

Simulation Credibility Assessment:

Introduction to Verification, Validation, and Uncertainty Quantification (VVUQ)

Task Group on VVUQ Concepts in Engineering Education

ASME Codes & Standards | Committee on Verification, Validation, and Uncertainty Quantification

Contacts: Lydia Stanford (stanfordl@asme.org) | Daniel Papert (papertd@asme.org)

V. 3, Draft, 2026

© 2026 by ASME Task Group on VVUQ in Engineering Education is licensed under CC BY 4.0. To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>

Outline

- Why do we care about simulation credibility?
- Structure of a simulation model and how are they are used
- Simulation Verification: Quantifying numerical errors
- Model Validation: Comparisons with experimental data
- Predictive Capability: Simulation results plus all uncertainties
- Uncertainty Quantification: Understanding uncertainty sources in simulation results

Why do we care?

- “All models are wrong – some are useful.” – Prof. George E. P. Box
- Why is this true?
 - All models rely on assumptions and approximations in the formulation of the model
 - All models require input data to describe the system of interest and its surroundings, which are approximate, possibly not measurable, or not knowable in advance
 - All models require numerical solution, which results in numerical errors
- Infamous system failures due to erroneous modeling:

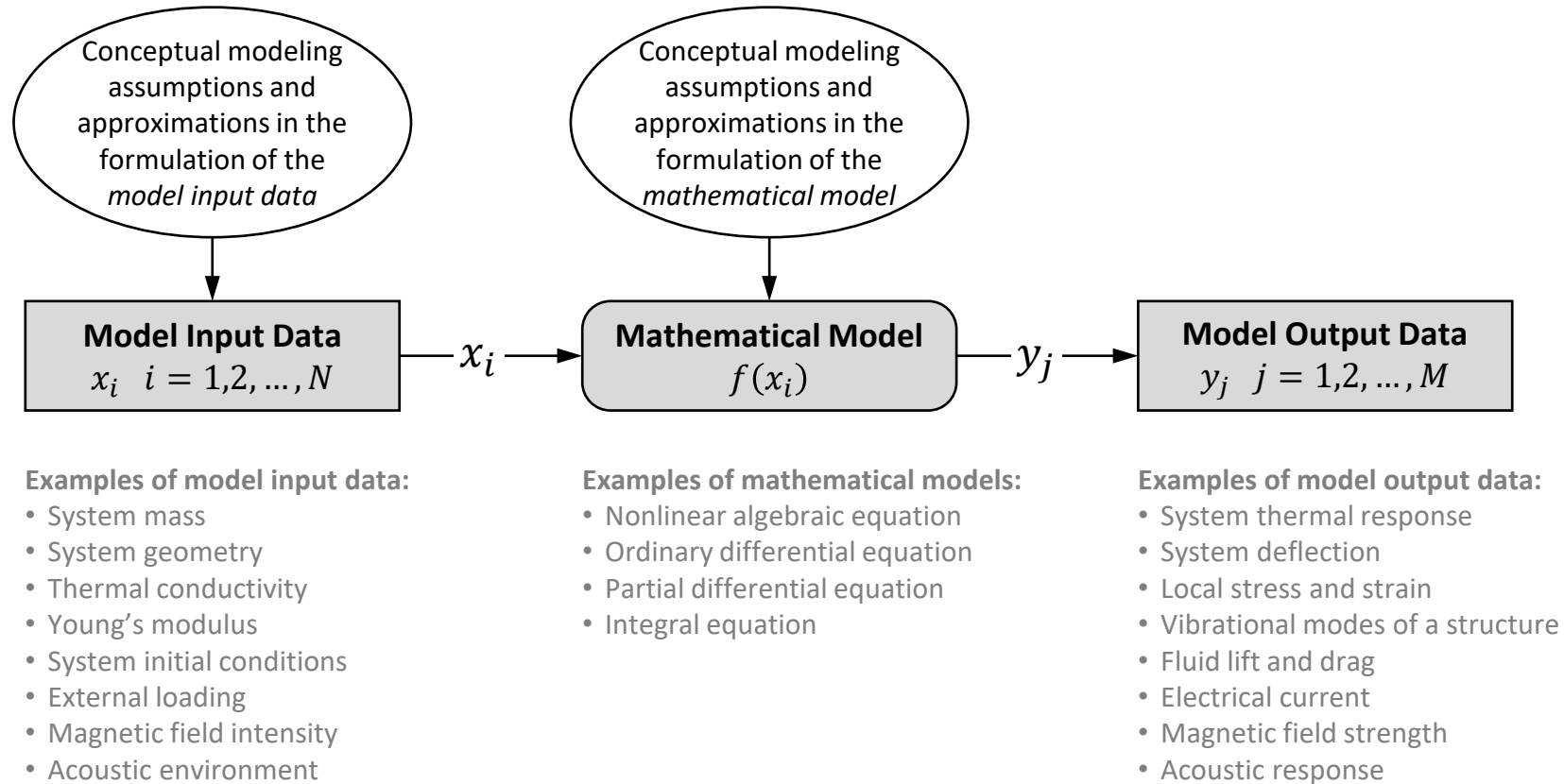


Space Shuttle Columbia Disaster



Fukushima Nuclear Disaster

Structure of a simulation model



What do simulation models produce and how is it used?

- Simulation models are used to produce **information** about the system of interest and its responses.
- When simulation results are used in business and government:
 - Simulation is referred to as a **decision support tool**
 - The process is also referred to as **simulation-informed decision making**
- Examples how this information can be used:
 - Design of new systems or modification of existing systems
 - Optimization of system design to increase performance, reliability, and safety
 - Reduce development time and physical testing of the final system
 - Optimize manufacturing processes
 - Assess system safety in untestable environments such as accident scenarios or those that produce unacceptable risks to humans and the environment

How is simulation credibility assessed?

- Numerical accuracy is assessed by simulation verification:
 - **Simulation verification:** assessment of the accuracy of the numerical solution relative to the exact solution to the mathematical model
- Physics-based accuracy is assessed by model validation:
 - **Model validation:** assessment of the accuracy of the simulation results relative to experimental measurements of system responses
- Uncertainty in the simulation results is assessed by uncertainty quantification:
 - **Uncertainty quantification:** estimation of the total uncertainty in the simulation result due to all sources of error and uncertainty in the modeling and simulation process
- These assessments are collectively referred to as **VVUQ**.
- Note: These concepts of verification and validation are *distinctly different* from the systems engineering concepts of V&V.

