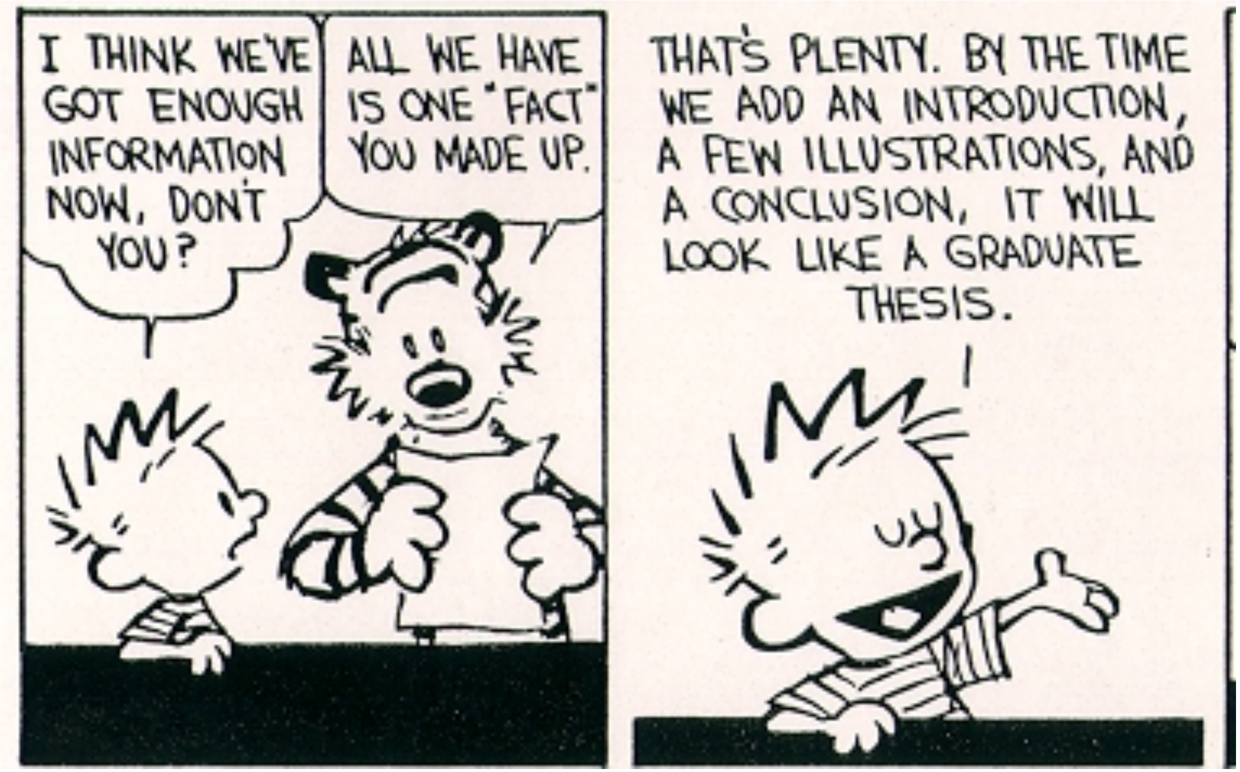
But First …


I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

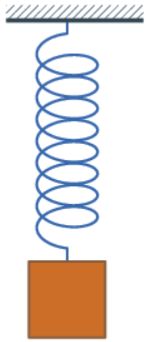
Frontiers in Energy Research
Nonlinear Mechanics & Granular Media

Joseph Lydon

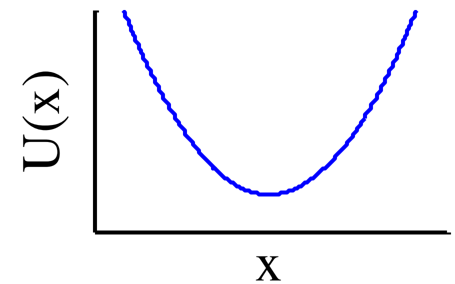
Frontiers In Energy Research

1. Introduce Nonlinear Mechanics
2. Discuss Two Areas of Energy Research
3. How Granular Crystals fit in with the Frontiers in Energy Research?

