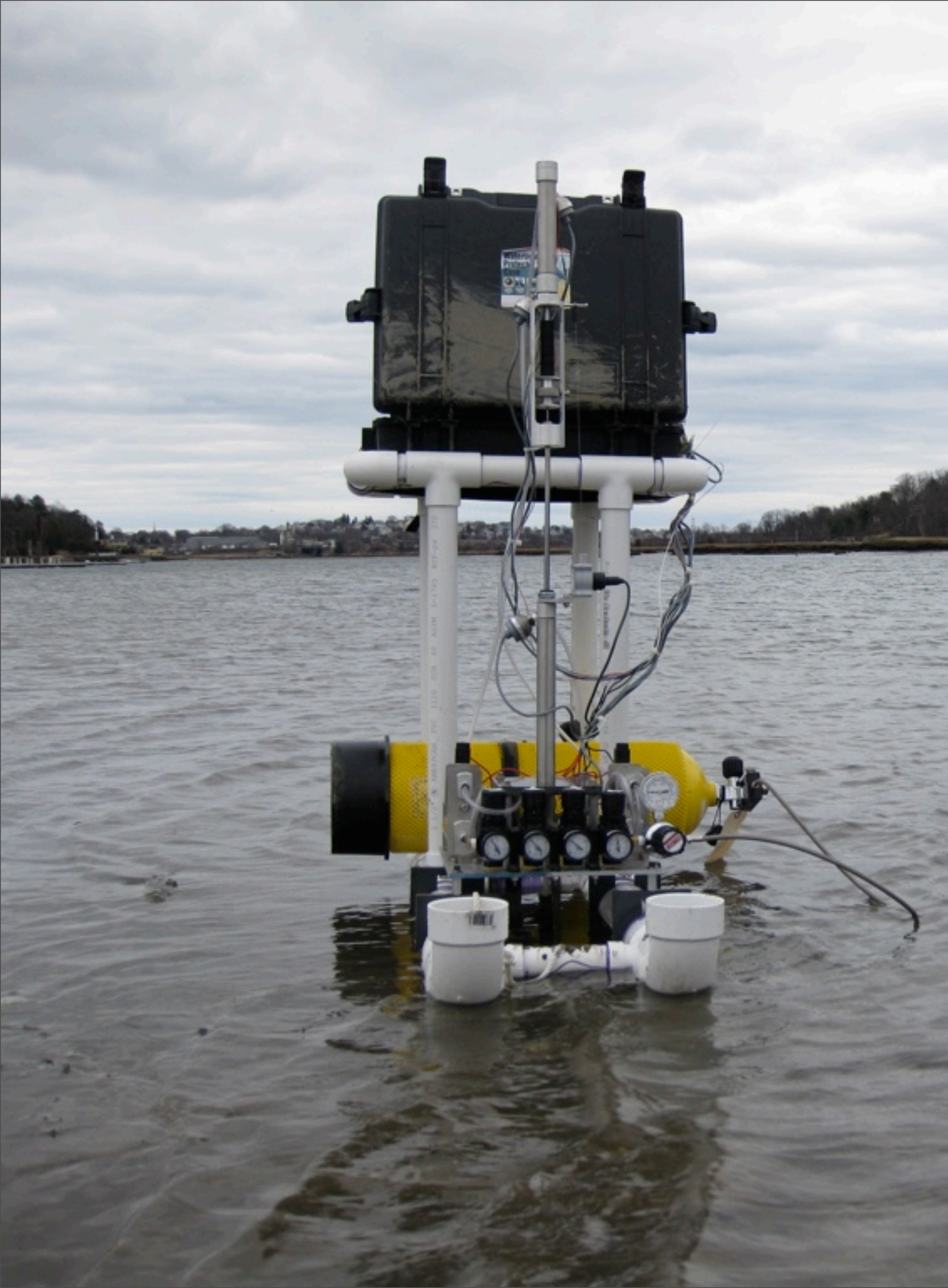


The Design and Performance of RoboClam: A Biologically-Inspired Burrowing Robot

Amos Winter
PhD Candidate in ME

Hosoi Research Group
