# Rigorous Modelling of Quantities for Model-Based Systems Engineering

Hans Peter de Koning (DEKonsult), Amsterdam, The Netherlands

MODELSWARD22 | 6-8 Feb 2022 | Virtual Event

«DigitalEngineering»
DEKonsult

# Outline

- Background
- Motivation
- Desirable Characteristics and History
- Vocabulary and Semantic Foundation
- Semantic Data Model
- Capturing ISQ as well as SI and US Customary Units in SysML v2
- Examples in SysML v2 – Demonstration with pilot implementation
- Wrap-up

# My background
# Space systems engineering at ESA

European Space Agency – Concurrent Design Facility – ESTEC
See https://www.esa.int/cdf

# OMG SysML version 2 Development

OMG Standards Development Organization

SysML v2

2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

## SysML v2 RFP WG

Request for Proposal

- Including SE Concept Model
- Started 2015
- Language RFP released Dec 2017
- API RFP released May 2018

## SysML v2 Submission Team (SST)

- Initially two submission teams – since end 2018 merged into one
- Started Jan 2018 on language (KerML & SysML)
- Started June 2018 on API & Services
- Agile workflow with monthly sprints
- Initial submission of language & API Spec's delivered to OMG on 17 Aug 2020 (3 parts: KerML, SysML language, API & Services)
- Includes working open-source pilot implementations and training material with examples
  - Monthly releases on GitHub

- Major stakeholders' review held in Feb 2021
- Revised submissions delivered to Aug & Nov 2021 for review
- Monthly releases of pilot software, specifications and training material
- Final submission to OMG scheduled for May 2022

## Finalization Task Force

- Finalization of the specifications
- Monthly releases of pilot software, spec's and training material
- Expected production tool developments (both COTS and open-source)

# Motivation

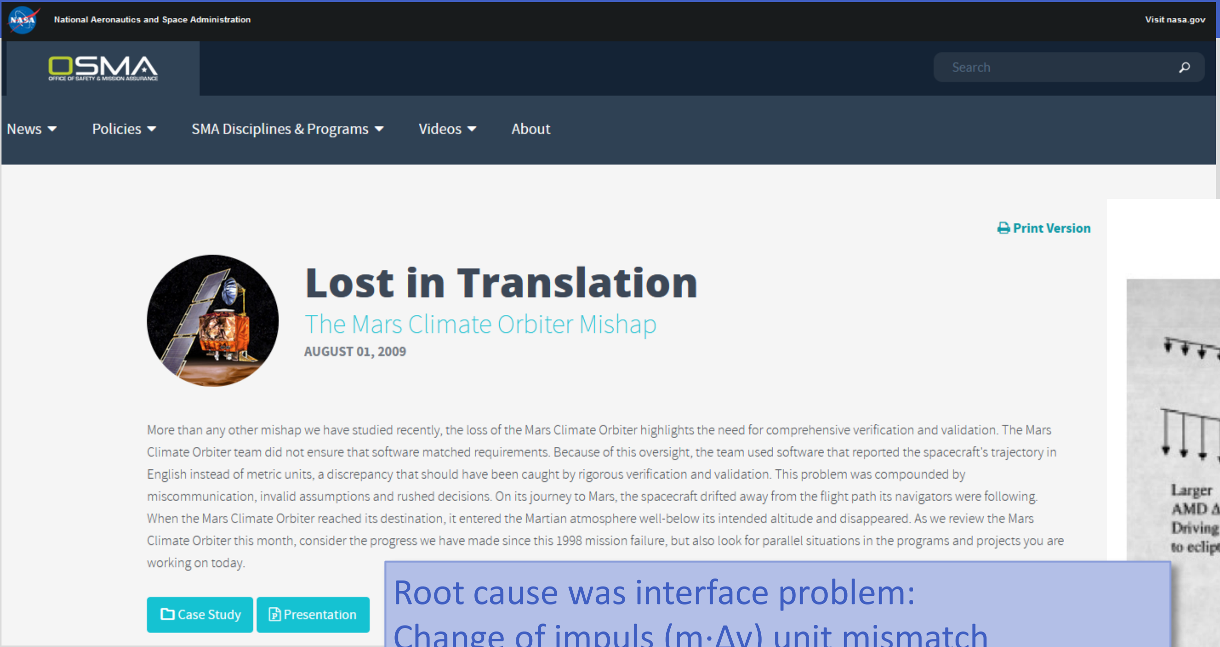
- Any engineering model – naturally – uses a lot of (physical) quantities
  - For properties, variables, parameters, etc.
- MBSE – being systems engineering – always involves coordination across multiple disciplines, life cycle stages, and organizations
- MBSE models therefore need a solid basis to represent quantities and their measurement references (units, scales, coordinate frames)
- Even stronger: MBSE needs a rigorous semantic model of quantities and measurement references to avoid costly mistakes and enable integration
- Important MBSE use case: (repeated) integration of contributed subsystem models into a higher level system model
  - Often models from different disciplines / organizations use different units, scales, coordinate frames
  - Need for reliable, automated method to rebase the integrated model on single set of units, scales, coordinate frames
  - E.g., for interface definition and verification, for conversion to analysis / simulation tools

# Slogan

All quantities in an MBSE model must have explicit semantics!

measurement unit ... and more!

# (In)Famous case: Mars Climate Orbiter crash (1999)


National Aeronautics and Space Administration

Visit nasa.gov

OSMA — OFFICE OF SAFETY & MISSION ASSURANCE

Search

News | Policies | SMA Disciplines & Programs | Videos | About

Print Version

## Lost in Translation

The Mars Climate Orbiter Mishap

AUGUST 01, 2009

More than any other mishap we have studied recently, the loss of the Mars Climate Orbiter highlights the need for comprehensive verification and validation. The Mars Climate Orbiter team did not ensure that software matched requirements. Because of this oversight, the team used software that reported the spacecraft's trajectory in English instead of metric units, a discrepancy that should have been caught by rigorous verification and validation. This problem was compounded by miscommunication, invalid assumptions and rushed decisions. On its journey to Mars, the spacecraft drifted away from the flight path its navigators were following. When the Mars Climate Orbiter reached its destination, it entered the Martian atmosphere well-below its intended altitude and disappeared. As we review the Mars Climate Orbiter this month, consider the progress we have made since this 1998 mission failure, but also look for parallel situations in the programs and projects you are working on today.

