Validation Issues Associated with Unsteady Flows

Dr. William L. Oberkampf
W. L. Oberkampf Consulting
wloconsulting@gmail.com
Austin, Texas

9th Annual Shock Wave/Boundary Layer Interaction
Technical Interchange Meeting
Ohio Aerospace Institute, Cleveland, Ohio
24 – 25 May 2016

Outline

- Traditional vs. validation experiments
  - Goals of model validation
  - Trade-off in model validation
  - Design of validation experiments
- Structure of computational simulation
  - Non-deterministic simulation
  - Validation versus calibration
- Areas in need of improvement
  - Experimental activities
  - Computational activities
- Conclusion and recommendations

Traditional Experiments vs. Validation Experiments

Goals of three types of traditional experiments:

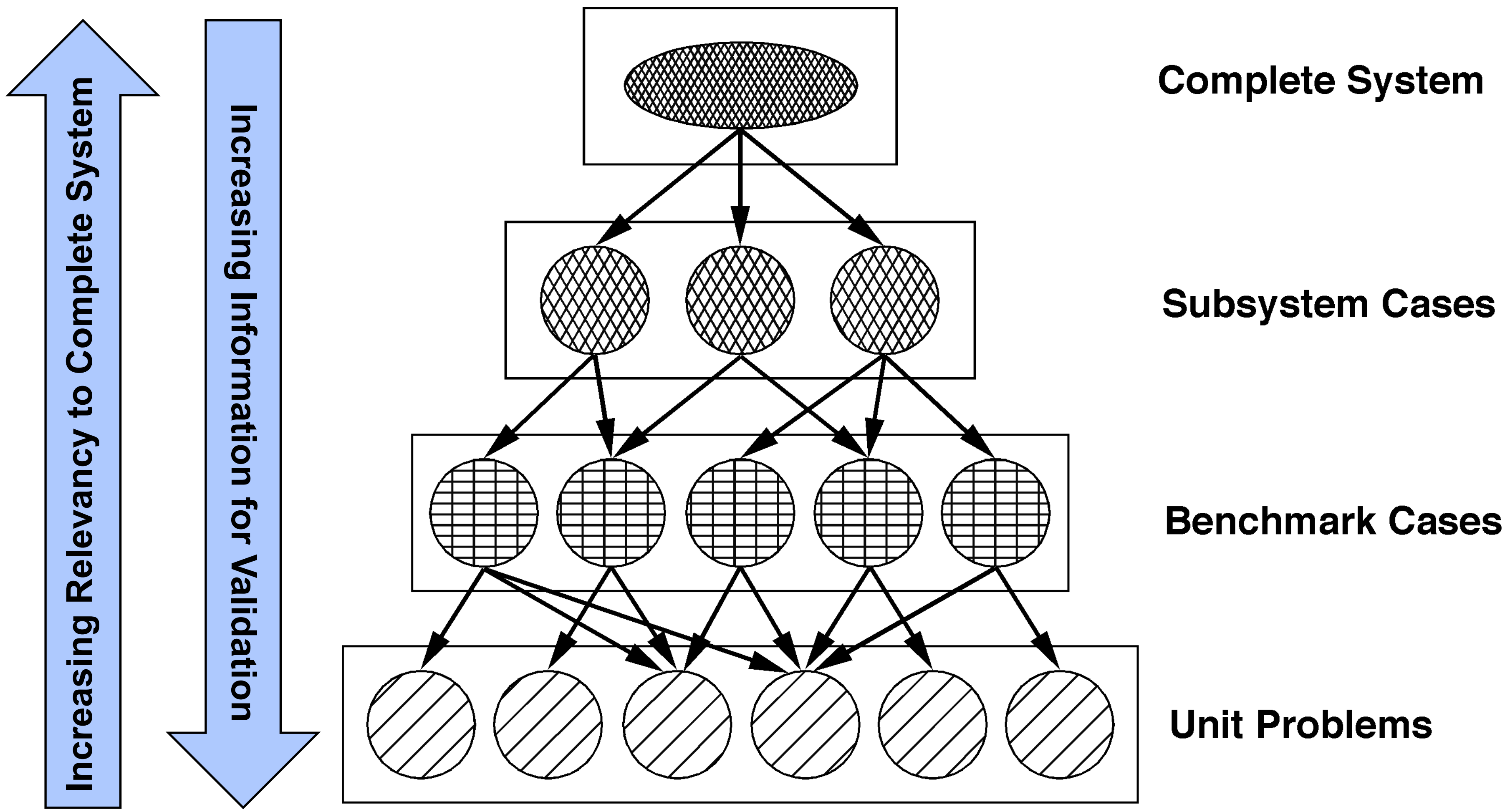
1. **Improve the fundamental understanding of the physics:**
   - **Ex: fluid dynamic turbulence experiment; experiment for understanding evaporation and condensation in multi-phase flows**
2. **Improve the mathematical models of some physical phenomena:**
   - **Ex: experiment to determine reaction rate parameters in reacting flow; experiment for calibrating parameters in two-equation turbulence models**
3. **Assess subsystem or complete system performance:**
   - **Ex: performance of a new combustor design in a gas turbine engine; tests of a new multi-element flap design for a wing**