Precision Engineering Research Group

Project overview

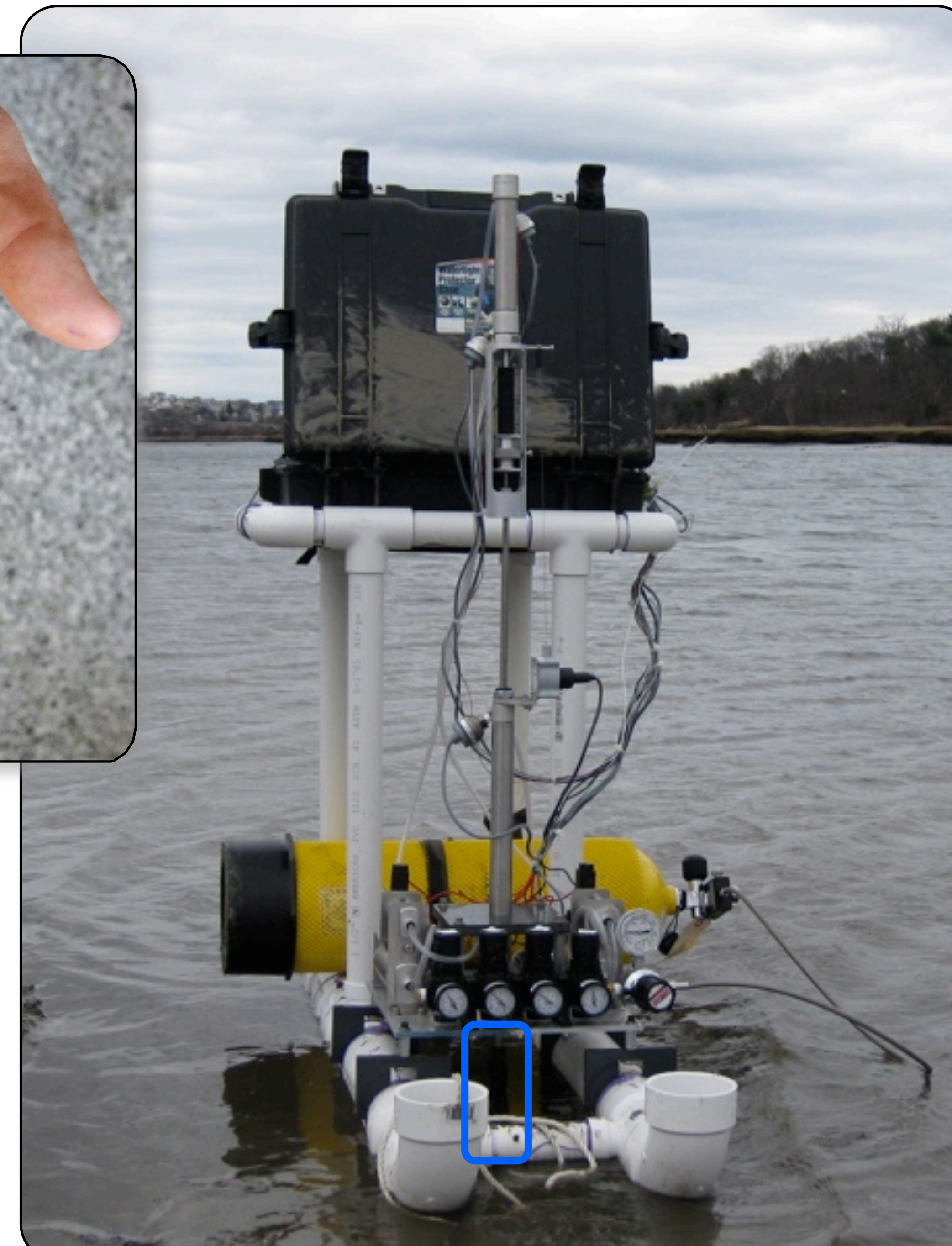
Our aim: Generate low-power, compact, light weight, reversible burrowing technology