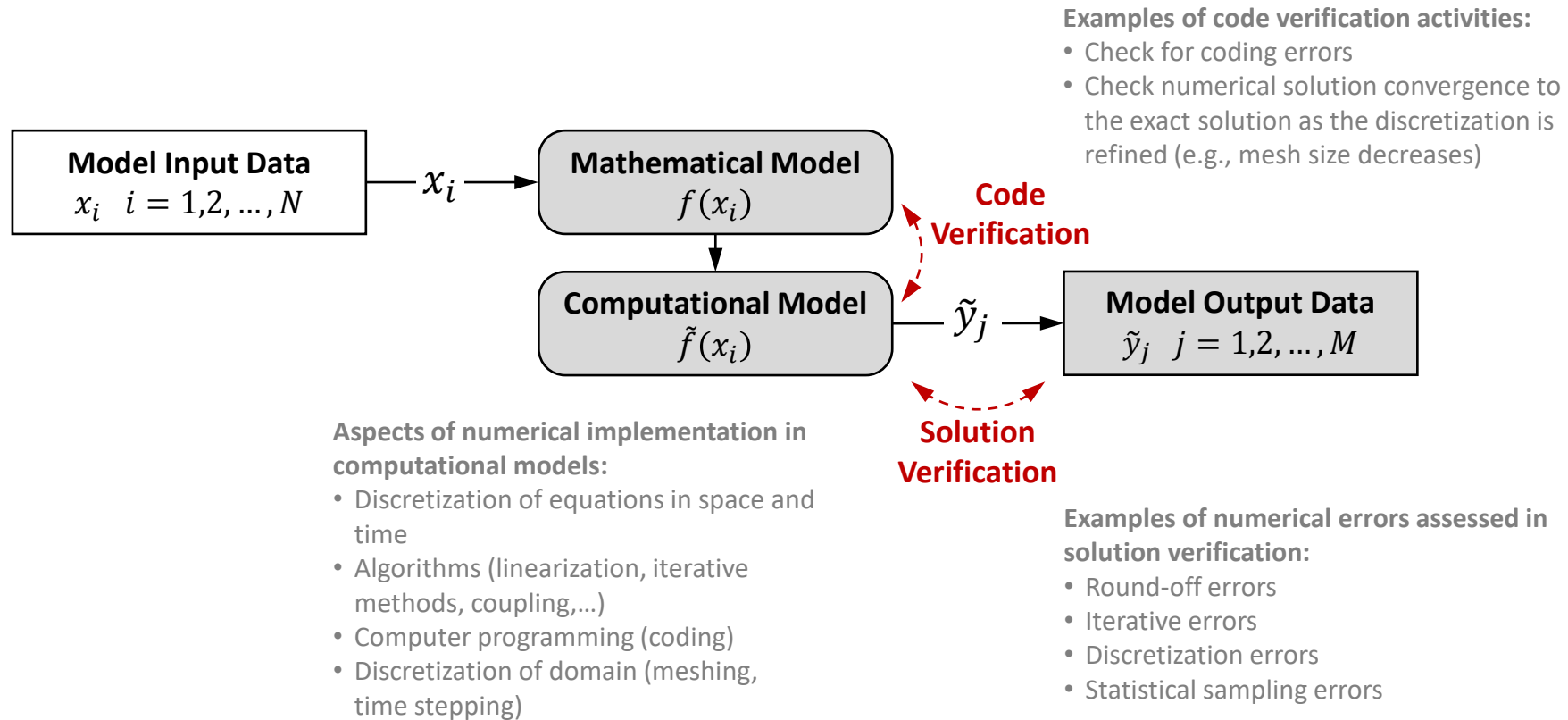
Context of use of the simulation

- **Context of use:** the relationship between the applicability and accuracy of the simulation model relative to the requirements for the intended use of the model.
- Examples of issues related to the context of use:
 - Are the assumptions and approximations of the formulation of the model consistent with the intended use of the model?
 - Is the accuracy and uncertainty of the simulation results sufficient for the needs of the intended use of the model?
 - Are the VVUQ assessment activities sufficient to insure credibility for the intended use of the model?
 - Are the conditions of model validation sufficiently relevant to the actual conditions of interest for the system/subsystem under considerations?
 - What are the consequences and risks involved if the simulation results are inaccurate?