Linear Systems

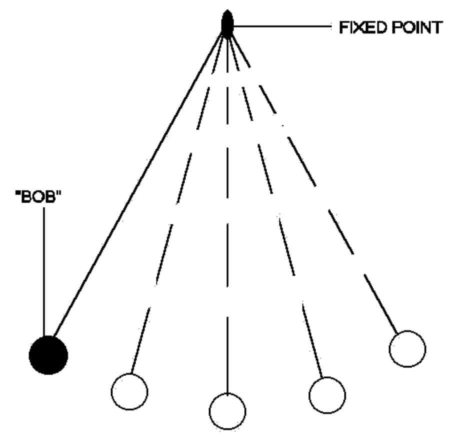


- "Simple Harmonic Motion"
  - $U=1/2\ kx\uparrow 2$ & $F=-kx$

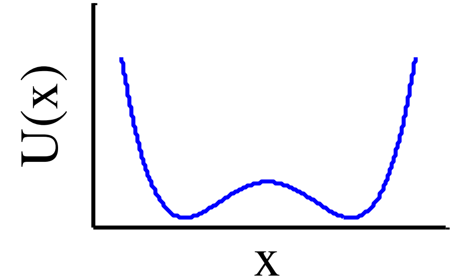


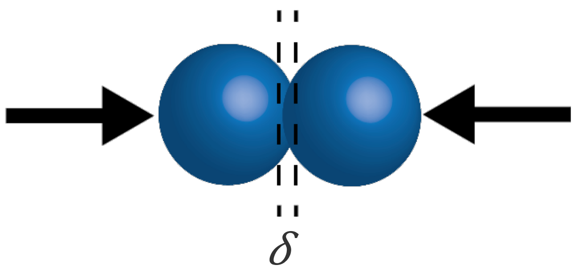
Advantages	Disadvantages
• Math Friendly • Low Amplitude • Predictable	• Quality Factor/ Bandwidth Tradeoff • Harmonic

Nonlinear Systems



- Complex Motion
  - $F = mg\sin(\theta)$
  - $F = ax + bx^3$
  - $F = \delta^{3/2}$

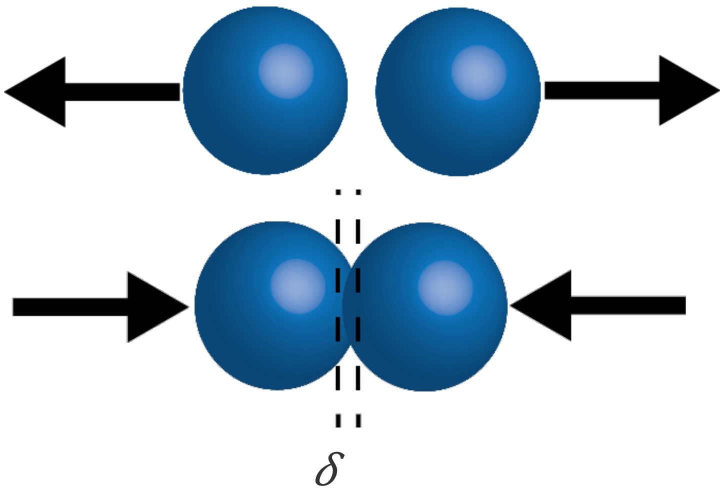




Advantages/ Disadvantages

- Unpredictable Response/Missing Math Tools
- Larger Amplitude
- Complex Dynamics
- Not Harmonic
- Not Described by Transfer Functions

Granular Crystals



$Force = 0$

Tensionless behavior

$Force = A\,\delta^{3/2}$

Nonlinear Compression

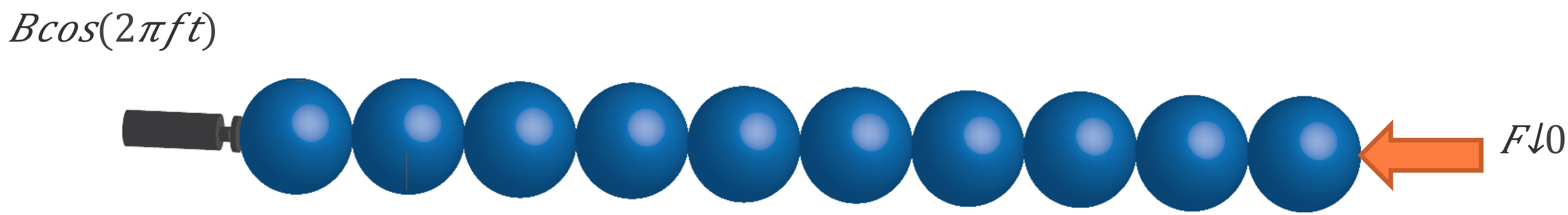
Leads to a Tunable Stiffness

$C = \frac{3}{2} A \delta_0^{1/2}$

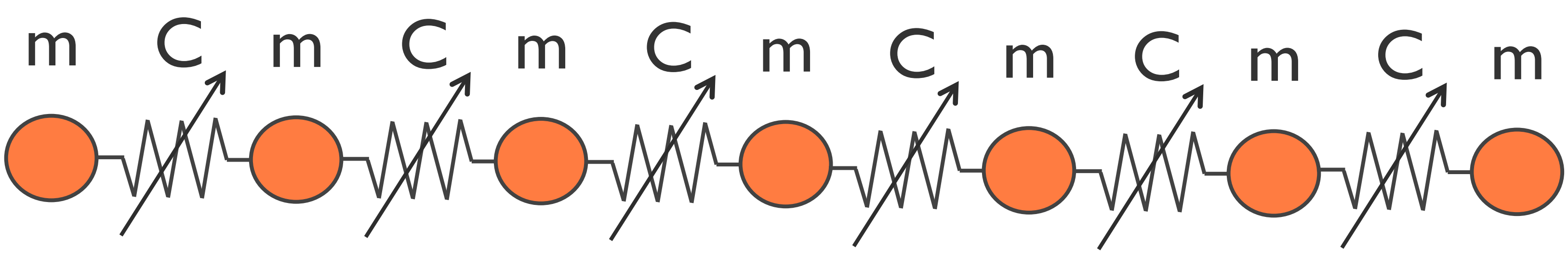
$C = \frac{3}{2} (A F_0)^{1/3}$

Hertz, H. (1882). Ueber die Berührung fester elastischer Körper. Journal für die reine und angewandte Mathematik (Crelle's Journal). **1882: 156.**

