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Rocket Science is not Brain Surgery

(Choose Easier Problems when You Can)

Daniel J. Segalman
Sandia National Laboratories

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University of California, Berkeley
1 October 2008

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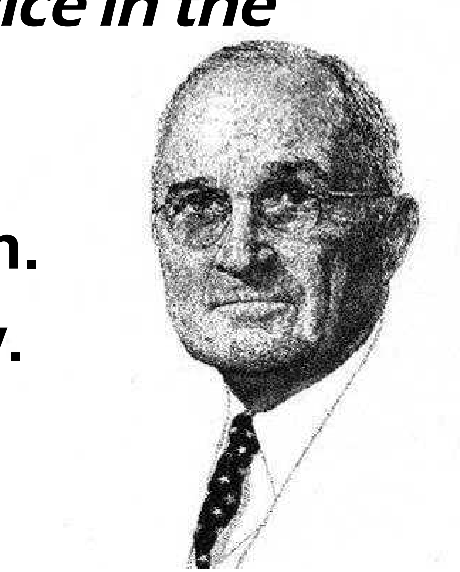
Sandia National Laboratories: Approaching 60 Years of *Exceptional Service in the National Interest*

- **Born of the atomic age.**
- **Heritage of engineering and production.**
- **Science mobilized for national security.**
- **A legacy of industrial management.**

- **Six key mission areas:**
  - Nuclear weapons
  - Nonproliferation
  - Assessments
  - Military technologies and applications
  - Homeland security
  - Energy and infrastructure assurance



"you have …an opportunity to render an exceptional service in the national interest."
May 13, 1949 Letter from President Truman to Mr. Wilson, President of AT&T

AT&T
1949-1993

LOCKHEED MARTIN
1993-Present

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Albuquerque,
New Mexico
(Includes Research Facilities)

Kauai Test Facility,
Hawaii

Tonopah Test Range,
Nevada

Livermore, California
(Includes Research Facilities)

Yucca Mountain,
Nevada

WIPP, New Mexico

Pantex, Texas

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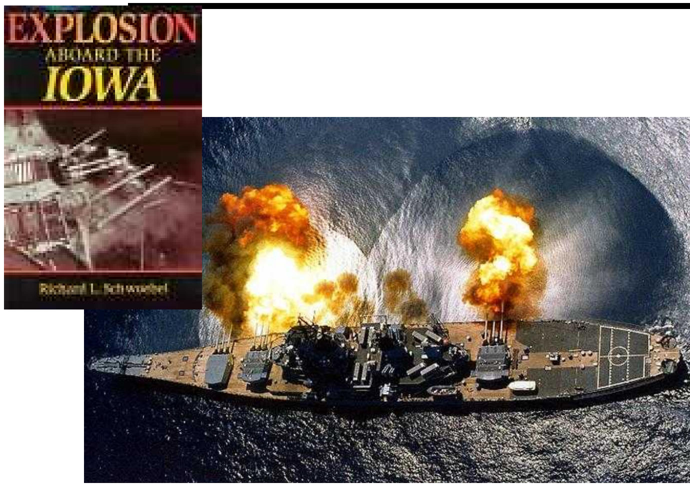
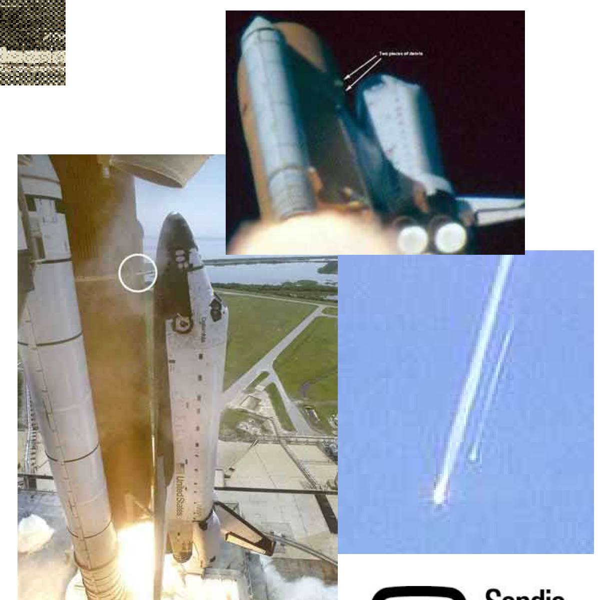
NNSA National Nuclear Security Administration