What is verification and why do we care?

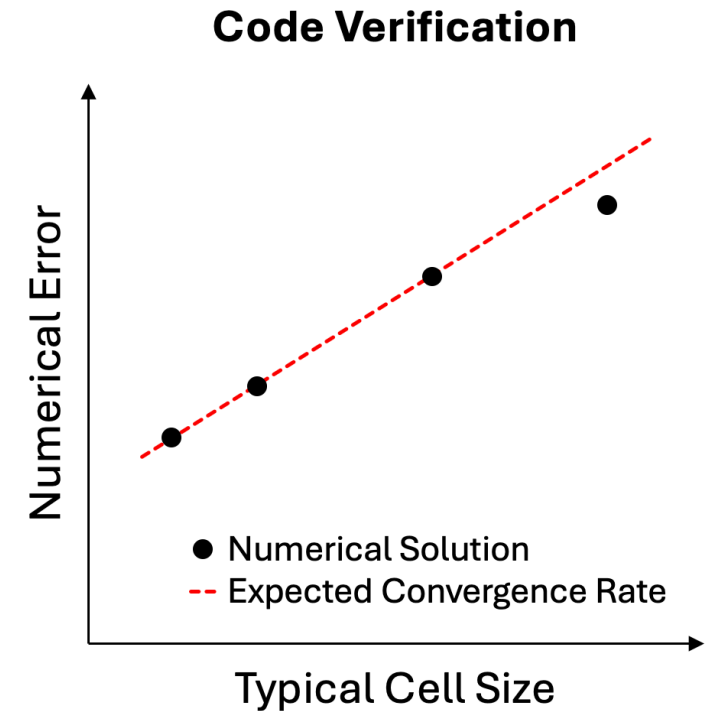
- Verification is the process that establishing the *mathematical correctness* of the computational model and determining the *accuracy* of a particular numerical solution.
- Verification includes two different activities:
 1. **Code verification** is the process of determining that the mathematical model and its numerical solution is correctly implemented in the computer code. Code verification *evaluates* the numerical error using a known reference solution.
 2. **Solution verification** is the process of estimating the *numerical accuracy* of output quantities of the computational model for the application conditions of interest. Solution verification *estimates* the numerical error of the output quantities of interest.

