Supporting Development of Complex System through Modeling & Simulation

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What is a model?

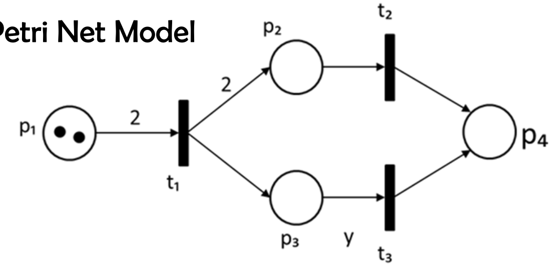
“Model”

Generally, the term “model” refers to an abstraction or representation of a system, entity, phenomenon, or process of interest.

Software Cost Reduction Event Transition Table

Old Mode	Event	New Mode
TooLow	@T(WaterPres ≥ Low)	Permitted
Permitted	@T(WaterPres ≥ Permit)	High
Permitted	@T(WaterPres < Low)	TooLow
High	@T(WaterPres < Permit)	Permitted

Petri Net Model



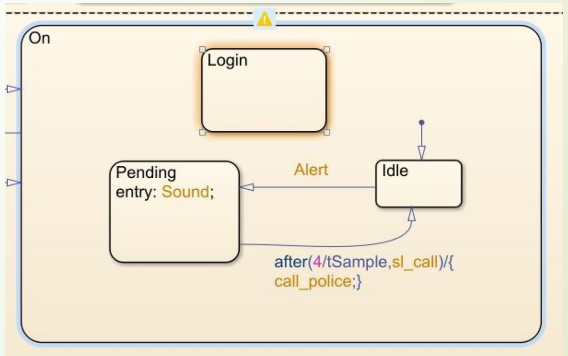
Types of models

mathematical, logical, physical, or procedural representations of a system.

Intended use of a model

describe selected aspects of the entity, e.g., geometry, functions, or performance.

State Transition Machine



Systems engineers

- use models to represent a system and its environment
- analyze, specify, design, and verify systems
- Different types of models represent different modeling purposes

Principles of Modeling

One of the first principles of modeling…

Clearly define the purpose of the model.

Some of the **purposes** that models can serve **throughout** the system **life cycle** include:

- Characterize an existing system
- **Mission** / concept formulation and evaluation
- System **architecture** design and requirements flow-down
- systems **integration** and verification
- Support for **training**
- **Knowledge capture** and system design evolution
- **Validating** your understanding with stakeholders
- Visual representation of abstract concepts

Source: INCOSE. 2015. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc

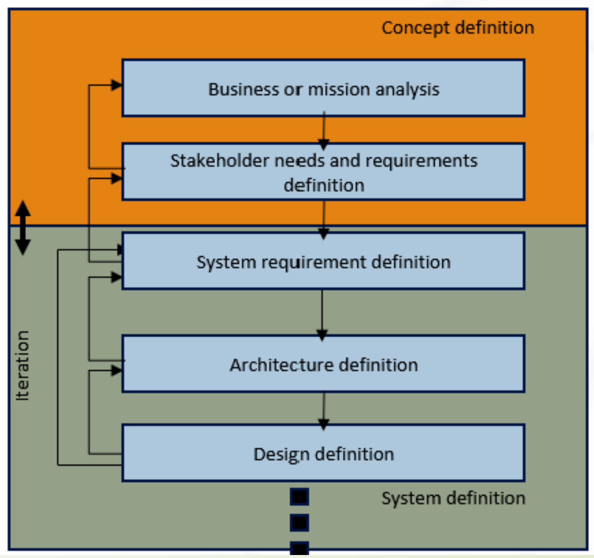
Purpose of Modeling

What is it that models represent?

Essential characteristics
SOI environment
SOI interactions.

Models and simulations **support** most system **life cycle processes**, for example:

- Business or **mission** analysis
- **Requirements** (stakeholder and system) definition
- **Architecture** definition
- **Design** definition
- System analysis
- **Verification** and validation
- **Operations**

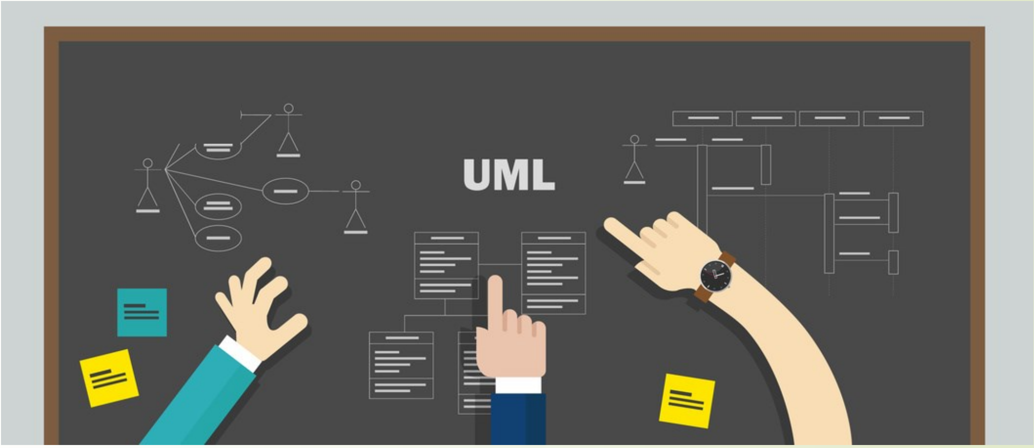


Source: INCOSE. 2015. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc

Model Scope

Scope your model to achieve its intended purpose: breadth, depth, & fidelity

Model breadth:
requirements coverage in terms of functional, interface, performance, and nonfunctional requirements.