We are often called upon to answer critical questions





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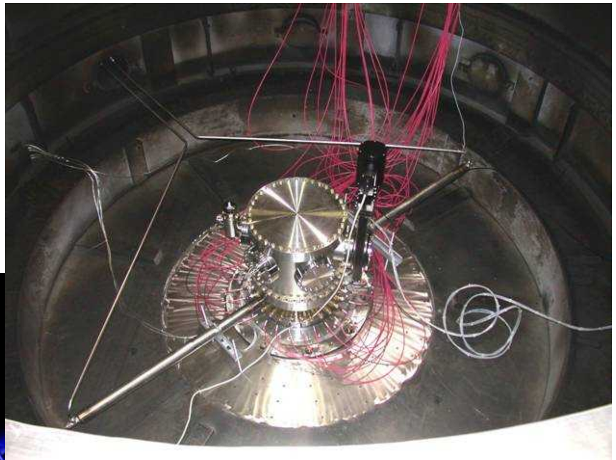
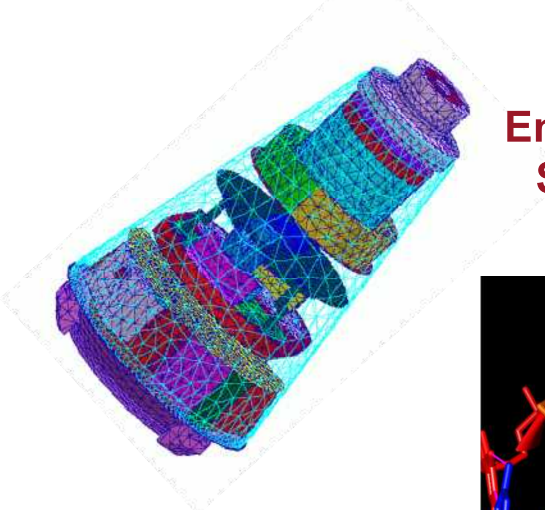
Our Mission Focus Relies on Strong Science and Engineering