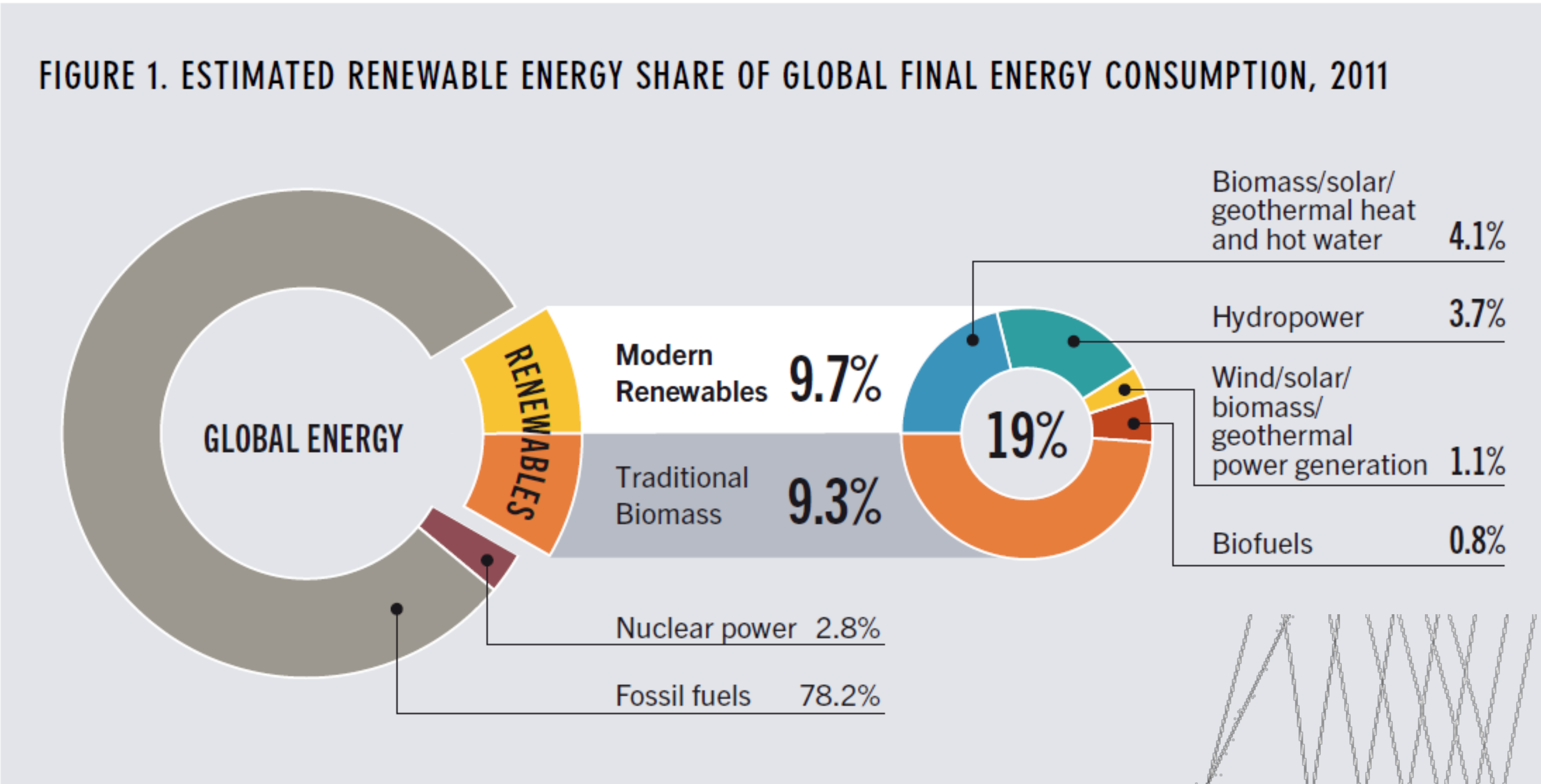
Granular Crystals



Modeled as a
Nonlinear Lattice



Energy Harvesting in Perspective



How & Where does Nonlinear Mechanics fit in?

