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Epistemic and Aleatoric Uncertainty in Joint Mechanics

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ASME IDETC

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Elements

- **Aleatoric and Epistemic Uncertainty**
  - **What do they mean?**
  - **How useful are these concepts?**

- **Features of Joint Mechanics and Joint Models**
  - **Variability in Measured Properties**
  - **Model Parameters and Features**

- **Uncertainty and Model Quality**

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Usually Uncertainty is Categorized into Two Sorts

- **Aleatoric Uncertainty: uncertainty due to intrinsic variability.**
- **There is a lot of this in mechanical joints!**

- **Epistemic Uncertainty: uncertainty which is due to things we could know in principle.**
- **This includes things that we are unlikely ever to know in practice.**

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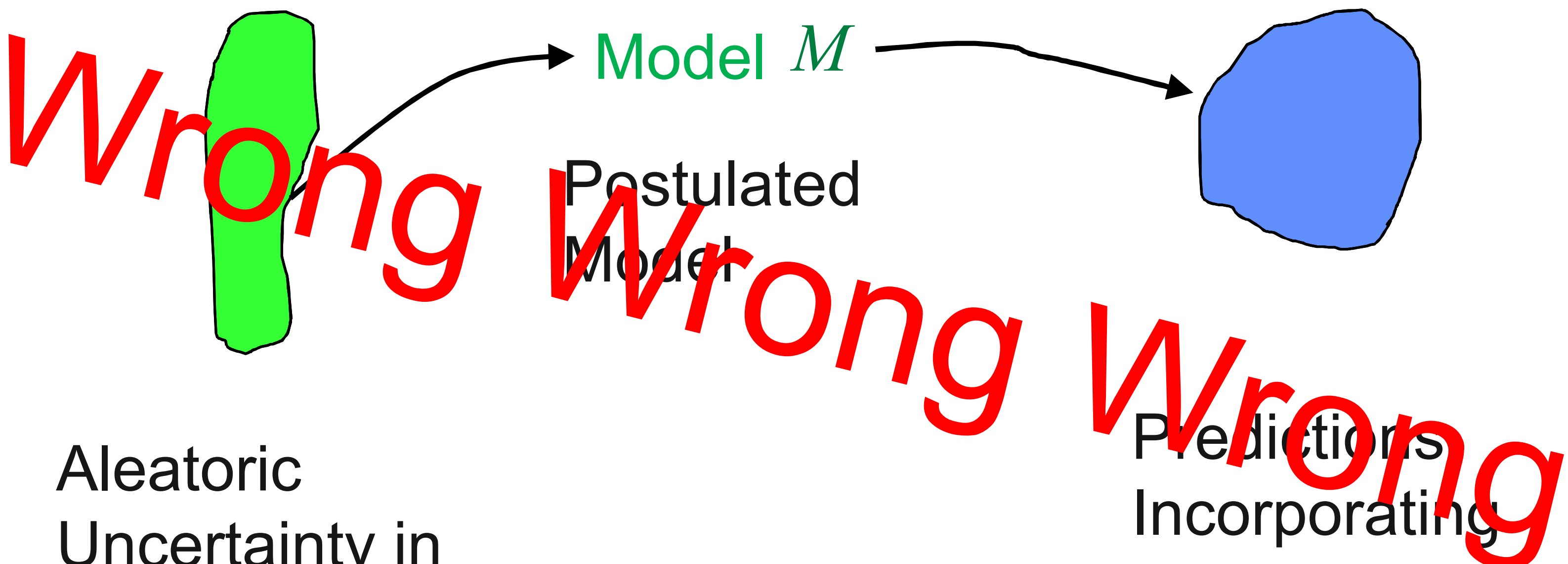
A Common View