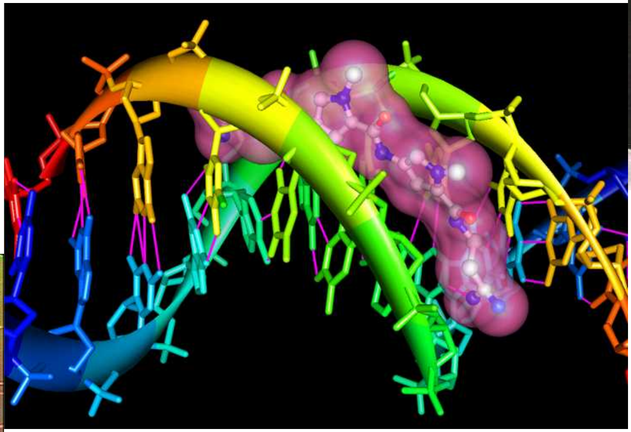
Five Research Foundations

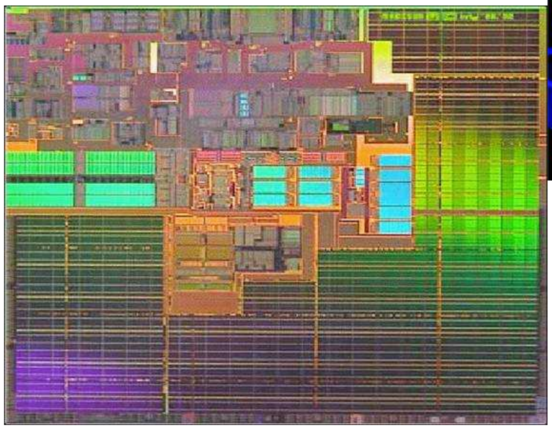
Pulsed Power Sciences



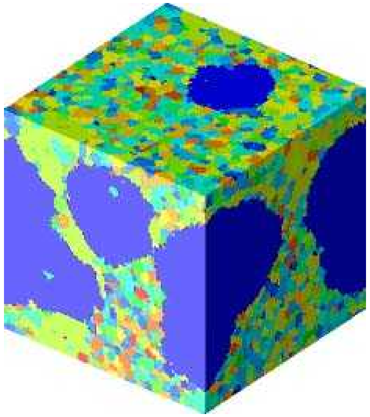


Engineering Sciences





Computational and Information Sciences



Materials and Process Science

Microelectronics and Photonics Sciences

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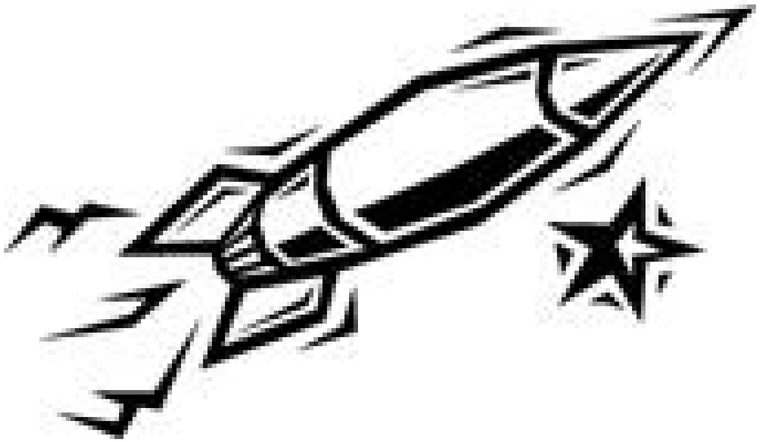
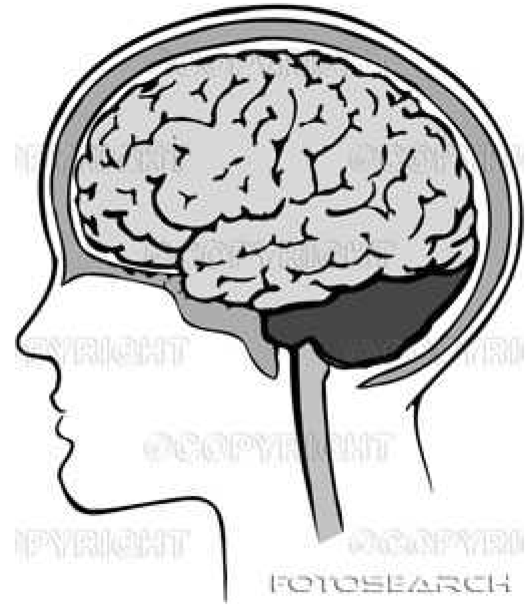
Features of Rocket Science and Brain Surgery





Rocket Science
- A few fundamental principles (conservation laws).
- A small number of simple approximations (rigid body motion).
- Represented succinctly by a few ODEs

Brain Surgery
- Fundamental principles are less helpful
- Huge reliance on empiricism and experience.

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About Dissertation Topics

- Carefully chosen
- Three year chunks
- Do not require decades of experience
- Anticipated to be Tractable

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Kinds of Idealizations We Like to Make to Make Problems Tractable

- All distributions are uniform, Gaussian, or Dirac
- All boundary conditions are uniform, periodic, …
- Elastic Materials – at worst elastic-plastic
- Physics maps nicely from one scale to another

Much of Engineering Often Looks More Like Brain Surgery than Rocket Science

- **Function of complex systems. For instance, anything that can jam.**
- **Failure of complex structures. Things that fail a little at a time.**
- **Anything with intrinsic variability.**
- **Anything that involves wear and must still function.**
- **Mechanics of salt (SPR, WIPP)**
- **Tire Mechanics**
- **Structural Dynamics**

Messy problems are messy in both analysis and design.

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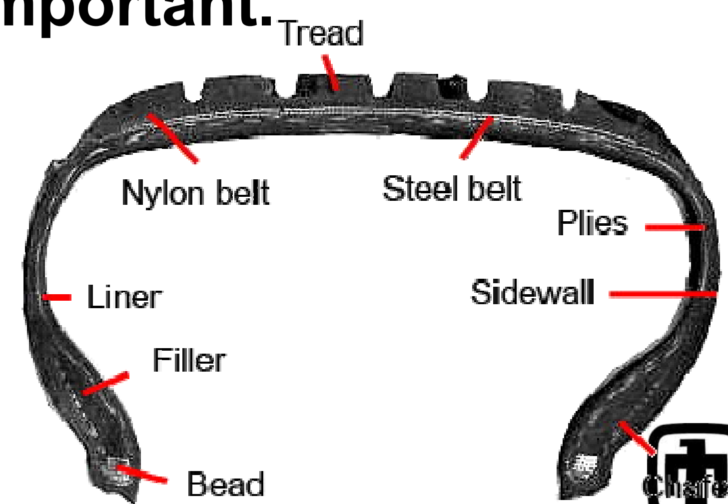
Tire Mechanics is Messy.
Consider Calculation of Rolling Resistance

- **First principles relate rolling resistance to energy dissipation.**
- **Require constitutive model form for carbon-filled rubber. Still a challenge after 60 years**
- **Require constitutive parameters for every rubber (and other polymer) in the tire.**
- **Need high fidelity kinematics of every location in the tire where energy dissipation is important.**

This problem is straight-forward and tractable, but with a lot of work.