Model depth
coverage of system decomposition down to the system elements.

A system may have different types of models

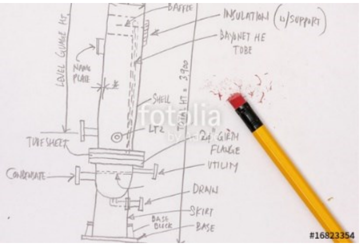
Model fidelity
level of detail the model must represent for any given part.

Source: INCOSE. 2015. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc

Forms/types of Models

Start with a mental model that is elaborated and translated in several stages to form a final model or simulation product.

A model maybe a mental image of selected concepts, and relationships between them, that can be translated to:



Sketches

Old Mode	Event	New Mode
TooLow	@T(WaterPres ≥ Low)	Permitted
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Permitted	@T(WaterPres < Low)	TooLow
High	@T(WaterPres < Permit)	Permitted

Textual Specifications

Graphics / Images

Emulations

Mock-ups

Scale models

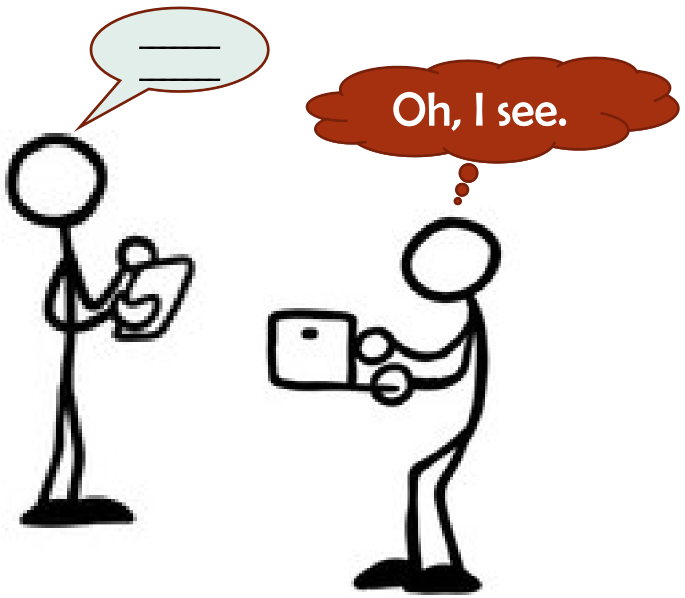
Prototypes

Several models are developed for distinct viewpoints:

- functional,
- behavioral,
- performance,
- reliability,
- operational availability,
- cost

Models have syntax and semantics

You must understand the *semantics* and *syntax* of the models that you develop.



Semantics

Intended meaning of a model.

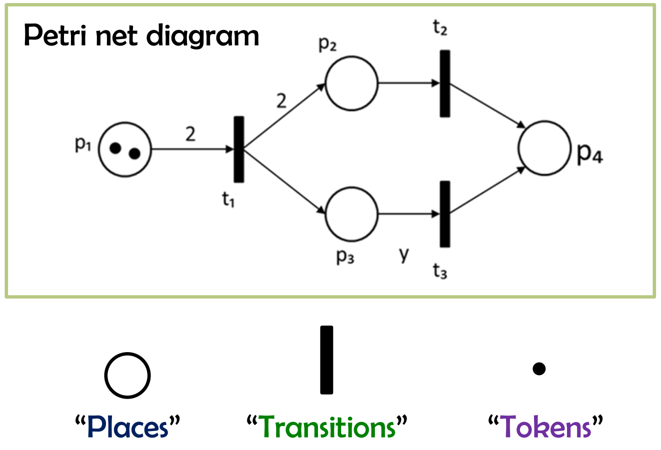
It is much like when speaking to someone, what is the meaning of the discussion?

Syntax

Components and Rules used to convey the intended meaning.

May use specific shapes to represent specific elements.

e.g., grammatical rules and spelling in the use of a language.



Selecting a model for use

Many types of models exist across different standards and methodologies, so the big question is:

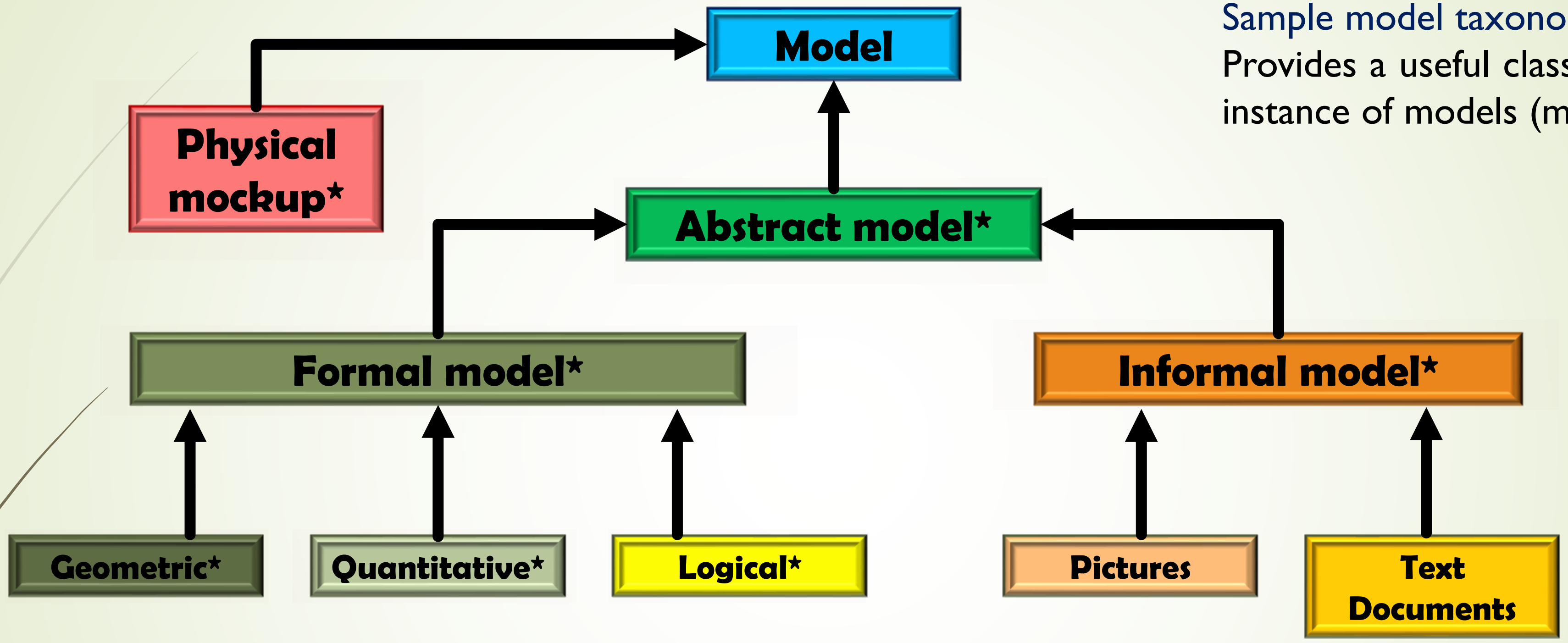
What model do I use?

When developing a model,
First consider **the goals** you are **trying** to **achieve** in **making** that **model.**

What is the **purpose** of the model?
What knowledge is it intended to **convey**?
Who is the **audience**?

Is it for validation with a customer or end user?
How technical or high level should it be?

Sample Model Taxonomy

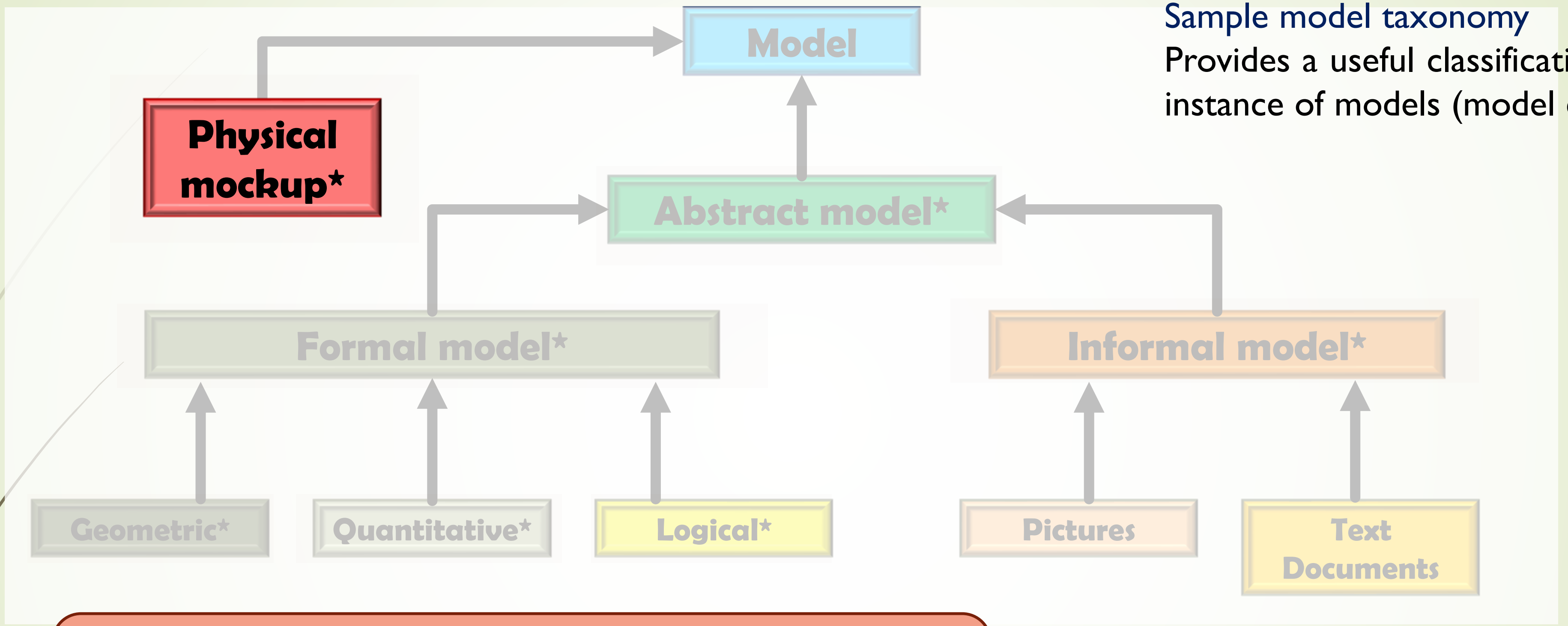


Sample model taxonomy

Provides a useful classification for one instance of models (model classes)