Case Study | Presentation

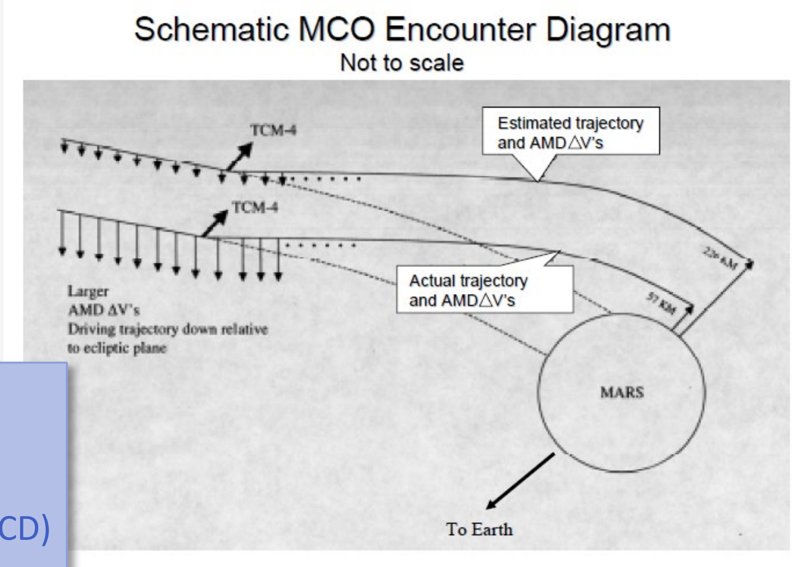



Figure 4

Root cause was interface problem:
Change of impuls (m·Δv) unit mismatch
- spacecraft software used N·s (as required)
- ground control software used lbf·s (violating ICD)
factor 4.45 difference

# Desirable Characteristics

Most appeared as requirements in SysML v2 RFP

- Grounded in formal logic
  - SysML v2 metamodel is expressed in Semantic MOF (SMOF)
  - Uses same first order logic foundation as RDF/OWL2
- Grounded in established international standards
  - Should provide digitalized libraries of ISQ, SI and US Customary Units
- Support scalar & vector & tensor quantities
- Support coordinate frames and transformations
- Provide intuitive, compact syntax for quantity expressions
- Enable automated quantity value conversion to different unit / scale
- Enable automated quantity expression checking
  - Compatible quantity dimensions i.e. dimensional analysis ... and more

# Starting Point – QUDV in SysML v1

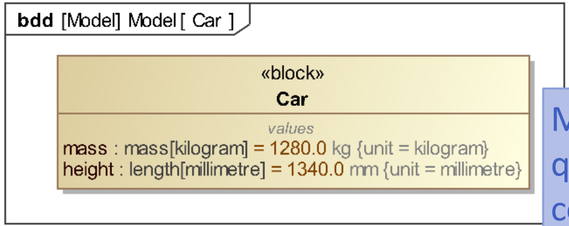
## Informative Annex E.5 in SysML v1.2 ~ v1.6

### E.5 Model Library for Quantities, Units, Dimensions, and Values (QUDV)

### E.5.1 Overview

For any system model, a solid foundation of well-defined quantities, units, and dimensions system is very important. Properties that describe many aspects of a system depend on it. At the same time, such a foundation should be a shareable resource that can be reused in many models within and across organizations and projects.

The most widely accepted, scrutinized, and globally used system of quantities and system of units are the International System of Quantities (ISQ) and the International System of Units (SI). They are formally standardized through [ISO31] and [IEC60027]. The harmonization of these two sets of standards into one new set [ISO/IEC80000] has been published by ISO in 2009 and 2010. The present QUDV model in SysML is based on ISO/IEC 80000-1:2009, which refers normatively to the ISO/IEC Guide 99:2007. The ISO/IEC 80000-1:2009 document is also the baseline for the 2010 revision of the IEEE/ASTM American National Standards for Metric Practice SI-10. All the relevant concepts underlying ISQ and SI are publicly available in [VIM]. See E.5.3, References for references to these documents.




Major issue in SysML v1:
quantity value property type
combines quantity type and unit ...
so, change of unit forces change of type!

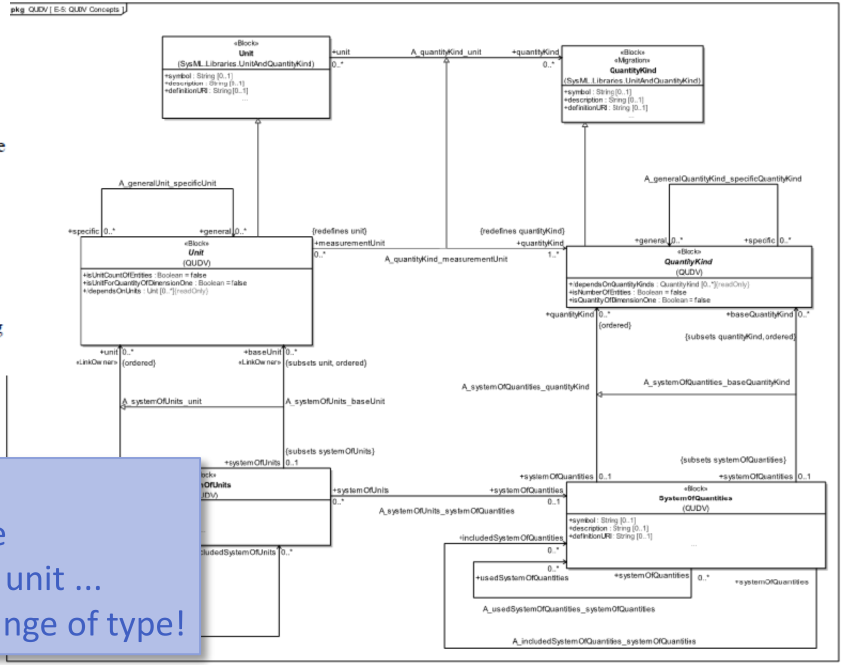
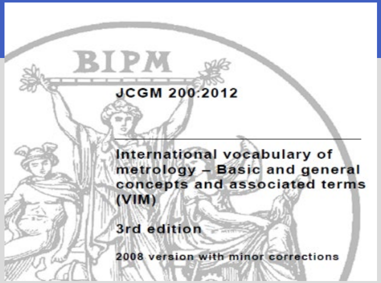


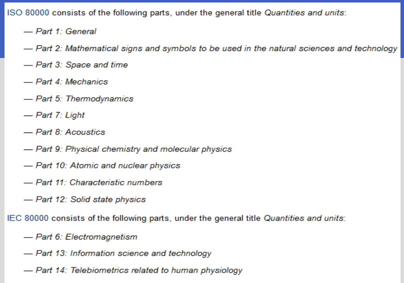

Figure E.6 QUDV Units Diagram

# Implementations in other languages

- Many languages (and tools) support measurement units and 'dimensions'
  - Mathematica, Maple, Modelica, Matlab, MathCAD, ...
  - Packages for Python, Java, Scala, C, C++, C#, Javascript, Julia, ..., mostly open source
- Some ontologies and schemas exist
  - QUDT (http://qudt.org/) – originally a spin off from SysML v1 QUDV (around 2009)
  - FIBO Quantities and Units (https://spec.edmcouncil.org/fibo/ontology/FND/Quantities/QuantitiesAndUnits/) adapted from SysML v1 QUDV
  - QUOMOS (https://www.oasis-open.org/committees/quomos/) – started but never completed
  - UnitsML (https://www.unitsml.org/) by NIST
- So, what is the big deal?
- Almost all only support simplest case: *value* · *unit* product
  - Do not support interval | ordinal | logarithmic | cyclic measurement scales
  - Limited support for quantity dimensions
  - Lacking or very limited support for vector | tensor quantities and coordinate frames
- SysML v1 QUDV already went a bit further, but was cumbersome to use in practice