Hypothesis: Nature has devised an efficient solution to subsea burrowing

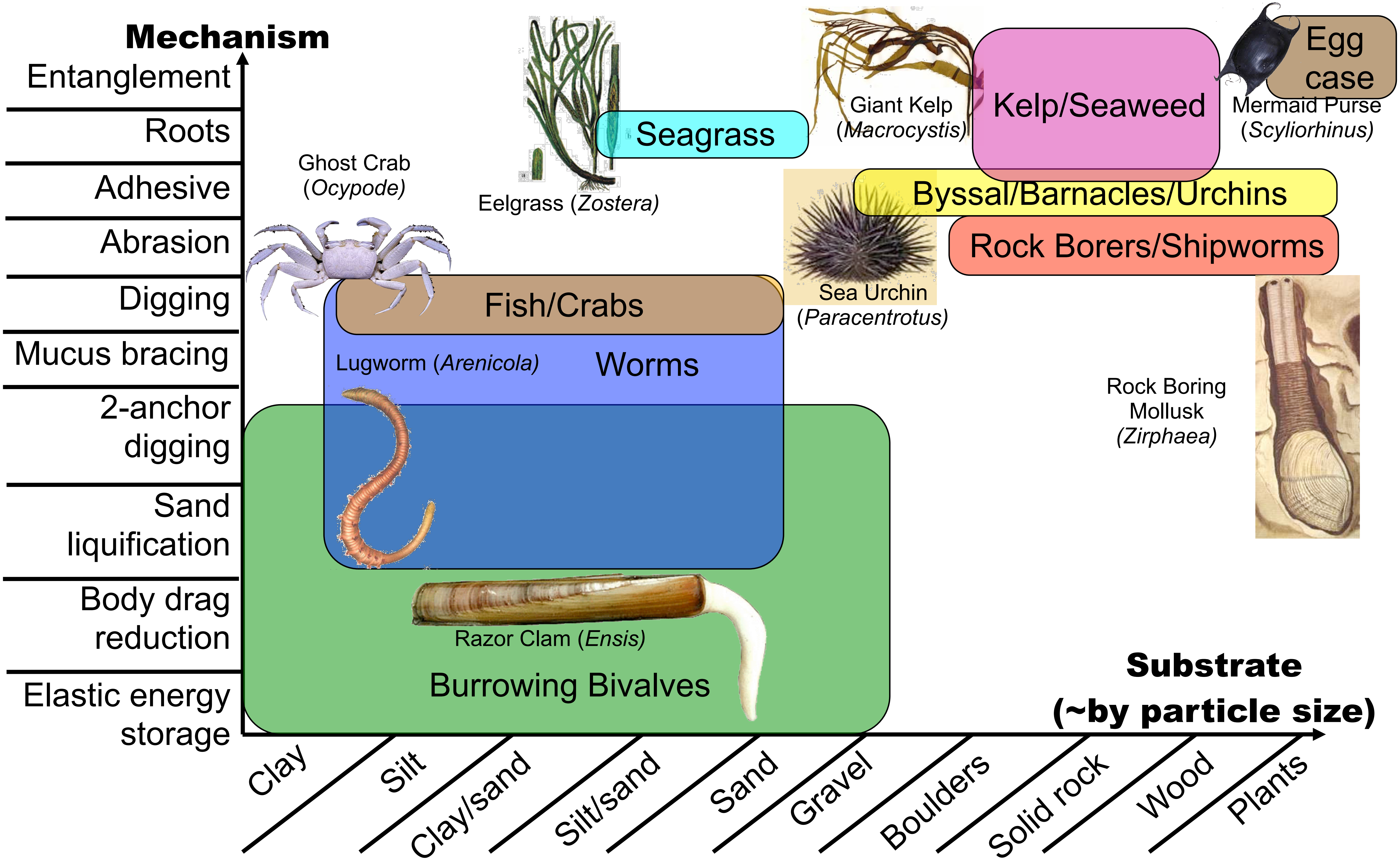
Razor clam

to