Frontiers of Energy Research

1. Nonlinear Resonance for Stability & Energy

2. Ambient (Vibrational) Energy Harvesting

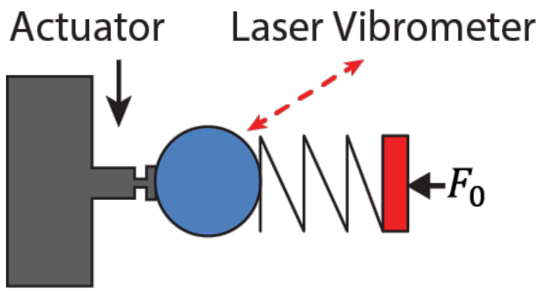
Resonance

Tacoma Narrows Bridge

1. Forced Resonance
2. Aeroelastic Flutter – Dynamic Instability

Billah, K.; R. Scanlan (1991). "Resonance, Tacoma Narrows Bridge Failure, and Undergraduate Physics Textbooks" (PDF). *American Journal of Physics* **59** (2): 118–124. Bibcode:1991AmJPh..59..118B. doi:10.1119/1.16590.

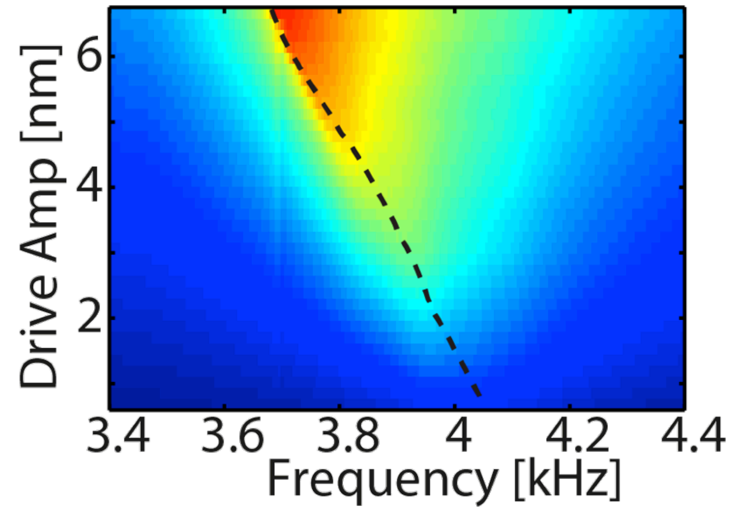
2. Nonlinear Resonance for Stability and Energy

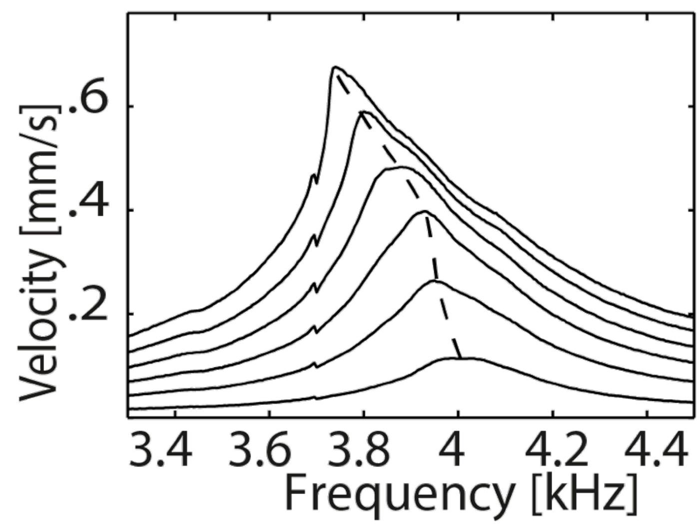


- Why use nonlinear systems?