Source: INCOSE. 2015. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc

Sample Model Taxonomy



Sample model taxonomy

Provides a useful classification for one instance of models (model classes)

<u>Physical mock-ups</u>

represents an actual system

- **a model airplane**
- **wind tunnel model**

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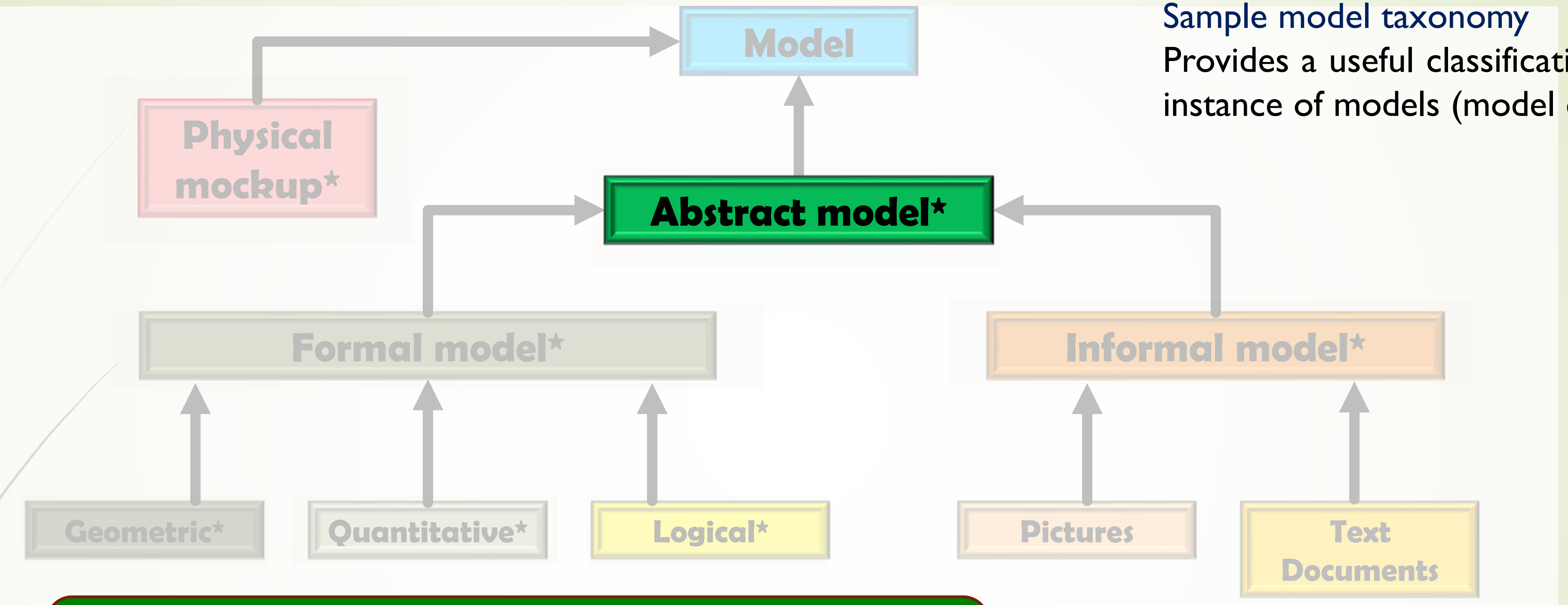
Sample Model Taxonomy



Sample model taxonomy

Provides a useful classification for one instance of models (model classes)

Abstract models

- have different expressions to represent a system
- vary in degrees of formalism.

