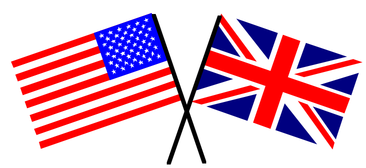
Welcome and Charge

Joints Workshop
Dartington, UK
AWE/SNL/NSF

27 April 2009

Dan Segalman (SNL) and Phil Ind (AWE)



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Why SNL and AWE are Funding This

- These issues are very important to us and to others.
- This is a very difficult problem class. We shall not solve it on our own.
- It makes sense to excite interest in these problems in the general research community.

Accounting for Joint Mechanics is Prerequisite to Prediction. Where We *Must* be Predictive

Where correct answers are necessary and either experiments are just too expensive or are impossible

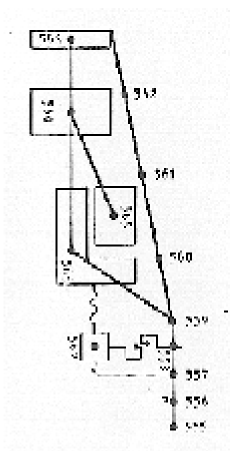
- satellites
- next generation space telescopes
- jet engines and jet engine failure
- nuclear weapons systems

Traditional Barriers to Predictive Modeling

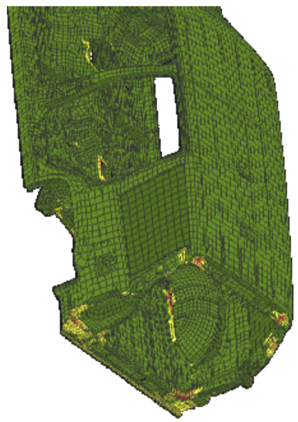
- **Discretization error**
- **Uncertainty in Material Properties**
- **Uncertainty in loads/boundary conditions**
- **Missing Physics - Interface Mechanics (Joints)**

We are not predictive?

Discretization Error: Less of an Issue Now Than in the Past



20 years ago:
Shellshock 2D
NASTRAN
200 dof



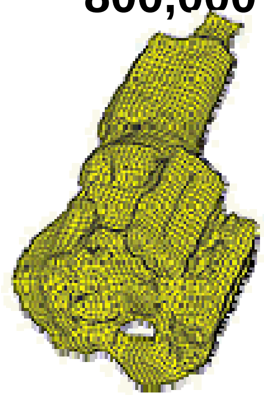
15 years ago:
NASTRAN
MC2912
30,000 dof

(Original Picture might be OUO if shown)

10 years ago:

- **Fine Meshes of Subsystems**
- **Or Coarse Meshes of Systems**

800,000 dof



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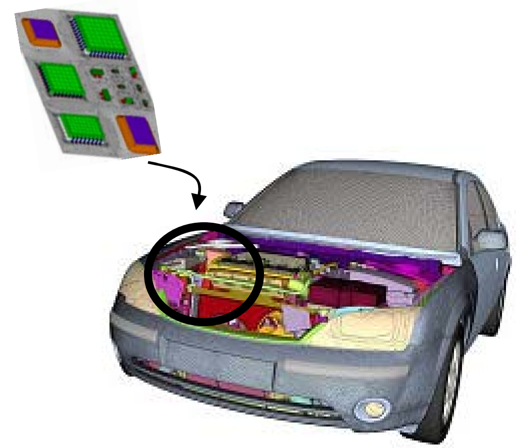
Today:
SALINAS MP
>10M dof.



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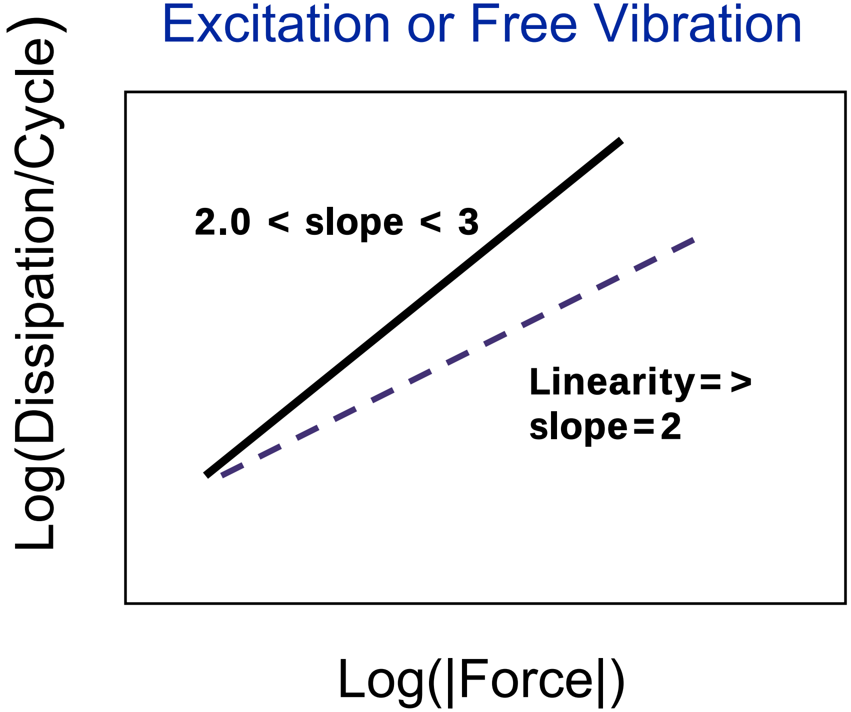
Traditional Barriers to Predictive Modeling