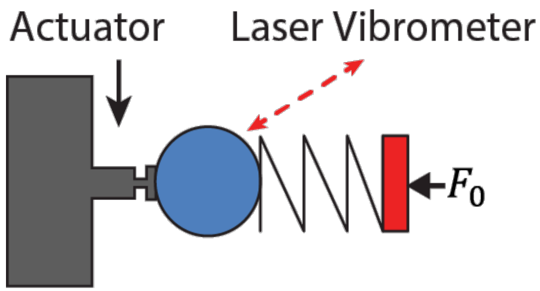
1. Frequency Shifting

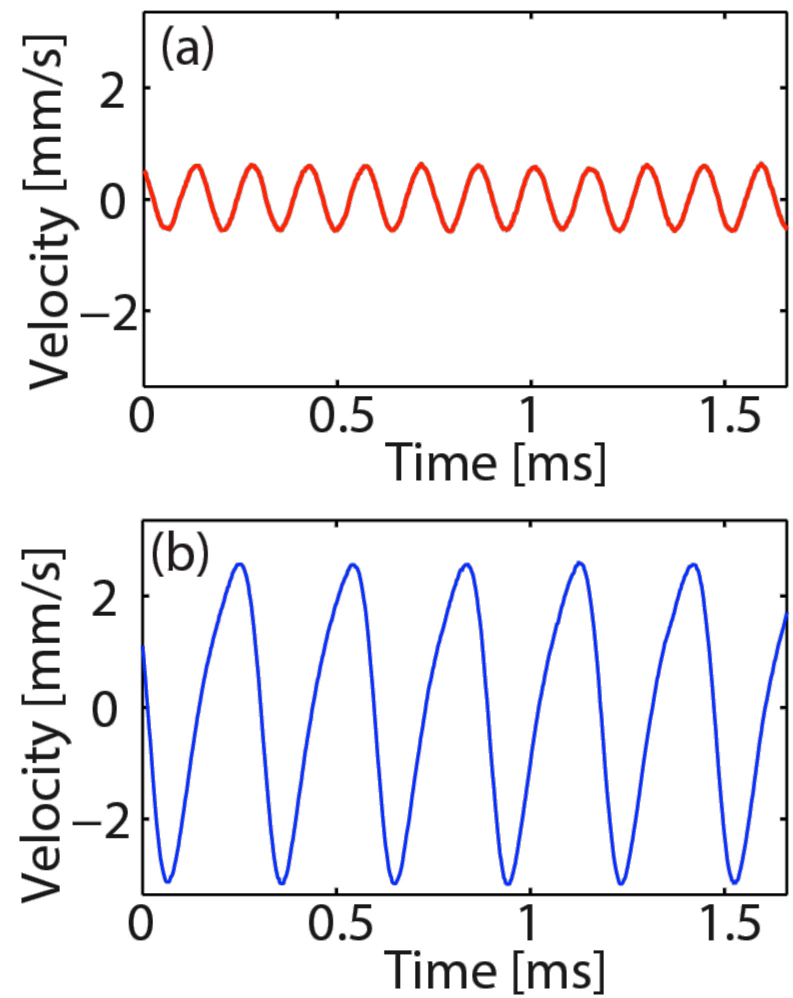
2. Predictable Breakdown





2. Nonlinear Resonance for Stability and Energy



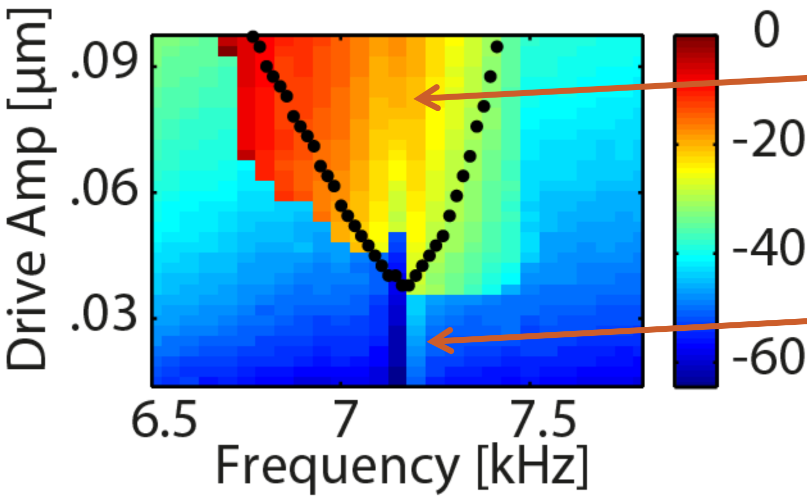


- Why use nonlinear systems?

1. Frequency Shifting

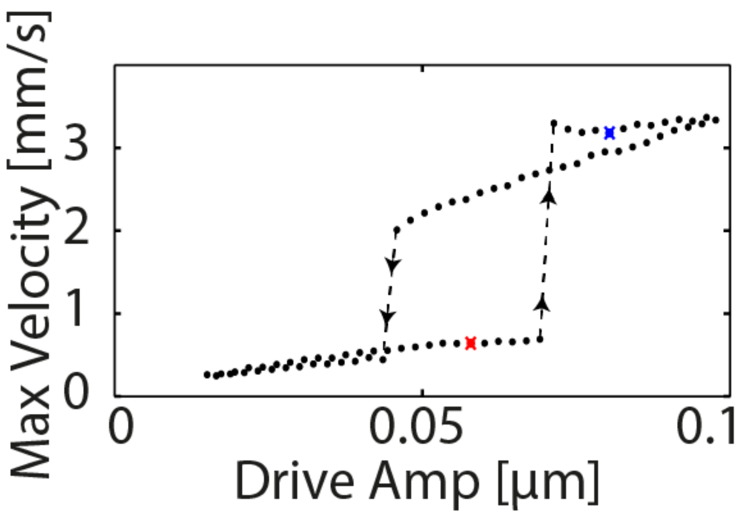
2. Predictable Breakdown

2. Nonlinear Resonance for Stability and Energy



Instability – Grows to High Amplitude and **Stabilizes**

Low Amplitude State is Stable



Takeaway Message:
Frequency Shifting Stabilizes the Resonance

Solution

2. Nonlinear Resonance for Stability

- Design Structures around resonances to more efficiently couple with harmonic energy sources nature.
- Use Nonlinear Mechanics to achieve a predictable breakdown mechanism.
- Harvest Energy in this high amplitude state.

