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An Uncertainty Structure Matrix for Models and Simulations

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Introduction
Acronyms

• AIAA	American Institute of Aeronautics and Astronautics
• CAIB	Columbia Accident Investigation Board
• CY	Calendar Year
• EMB	Engineering Management Board
• M&S	Modeling and Simulation
• MER	Mission Evaluation Room
• MMT	Mission Management Team
• NASA	National Aeronautics and Space Administration
• OCE	(NASA) Office of Chief Engineer
• RTFTG	Return to Flight Task Group
• SME	Subject Matter Expert
• UA	Uncertainty Analysis
• UM	Uncertainty Management
• UP	Uncertainty Propagation
• UQ	Uncertainty Quantification

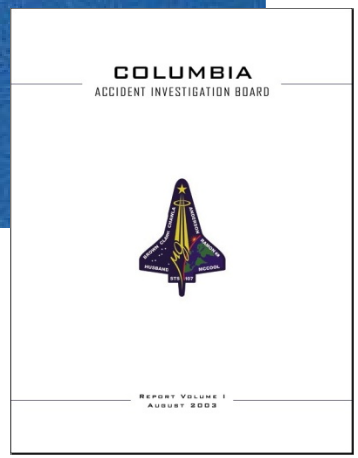
Introduction
Comparison of Software Types

- Command, control, display, and support software
  - **Provides a service function to its operators**
    - **Flight command / control within certain sets of predefined operational conditions**
    - **Information about the past, current, or future states of an aerospace vehicle during operations**
    - **Automation of a sequence of steps**
      - **For safety reasons (i.e., pilot cannot respond quickly enough)**
      - **Eliminate drudgery**
  - **Transforms the responses from various vehicle sensors into digital or analog displays for human interpretation**
  - **Enables access to information at the proper times and in the proper formats**
- Modeling and Simulation (M&S) software
  - **Intended *to represent* an actual physical, or imagined, reality**
  - **Involves *uncertainty* from various sources**
  - **Must be *credible* within a given decision-making situation**

Introduction
Comparison of Software Types (2)

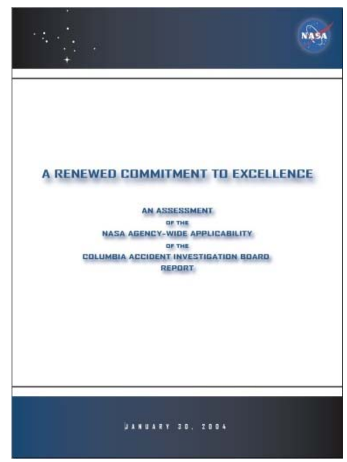
- Command, control, display, and support software
  - **Universally expected to work correctly all the time**
    - **Incorrect data input flagged; incorrect answers are not permitted**
    - **Verification means that the software contains no errors**
    - **Validation means that the software commands or controls the vehicle, system, or subsystem as intended**
    - **Correctness can usually be demonstrated easily / without question**
  - **Generally developed under strict management processes**
  - **Requirements, policy, guidelines, and best practices generally target, and use language familiar to, the software engineering community**
  - **No consideration of uncertainty**
- M&S software
  - **Explicit consideration of uncertainty is required**
    - **Imperfectly modeled physics (approximation of, or unknown, physics)**
    - **Numerical approximations (e.g., curve fits and response surfaces)**
    - **Variability within the physical processes modeled**
  - **Natural consideration of <u>UQ</u> and <u>UM</u> practices and <u>credibility</u> of the M&S effort for intended application (e.g., see AIAA 2008-2156)**