- Discretization error
  - Mitigated substantially by MP technology
- Uncertainty in Material Properties
  - Subject of separate research efforts
- Uncertainty in loads/boundary conditions
  - Better measured, calculated, or bounded
- Missing Physics
  - Interface Mechanics (Joints)
  - The Tall Pole in the Tent
  - Topic of this workshop

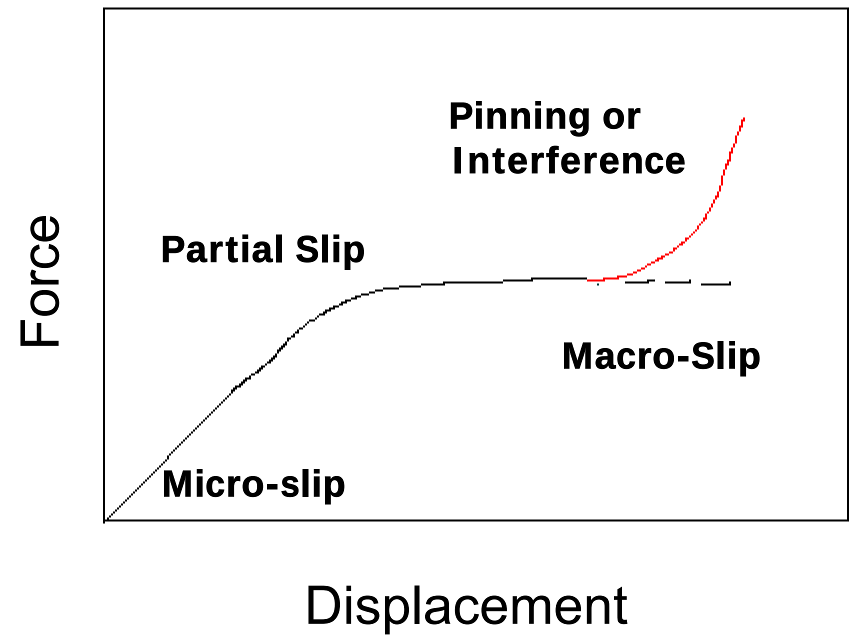
Topics include misfit, interference, and variability