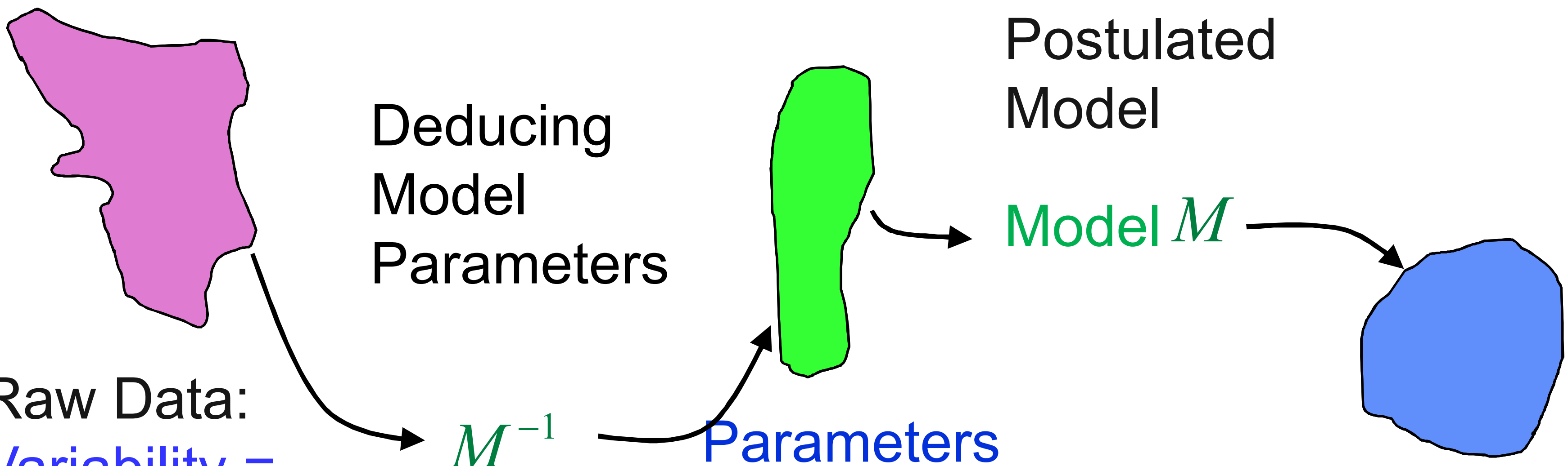
Aleatoric
Uncertainty in
Parameters

Predictions
Incorporating
Aleatoric
Uncertainty

Aleatoric
Uncertainty

Epistemic
Uncertainty

As It ACTUALLY Happens



Raw Data:
Variability = Aleatoric Uncertainty

Model Inverse

Parameters Contain Aleatoric & Epistemic Uncertainty

Predictions Containing Aleatoric & Epistemic Uncertainty

We cannot systematically decouple aleatoric and epistemic uncertainty in any but the most simple problems.

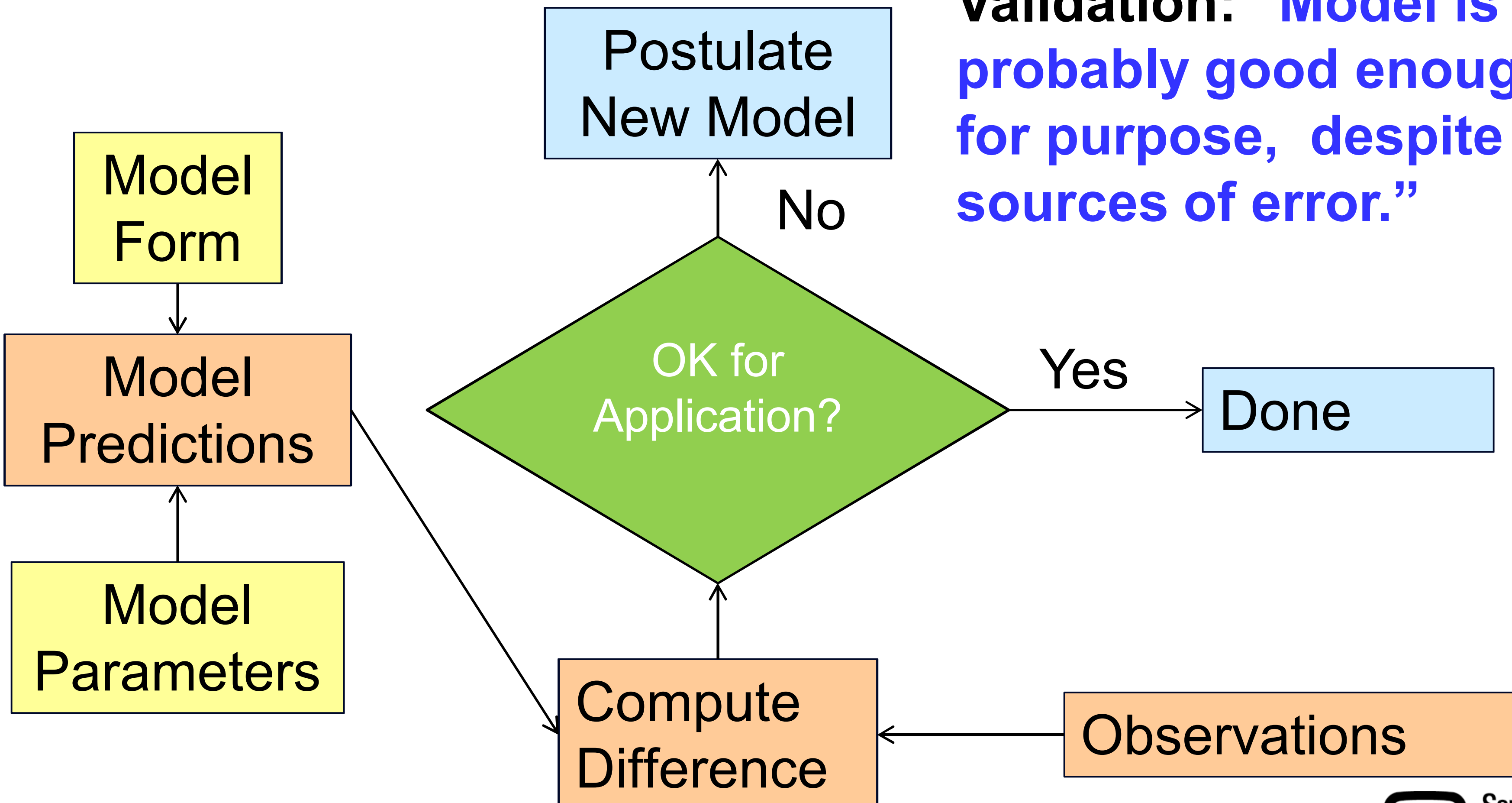
From Where Does the Confusion Arise?

- **There is a common misunderstanding of what is a validated model.**

- **Definition - Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.**

The Validation Process

Validation: “Model is probably good enough for purpose, despite all sources of error.”