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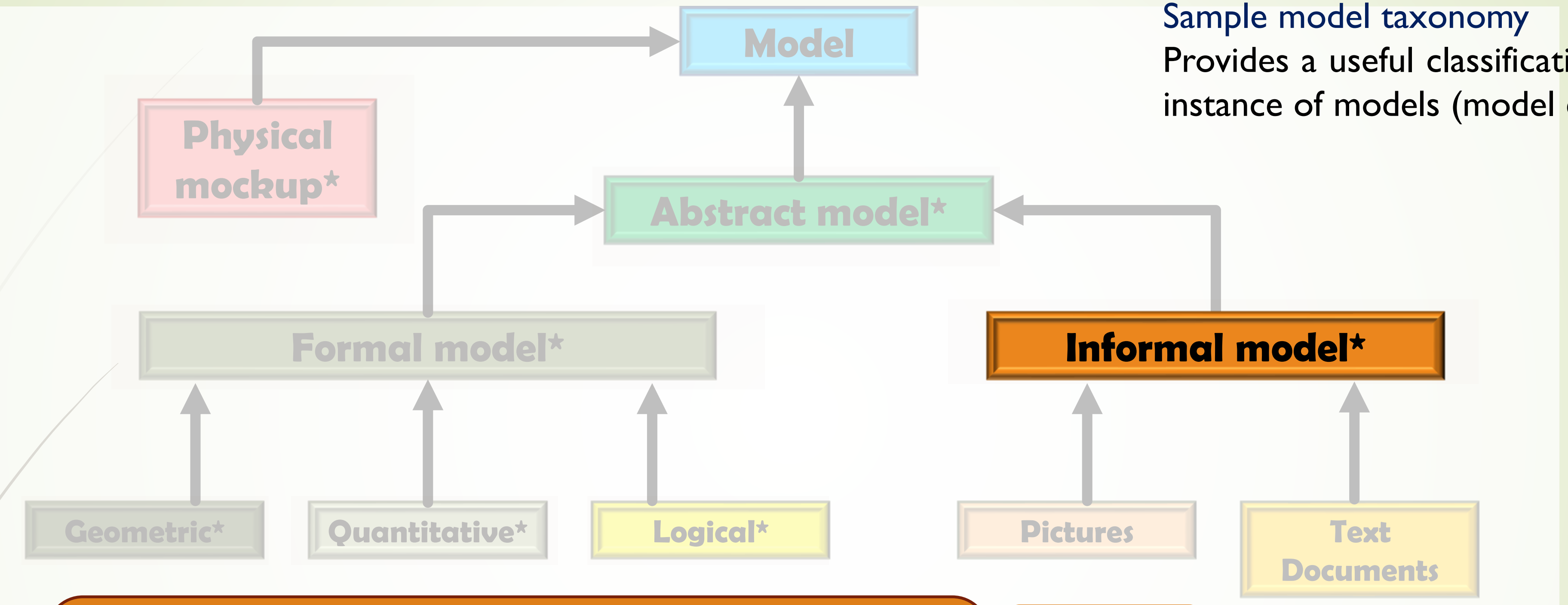
Sample Model Taxonomy



Sample model taxonomy

Provides a useful classification for one instance of models (model classes)

Informal models

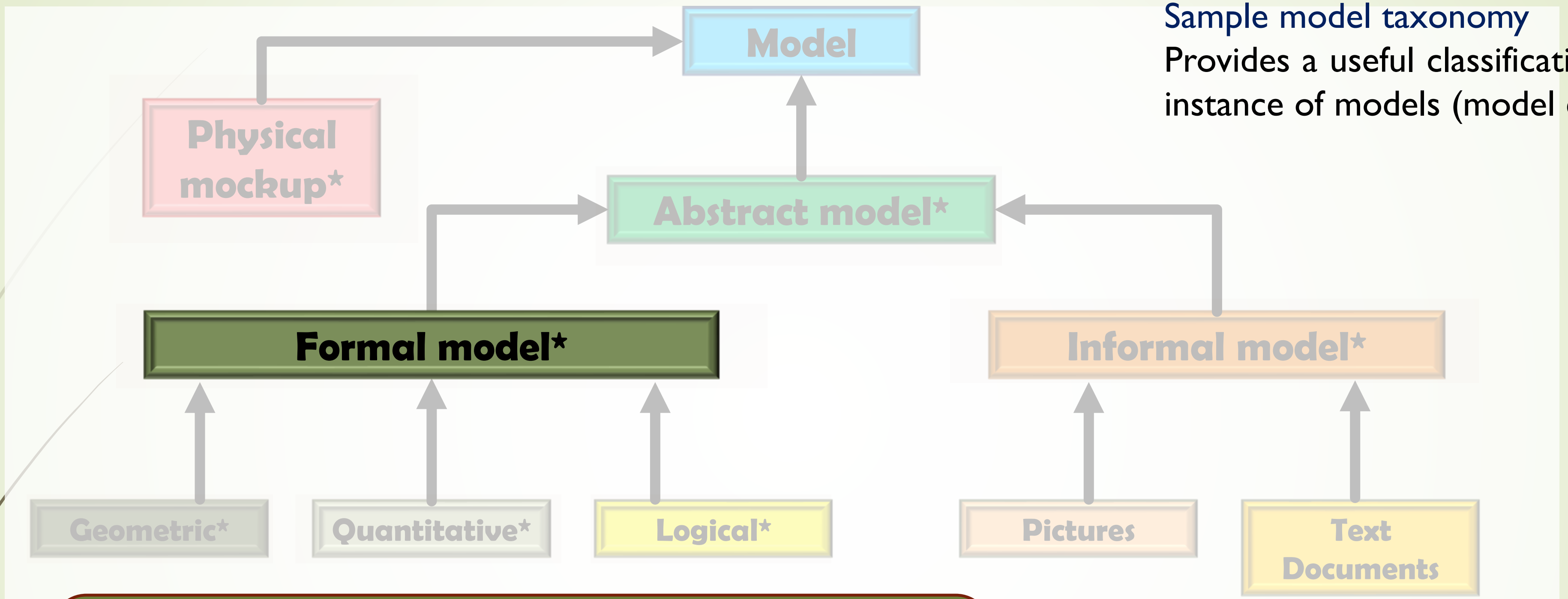
- simple drawing or textual description.
- Should have clear agreement on terms' meaning
- If missing agreement ➔ may lack of precision and have ambiguity in the representation.

Note

While such informal representations can be useful, a model must meet certain expectations for it to be considered within the scope of modeling and simulation for SE.

Source: INCOSE. 2015. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc

Sample Model Taxonomy



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Formal models

Further classified as

- Geometric
- Quantitative (i.e., mathematical),
- Logical models.