Empirical Nonlinearity of Joints

Dissipation from Base Excitation or Free Vibration



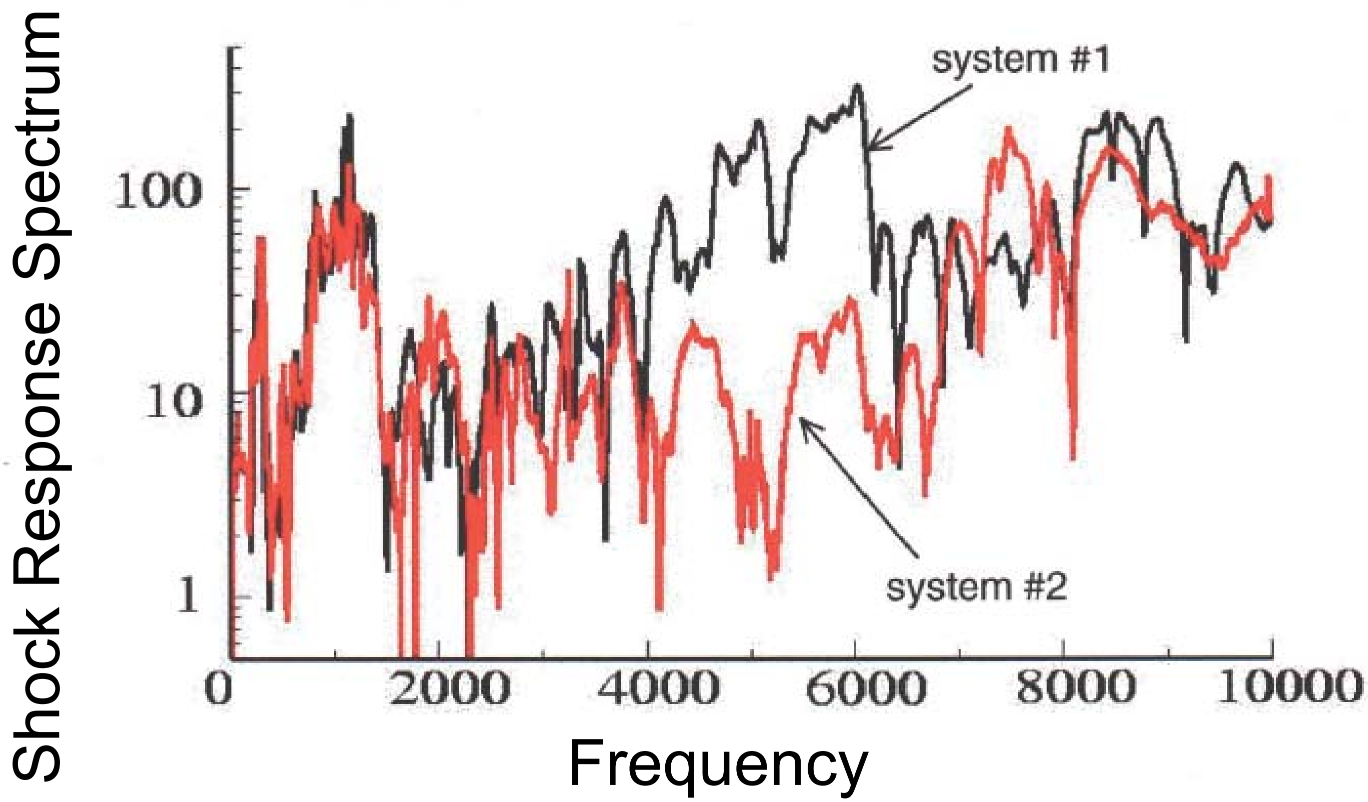
Monotonic Pull



Nonlinearities even at Small Displacement

Large Displacement

Example of Variability Due to Joints



Further Complications of Joint Mechanics to Structural Dynamics

- **Part-to-Part and System-to-System Variability**
- **Aging Effects – a little oxidation or rubbing goes a long way.**

- **How are we expected to predict dynamic properties of systems put into the stock pile years ago?**

Standard Practice for Ignoring the Nonlinearity of Joints in Structural Dynamics

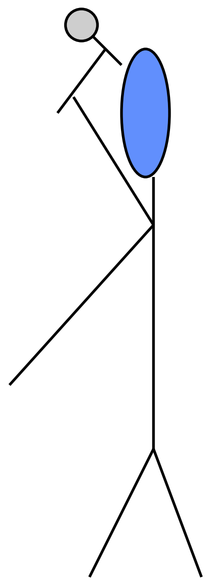
How we traditionally do structural dynamics analysis

Analyst creates coarse mesh of model putting tunable springs at interfaces and postulating proportional/modal damping

Standard Practice for Ignoring the Nonlinearity of Joints in Structural Dynamics

How we traditionally do structural dynamics analysis

Build full structure or subsystem and test in modal lab at relevant amplitudes



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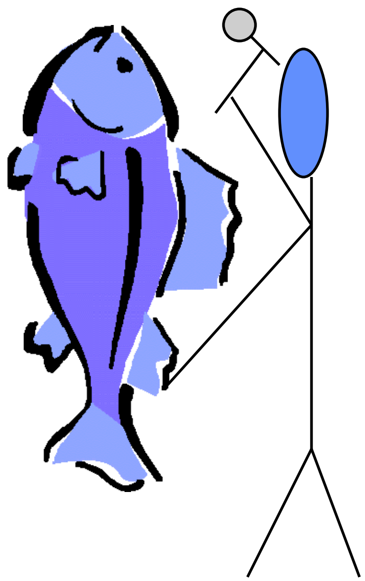

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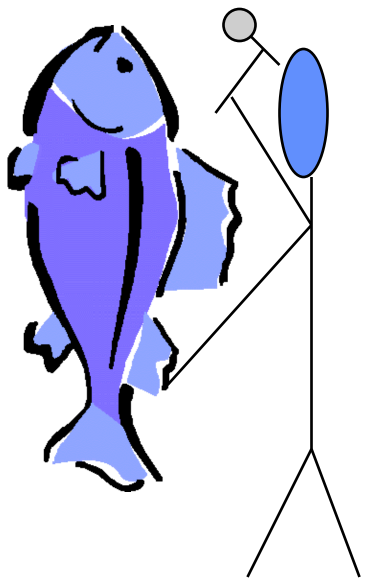

Analyst <u>tunes joint stiffness and modal damping</u> to match test. He then makes prediction