A Common Misperception

A validated model is accurate and correct, modulo aleatoric – generally parametric – uncertainties.

This is WRONG

A validated model is sufficiently close to reality that using it for our intended purpose would not be imprudent.

Why Do We Care?

- **In this process, we have not quantified our model form error – we do not even know how.**
- **We cannot in general distinguish error in our predictions due to model form (epistemic uncertainty) from parametric uncertainty.**
- **Our ability to do overall uncertainty quantification (UQ) of our predictions is compromised.**

Let us talk specifically about the mechanics of jointed structures.

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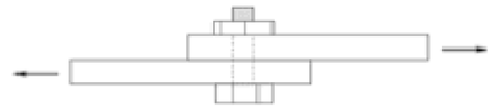
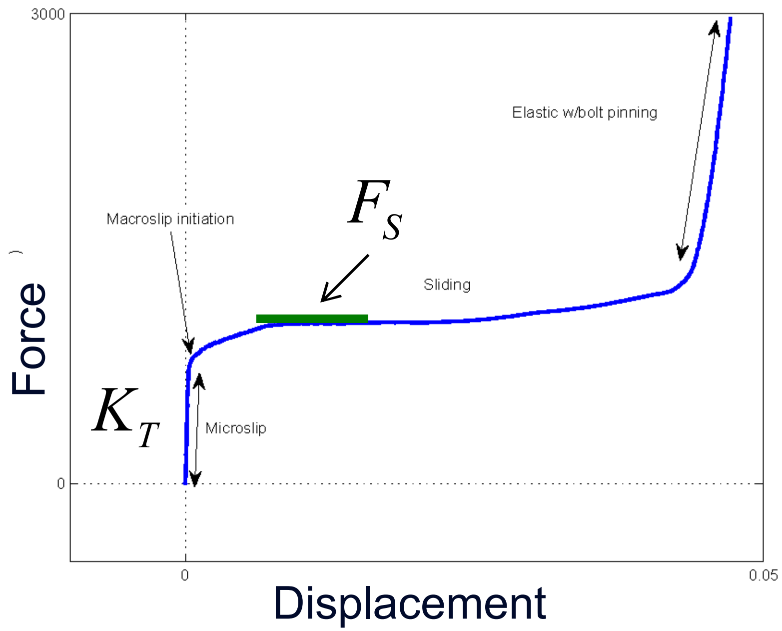
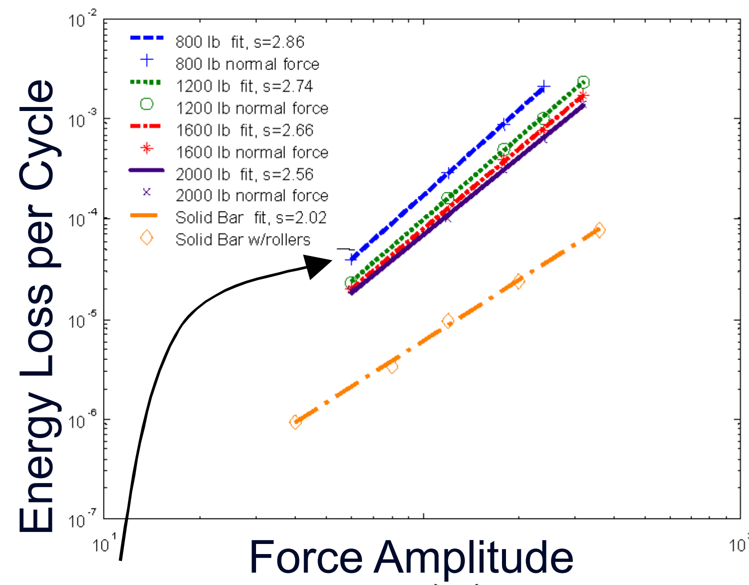
Possibly Measurable Features of Joints







$$D = CF^{3+\chi}$$

For small Displacement

If considering macro-slip, we need at least four parameters

possibly K_T, C, χ, F_S

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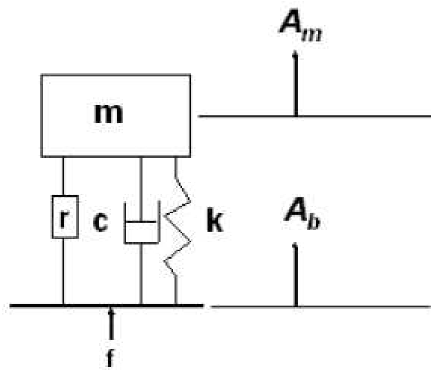
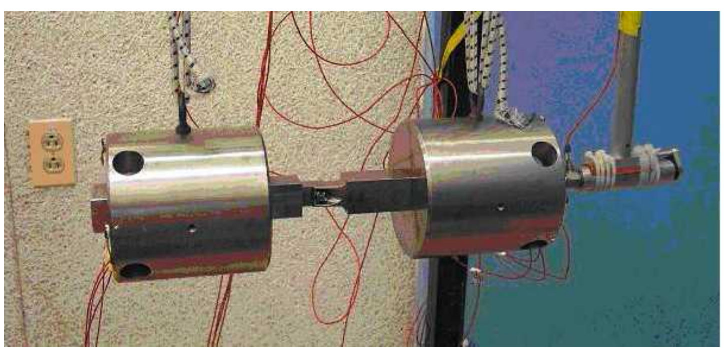
Resonance Tools for Measuring Stiffness and Dissipation



