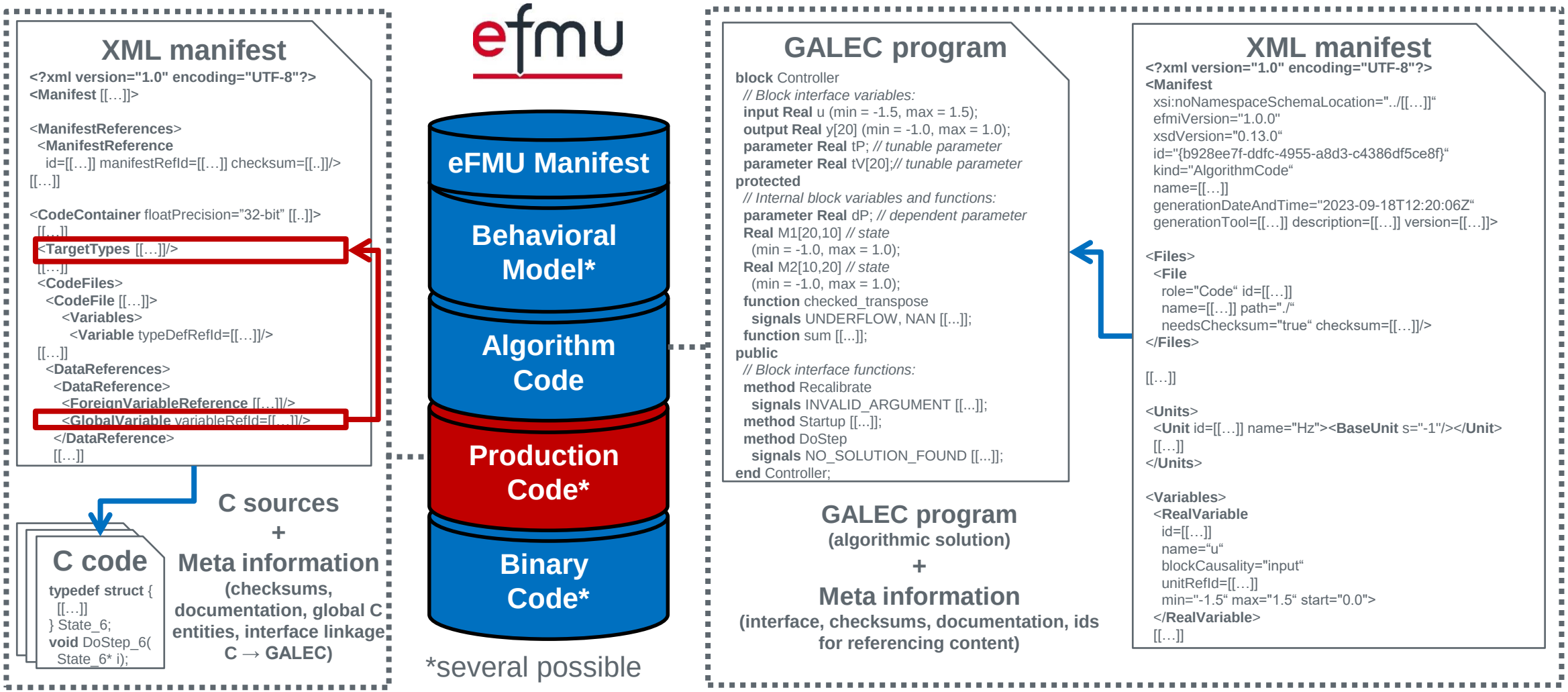
Production Code container features:

- Documentation of C sources, dependencies, global entities & interface in manifest
- C data layout & interface not standardized
  ⇒ Enables target environment tailoring
- Links C code to variables and functions of Algorithm Code manifest
  ⇒ Links implementation to GALEC block interface & life-cycle
  ⇒ Documents how to system integrate the production code