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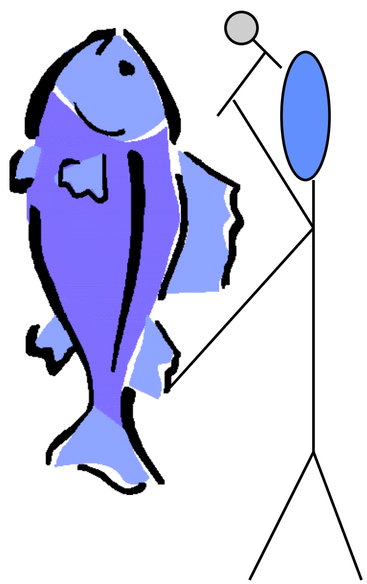

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Systems test is performed on updated model

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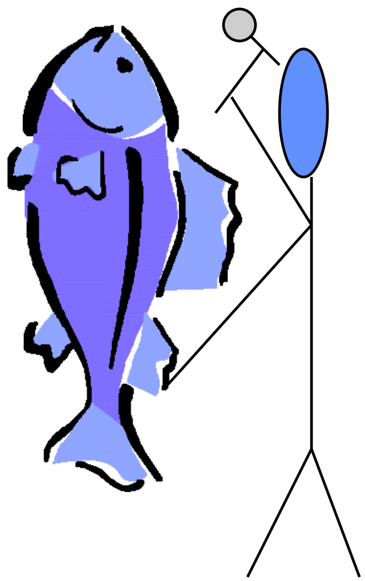

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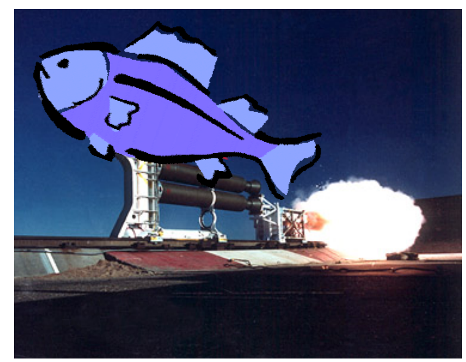

Standard Practice for Ignoring the Nonlinearity of Joints in Structural Dynamics

How ... sis

Elements of Process

- Assume system to be linear
- Represent each joint DOF as a linear spring
- Build and test a prototype structure
- Tune the spring stiffnesses to match frequencies
- Tune modal (or more complicated) damping to match damping of structure

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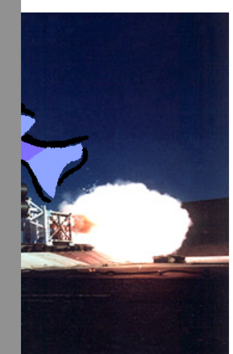