- **Model validation experiment**
  - **An experiment that is designed and executed to quantitatively estimate a mathematical model's ability to simulate a physical system or process.**
- **The computational model developer or code user is the customer.**

Goals of Model Validation

- **Tactical goals of validation:**
  - Quantification of the effects of mathematical modeling assumptions and approximations by comparison of simulation results with experimental measurements
  - Identification of the effect of physics modeling weaknesses, i.e., quantification of model form uncertain
  - Model form uncertainty is distinct from model parameter uncertainty
- **Strategic goals of validation:**
  - Improve the separation of model form uncertainty from all other forms of uncertainty, particularly model parameter uncertainty
  - Improve physics modeling to improve predictive capability
- **What are the crucial elements of model validation?**
  - Experimental measurement of the important input data for the model
  - Validation metrics: mathematical operators that quantify the difference between simulation and experimental results

Trade-Off in Model Validation Experiments

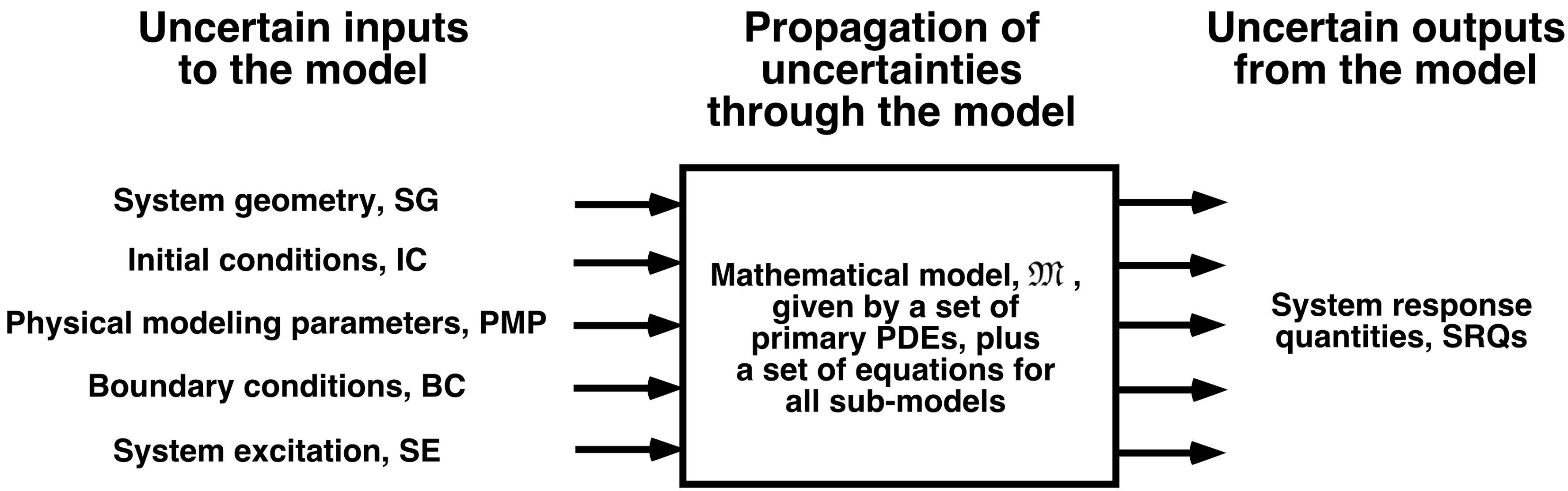


(Ref: AIAA Guide, 1998)

Design of Validation Experiments

- Key elements in the design of validation experiments:
  - Modelers and experimentalists jointly design the experiment
  - Experimentalist should measure all important model input data
  - Achievement of a blind prediction is the most effective approach
  - Experimentalist should estimate uncertainty on both input data and system response quantities measured
- Five categories of input data:
  - System geometry
  - Initial conditions
  - System physical parameters
  - Boundary conditions
  - System excitation
- What makes validation particularly difficult?
  - Connecting modelers and experimentalist, on the same time frame
  - Separation of input uncertainty and model form uncertainty

Structure of Computational Simulation



- **Examples of uncertainty in input data for validation experiments:**
  - Geometry; detailed measurement of the actual as-tested geometry
  - Initial conditions; flow field at the beginning of engine-unstart
  - Physical parameters; non-equilibrium chemistry in a high enthalpy facility
  - Boundary conditions; spatial and temporal characterization of inflow conditions in a wind tunnel
  - System excitation; acoustic excitation of a turbulent boundary layer

Where Do We Stand in Model Validation?

- Common approach to validation is actually model calibration:
  - Input data and parameters in the model (either scalars or probability distributions) are calibrated to improve agreement with experimental data