# Foundation – VIM and ISO/IEC 80000 (ISQ & SI)

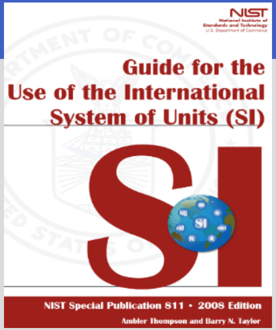




ISO 80000 consists of the following parts, under the general title *Quantities and units*:

- — *Part 1: General*
- — *Part 2: Mathematical signs and symbols to be used in the natural sciences and technology*
- — *Part 3: Space and time*
- — *Part 4: Mechanics*
- — *Part 5: Thermodynamics*
- — *Part 7: Light*
- — *Part 8: Acoustics*
- — *Part 9: Physical chemistry and molecular physics*
- — *Part 10: Atomic and nuclear physics*
- — *Part 11: Characteristic numbers*
- — *Part 12: Solid state physics*

IEC 80000 consists of the following parts, under the general title *Quantities and units*:

- — *Part 6: Electromagnetism*
- — *Part 13: Information science and technology*
- — *Part 14: Telebiometrics related to human physiology*




- BIPM VIM, JCGM 200:2012, "International vocabulary of metrology"
  - https://www.bipm.org/en/publications/guides or https://jcgm.bipm.org/vim/en/
- BIPM GUM, 3rd Edition, "Evaluation of measurement data – Guide to the expression of uncertainty in measurement"
  - https://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008.pdf
- ISO/IEC 80000 "Quantities and Units" – International System of Quantities (ISQ) and International System of Units (SI)
  - https://www.iso.org/standard/30669.html and https://www.bipm.org/en/publications/si-brochure/
  - https://en.wikipedia.org/wiki/ISO/IEC_80000 for quick overview
- The NIST Reference on Constants, Units, and Uncertainty
  - https://www.nist.gov/pml/productsservices/special-publications-tutorials - Look for "Constants, Units, & Uncertainty"
- NIST SP811, 2008 Edition, "Guide for the Use of the International System of Units"
  - In particular Appendix B "Conversion Factors" – links US Customary Units to SI
  - https://www.nist.gov/pml/special-publication-811

# VIM – Selected vocabulary terms (1/3)

https://jcgm.bipm.org/vim/en/1.19.html

| term | definition |
|---|---|
| **quantity** | property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference |
| **kind of quantity** | aspect common to mutually comparable quantities<br>Note 1: The division of 'quantity' according to 'kind of quantity' is to some extent arbitrary.<br>Note 2: Quantities of the same kind within a given system of quantities have the same quantity dimension. However, quantities of the same dimension are not necessarily of the same kind. |
| **base quantity** | quantity in a conventionally chosen subset of a given system of quantities, where no subset quantity can be expressed in terms of the others |
| **derived quantity** | quantity, in a system of quantities, defined in terms of the base quantities of that system |
| **quantity dimension** | expression of the dependence of a quantity on the base quantities of a system of quantities as a product of powers of factors corresponding to the base quantities, omitting any numerical factor |
| **quantity of dimension one** (aka "dimensionless quantity") | quantity for which all the exponents of the factors corresponding to the base quantities in its quantity dimension are zero |

# VIM – Selected vocabulary terms (2/3)

https://jcgm.bipm.org/vim/en/1.19.html

| term | definition |
|---|---|
| **quantity value** | number and reference together expressing magnitude of a quantity |
| **ordinal quantity** | quantity, defined by a conventional measurement procedure, for which a total ordering relation can be established, according to magnitude, with other quantities of the same kind, but for which no algebraic operations among those quantities exist |
| **quantity-value scale** | ordered set of quantity values of quantities of a given kind of quantity used in ranking, according to magnitude, quantities of that kind<br>Examples: Celsius temperature scale, Time scale |
| **ordinal quantity-value scale** | quantity-value scale for ordinal quantities<br>Examples: Rockwell C hardness scale, Scale of octane number for petroleum fuel |

# VIM – Selected vocabulary terms (3/3)

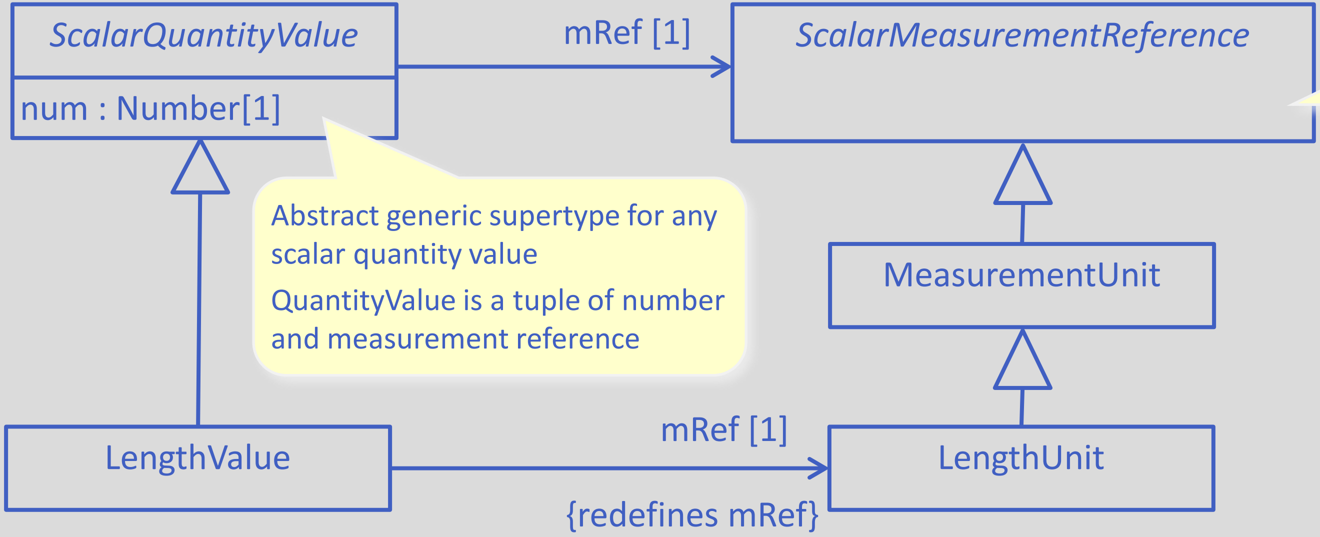
https://jcgm.bipm.org/vim/en/1.19.html

| term | definition |
|---|---|
| **measurement unit** | real scalar quantity, defined and adopted by convention, with which any other quantity of the same kind can be compared to express the ratio of the two quantities as a number |
| **base unit** | measurement unit that is adopted by convention for a base quantity |
| **derived unit** | measurement unit for a derived quantity |
| **multiple of a unit** | measurement obtained by multiplying a given measurement unit by an integer greater than one |
| **submultiple of a unit** | measurement unit obtained by dividing a given measurement unit by an integer greater than one |