Analyst c
coarse m
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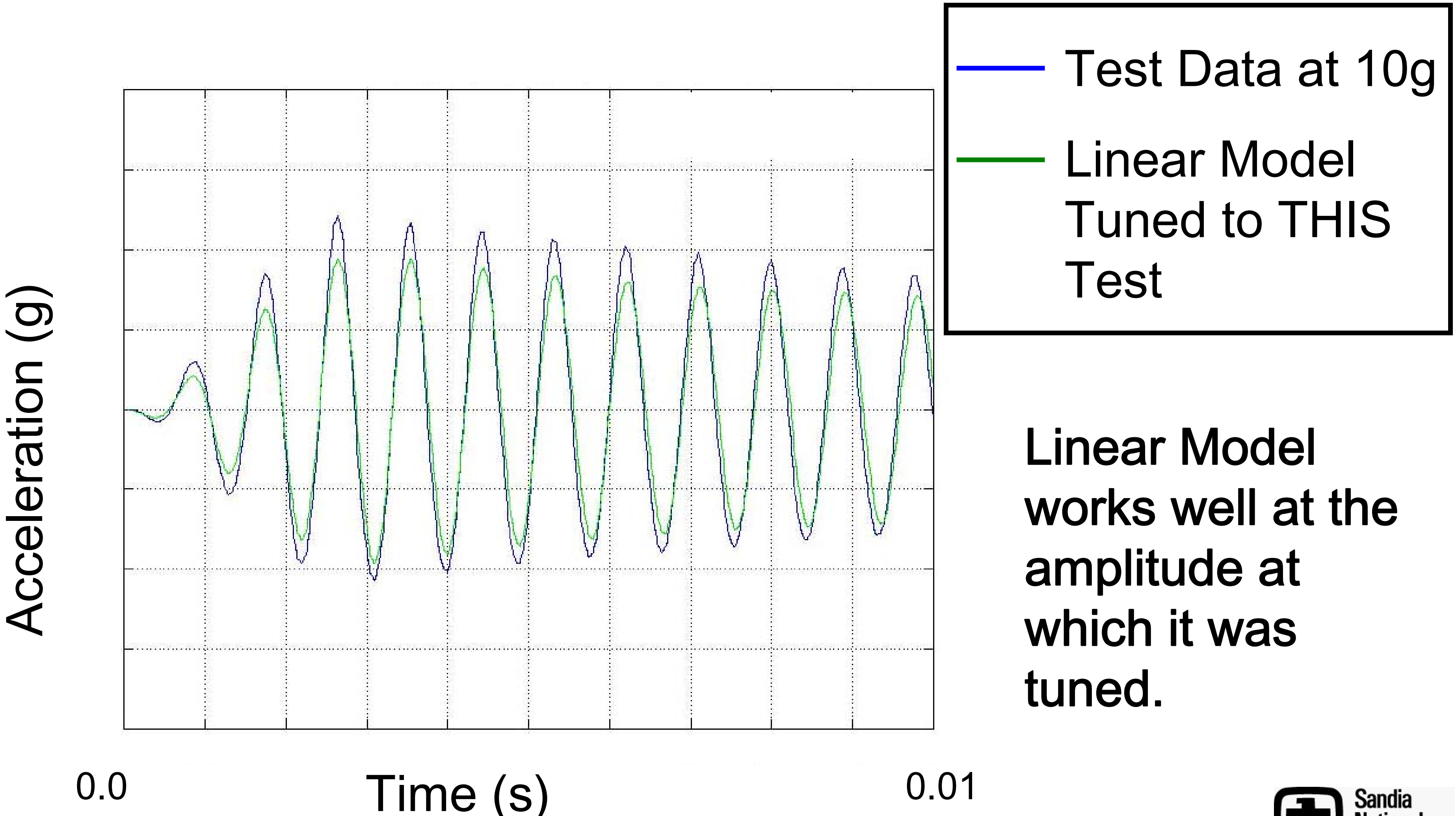
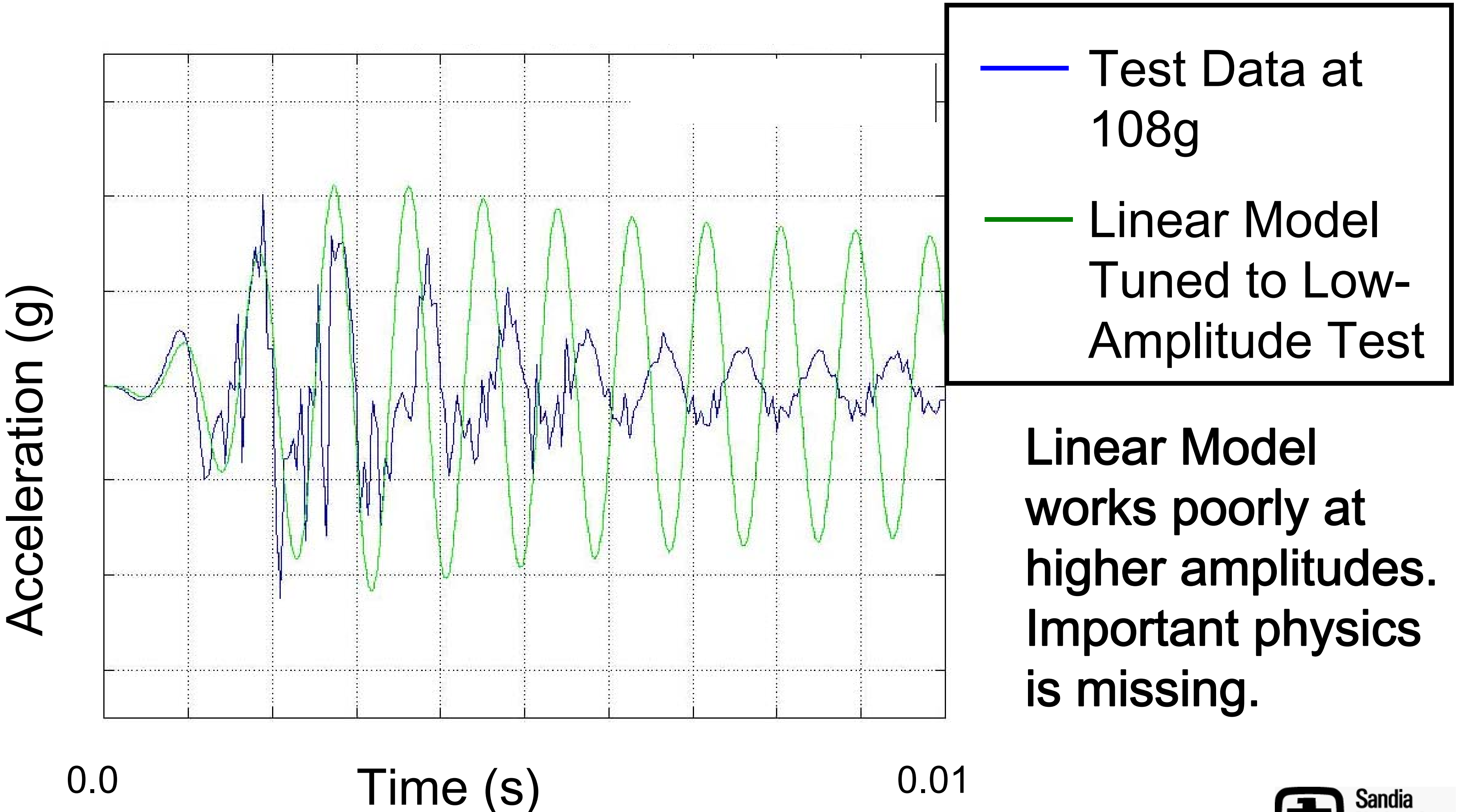
How Well Does a Linear Model Do when Tuned to a Given Experiment?