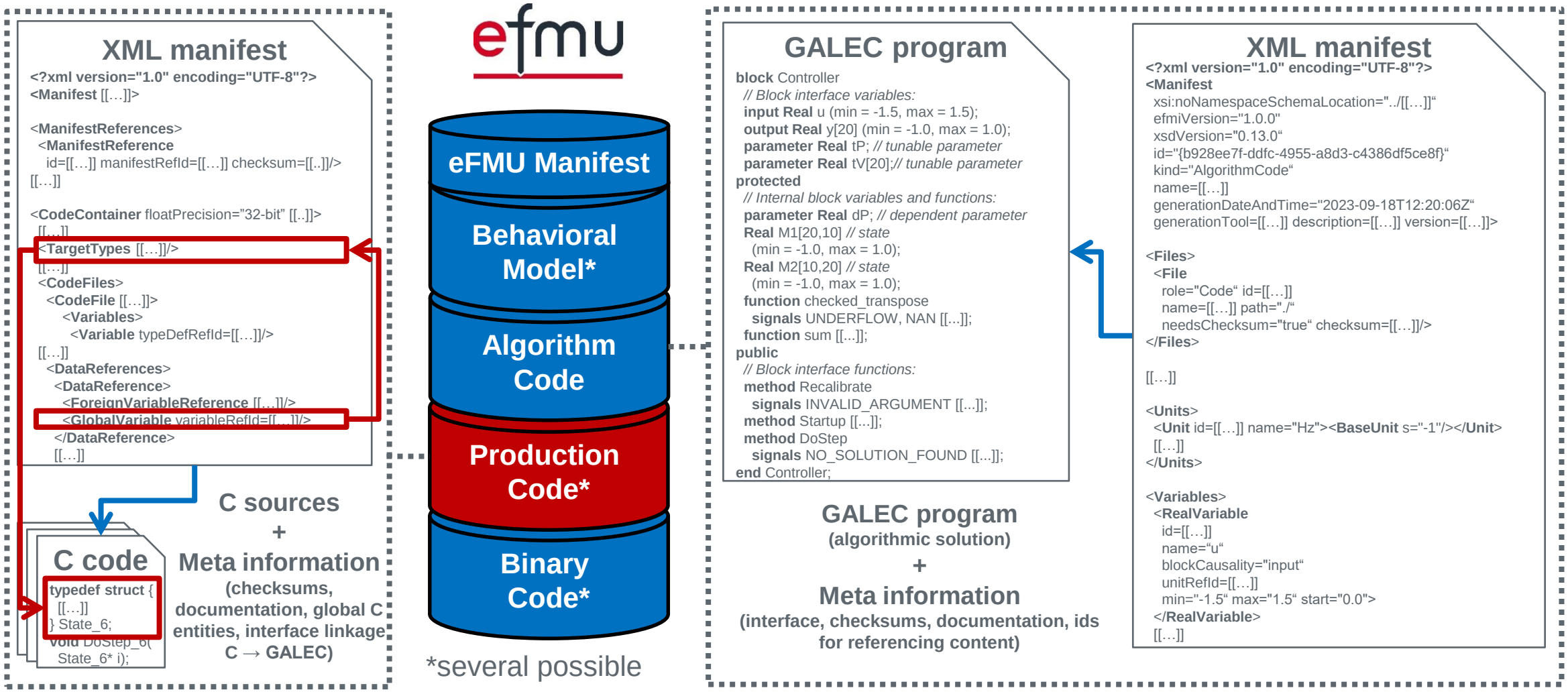
eFMI Standard: Container architecture & traceability