Quantity dimension in ISO/IEC 80000 (ISQ) is defined using 7 base quantities:
Length (L), Mass (M), Time (T), Electric Current (I), Thermodynamic Temperature (Θ), Amount of Substance (N), Luminous Intensity (J)
$\mathrm{qdim}(q) = \mathrm{L}^{\alpha}\cdot\mathrm{M}^{\beta}\cdot\mathrm{T}^{\gamma}\cdot\mathrm{I}^{\delta}\cdot\Theta^{\varepsilon}\cdot\mathrm{N}^{\zeta}\cdot\mathrm{J}^{\eta}$ (where α, β, γ, δ, ε, ζ, η are the dimensional exponents)

Examples:
length: $\mathrm{qdim}(L) = \mathrm{L}$
velocity: $\mathrm{qdim}(v) = \mathrm{L}\cdot\mathrm{T}^{-1}$
energy: $\mathrm{qdim}(E) = \mathrm{L}^{2}\cdot\mathrm{M}\cdot\mathrm{T}^{-2}$
torque: $\mathrm{qdim}(M_Q) = \mathrm{L}^{2}\cdot\mathrm{M}\cdot\mathrm{T}^{-2}$

# Quantity modelling basics in SysML v2 (simplified)




Abstract generic supertype for any scalar measurement reference:

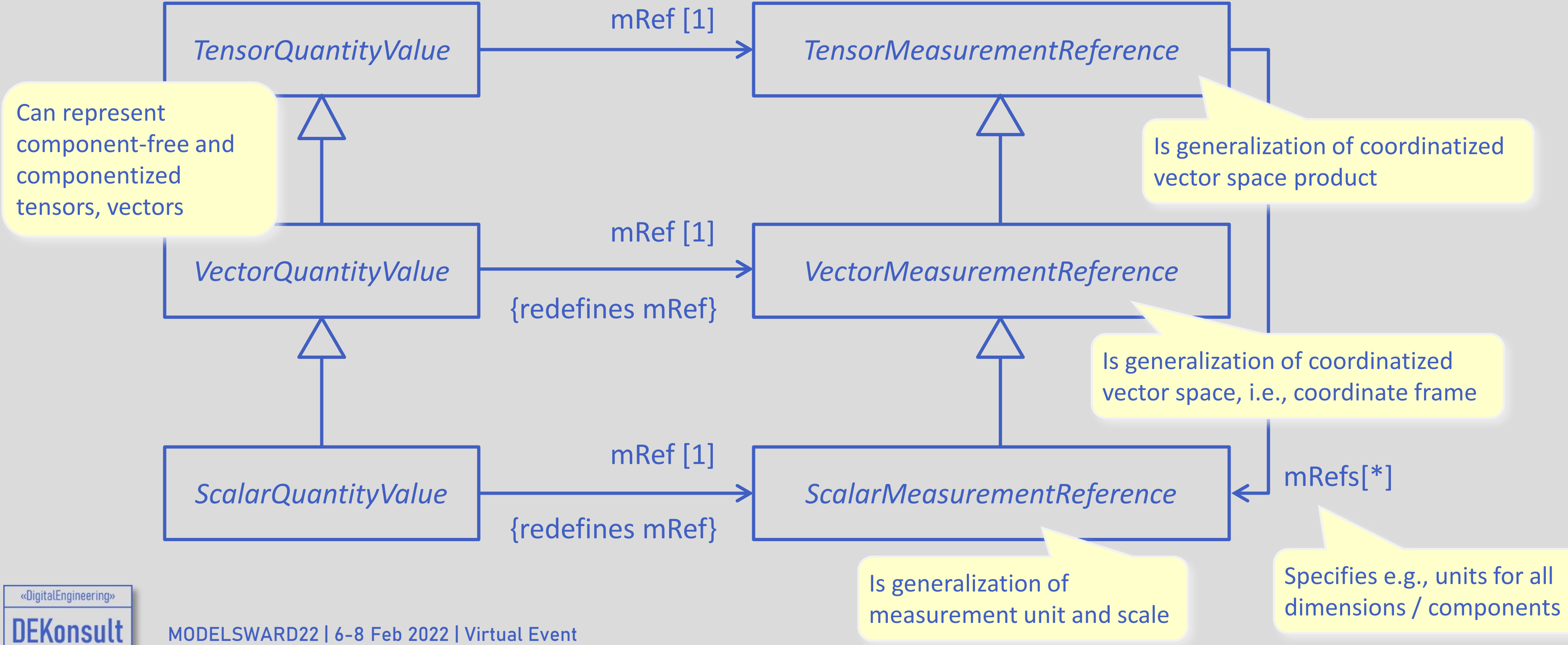
- MeasurementUnit
- MeasurementScale

```
attribute length : LengthValue = 1340 [mm];
```

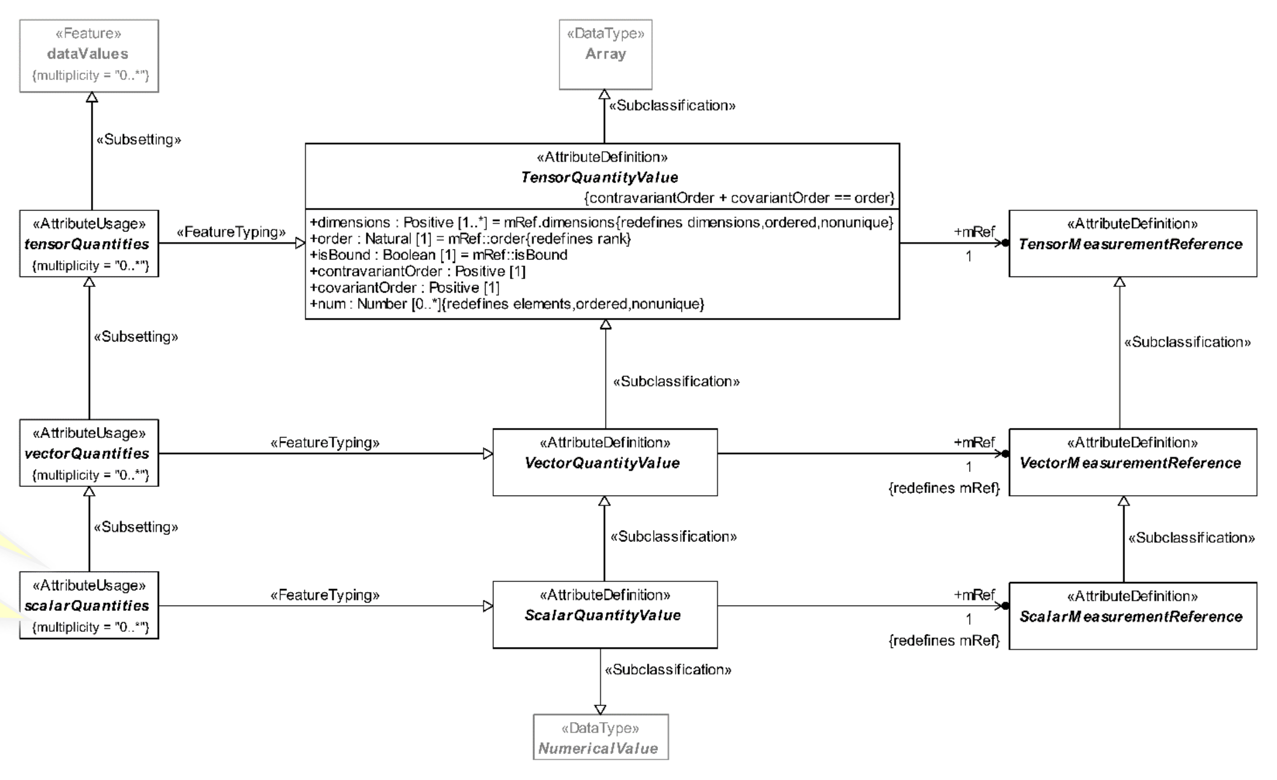
Example concrete textual syntax in user model (M1)