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SEBoK Taxonomy

Systems Engineering Body of Knowledge (SEBoK) model taxonomy.

Descriptive Model

Logical relationships (e.g., whole-part)
- parts tree
- interconnection between its parts
- Components functions
- Test cases to verify requirements

Analytical Model

Mathematical relationships (e.g., differential equations)
- quantifiable analysis of system parameters.
- **Dynamic models:** time-varying state of a system.
- **Static models:** not time-varying state of a system.

Domain-specific Model

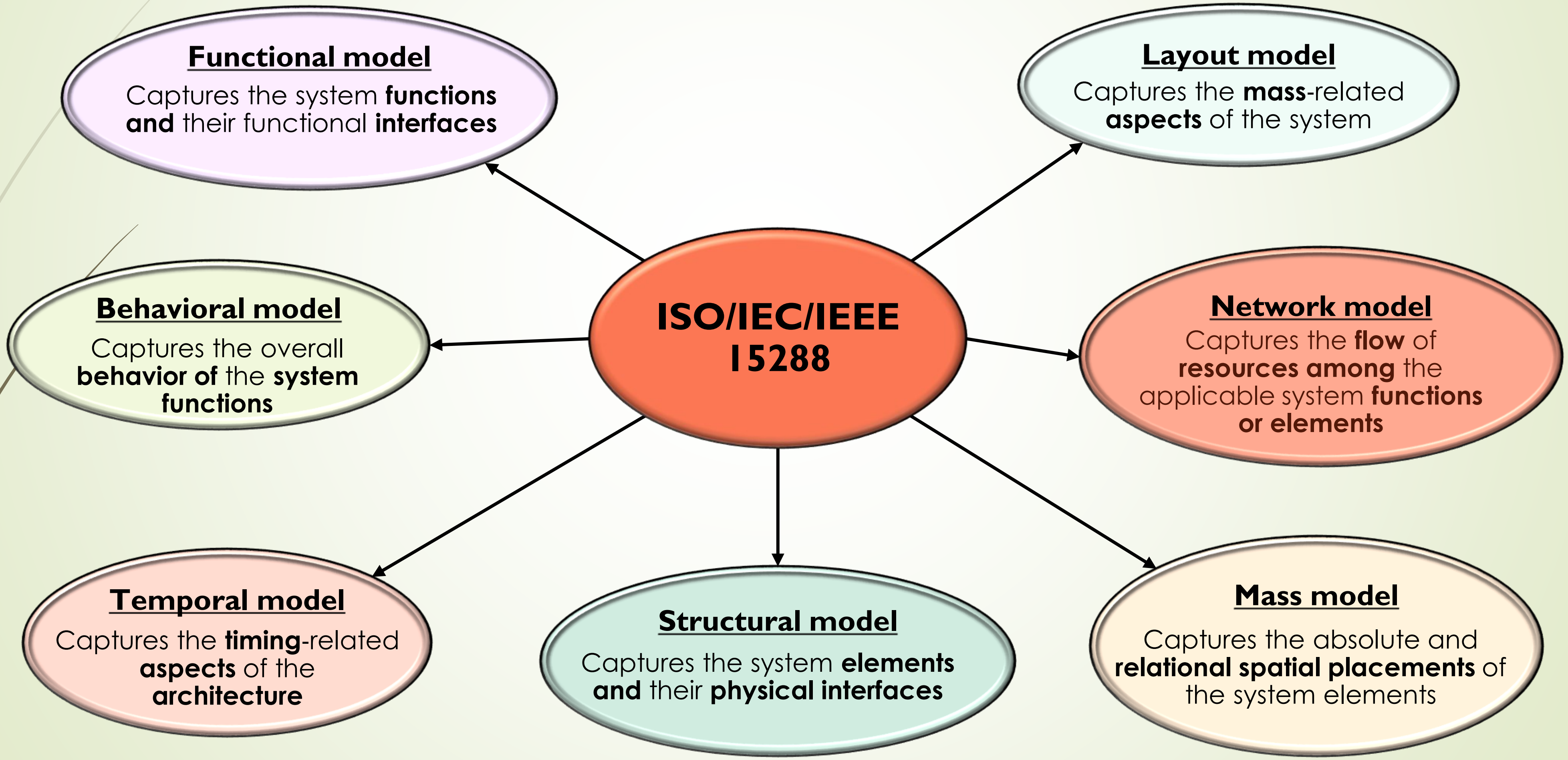
Descriptive & Analytical models
Their classification, terminology and approach is adapted to a application domain.

System Model

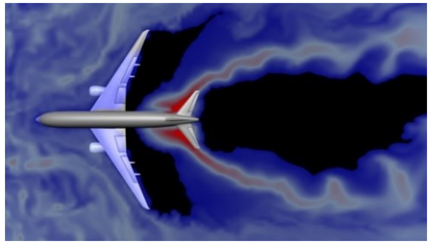
Descriptive and Analytical
- Span several modeling domains
- Must be integrated to ensure a consistent and cohesive system representation.

Adapted from the Systems Engineering Body of Knowledge (SEBoK) v1.8

Other classifications of models



What is a simulation?



"Simulation"

- implementation of a model(s) in a specific environment
- allows the model's execution over time.

- Not necessarily takes place in a computer
- Executes a model over time.

Simulations:

provide a means for analyzing complex dynamic behavior of systems, people, and physical phenomena.