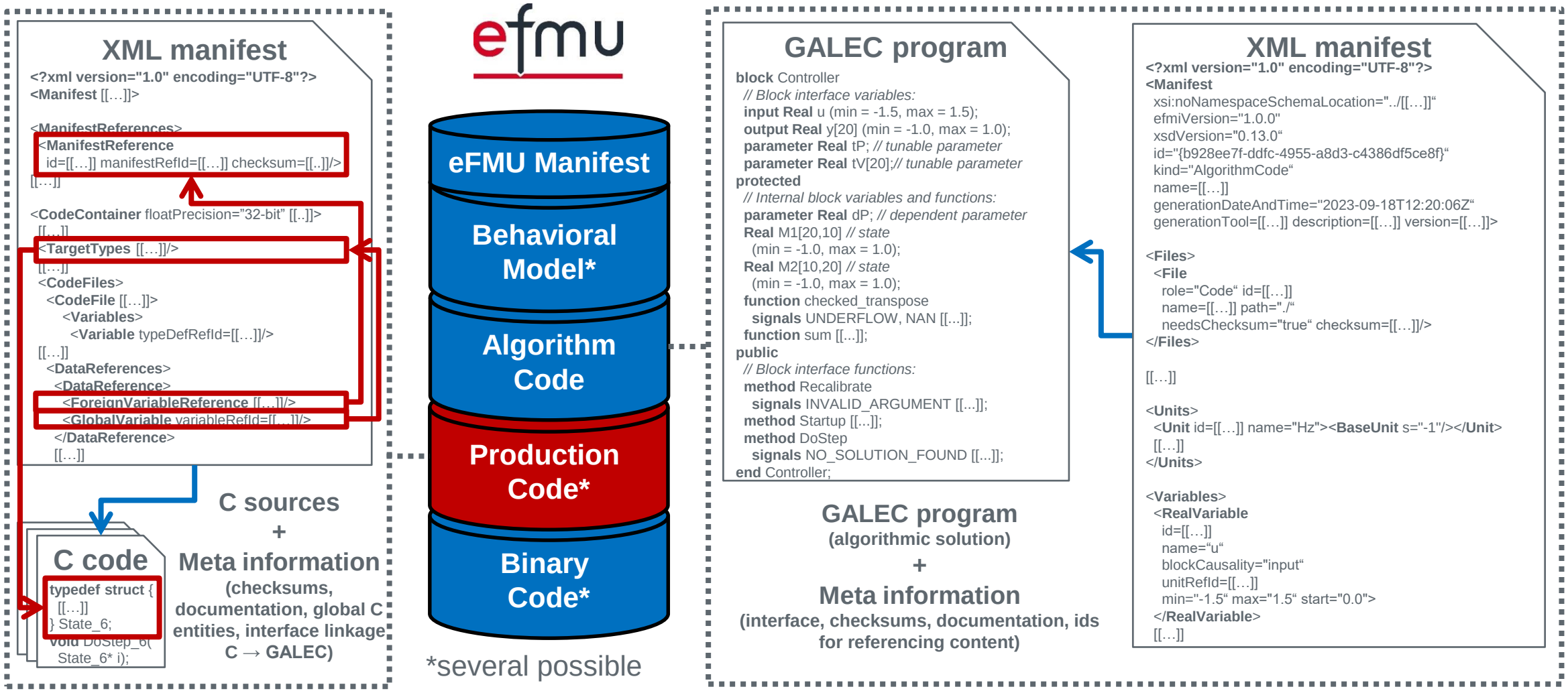
eFMI Standard: Container architecture & traceability