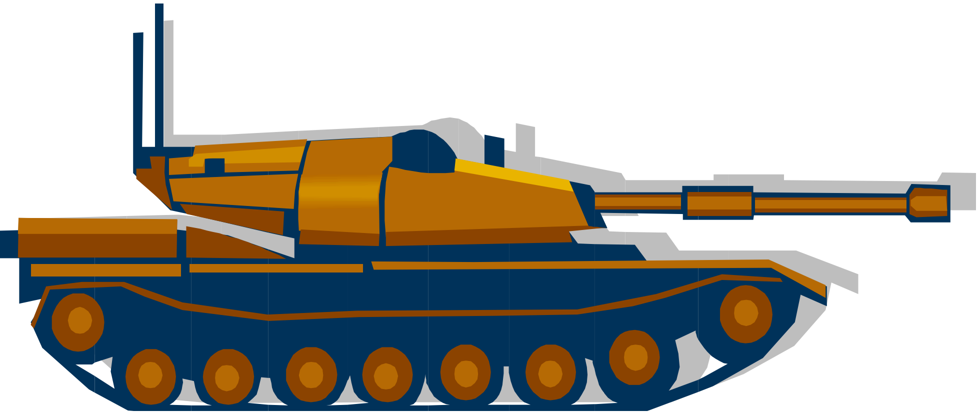
There are no short cuts.

There are many dissertations left to be written on this problem.

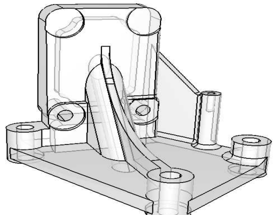


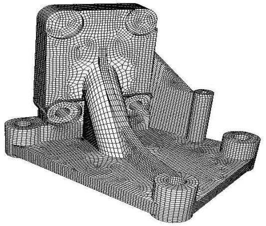
What is the Problem with Structural Dynamics?

- The problems are large (millions of d.o.f.)
- Nonlinearities mean that we must re-solve at every iteration within each time step.
- We must calculate out to long times.



Root Cause: Our structures have many parts. The parts are each modeled with MANY finite elements, and all those parts are connected.





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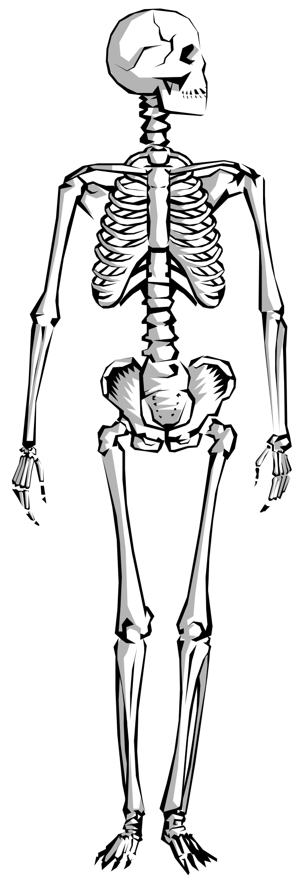
How Structural Dynamics Analysis is Done Now

Begin with Solid Model.

Understanding of the actual structure always misses much detail.



Create a least one Finite Element Mesh.

Leaving in only the important parts

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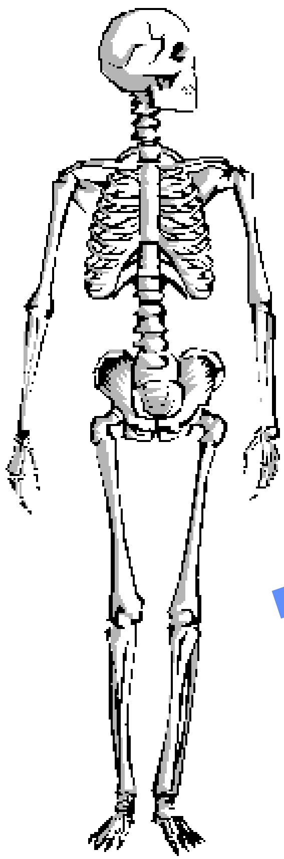
Predict Modes and Frequencies via Finite Element Analysis



$$\omega_n^2 M x_n = K x_n$$

Calculate Eigenmodes and Eigenfrequencies

Approximate all joints as with torsional and extensional springs.