Linear Model works well at the amplitude at which it was tuned.

How Well Does that Linear Model Do when Tested on a Different Experiment?



Linear Model works poorly at higher amplitudes. Important physics is missing.

Not Predictive for Real Systems

If you have to build the full structure in order to predict structural response, then you are not predictive.

The problem is fundamentally nonlinear and important phenomena cannot be captured by tuned linear models. (Silk purse/Sow's ear issue.)

Why Big Computers Alone are Not Enough

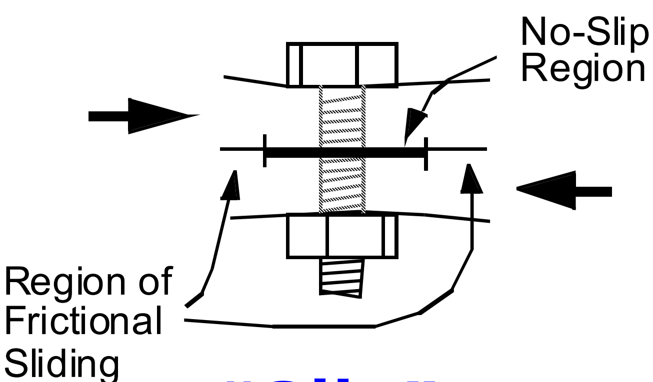
- Multi Length Scales
- Long Duration Events (launch, steady state, …)
- Short Duration Events (blast)
- Very Low to Very High Amplitude Loads

Why Joint Modeling is So Difficult

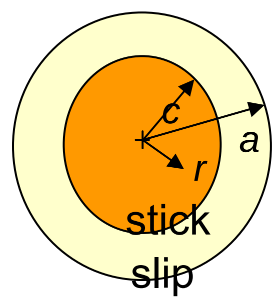
- **Moving boundaries**
- **Intrinsically multiscale**
- **Nonlocal**

Structure
~ meters

component ~
centimeters



“Slip”