Big Mass Device:
Forced oscillation around resonance



Dumbbell Configuration:
Ring-down experiments

Credit Dan Gregory & Brian Resor,
Facilities in SNL Albuquerque

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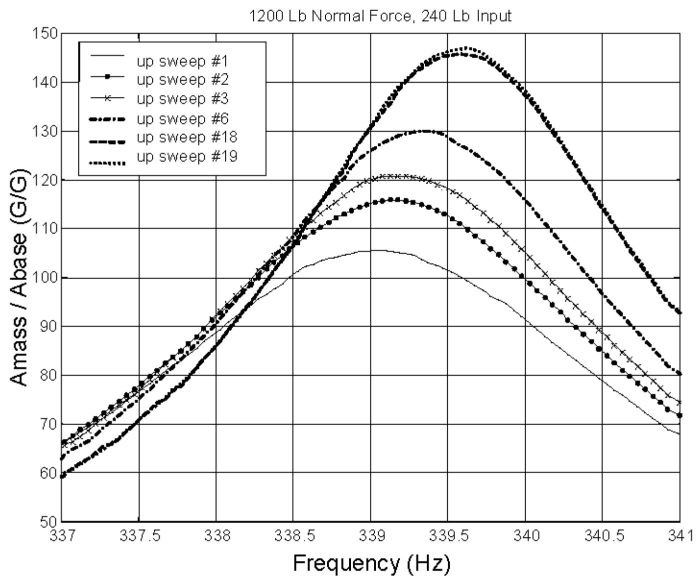
Meaningful Experimentation is Very Difficult



- Wearing in phenomena in steel and titanium
- Galling in aluminum
- Alignment issues

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Static Test Fixture

Quasi-static testing is intrinsically difficult: The displacements across the joint are difficulty to define and very hard to measure before macro-slip.

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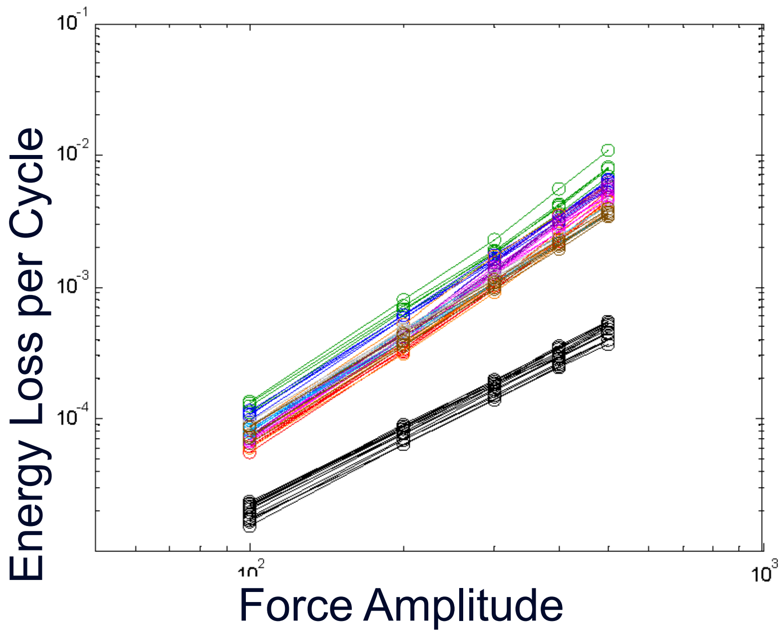
Intrinsic Part-to-Part Variability with respect to Stiffness & Dissipation



It is common for **stiffness measurements** of nominally identical bolted joint hardware to vary by as much as 25%.

It is common for **energy dissipation measurements** on nominally identical bolted joint hardware to vary by as much as 300%.