  - When model validation (i.e., model accuracy assessment) is mixed with model calibration, it underestimates model form uncertainty by adjusting input data uncertainty
- To improve confidence in our simulations, validation should:
  - Improve the separation of calibration and validation activities
  - Emphasize the assessment of simulation accuracy by using blind-predictions of experimental data
  - Improve cooperation and teamwork between experimentalists and computational analysts so as to conduct improved validation experiments

Areas in Need of Improvement: Experimental Activities

- Improved spatial and temporal characterization of inflow boundary conditions for CFD simulation
- Improved spatial and temporal measurement of flow in an empty test section of a wind tunnel, including the tunnel walls
- Improved measurement and documentation of time-dependent quantities, especially in high-enthalpy shock tunnels
- Comparison of measurements using different experimental techniques, e.g., PIV versus LDV
- Improved experimental uncertainty estimation by way of:
  - Comparison of run-to-run and facility-to-facility variability
  - Comparison of runs with the test article at different locations in the test section
- Improved assessment of experiments regarding completeness of information for model validation

Areas in Need of Improvement: Computational Activities

- Use of simulation to guide the design and execution of validation experiments, e.g., use of sensitivity analyses
- Improved code verification testing and documentation
- Improved quantification and documentation of numerical error due to temporal and spatial discretization
- Willingness to compute the flow in the entire test section
- Construction of improved validation metrics for unsteady flows
- Improve cooperation and teaming with experimentalists

This is the responsibility of management and funding sources

Conclusions and Recommendations

- "Quality" of a validation experiment should be ranked on the following characteristics (in priority order):
  - Measurement and documentation of important input data needed for the simulation
  - Estimation of experimental uncertainty on both input and output data
  - Assessment of model accuracy by way of a blind prediction
  - Separation of model calibration and model validation
- Validation is focused on simulation of the flow field inside the wind tunnel or in flight
- The burden of improving the quality of validation experiments falls primarily on experimentalists
- Sponsors should recognize the need to fund new validation experiments

This is the path to critically assessing our simulations

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