Build a Prototype and Test it in a Modal Laboratory

Measure Modes and Frequencies, and Approximate Modal Damping Values

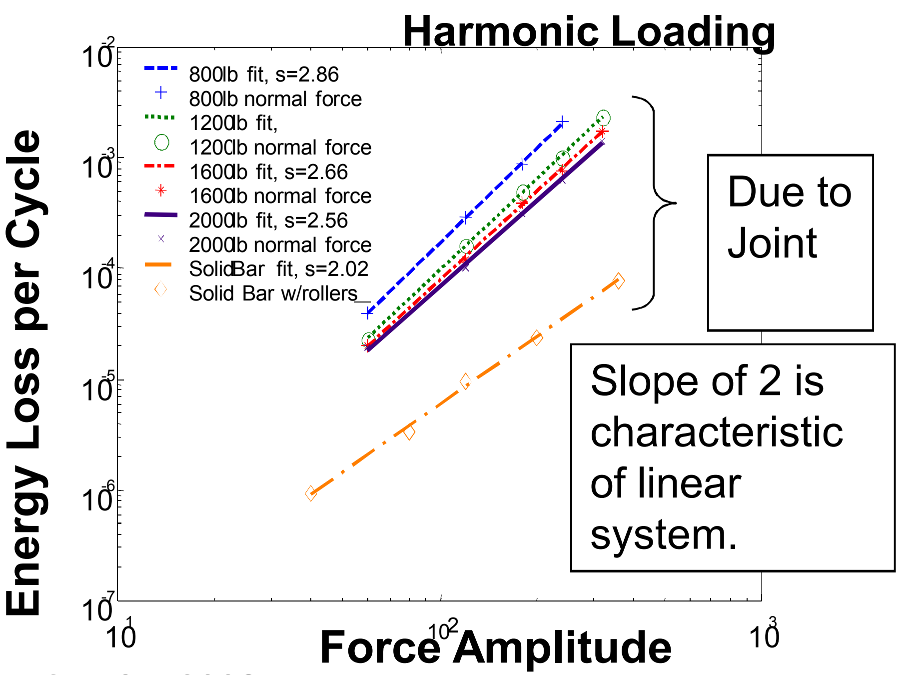
Call the analyst and tell him the values so that he can tune his model.

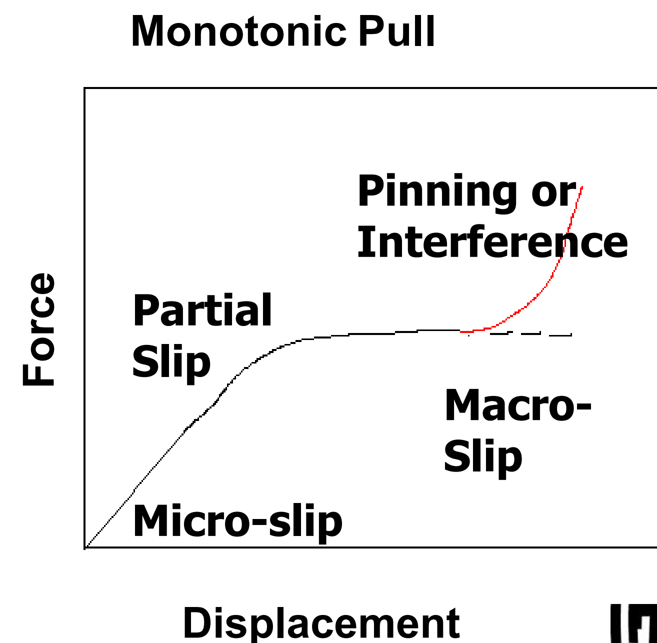
This linear model is then used to predict structural response.

If the resulting model is valid at all, it is only in the range of loads comparable to those used in calibration

Why Must We Do Backwards Prediction in Structural Dynamics?

- **Most of the energy dissipation in built-up structures is due to mechanical interfaces.**
- **The energy dissipation is highly nonlinear.**
- **There is tremendous variability between nominally identical joints.**





Fundamental Experimental Difficulties

- The physics to be measured all takes place exactly where it cannot be measured directly.
- Kinematics of joint displacements cannot be well defined in an experimental context.
- Every specimen mounting adds its own features to measurements
- Specimen compliances drown out joint response except at very large loads.