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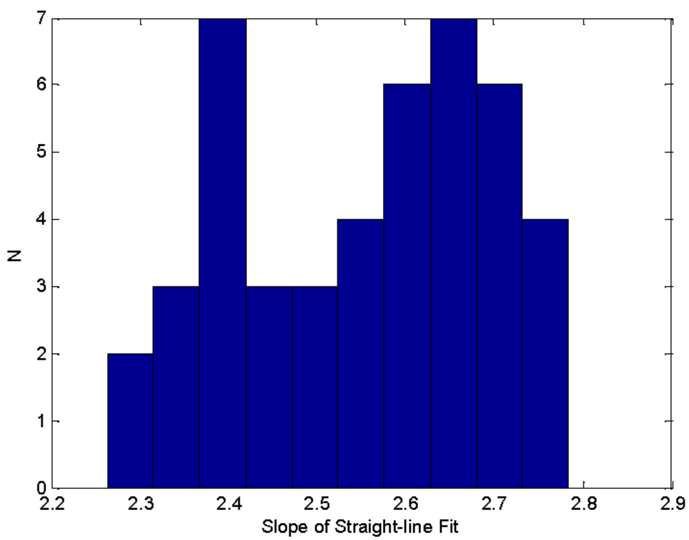
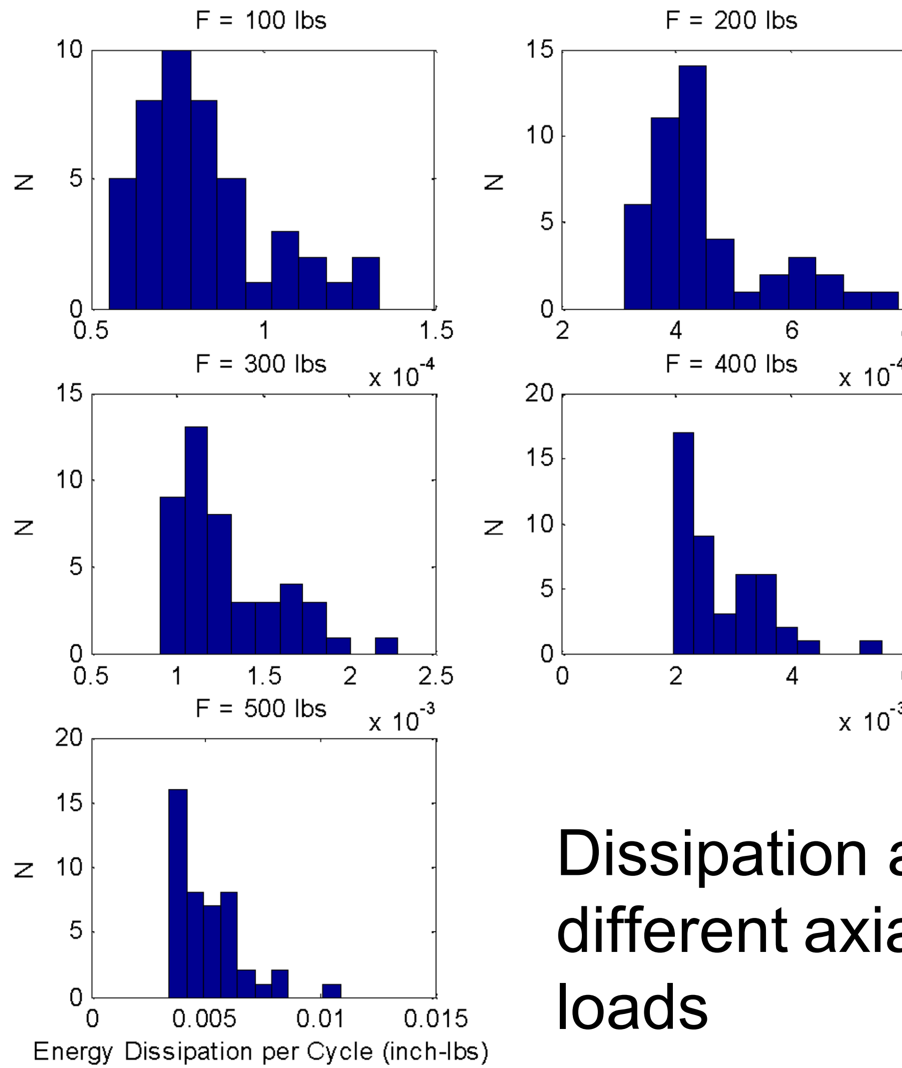
Histograms of Slope and of Dissipation



slope



Dissipation at different axial loads

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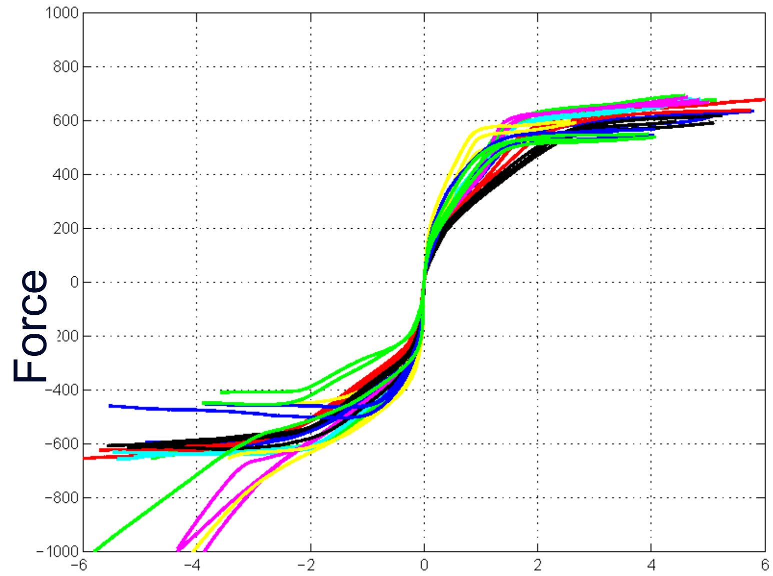
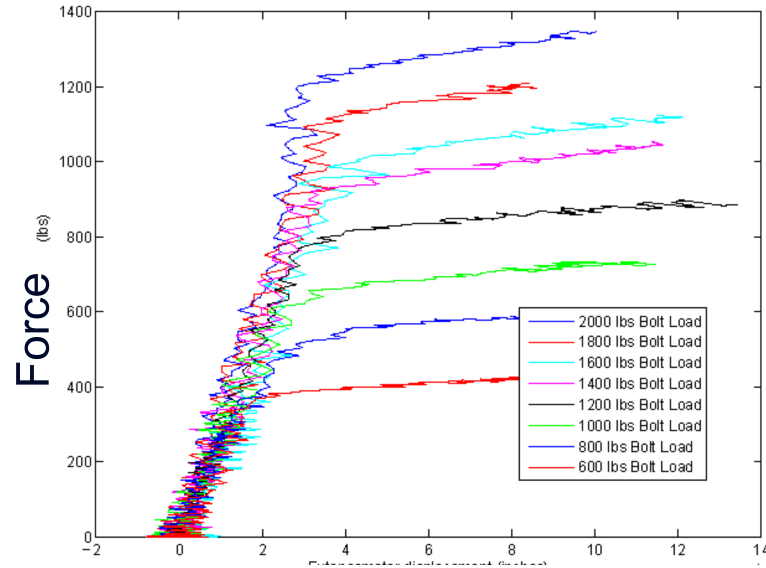
Quasi-Static Data Has Some Clear Trends



LVDT Displacement



Extensometer Displacement

Displacement includes elastic displacement of everything else. Only the force information can be interpreted directly.