Note: **attribute** replaces **value property** of SysML v1

# Extend taxonomy to model multi-dimensional quantities



# SysML v2 Quantity model in UML

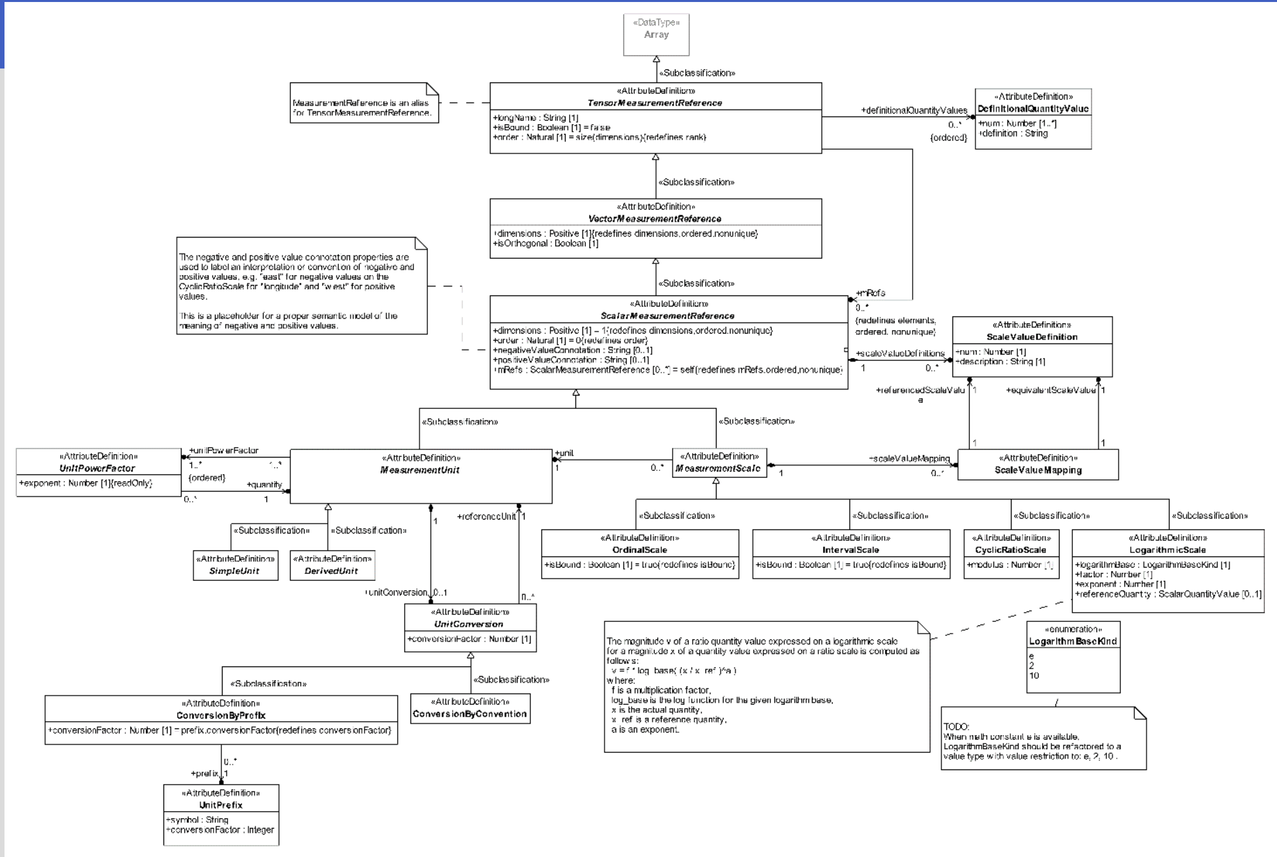



New in KerML and SysML v2 are self-standing features (here AttributeUsage)

E.g. can declare reusable **attribute** mass : MassValue[1]; directly at package level, not owned by an **Item** or **Part Definition** (which replaces SysML v1 **Block**)

«DigitalEngineering»
DEKonsult

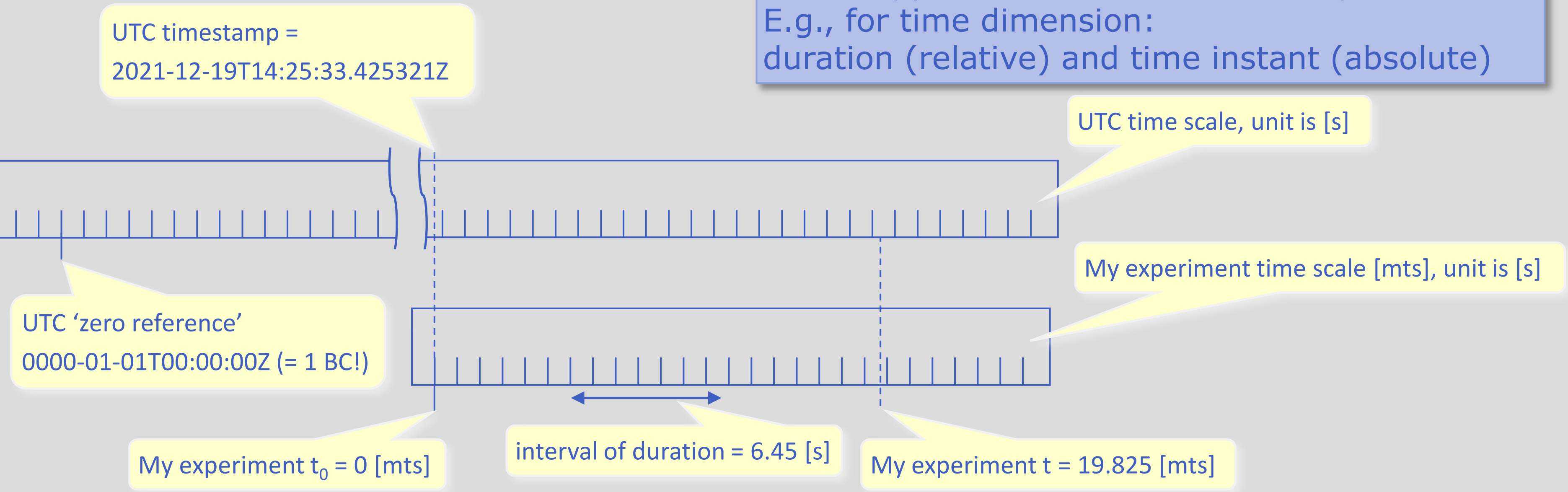
# SysML v2 Measurement reference model in UML




«DigitalEngineering»
DEKonsult

# Q: Why Interval Scale in addition to units?

A: To support relative and absolute quantities
E.g., for time dimension:
duration (relative) and time instant (absolute)




Note: A simplification of course, assuming a Newtonian global clock
may need to consider different clocks, precision, other time scale without leap seconds, etc.