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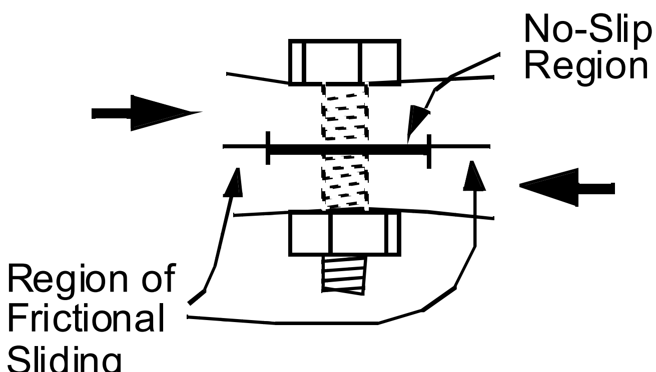
Fundamental Difficulty in Finite Element Modeling of Jointed Structures

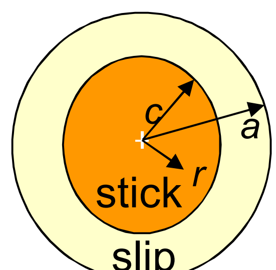
- **Moving boundaries**
- **Intrinsically multiscale**
- **Nonlocal**

Structure ~ meters

component ~ centimeters



"Slip"



Contact patch ~ cm

Slip zone ~100 µm

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Simply Employing More Elements is not the Solution

- One cannot reasonably directly slave a micro-mechanics contact algorithm to a structural dynamics analysis.
- Micro-meshed models will be useful for studying and understanding joint mechanics
- Tools are needed to cross the dimensions

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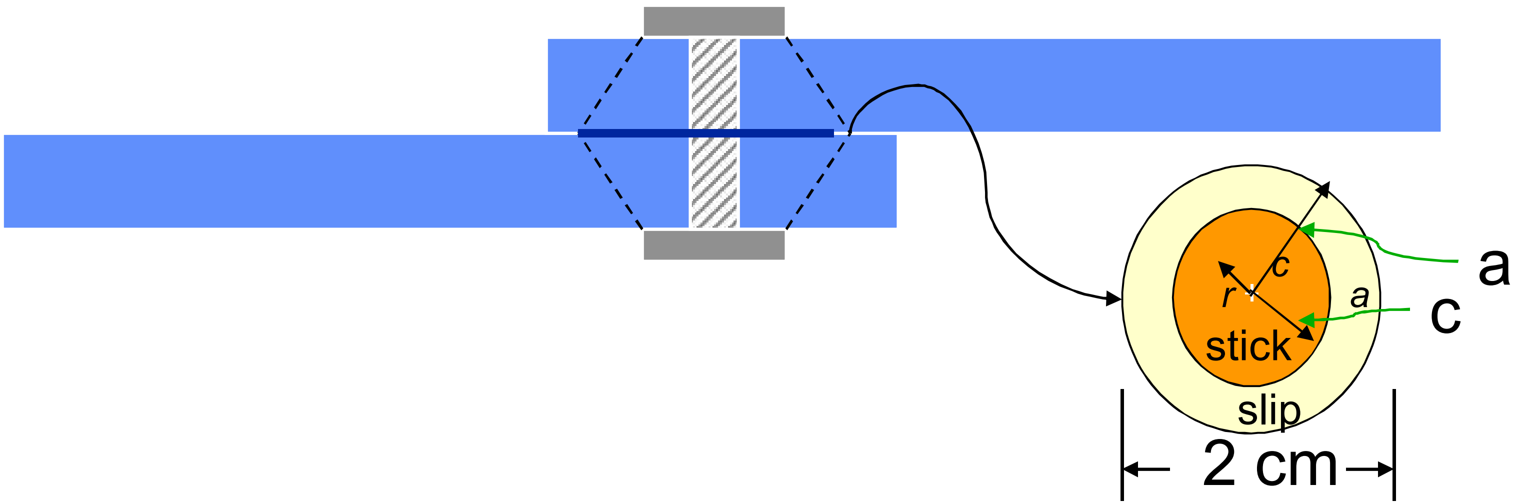
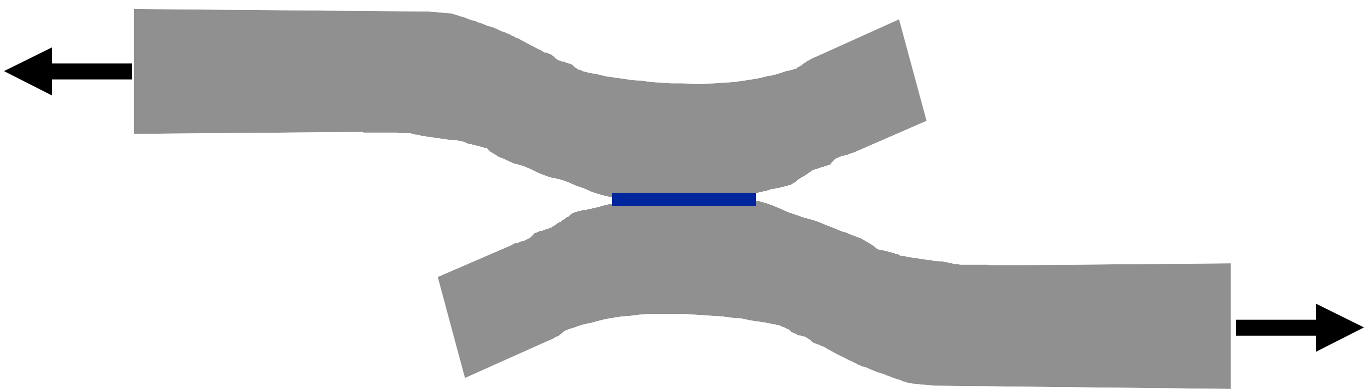
Illustration of Computational Difficulties