Verification activities



How is it code verification performed?

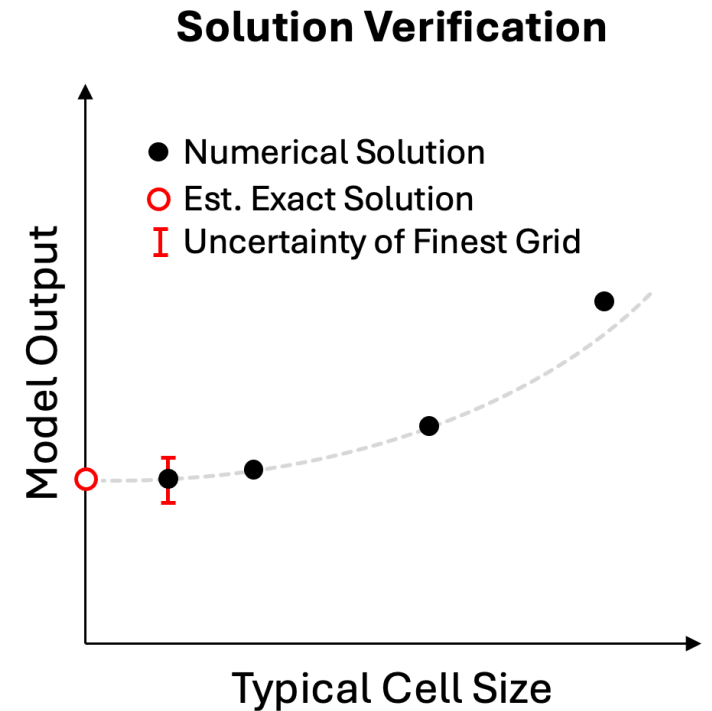
- Code verification requires a *known solution* to a problem that is solved with the same mathematical model. For example, a problem that uses the same terms for the transport of mass, momentum, and energy as the application of interest.
- Known reference solutions can come from:
 - Classical analytical solutions
 - Manufactured solutions
 - Highly accurate numerical solutions
- Numerical solutions are computed and the error is *evaluated* on a series of refined grids and time steps to determine the numerical order of accuracy.
- Code verification is a *software testing procedure*.



How is it solution verification performed?

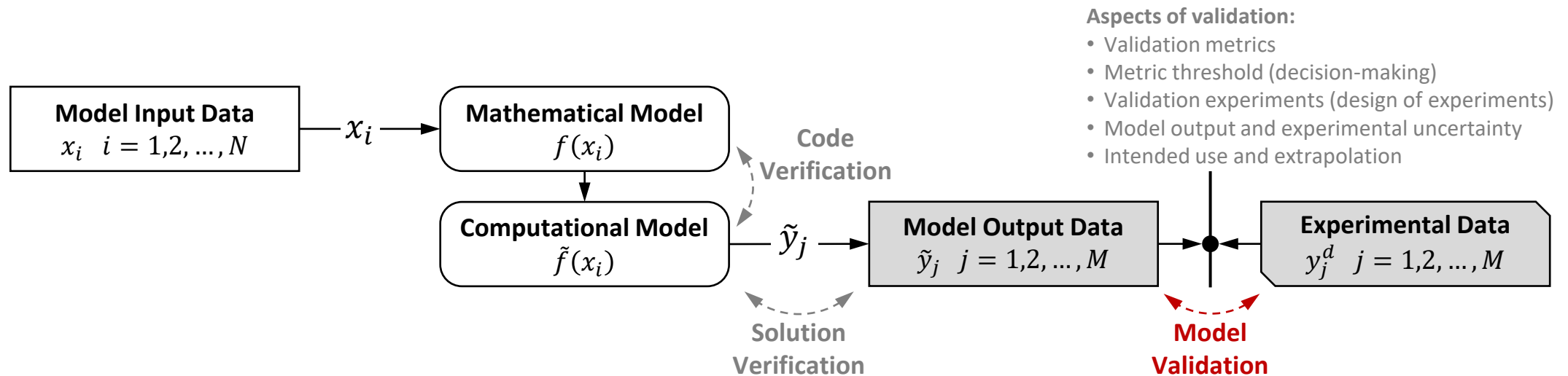
- Solution verification is the process of estimating the numerical solution error in the model outputs ϕ for the application of interest. Since the exact solution ϕ_{exact} is unknown, there will be uncertainty $U(\phi)$ in the model outputs of interest ϕ .
- Similar to code verification, computing solutions on a series of refined grids and time steps is a common technique for estimating the numerical uncertainty $U(\phi)$.
- Since the sign of the numerical uncertainty is not known, the estimated bound on the numerical uncertainty is written as