History and Context
Chronology of Relevant Events

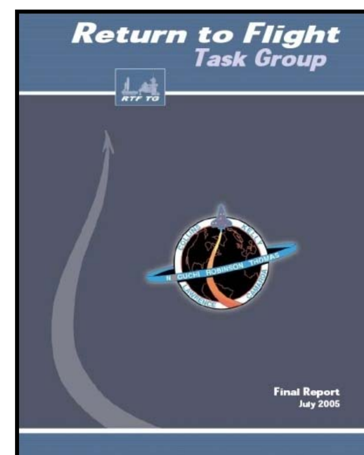


Columbia Accident Investigation Board (CAIB Report) August 26, 2003

A Renewed Commitment to Excellence (Diaz Report) Feb. 9, 2004



Uncertainty Structure Matrix



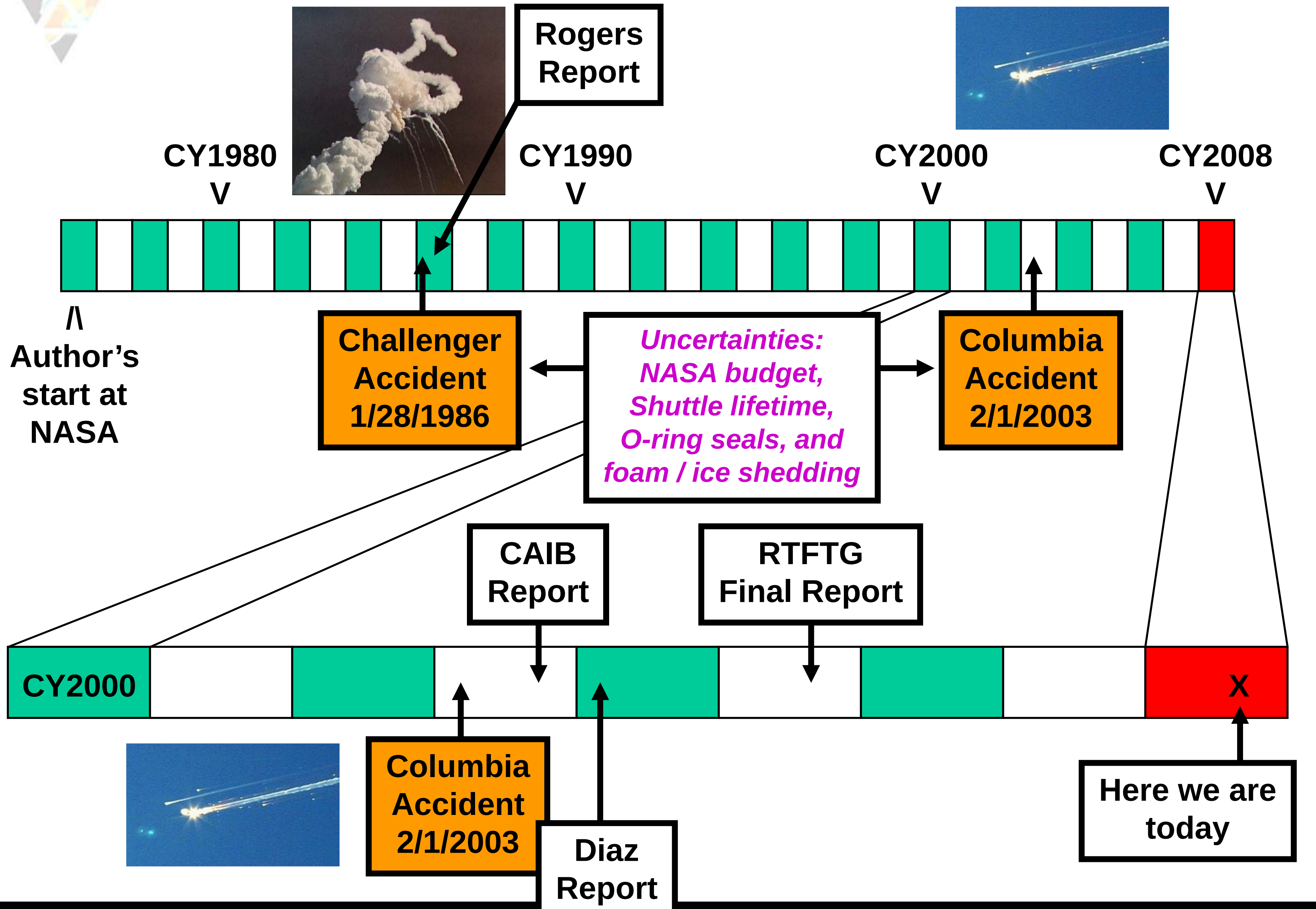
Return to Flight Task Group (Stafford-Covey Report) August 17, 2005

CAIB: Shuttle-specific Recommendations, Observations and Findings

Diaz: More generalized Recommendations, Observations, Findings and Actions
=> Action: develop NASA Standard for Models & Simulations