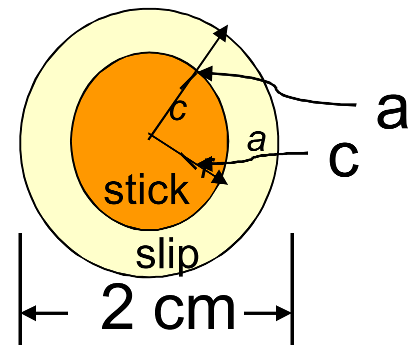
- **Consider a lap joint with dimensions selected so that the contact patch is circular of radius a=1 cm**



- **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

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

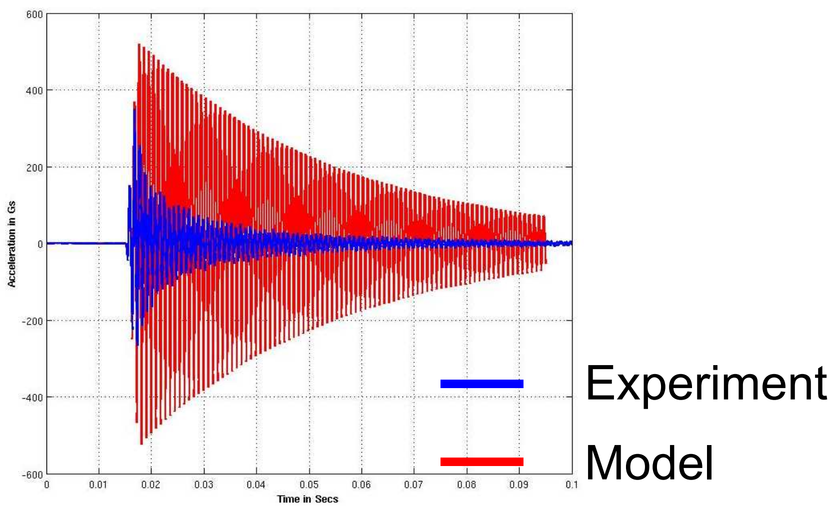
Necessary Finite Element Scales
Courant Times

- **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.**

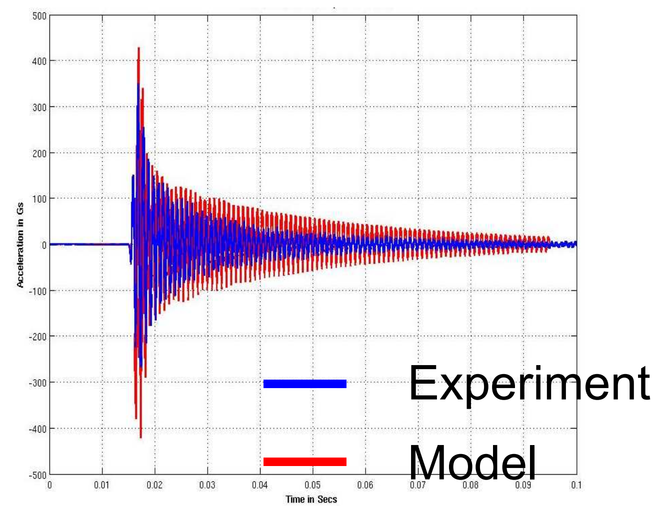
  Compare this with 3E4 time steps if the problem were linear and solved implicitly

A Bite-Size Approach

- Measure Individual Joint Properties in the Laboratory.
- Develop Constitutive Models for the Whole Joints.
- Incorporate those Joint Models in Structural Dynamics Models.



Linear model tuned to low-amplitude experiment.