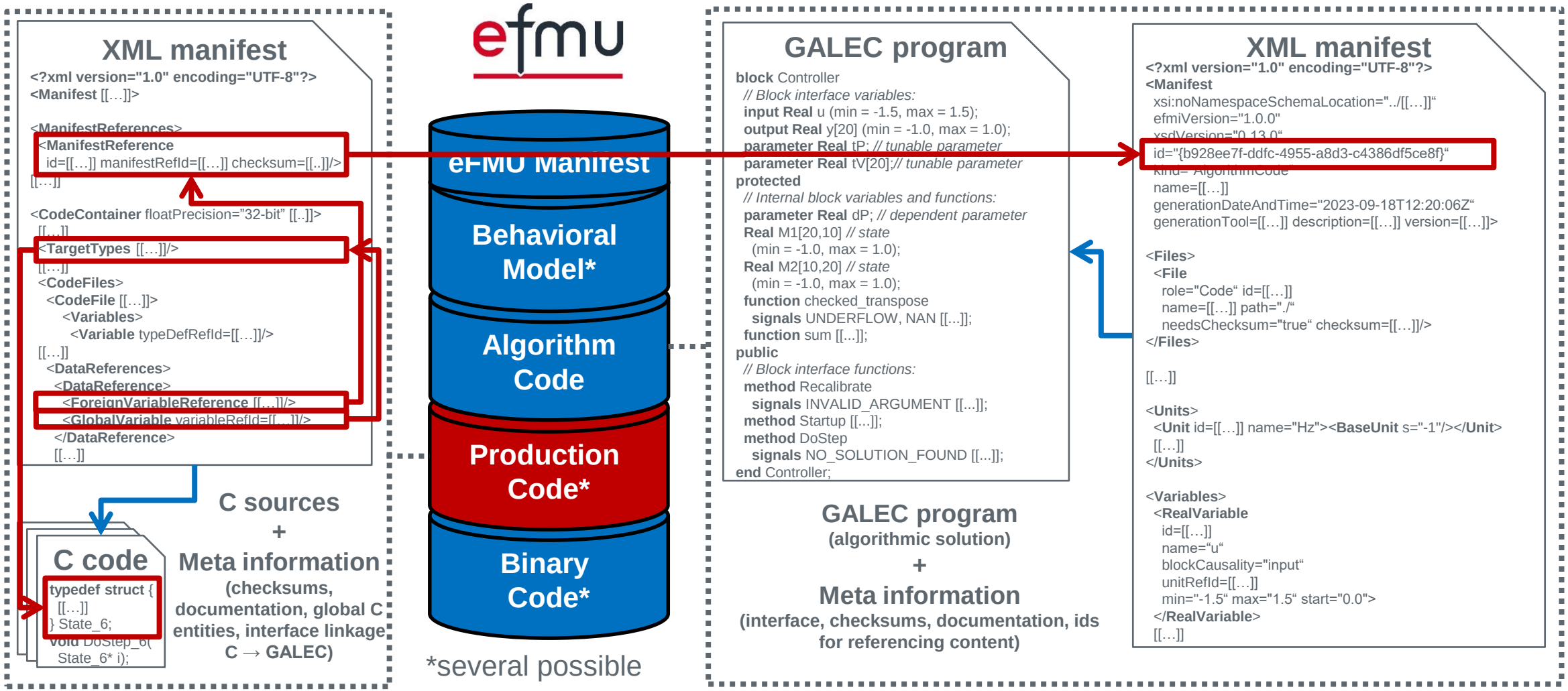
eFMI Standard: Container architecture & traceability



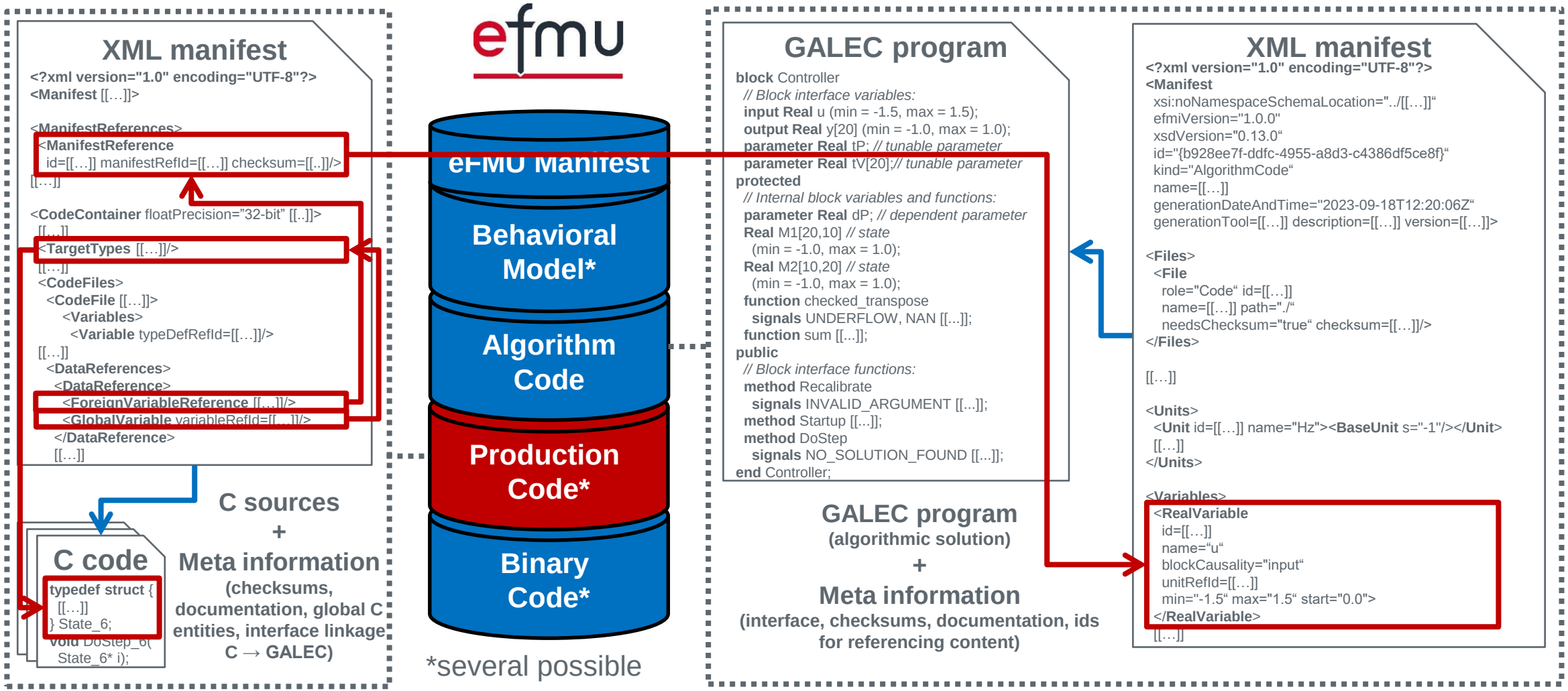
eFMI Standard: Container architecture & traceability