RTFTG: Evaluation of CAIB follow-up

History and Context: Detailed Timeline



History and Context: Relevant Comments

About the Challenger Accident

- **Rogers Report (1986):** NASA should **establish an STS Safety Advisory Panel** reporting to the STS Program Manager ... [on] ... **operational issues** … and **risk management**.
- **Rogers Report (1986):** NASA should establish an **Office of Safety, Reliability and Quality Assurance** … [with] ... direct authority for safety, reliability, and quality assurance **throughout the agency** … [including] … **reporting and documentation of problems, problem resolution and trends**
- **CAIB Report (2003):** Shuttle reliability is uncertain, but has been estimated to range between 97 and 99 percent. **If the Shuttle reliability is 98 percent, there would be a 50-50 chance of losing an Orbiter within 34 flights** [Challenger was flight 25] **… The probability of maintaining at least three Orbiters in the Shuttle fleet declines to less than 50 percent after flight 113.** - **The Office of Technology Assessment, 1989**
- **CAIB Report (2003):** And although it is a subject that meets with reluctance to open discussion, and has therefore too often been relegated to silence, **the statistical evidence indicates that we are likely to lose another Space Shuttle in the next several years** … probably before the planned Space Station is completely established on orbit. This would seem to be the weak link of the civil space program – unpleasant to recognize, involving all the uncertainties of statistics, and difficult to resolve. - **The Augustine Committee, 1990**

Note: Endeavor built to replace Challenger; finished in May 1991; Shuttle fleet then back up to 4 vehicles; Columbia was flight 113!

History and Context

Relevant Comments from the CAIB Report *about the Columbia Accident*

- Engineering solutions … should have included a **quantifiable range of uncertainty and risk analysis**
- Management … **should have demanded such information …**
- The … absence of a **clear and open discussion of uncertainties** … should have caused management to probe further …
- The … **uncertainties … were never presented or discussed in full** to either the Mission Evaluation Room (MER) or the Mission Management Team (MMT) …
- The **uncertainties and assumptions** that signaled danger **dropped out of the information chain** when the MER manager condensed the Debris Assessment Team's formal presentation to an informal verbal brief at the MMT meeting

History and Context

Relevant Comments from the RTFTG Report *about the Columbia Accident*

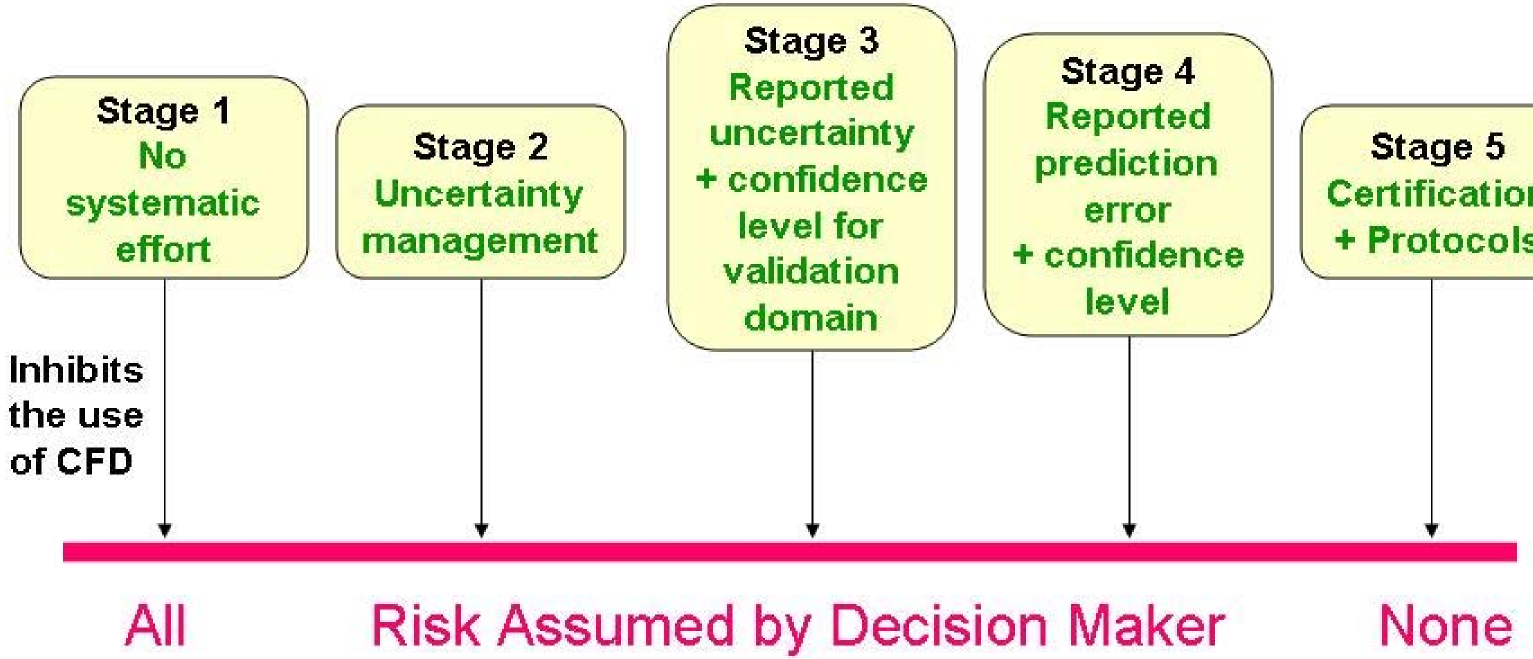
- The MMT needs to continue to improve and mature their integrated risk-versus risk identification, assessment, decision making … this **includes the certainties and uncertainties that exist in the various analytical tools and models** used by the MMT