$$\phi_{\text{exact}} - \phi = \pm U(\phi)$$



What is model validation and why do we care?

- Computational modeling and simulation are used to aid the decision-making process
 - e.g., Predicting deformation of a structure: an inaccurate model could lead to poor decisions, potentially resulting in excessive deformation or even failure of a bridge or building.
- **Validation** compares the simulation model results to real-world observations (data) to ensure it captures essential features (physical phenomena) of the real system.
- Validation data should reflect the conditions of the intended use of the model.
 - e.g., Assessing the predicted deformation of a structure against measured deformation under realistic or maximum loading conditions.



How are validation experiments different from other experiments?

- Traditional experiments/tests are conducted to:
 - Improve physical understanding of the physical processes occurring
 - Calibrate/update model input parameters
 - Assess or certify system/subsystem performance or safety
- **Model validation experiments** are conducted for the primary purpose of assessing the ability of the simulation model to predict the system responses for the experiment that is conducted.
- Validation experiments can be conducted on the actual system of interest, but more commonly it is:
 - A subsystem, assembly, or component of the actual system of interest
 - The experimental conditions are not fully representative of the actual operating conditions of the system
- Other important features of validation experiments:
 - Experimental measurement uncertainty should be estimated in both the system response quantities of interest and the input quantities that are used the simulation model
 - Quantitative methods should be used to assess the agreement between simulation and experimental results
 - *Blind model predictions* of the validation experiment are the most informative of predictive capability

What is model prediction?

- **Prediction** involves producing model outputs for which corresponding measured data is *not available*.
- **Validation domain:** A model is validated against experimental results at a specific set of input conditions ('validation points') that form the *validation domain*.
- **Intended use domain:** Predictions in the *intended use domain* of the model input space may be **interpolative** or **extrapolative** with respect to the *validation domain*.