Contact
patch ~ cm

Slip zone
~100 µm

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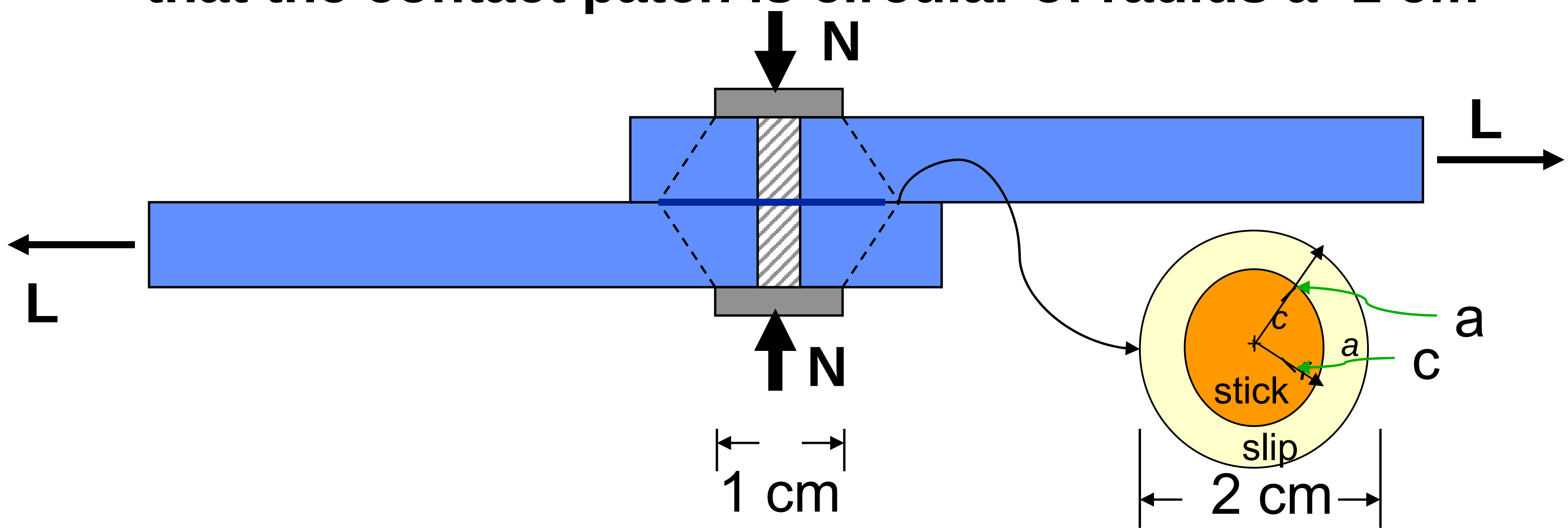
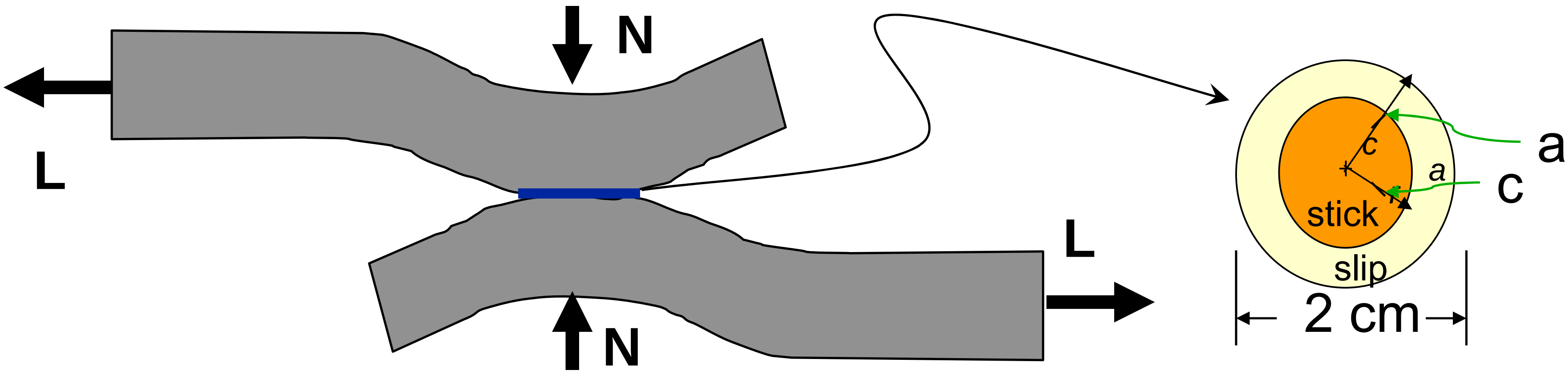
Illustration of Computational Difficulties

- Consider a lap joint with dimensions selected so that the contact patch is circular of radius a=1 cm



- Approximate the elastic contact problem with the Mindlin solution for two spheres.

Estimation of Interface Dimensions



- **Normal Load** $N = 4000\,\text{Newtons}$
- **Lateral Loads** $L \in \left(0.05\mu N, 0.8\mu N\right)$
- **Elasticity that of Steel**
- **Slip Zone:**

Say our interest in structural response is in 100Hz-3500Hz

$$\frac{c}{a} = \left[1 - \left(\frac{L}{\mu N}\right)\right]^{1/3} \Rightarrow \frac{c}{a} \in (0.58, 0.98) \Rightarrow \frac{a-c}{a} \in (0.02, 0.42)$$

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Necessary Finite Element Scales Courant Times

- **For case of small tangential loads** $L = 0.05\mu N$ **element dimension in slip zone necessary to capture dissipation is** $l = \frac{a-c}{10} = 20\mu m$ **and Courant time is 4 ns**
- **To simulate 10 ms (one cycle of 100 Hz vibration) requires 2.5E6 time steps.**

Compare this with 3E4 time steps if the problem were linear and solved implicitly

Even if This Problem is Solved Quasi-Statically

- In each load cycle, the width of the slip zone twice spans from $a - c = 0$ to $a - c = 0.42$
- With characteristic element size in the contact patch

$$l = \frac{a - c}{10} = 20\mu m$$

- Observing that quasi-static contact has difficulty changing stick-slip status of more than one node at a time and each time step required numerous iterations
- Approximately 800 steps per cycle are required, <u>each representing hundreds of iterations</u>.

Conservation of Cussedness

Simply Employing More Elements is not the Solution

- One cannot reasonably directly slave a micro-mechanics contact algorithm to a structural dynamics analysis.
- Tools are needed to cross the dimensions

What We Need

- Better Models
  - Capture at least the qualitative properties of jointed structures.
  - Lend themselves to tractable – even routine – calculation.
  - Cover the full range of environments.
- Better Methods (experimental and computational) to populate the models.
- Better Methods to validate models for joints and jointed structures.