- The **uncertainties** in one model (or system) inherently **feeds into and compounds the uncertainty** in the second model (or system) … Further compounding the modeling challenge is the fact that the models … are deterministic, yielding point estimates, **without incorporating any measure of uncertainty in the result**. Methods exist to **add probabilistic qualities to the deterministic results**, but they require knowledge of the statistical distribution of the many variables affecting the outcome

- **But, as the *Columbia* accident showed, in a high risk environment that involves many unknowns like human space flight, experience and instinct are poor substitutes for careful analysis of uncertainty**

Early Form of Uncertainty Structure

Impact of Uncertainty Quantification (UQ) to Risk



Presented to NASA LaRC management in Feb. 2005. A question about how we know at what stage an M&S is led to current form, described subsequently, with canonical elements and levels of achievement.

Uncertainty Structure Matrix: Overview

	Canonical Elements					
	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6
Level 1				M&S current state		
Level 2	M&S current state				M&S current state	
Level 3		M&S current state		M&S future state	M&S future State	
Level 4	M&S future state	M&S future state	M&S current & future States			M&S current & future States
Level 5						

Lower level of achievement = greater potential for uncertainty under estimation and greater risk assumed by the decision maker

Uncertainty Structure Matrix
Canonical Elements

A. **Code verification:** The process of determining that a model implementation accurately represents the developer's conceptual description of the model and that numerically correct answers to the coded equations are obtained.
B. **Parameter calibration:** The process of optimization/adjustment of model parameters in the presence of numerical and experimental error.
C. **Model validation:** The process of determining the degree to which a model is an accurate representation of the real world.
D. **Numerical error estimation:** The process of determining an estimate of the residual numerical error based on the computed results.
E. **Model error estimation:** The process of estimating the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.
F. **Outcome adjustment:** The process of adjustment/update of solutions based on either experimental data or higher-fidelity simulations.

Uncertainty Structure Matrix
General Level Definitions

1. **No process:** verification and validation are clearly inadequate; uncertainty is unknown.
2. **UM:** confidence building process that is achieved through unit problems and comparisons. SME must be used.
3. **UQ for validation:** a defined, systematic, documented process is followed to bound and quantify uncertainty for validation.
4. **UQ for prediction:** a defined, systematic, documented process is followed to bound and quantify uncertainty for prediction. The structure of the problem is understood adequately for safe prediction.
5. **Independent UQ for prediction:** an additional, independent process is carried out for high-confidence prediction error quantification

Uncertainty Structure Matrix
Specific Level Definitions: Code Verification

1. The code has not been verified for the intended uses.
2. Verification has been performed for *related problems*, including *unit problems* and problems that are similar to the intended application. Comparisons have been made across codes for problems that are *similar to the intended application*. [*Logically also includes formal methods*]
3. A systematic, documented process (including all relevant unit problem) has been carried out to *verify the code for validation*.
4. A systematic, documented process (including all relevant unit problems) has been carried out to *verify the code for prediction*.
5. An *additional systematic, documented process* (including all relevant unit problems) has been independently carried out to verify the code for the intended application.