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Observation

- **There is a lot of intrinsic variability (aleatoric uncertainty) associated with nominally identical joints.**
- **Even how we define the parameters we use to characterize the experiments is imprecise – epistemic uncertainty.**
- **Of course how we map from parameters of the experiment to parameter of the model is model dependent.**

On to Model Form and Model Form Error

A Thought Experiment

- **Problem – Given a bowl of small objects, estimate the statistical distribution of their volumes**

- **Procedure**
  1. **Data: taking one specimen at a time, and without looking, measure a dimension**
  2. **Model Form: assume the specimens are spherical**

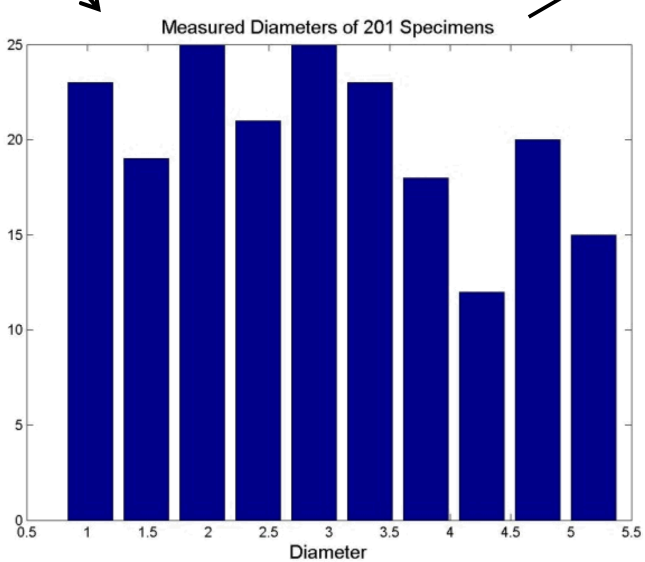
$$V = \frac{4\pi}{3}\left(\frac{D}{2}\right)^3$$

  3. **Calculations: using that model, estimate the statistical distributions of specimen volume**