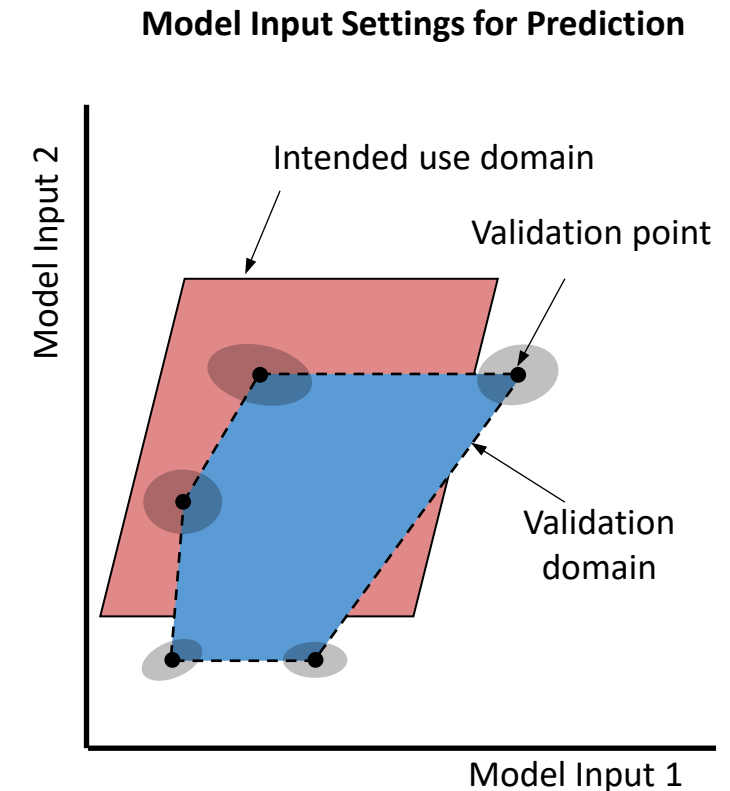


Image credit: adapted from V&V 10

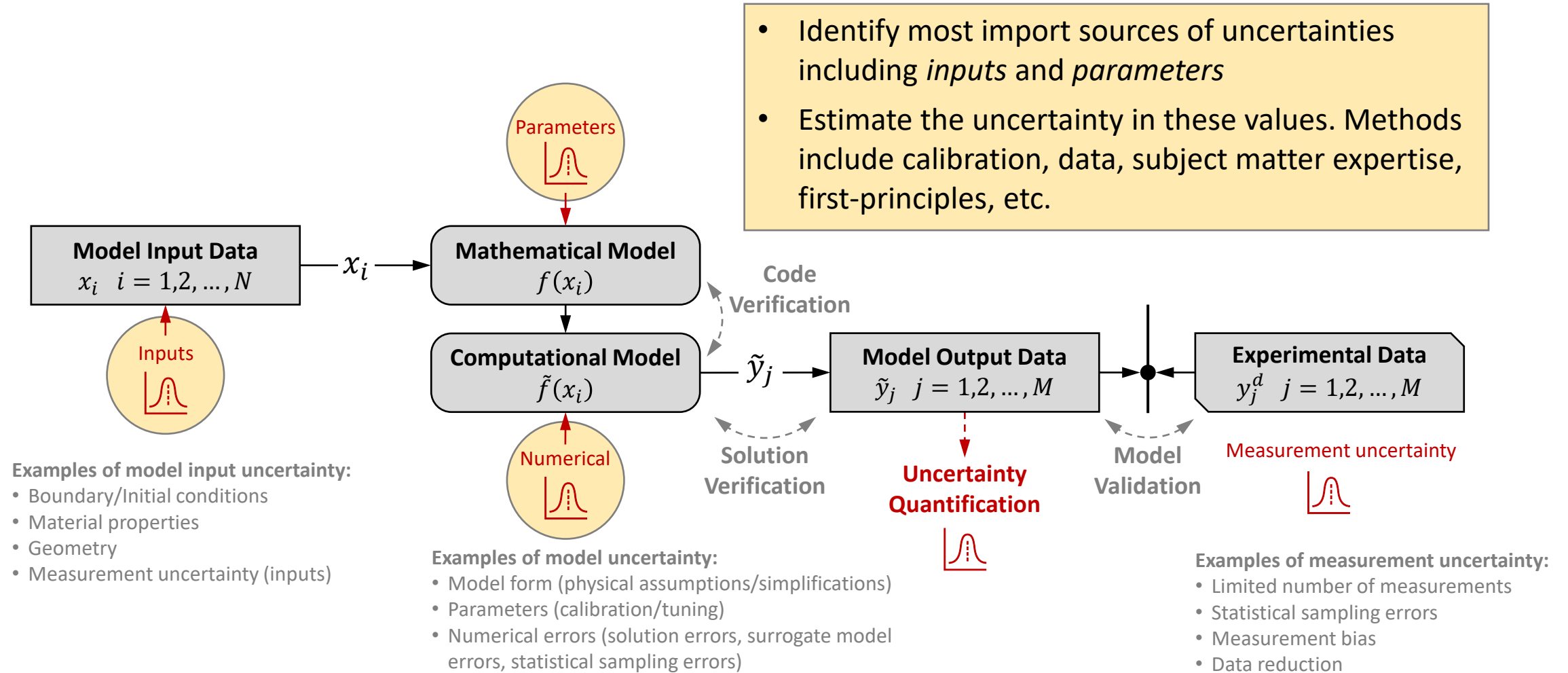
What is predictive capability of a model?