EXAMPLE

A computer simulation includes the **analytical model** that is represented **in executable code**, the **input conditions** and other input data, **and** the **computing infrastructure (CI)**.
CI includes the **computational engine** needed to **execute** the **model**, **input** and **output** devices.

Run a simulation

Analytical Model
(executable code)

Inputs
- Conditions
- Data

Simulation

Executes the code with the given inputs over a set amount of time.

Outputs
- Test report
- Visual Representation
- Other output

Main Goal of Simulations

Simulation Goals

Investigate, verify and validate a system's behavior in relation to its context

The simulation model and its insights can be used to do:

- **Performance evaluation**
- **Evaluation of design alternatives**
- **Uncertainty reduction in decision making**
- **Determine if a performance requirement can be achieved**
- **Create a rapid prototype**
- **Risk assessment**
- **Validate your understanding with customers and end users**

Operating simulations

May operate in real-time e.g. there is an operator in the loop.

May operate faster than real-time

- performing thousands of simulation runs
- provide statistically valid simulation results.

May use artificial intelligence to prune the searches.

Physical Simulations

Use physical models and aim to replicate a **small number** of system **attributes** to a **high degree** of **accuracy** (fidelity).

When would it be used?

Physical model of environmental attributes with similar levels of fidelity.

- These simulations are costly* to construct
- limited number of system and environment attributes restricts the range of questions that can be answered.

EXAMPLE

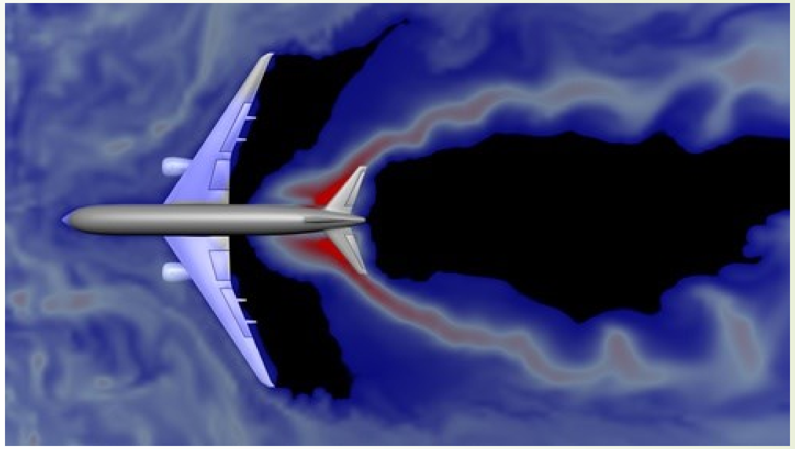
- Wind tunnels tests,
- Environmental tests,
- Mock-ups of manufacturing processes.

Computer-based Simulations

- Cover a broad scope of system attributes
- Become complex
- Include models of many types of systems
- Interact in many different way

Further classified based on Models of Computation (MoC):

- **Discrete event**
- **Monte Carlo**
- **Continuous time solving**
- **Finite element: numerical method for solving partial differential equations (structural analysis, heat transfer)**



Computer-based fluid mechanics simulation of air flow across a jet liner model

Monte Carlo use a repeated random sampling of input data into a model, using randomness to obtain results.

- complex models with coupled degrees of freedom
- significant uncertainty
- unknown correlations
- probabilistic in nature

May use as starting model when not enough data for correlations

Hardware Simulations

A cockpit of a flight simulator used in training pilots.

Human-in-the-loop simulations

- execute in real-time
- use computer-based models
    - close loop on inputs and outputs
- has hardware and/or human element

- have a high level of **fidelity**
- costly when physical stimulation is required
    - motion or visual scene generation

Within the US defense community, it is common to refer to simulations as live, virtual, or constructive, where you have:

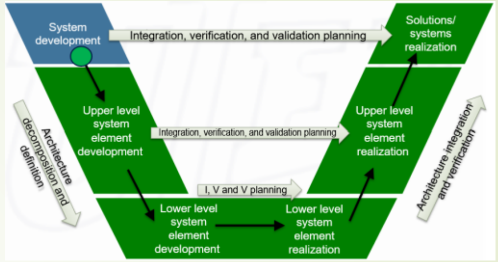
Live Simulations	**Virtual Simulations**	**Constructive Simulations**
live operators operating real systems.	live operators operating simulated systems	simulated operators operating with simulated systems

Source: INCOSE. 2015. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc

Developing Models and Simulations

In developing your models and simulations,

apply the SE approach



What does that involve?

- **must have a project**
- **Manage it as a project**
- **Create a plan**
- **Use a lifecycle process**
- **apply configuration management**
- **enforce change management**
- **Involve experts to collect knowledge**
- **Mitigate Risk**

So, the completed model or simulation can be considered a system in its own right.

Therefore…

- **Follow SE life cycle processes.**
- **Model/simulation development need to be planned and tracked,**
  - **as any other developmental effort.**

Validation & Verification of Models

Developing the model

Verifying the model

How many characteristics are being modeled?

Can you verify the model using these characteristics?

Validating the model

Taking important questions into consideration, such as…

Who provided the information to create the model?

How much information was provided by experts versus non-experts?

Can you trust the experts that were consulted?

Model and Simulation Integration

A key activity is to facilitate the integration of models and simulations across multiple domains and disciplines.

EXAMPLE

System models can be used to specify the elements of the system.