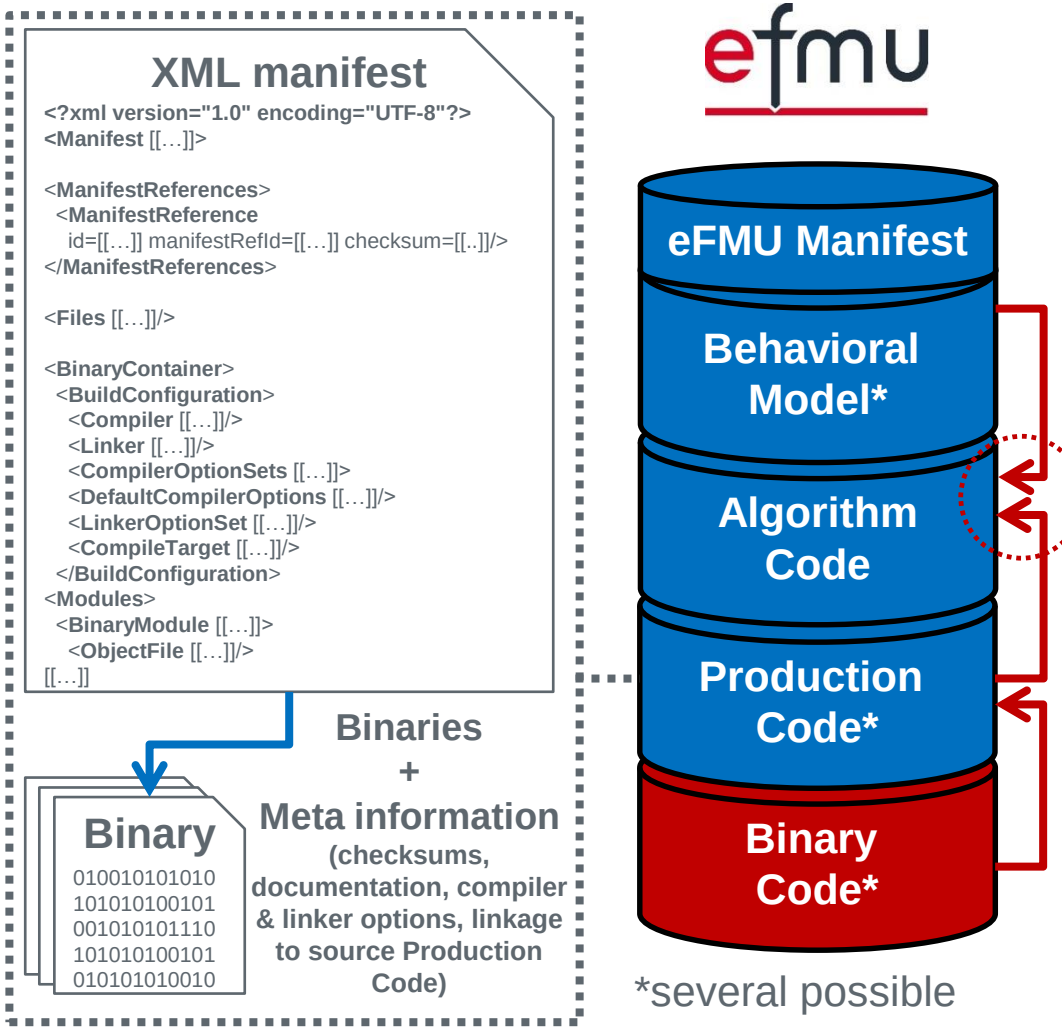
eFMI Standard: Container architecture & traceability