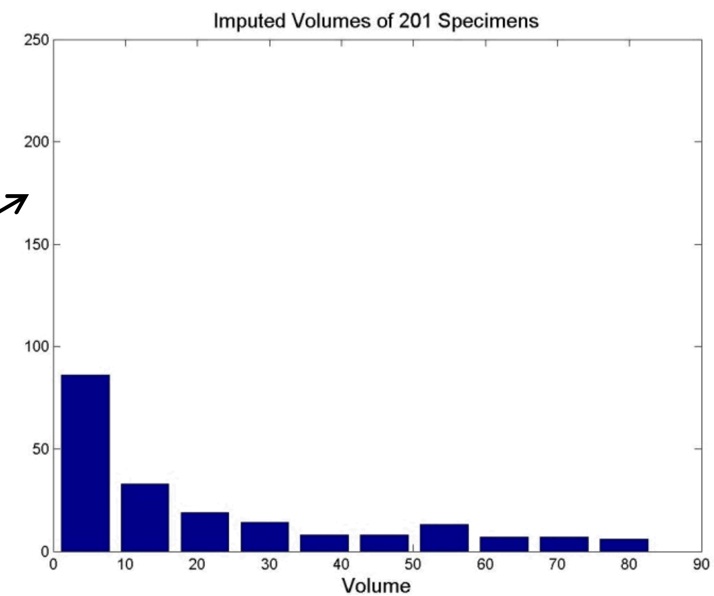
As We See the Process

Sampling

Calculations using model



Distribution of Diameters



Distribution of Volume

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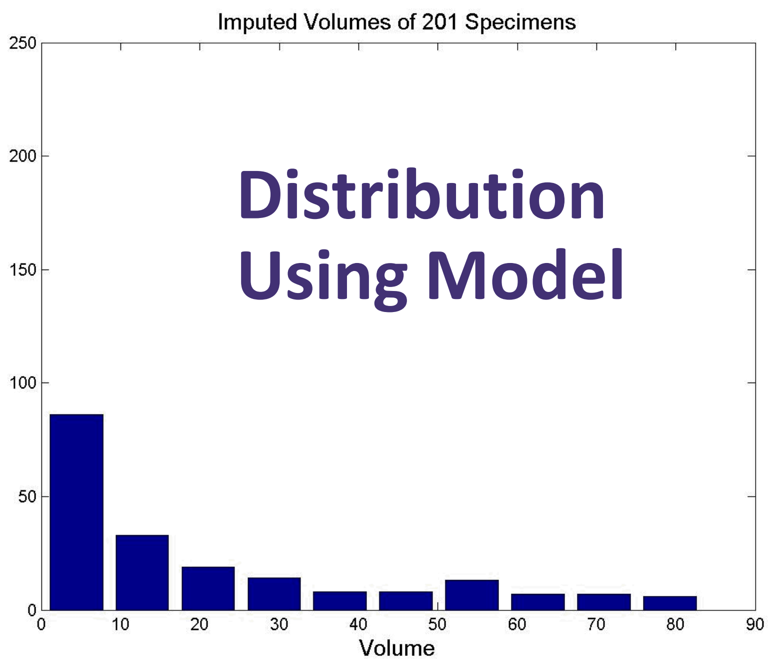
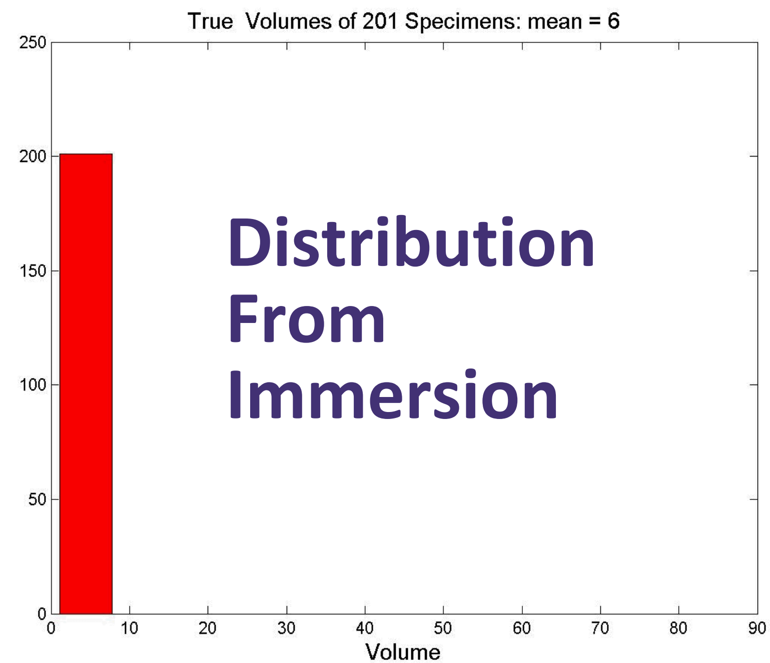
Now We Set Aside the Model and Measure Volume by Immersion





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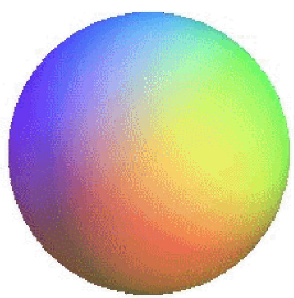
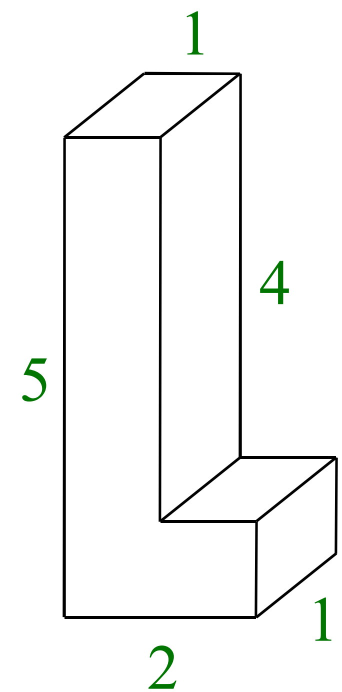
What is Going On?

Model Form Error

- Model assumed shape as spherical



- True shape is quite different



Observation

- **Model form error can manifest itself as fallacious variability**

  (In this case, the model was insensitive to a dependence on orientation.)

- **Perhaps we can use some feature of apparent variability of the predictions or of the parameters to assess the model overall.**

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Look to Analogous Problem

- **Consider some sample of random data.**
- **Pose the problem: Which <u>form</u> of probability distribution is an appropriate fit to this data?**
- **Reasonable considerations**
  - **The better the fitted distribution matches the histograms of sampled data the better**
  - **The more parameters needed to fit the data, the less natural the fit.**

Akaike Information Criterion (AIC)

$$AIC = 2k - \ln(L(\{X_j\}))$$

- k **is the number of parameters in the statistical model.**
- L **is the maximized value of the likelihood function for the estimated model given observations** $\{X_j\}$.
- **Based on information theory**

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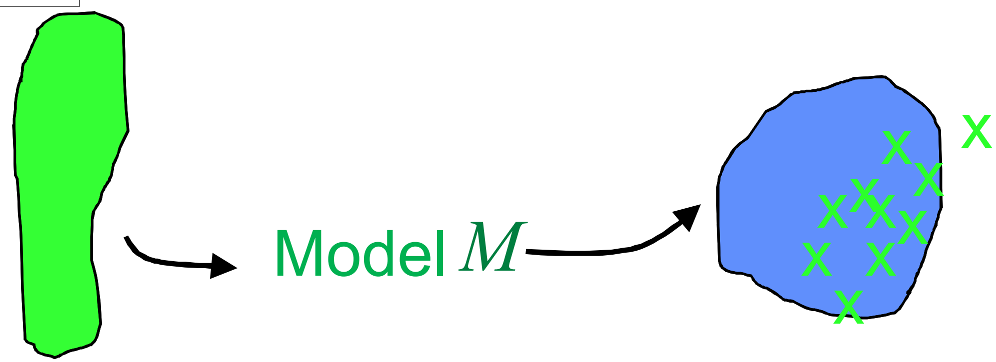
Map onto our problem