Logical model
define their interconnection or other relationships among the elements.

Quantitative models
for performance, physical, and other quality characteristics, such as reliability

Executable system models
for the for interaction of system elements to validate behavioral requirements.

These models represents **different facets** of the same system.

The different engineering disciplines for electrical, mechanical, and software each create their own models representing different facets of the same system.

The different models must be sufficiently integrated to ensure a cohesive system solution.

Prototyping

- enhance the likelihood of providing a system that will meet the user's need.
- facilitate both the awareness and understanding of user needs and stakeholder requirements.

The original use of a prototype…

As the first-of-a-kind product from which all others were replicated.

Not "the first draft" of production entities.

The intent in using a prototype…

- Only intended to enhance learning (validation)
- Only intended to determine if a technical aspect, function, quality attribute is feasible (verification)

Two types of prototyping are commonly used: rapid and traditional.

Rapid Prototyping

Rapid prototyping

- easiest and fastest ways to get user performance data
- evaluate alternate concepts

What is it?

- A particular type of simulation quickly assembled from a menu of existing physical, graphical, or mathematical elements

Used to investigate:

- form and fit,
- human–system interface,
- operations,
- feasibility considerations.

Should be discarded after achieving its pourpose

Additive Manufacturing

Additive Manufacturing (3D printing)

- **provides a rapid and low cost alternative for physical simulations**
- creates parts by adding material in a layer-by-layer manner
- include various types of materials
  - plastics, polymers,
  - elastic polymers, and metals
- May create complex geometry models
  - very hard to produce with subtractive techniques

Additive manufacturing preferred over subtractive manufacturing:

- Using less material
- Built on reasonable period of time

W.M. KECK CENTER
FOR 3D INNOVATION

Traditional Prototyping -1

Source: www.spectrum.ieee.org

Engineer Jonathan Kuniholm wears a full prototype of the prosthetic arm created by the DARPA Revolutionizing Prosthetics project.

May **reduce risk** or **uncertainty** through either **partial** or full **higher-fidelity interactive** prototypes.

Partial prototype:
verify **critical elements** of SOI

Full prototype
- **complete representation** of the system.
- must be complete and accurate in the **aspects of concern**.

Benefit of traditional prototyping?

- Collect objective and quantitative data on performance times and error rates
- Identify changes to improve performance, reduce production costs, quality, …

Traditional Prototyping -1

EXAMPLE

A maglev train system is developed for the purpose of testing:
form, fit, and function.

- not intended to provide transportation
- test within an established short-distance

Is it a prototype?

may be considered a prototype
proof of concept for longer distance systems

engineers evaluate modifications needed for long distance system

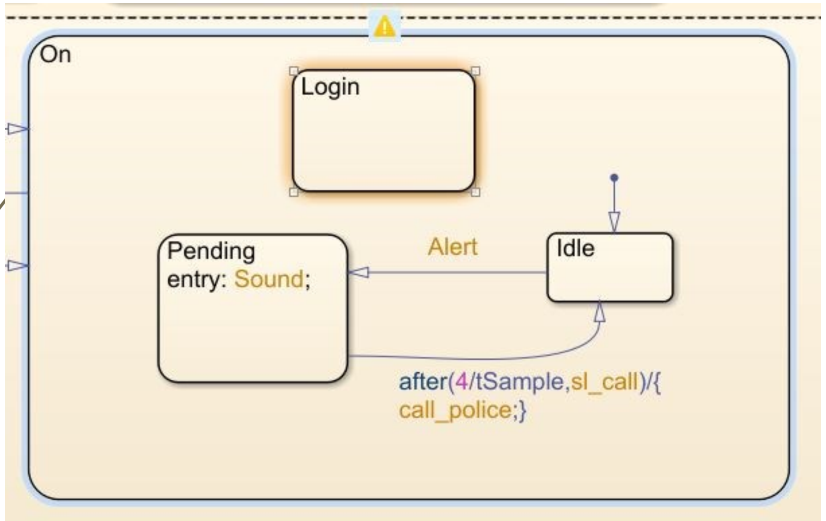
Modeling & Simulation Tool

Checking the model

A modeling tool

- Verifies and enforces compliance to the syntax & semantics
- helps the modeler to create a well-formed model.

EXAMPLE



Error checking of a given Stateflow diagram produces an alert to detected errors in the model.

Tool support

Modeling and simulation tools support the system development environment.

emphasis to promote information exchange among different tools.

Model and Simulation-Based Metrics

- **provide technical and management metrics**
- **assess modeling and simulation efforts**

Types of metrics

Models and Simulations provide information that enables one to:

Assess progress

Determine if a performance requirement can be achieved

Estimate effort and cost

Assess model quality

Assess technical quality and risk

Predict Number of defects in system testing based on peer reviews **

Summary Modeling & Simulation (M&S)

A Model is …

A representation of the essential characteristics of a system, its intended environment, and the its interactions with other systems and user.

Simulation is…

- **The implementation of a model in a specific environment**
- **allows the model's execution over time.**

Selecting a model or simulation involves…

- **Considering the goals of the model's use**
- **Reviewing audience, purpose, and knowledge to be conveyed**

Use M&S to enhance the learning of a system.

- M&S are good for verification and validation

M&S are abstraction and **not the actual real system**

Measure the quality of your M&S
ensure you have a usable / trustable product.

References

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