Frontiers of Energy Research

1. Nonlinear Resonance for Stability & Energy

2. Ambient (Vibrational) Energy Harvesting

1. Ambient (Vibrational) Energy Harvesting

Energy Source	Harvested Power
Vibration/Motion	
Human	4 μW/cm^2
Industry	100 μW/cm^2
Temperature Difference	
Human	25 μW/cm^2
Industry	1–10 mW/cm^2
Light	
Indoor	10 μW/cm^2
Outdoor	10 mW/cm^2
RF	
GSM	0.1 μW/cm^2
WiFi	0.001 μW/cm^2

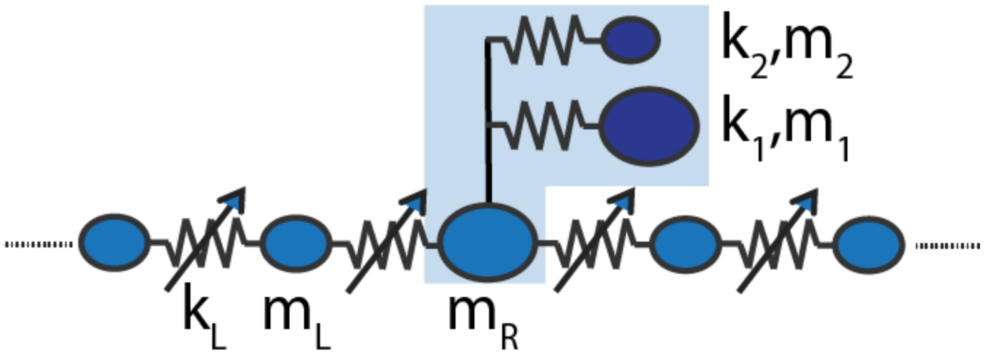
1. Ambient (Vibrational) Energy Harvesting

Energy Source	Harvested Power
Vibration/Motion	
Human	4 μW/cm^2
Industry	100 μW/cm^2

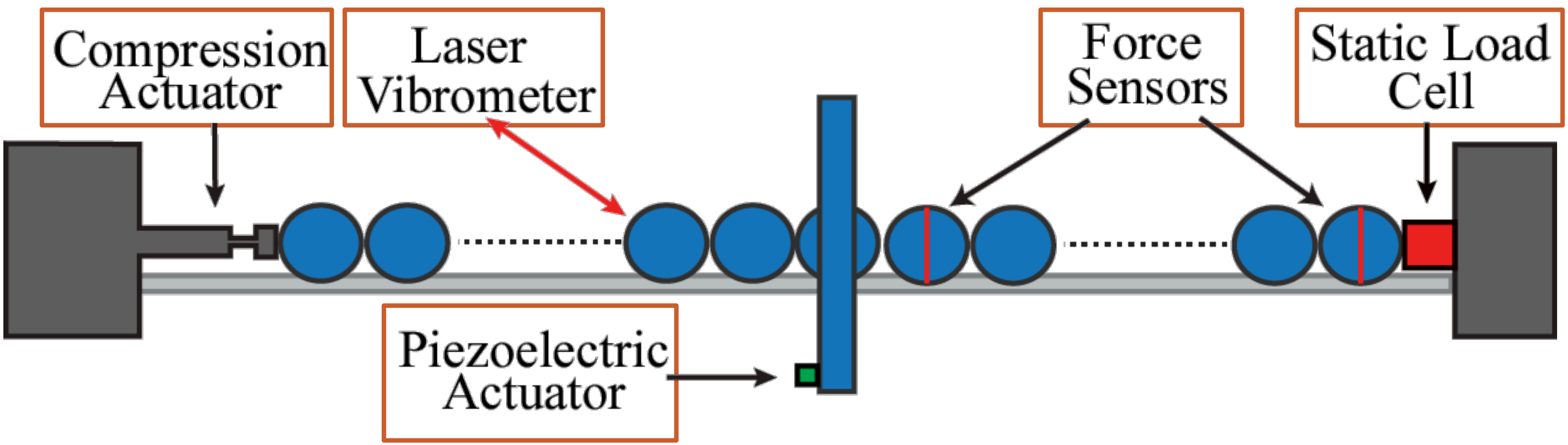
- Low Power
  - My Samsung – 7.98Wh
  - 220 mW Avg. Consumption
- Distributed Energy
  - $1 m^2 = 10,000 cm^2$

- Tunable Nonlinearity
  - Different Amplitude Signals
- Localization Mechanism

Tunable Localization

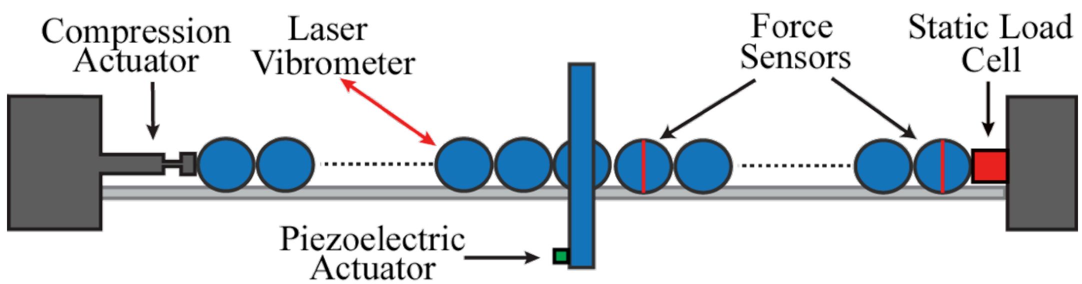


Introduce a resonator defect to localize energy.