N Dimensional Parameter Space



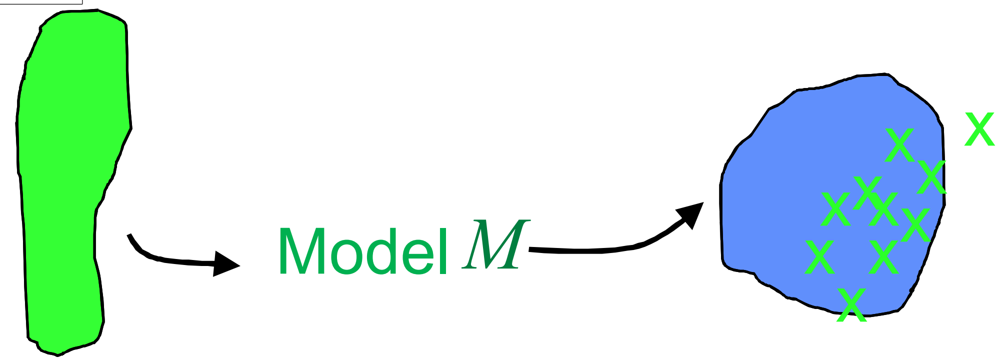
Predictions & Sparse Data

$$P = 2k - \ln(L(\{X_j\}))$$

- **In this case**
  - ***k* is the number of parameters of our model**
  - ***L* is a "likelihood" computed using random input loads and a finite number of observed outputs**
- **We still do not capture the artificial variability in our parameters**

Map onto our problem

N Dimensional Parameter Space



Predictions & Sparse Data

$$P = 2k - \ln(L(\{X_j\})) + \mathrm{E}_P$$

- **In this case**
  - ***k*** **is the number of parameters of our model**
  - ***L*** **is a "likelihood" computed using random input loads and a finite number of observed outputs**
  - E_P **is the entropy of the parameter space**

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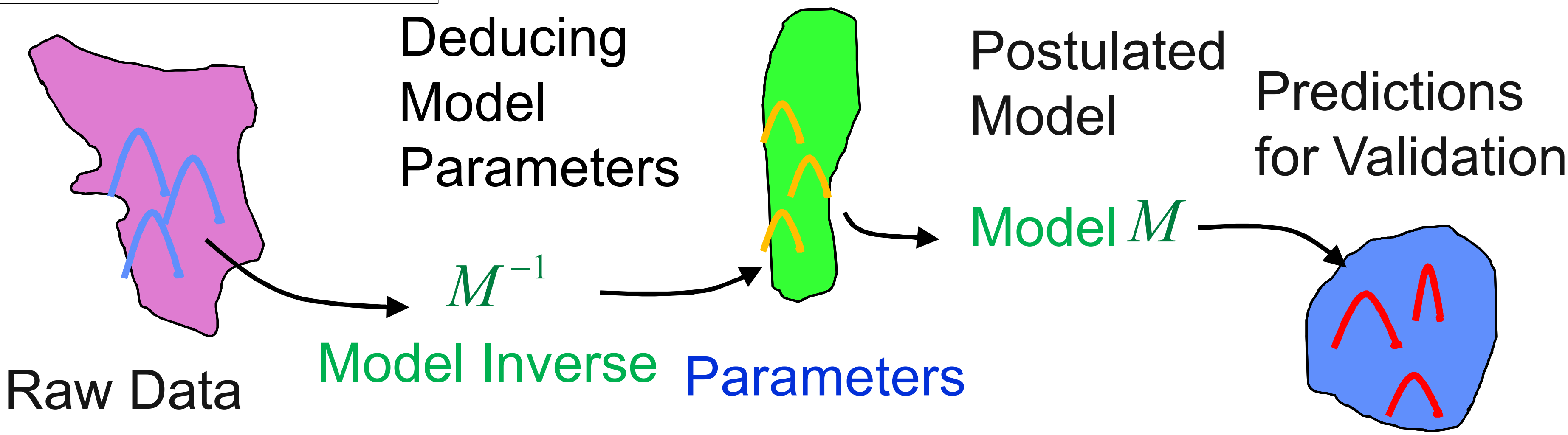
A Similar Approach Using Fuzzy Sets (Hagg, González, Hanss)



- Experimental calibration is represented by fuzzy sets.
- These map via M^{-1} to other fuzzy sets in parameter space.
- Fuzzy sets representation in parameter space maps to other fuzzy sets in test space.
- A measure is devised employing the features of these fuzzy sets to capture the information entropy and accuracy of the model.

Conclusion

- **There is much aleatoric uncertainty (intrinsic variability) among nominally identical joints.**
- **There is at least as much uncertainty in our predictive capability due to incomplete understanding of joint mechanics (epistemic).**
- **Separating out how each source of uncertainty affects various aspects of prediction is not straightforward.**
- **Assessment of model forms requires consideration both conformance to test and the uncertainties involved.**

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Conditions: slide 3, repeated "know" what is the hardware in the load-frames on slide 12? I do not recognize those test configurations.

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Update funding statement/contract language. Emailed requestor instructions to upload the record copy to FileNet. 8/1/13 (lg)

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