Non-linear (with nonlinear joints) model

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Notions for Fertile (though possibly difficult) Research Areas

- **Examine the normal engineering practice. Wherever "fudging" takes place, there is research opportunity.**
- **Identify situations where the prevailing models are *too convenient*. (such as modal damping)**
- **Look for situations where the best theory does not work as well as "rules of thumb".**
- **Note areas where there is a developed body of theory, but practitioners do not use it.**
- **Look for places where constitutive and structural properties are co-mingled. This is common in messy topics like ice or rubber.**

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Summary

- Tractable – small bite – problems are important. This is were new ideas come from.
- The trick to very messy (hard) problems is to break them into small bites.
- Important problems can be found through systematic examination of common engineering practice.
- Only take on hard problems if your employer has a very long attention span.

Appendix

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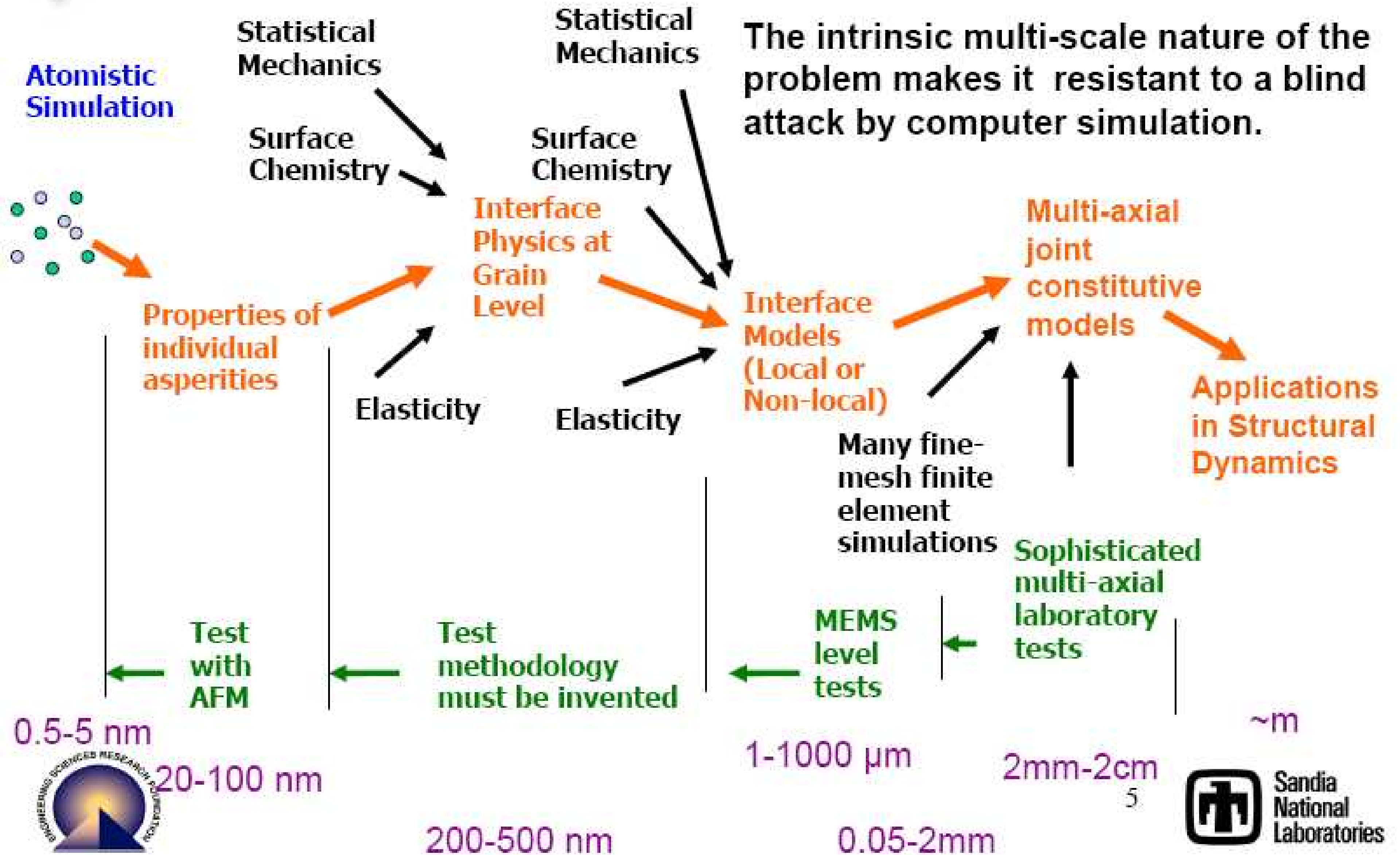
Bottom-Up and Top-Down Vision for Research in Physics of Joint Mechanics

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.



R&A

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