Uncertainty Structure Matrix
Specific Level Definitions: Parameter Calibration

1. The parameters have not been calibrated for the intended uses.
2. Parameters have been *calibrated for unit problems* and are believed to be *reasonable for the intended application*.
3. A systematic, documented process has been carried out to calibrate the model(s), *including estimates of numerical and experimental error*, for all relevant unit problems.
4. Not applicable (no additional requirement beyond Level 3).
5. An *additional systematic, documented process* has been independently carried out to verify the calibration of the code, including estimates of numerical and experimental error.

Uncertainty Structure Matrix
Specific Level Definitions: Model Validation

1. The model has not been validated for the intended uses.
2. Validation has been performed for *related problems*, including *unit problems* and problems that are *similar to the intended application*.
3. A systematic, documented process has been carried out to validate the model(s), for all relevant unit problems, to *include estimates of numerical and experimental error*.
4. A systematic, documented process has been carried out to *validate the model structure* for the intended application (including uncertainty and physics boundaries) *adequately for safe prediction*.
5. An *additional systematic, documented* model validation has been independently performed by an SME.

Note: this element really only addresses software issues; approximations introduced through execution of the software are better addressed by the NASA Standard for M&S.

Uncertainty Structure Matrix
Specific Level Definitions: Numerical Error Estimation

1. Numerical error estimation has not been performed for the intended uses.
2. Convergence residuals have been *estimated for problems that are similar to the intended application*.
3. A systematic, documented process has been carried out to *quantify the residual numerical error for the intended application*.
4. Not applicable (no additional requirement beyond Level 3).
5. An *additional systematic, documented process* has been independently carried out to quantify the residual numerical error for the intended application.

Note: this element readily applies to the solution of partial differential equations; the authors believe this can be easily extended to include any strict examination of the modeled temporal, spatial, or statistical behaviors.

Uncertainty Structure Matrix
Specific Level Definitions: Model Error Estimation

1. Model form error has not been estimated for the intended uses.
2. Model form error has been estimated for *unit problems*. Comparisons have been made across models for problems that are *similar to the intended application*.
3. A systematic, documented process has been carried out to *quantify the model error based* upon comparisons with available experimental data.
4. A systematic, documented process has been carried out to *quantify the prediction model error*.
5. An *additional systematic, documented process* has been independently carried out by an SME for the intended application to quantify the model error.

Note: this element really only addresses software issues; approximations introduced through execution of the software are better addressed by the NASA Standard for M&S.

Uncertainty Structure Matrix
Specific Level Definitions: Outcome Adjustment

1. The adjustment uncertainty has not been estimated for the intended uses.
2. The ***uncertainty of the adjustment process***, and the ***uncertainty associated with the higher fidelity source*** that was used to provide input to the adjustment process, have been ***captured at least at level two*** across the other five canonical elements.
3. A defined, systematic, documented process has been followed to ***bound and quantify uncertainty for the adjustment*** with respect to validation.
4. A defined, systematic, documented process has been followed to bound and quantify uncertainty of the adjustment with respect to prediction. The structure of the problem is understood adequately for ***safe prediction of the adjustment***.
5. An ***additional, independent process*** has been carried out for high-confidence prediction error quantification for the adjustment.

Example: an aerodynamic database developed for one configuration or flight condition that is later applied to a different configuration or flight condition through the use of defensible increments

Conclusions

- Uncertainty structure matrix presented and described with
  - Six canonical elements common across many M&S: code verification, parameter calibration, model validation, numerical error estimation, model error estimation, outcome adjustment
  - Five rows that describe progressively more rigorous levels of UQ and UM practices for M&S applications
- Lower level of achievement = more risk assumed by the decision maker due to the potential that uncertainties have been underestimated
- Higher level of achievement = less risk assumed by the decision maker
- The matrix was intended to be inclusive of all M&S
- M&S practitioners can identify current and possible future states of their M&S application
- Estimates can be developed regarding the specific steps, cost, and schedule that would required to move an M&S to higher levels of achievement
- Supports design under uncertainty, improved products, and risk-informed decision making processes