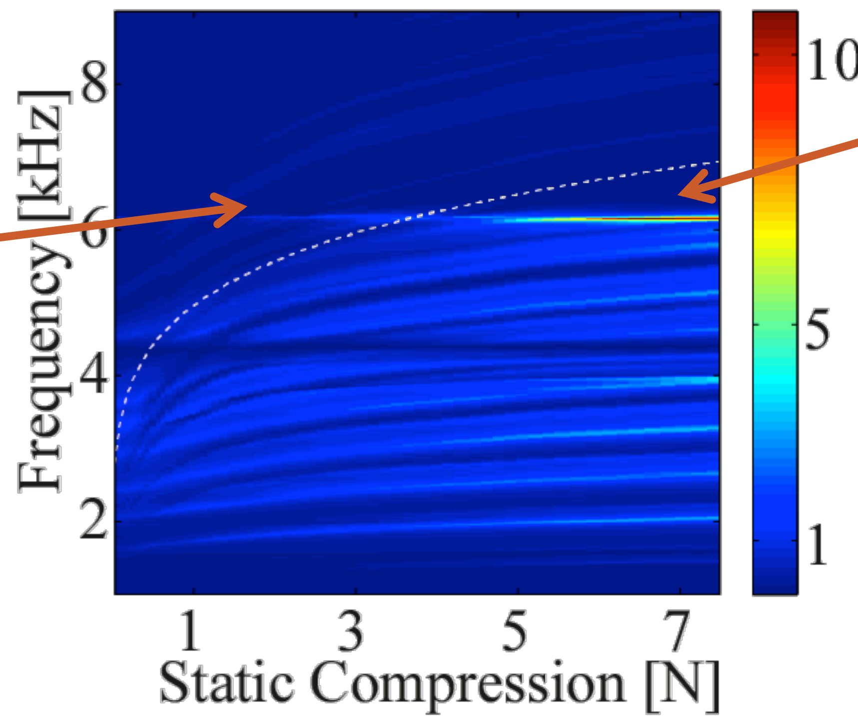


Localization in Granular Crystals

Measure Signal from Far Force Sensor (i.e. bright region corresponds delocalized)