Conclusions

- This problem appears to be intrinsically difficult. We are not expecting magic bullets.
- There is room for significant improvement on all fronts.

Backup

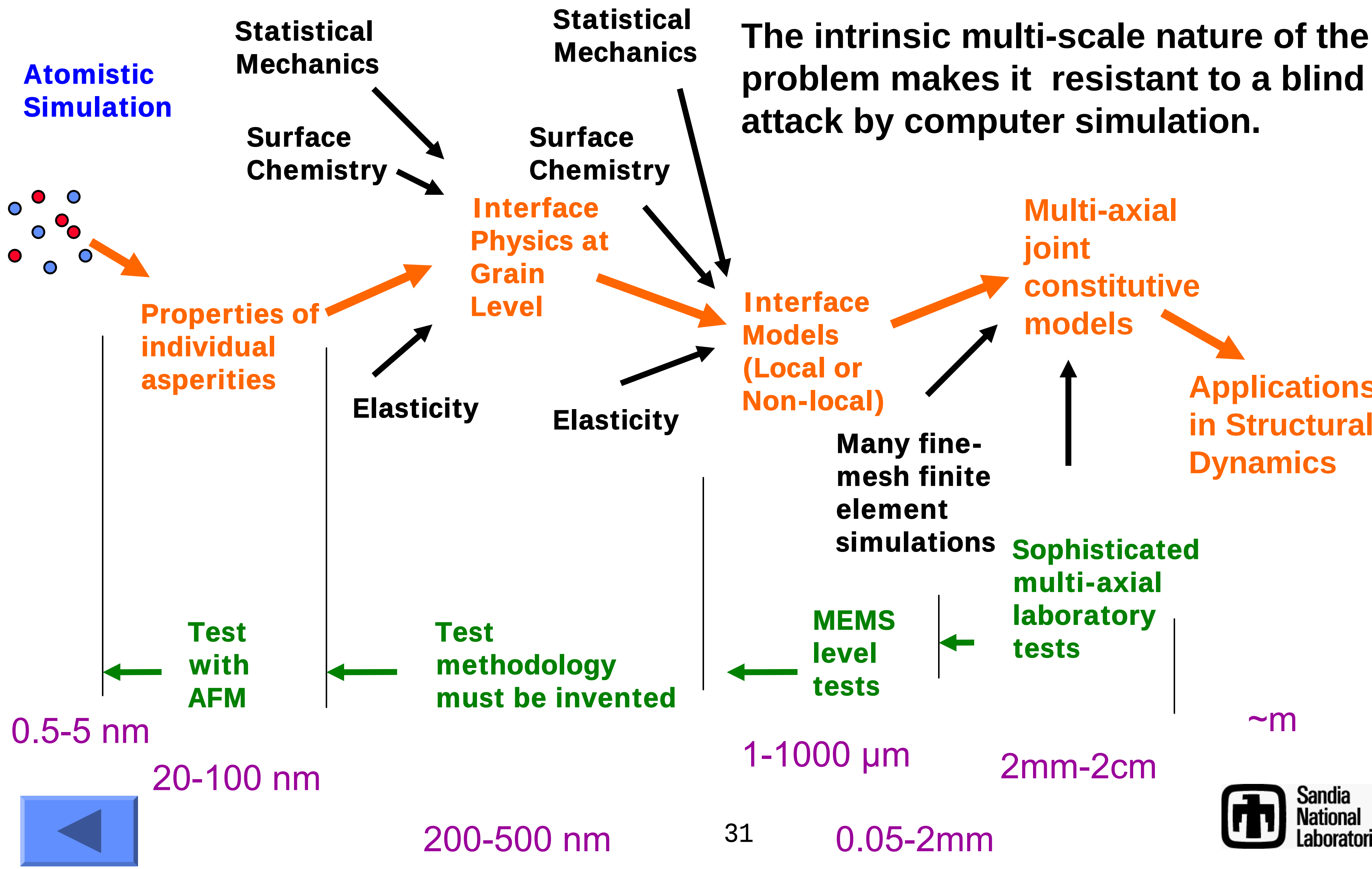
Predictive Modeling – Is that not what we already do?

- In general, engineers use simulation
  - To interpolate/extrapolate among experiments
    Note the tuned parameters
  - To help explain experiments
  - To help design experiments
  - To provide design guidance
  - To estimate factors of safely
- We generally do not try to predict with precision
  - Finer than the intrinsic variability of the problems
  - That which requires physics for which there are no models

Bottom-Up and Top-Down Vision for Research in Physics of Joint Mechanics

Much of the underlying physics is not understood.

The intrinsic multi-scale nature of the problem makes it resistant to a blind attack by computer simulation.



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