# Also Ordinal, Logarithmic, Cyclic Ratio Scales

OrdinalScale
Beaufort Wind Force
no unit, just ordering

**Beaufort Scale**[9][10][11][12]

| Beaufort number | Description | Wind speed | Wave height | Sea conditions | Land conditions | Sea conditions (photo) |
|---|---|---|---|---|---|---|
| 0 | Calm | < 1 knot<br>< 1 mph<br>< 2 km/h<br>< 0.5 m/s | 0 ft (0 m) | Sea like a mirror | Smoke rises vertically. | |
| 1 | Light air | 1–3 knots<br>1–3 mph<br>2–5 km/h<br>0.5–1.5 m/s | 0–1 ft<br>0–0.3 m | Ripples with appearance of scales are formed, without foam crests | Direction shown by smoke drift but not by wind vanes. | |
| 2 | Light breeze | 4–6 knots<br>4–7 mph<br>6–11 km/h<br>1.6–3.3 m/s | 1–2 ft<br>0.3–0.6 m | Small wavelets still short but more pronounced; crests have a glassy appearance but do not break | Wind felt on face; leaves rustle; wind vane moved by wind. | |
| 3 | Gentle breeze | 7–10 knots<br>8–12 mph<br>12–19 km/h<br>3.4–5.5 m/s | 2–4 ft<br>0.6–1.2 m | Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses | Leaves and small twigs in constant motion; light flags extended. | |
| 4 | Moderate breeze | 11–16 knots<br>13–18 mph<br>20–28 km/h<br>5.5–7.9 m/s | 3.5–6 ft<br>1–2 m | Small waves becoming longer; fairly frequent white horses | Raises dust and loose paper; small branches moved. | |
| 5 | Fresh breeze | 17–21 knots<br>19–24 mph<br>29–38 km/h | 6–10 ft<br>2–3 m | Moderate waves taking a more pronounced long form; many white horses are formed; chance of some | Small trees in leaf begin to sway; crested wavelets form on inland waters | |

From https://en.wikipedia.org/wiki/Beaufort_scale

LogarithmicScale
Sound Pressure Level
symbol = dB(A) or $dB_A$
unit = dB
reference level = 20 [μPa]

## Sound pressure level [ edit ]

*For other uses, see Sound level.*

**Sound pressure level** (SPL) or **acoustic pressure level** is a logarithmic measure of the effective pressure of a sound relative to a reference value.

Sound pressure level, denoted $L_p$ and measured in dB, is defined by[4]

$$L_p = \ln\left(\frac{p}{p_0}\right)\text{ Np} = 2\log_{10}\left(\frac{p}{p_0}\right)\text{ B} = 20\log_{10}\left(\frac{p}{p_0}\right)\text{ dB},$$

where

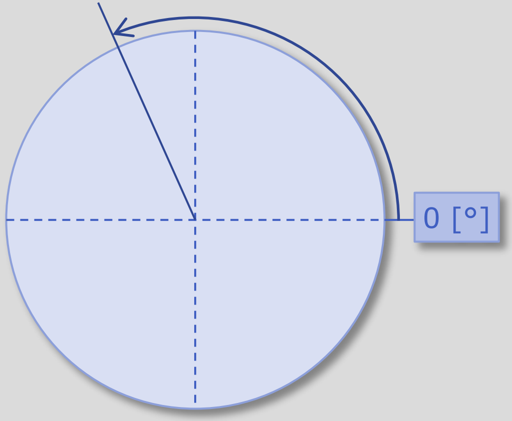
- $p$ is the root mean square sound pressure,[5]
- $p_0$ is the *reference sound pressure*,
- 1 Np is the neper,
- 1 B = $(\frac{1}{2}\ln 10)$ Np is the bel,
- 1 dB = $(\frac{1}{20}\ln 10)$ Np is the decibel.

The commonly used reference sound pressure in air is[6]

$p_0$ = 20 μPa,

From https://en.wikipedia.org/wiki/Sound_pressure

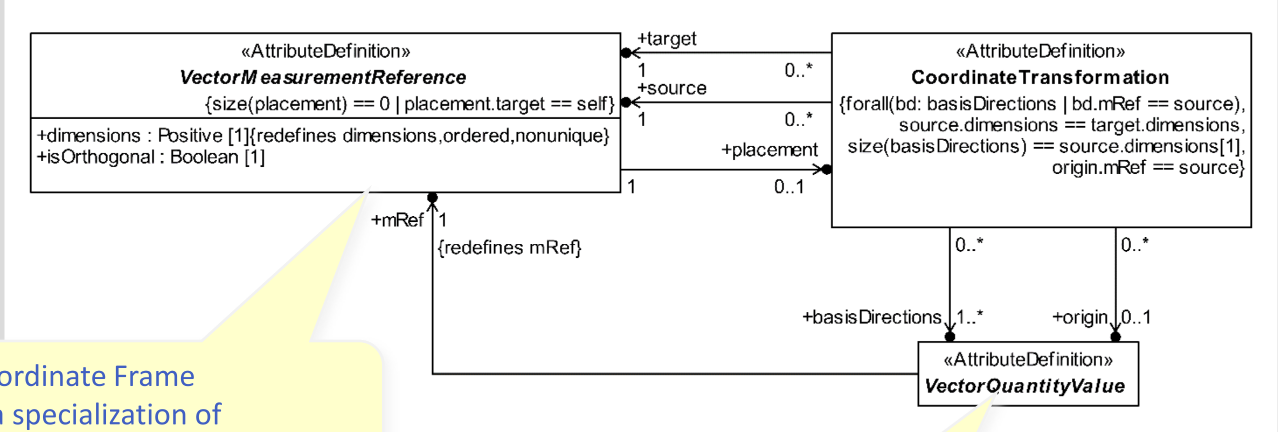
CyclicRatioScale
Rotation Angle
unit = °
modulo = 360 [°]