Localized

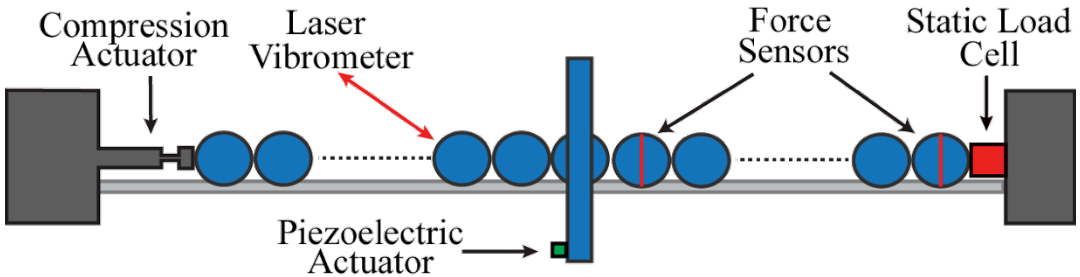


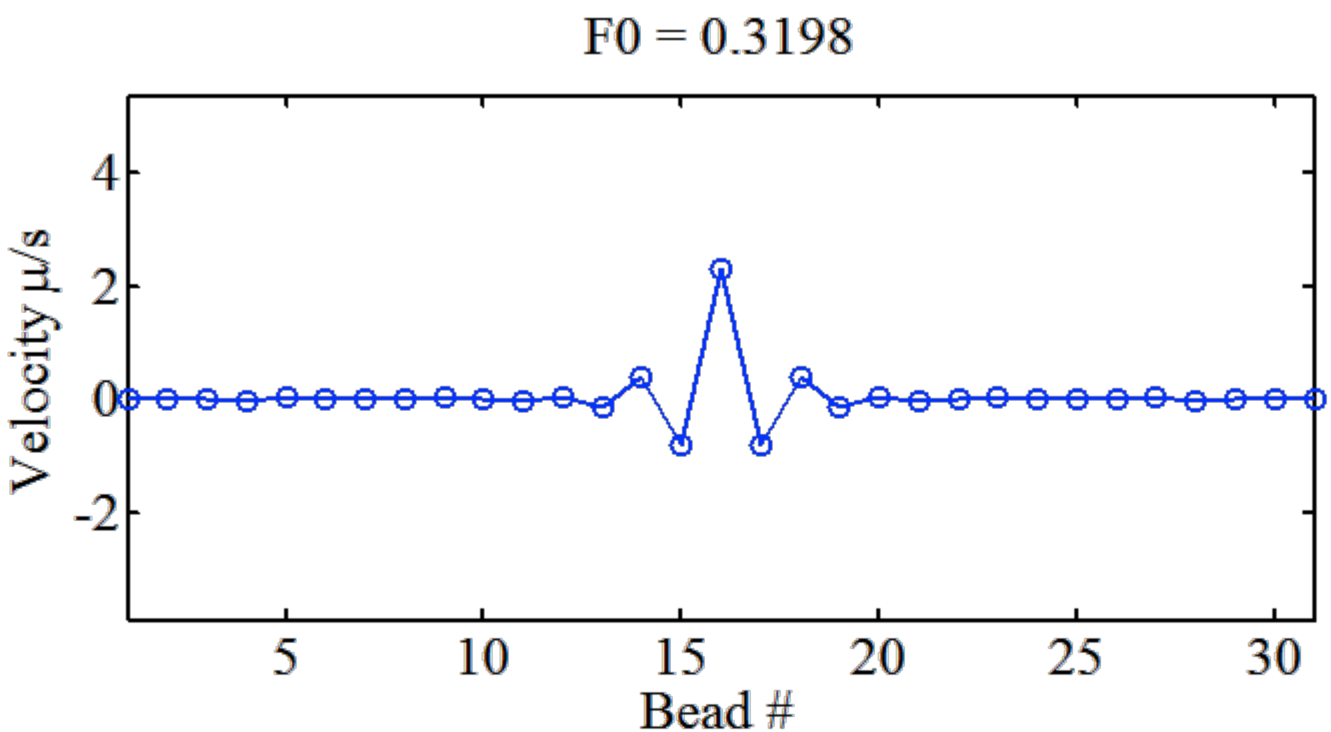
Delocalized

Control Localization

Increase Static Compression

Delocalize Mode





Conclusion

- Nonlinear Mechanics introduces new possible directions for energy research

1. Localize low amplitude vibrations
   - For more efficient energy harvesting
2. Utilize Resonances to more efficiently couple to natural systems
   - Nonlinear systems can be used to stabilize the oftentimes destructive breakdowns

Acknowledgments

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  - Marc Serra Garcia
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- ETH – IDES

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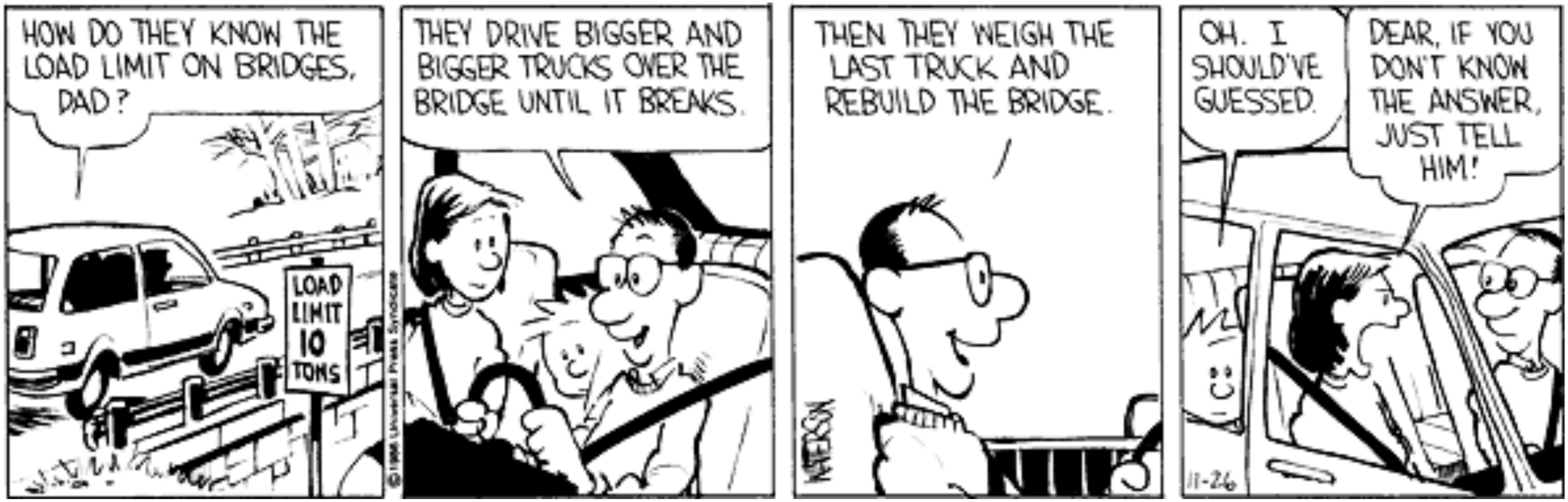
  - US-AFOSR (FA9550-12-1-0332)

Questions


HOW DO THEY KNOW THE LOAD LIMIT ON BRIDGES, DAD?
LOAD LIMIT 10 TONS
THEY DRIVE BIGGER AND BIGGER TRUCKS OVER THE BRIDGE UNTIL IT BREAKS.
THEN THEY WEIGH THE LAST TRUCK AND REBUILD THE BRIDGE.
WATTERSON
OH. I SHOULD'VE GUESSED.
DEAR, IF YOU DON'T KNOW THE ANSWER, JUST TELL HIM!
11-26