- **Predictive capability** is producing a simulation result, including all sources of uncertainty, at conditions where *no experimental measurements* are available.
- Predictive capability is informed by:
 - Quantitative validation assessment at conditions relevant to the prediction conditions of interest
 - The similarity of the conditions at the prediction conditions to the model validation conditions
 - The estimated magnitude of all the numerical solution uncertainties at the prediction conditions of interest
 - The effect of the model input uncertainties at the prediction conditions of interest
 - The uncertainty due to the model formulation itself, i.e., model form uncertainty
- A simulation model's **adequacy** for intended use involves diverse requirements such as:
 - Requirements for model accuracy plus uncertainty at the prediction conditions of interest
 - Economic, safety, and liability risks if the simulation model is potentially *inaccurate*
 - Personnel, computer, and software costs to produce the simulation results
 - Experience level required of the personnel to produce credible simulation results

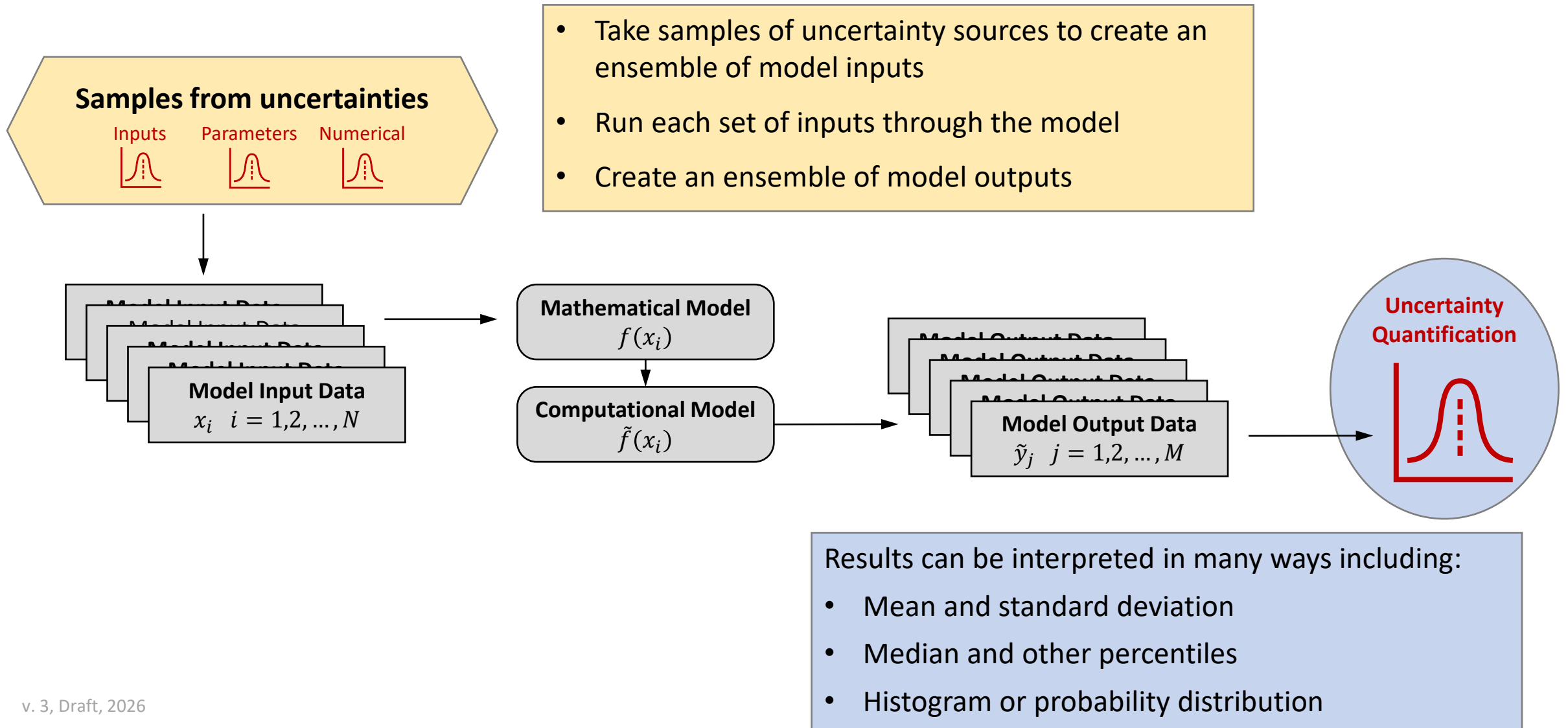
What is uncertainty quantification and why do we care?