# Coordinatization – Coordinate Frames

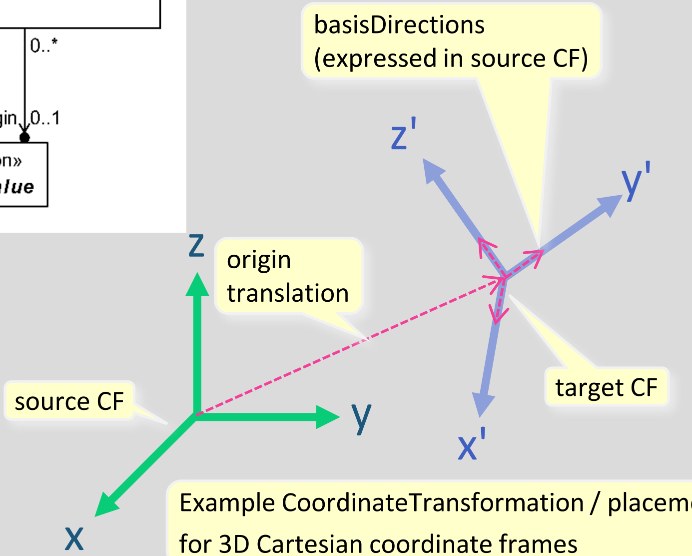
- In order to quantify vectors and tensor coordinate frames are needed
- Predefined typical coordinate frames and transformations for engineering
  - 2D / 3D Cartesian, 3D Spherical, 3D Cylindrical, 2D Polar
  - Geographic coordinate system (lat, long, altitude)
  - ISO 10303-242 (STEP) axis placement
  - Transformation matrix (translation and rotation about principal axes)
- Domains can add their particular coordinate frames by extension
  - E.g., rotation via quaternions, ...

# Coordinate Frames and Placement Model




Coordinate Frame
is a specialization of
VectorMeasurementReference

Origin translation and basis direction
vectors are specializations of
VectorQuantityValue




Example CoordinateTransformation / placement
for 3D Cartesian coordinate frames

# Free and Bound Vectors

- Multi-dimensional equivalent of relative and absolute (scalar) quantities are free and bound vector quantities
- For many quantity dimensions there are pairs of free and bound quantities
  - In case of a vector the quantity dimension is taken from its magnitude

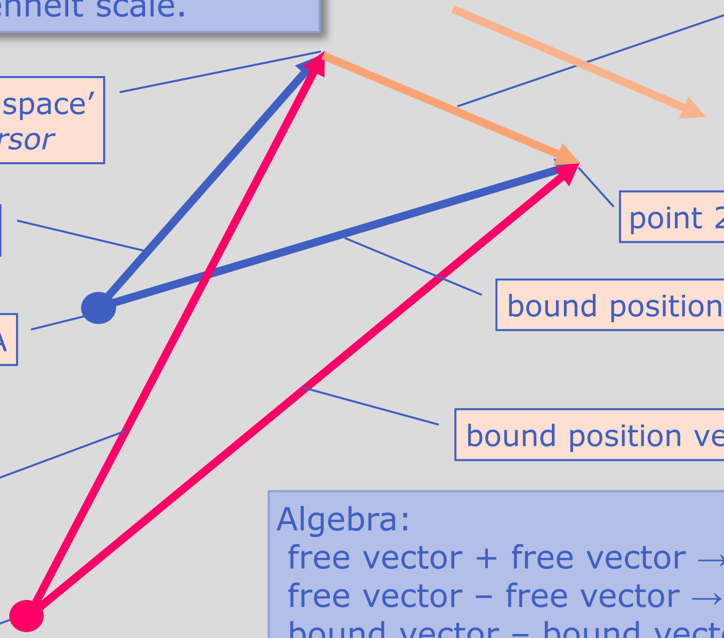
| quantity dimension | relative / free | absolute / bound | tensor order | dimension |
|---|---|---|---|---|
| Time (T) | duration | time instant | 0 | 1 |
| Energy ($L^2 \cdot M \cdot T^{-2}$) | kinematic energy | potential energy | 0 | 1 |
| Length (L) | displacement vector | position vector | 1 | 1, 2 or 3 |

- Observation:
  Interval Scale is same as 1D bound vector space with 1D coordinate frame
  Interval Scale zero shift (offset) is same as origin translation

«DigitalEngineering»
DEKonsult

# Operations on Free and Bound Vectors

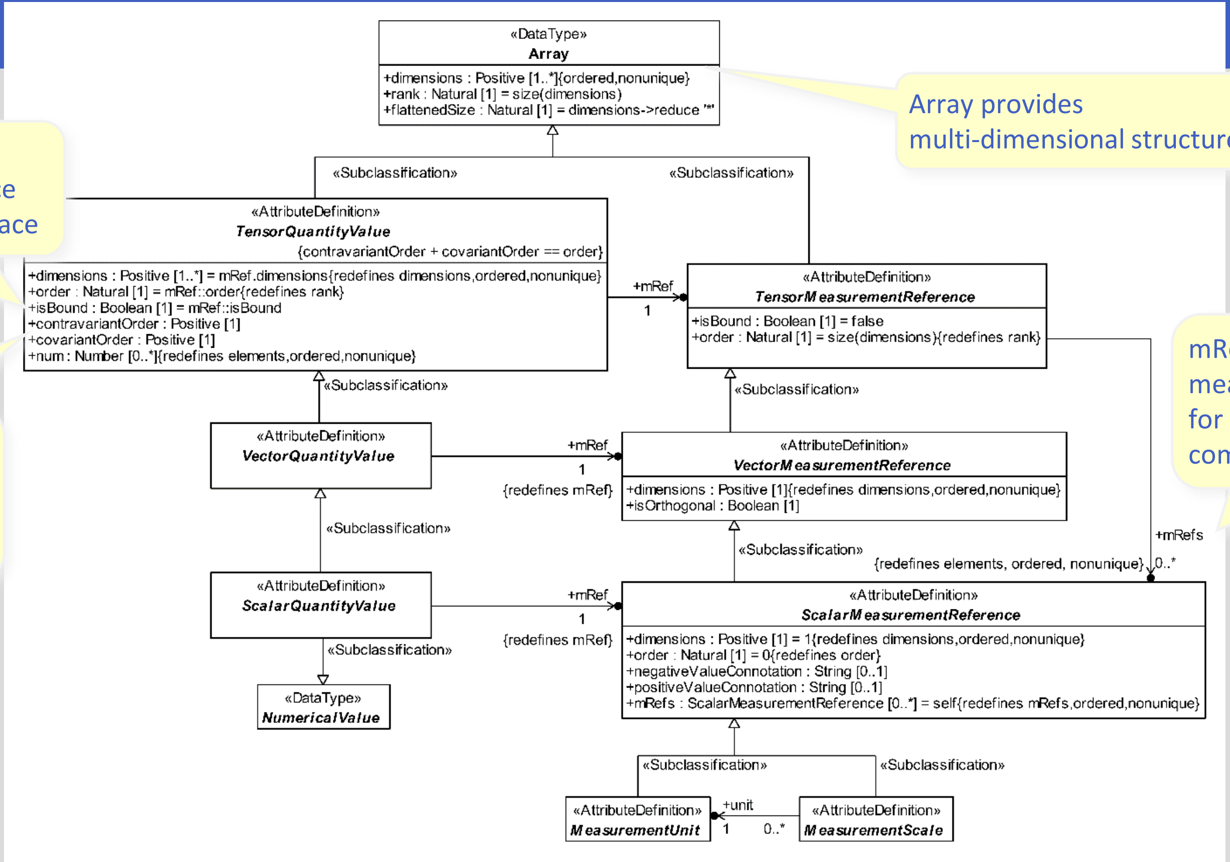
Example 2D but holds for any N-dimensional space
Same algebra as for absolute quantity on interval scale!
E.g., temperature on Celsius or Fahrenheit scale.