eFMI Standard: Container architecture & traceability



eFMI Standard: Container architecture & traceability



*several possible

Binary Code container features:

- Documentation of binaries & how they are build
  - used compiler & linker and their options
- Links to source Production Code container

To conduct tests:

- Match Behavioral Model with Production Code containers (via indirect linking)
- Use production code → GALEC interface linking for setup (i.e., for system integration in test environment)

eFMI Standard: Summary

The open standard for model-driven development of advanced control functions for safety-critical and real-time targets:

- Container architecture with well-defined model representations
  - Abstraction levels from expected behavior to binary code, from implementation to system-integration & testing

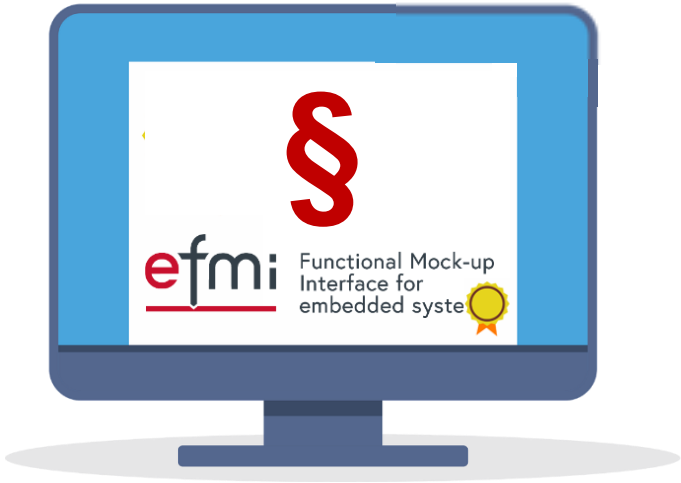
  ⇒ Enable collaboration of development stakeholders with different backgrounds, view-points & tooling (physics modeling, control engineering, embedded software development, etc)
  - Traceability & checksums

  ⇒ Enable detection of stale artefacts, toolchain automatization & code review
- GALEC with safety & real-time guarantees

  ⇒ Once algorithmic solution is found (not trivial modeling tool task), eFMI ”conveys” it to the embedded target (not trivial target environment tailoring & optimization task)
- Simple standard (only “what” has to be provided, not “how was it achieved”; no optional features)

  ⇒ The “Magic” is in the tools which are expert in their domain

Congratulations, you got the basics of the eFMI Standard!



Now let’s move on to some practice.

efmi Functional Mock-up Interface for embedded systems

eFMI® Tutorial – Agenda

Part 1: eFMI® motivation and overview (40 min)

Part 2: Running use-case introduction (10 min)

Part 3: Hands-on demonstration in Dymola and CATIA ESP (25 min)

Coffee break (30 min)

Part 3: Hands-on demonstration in Dymola and CATIA ESP (35 min)

Part 4: Live demonstration in TargetLink (30 min)

Part 5: Short presentation of further tooling (5 min)

Part 6: Conclusion (5 min)

Tutorial leader:
Christoff Bürger

DASSAULT SYSTEMES

Presenter:
Oliver Lenord

BOSCH
Invented for life

Presenter:
Jörg Niere

dSPACE

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