- **Uncertainty Quantification (UQ)** is the process of using statistical models to provide an estimate of uncertainty in the experimental and simulation results.
- Uncertainty Quantification has three basic steps:
 - **Characterize Uncertainties:** Identify all relevant uncertainties and characterize the uncertainties as much as is possible
 - **Propagate Uncertainties:** Perform model evaluations to estimate the impact of model input uncertainties on the system response quantities of interest (QoIs)
 - **Interpret Results:** Compute and explain the sources and impact of the uncertainties to the simulation customer
- Uncertainty quantification is important because it informs the customer of the simulation results how the uncertainties impact the simulation results.

Characterize uncertainties



Propagate uncertainties and interpret results



Rank the impact of uncertain inputs using sensitivity analysis

Closely related to UQ is **Sensitivity Analysis** where the importance of the model parameters are identified and potentially ranked.

Various approaches:

- **Local Sensitivity Analysis:** Estimate sensitivity with small perturbations to the nominal model parameters
- **Global Sensitivity Analysis:** Evaluate the sensitivity over the full range of the parameters

Sensitivity Analysis can be used to:

- Select optimal design parameters to achieve system performance requirements
- Identify the largest contributors to uncertainty in system responses

References

- AIAA (2024), "Standard for Code Verification in Computational Fluid Dynamics." American Institute of Aeronautics and Astronautics, AIAA S-141-2024, Reston, VA.
- ASME (2009), "Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer." American Society of Mechanical Engineers, [ASME Standard V&V 20-2009\(R2021\)](#), New York, NY.
- ASME (2018), "Assessing Credibility of Computational Modeling Through Verification and Validation: Application to Medical Devices," American Society of Mechanical Engineers, New York, NY, [ASME V&V 40-2018](#), New York, NY.
- ASME (2019), "Standard for Verification and Validation in Computational Solid Mechanics." American Society of Mechanical Engineers, [ASME Standard V&V 10-2019](#), New York, NY.
- ASME (2021), "The Role of Uncertainty Quantification in Verification and Validation of Computational Solid Mechanics Models," American Society of Mechanical Engineers, [ASME VVUQ 10.2-2021](#), New York, NY.
- ASME (2022), "Verification, Validation, and Uncertainty Quantification Terminology in Computational Modeling and Simulation," American Society of Mechanical Engineers, [ASME VVUQ 1-2022](#), New York, NY.
- McClarren, R. G. (2018), [Uncertainty Quantification and Predictive Computational Science](#), Springer, Cham, Switzerland.
- NA (2024), "Foundational Research Gaps and Future Directions for Digital Twins." National Academies of Sciences, Engineering and Medicine, DOI 10.17226/26894, Washington, DC.

References (continued)

- NaRC (2012), "Assessing the Reliability of Complex Models: Mathematical and Statistical Foundations of Verification, Validation, and Uncertainty Quantification." National Research Council of the National Academies, ISBN-13: 978-0-309-25634-6, Washington, DC.
- NASA (2010), "NASA Risk-Informed Decision Making Handbook." National Aeronautics and Space Administration, NASA/SP-2010-576, Washington, DC.
- NASA (2016), "Standard for Models and Simulations." National Aeronautics and Space Administration, NASA-STD-7009A, Washington, DC.
- Oberkampf, W. L. and C. J. Roy (2025), Verification, Validation and Uncertainty Quantification in Scientific Computing, 2nd edition, Cambridge University Press, UK.
- Roache, P. J. (2009), Fundamentals of Verification and Validation, Hermosa Publishers, Socorro, New Mexico.
- Smith, R. C. (2024), Uncertainty Quantification: Theory, Implementation, and Applications, 2nd edition, Society for Industrial and Applied Mathematics, Philadelphia, PA.
- Saltelli, A., Ratto, M., Adres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., Taratola, S., (2008), Global Sensitivity Analysis: The Primer, Wiley, England
- Sullivan, T. J. (2015), Introduction to Uncertainty Quantification, Springer, Heidelberg.
- TMS (2019), Verification & Validation of Computational Models Associated with the Mechanics of Materials, The Minerals, Metals & Materials Society, ISBN 978-0-578-45369-9, Pittsburgh, PA.