Algebra:

- free vector + free vector → free vector
- free vector – free vector → free vector
- bound vector – bound vector → free vector
- bound vector + free vector → bound vector
- Cannot add two bound vectors, only subtract

# SysML v2 Measurement reference model details




Array provides multi-dimensional structure

isBound
- false declares free vector space
- true declares bound vector space

contravariantOrder
covariantOrder
- declare index conventions for some kinds of tensors

mRefs specifies measurement references for all tensor or vector components

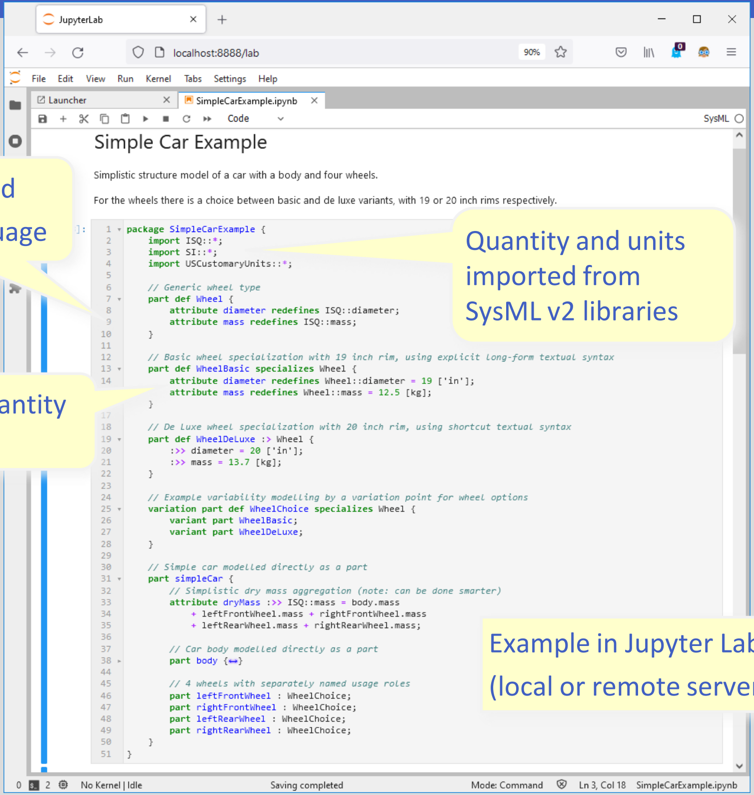
«DigitalEngineering»
DEKonsult

# Examples of Implementation in SysML v2

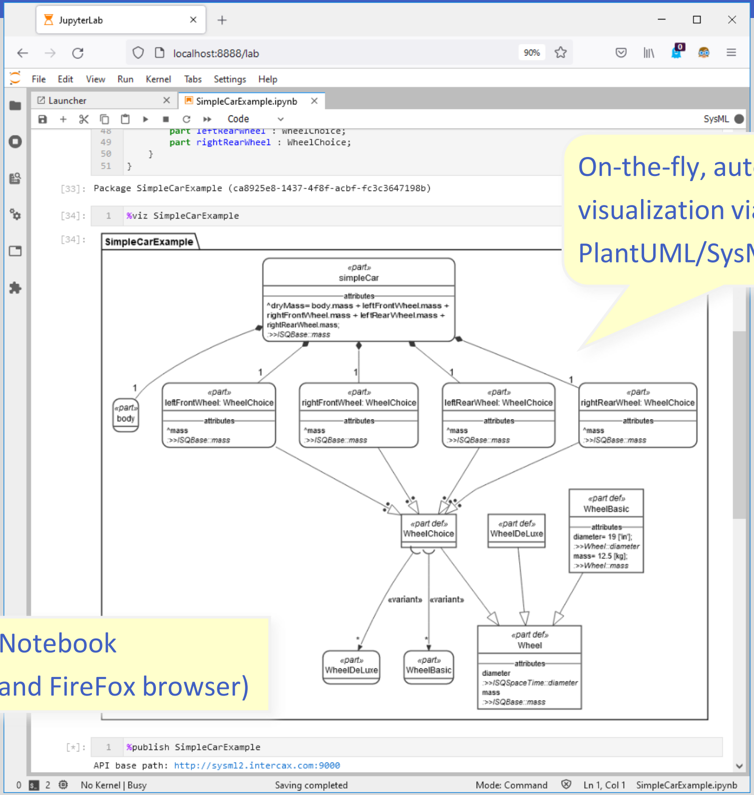
Model authored in textual language

Example quantity attributes

Quantity and units imported from SysML v2 libraries




On-the-fly, auto-layout visualization via built-in PlantUML/SysMLv2 visualizer




Example in Jupyter Lab Notebook (local or remote server and FireFox browser)

# Wrap-up

- SysML v2 well underway – has very a solid quantities and units model
  - ISO/IEC 80000 parts 3-12 captured as semantic model libraries (700+ quantities, few hundred units)
  - NIST SP811 captured for US Customary Units with official conversion factors (300+)
  - Integrated with SysML v2 expression language
- Currently working on complete coordinate frames and transformations
  - Including basic geometry modelling capabilities
- Next steps
  - Implement automated conversion algorithm and quantity dimensions checking
  - Develop expression of uncertainties and probability distributions

# References


| | |
|---|---|
| SysML v2 Submission Team (SST) public repositories on GitHub | https://github.com/Systems-Modeling/ |
| SysML v2 monthly public releases of:<br>specifications, training material and open-source pilot implementations | https://github.com/Systems-Modeling/SysML-v2-Release |
| General information on MBSE across all industry sectors, INCOSE/OMG MBSE Wiki | http://www.omgwiki.org/MBSE/doku.php |
| General information on the OMG Systems Modeling Language (SysML) | http://www.omgsysml.org |
| Systems Modeling Language (SysML®) v2 Request For Proposal (RFP), OMG, December 2017 | https://www.omg.org/cgi-bin/doc.cgi?ad/2017-12-2 |
| Systems Modeling Language (SysML®) v2 API and Services Request For Proposal (RFP), OMG, June 2018 | https://www.omg.org/cgi-bin/doc.cgi?ad/2018-6-3 |
| Systems Modeling Language v1.6, OMG, November 2019 | https://www.omg.org/spec/SysML/1.6/ |
| Friedenthal, S., and R. Burkhart, "Evolving SysML and the System Modeling Environment to Support MBSE", INCOSE INSIGHT, August 2015 Volume 18 Issue 2, Pages 39-42 | link |
| Ed Seidewitz, "SysML v2 and MBSE: The Next Ten Years", MODELS 2018 Conference, Copenhagen, Denmark, Oct 2018 | link |
| Hans Peter de Koning, "SysML Version 2 Approaching Industrial Use", ESA MBSE2021 Workshop | link |