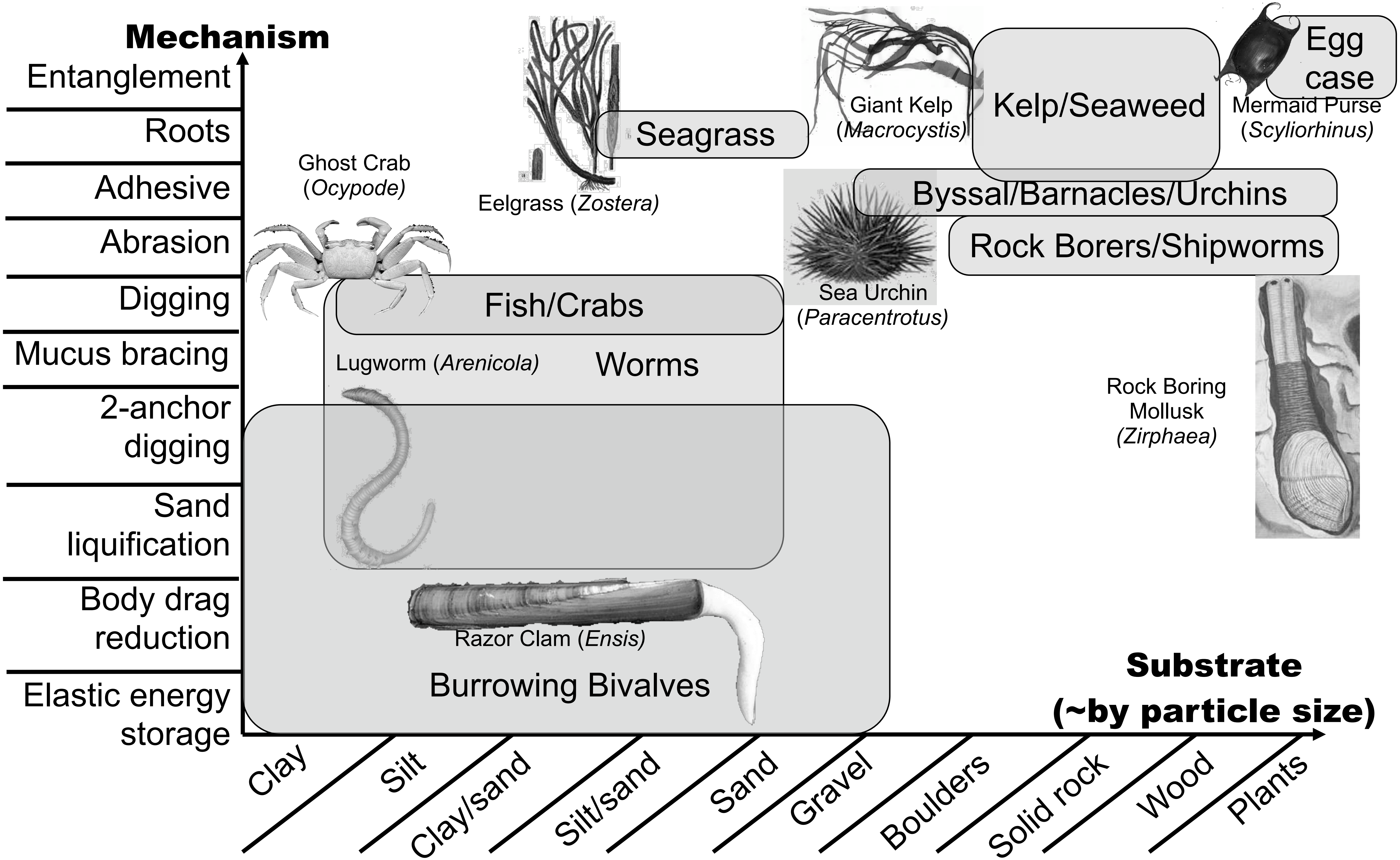
RoboClam



Nature's bottom dwellers



Chosen organism



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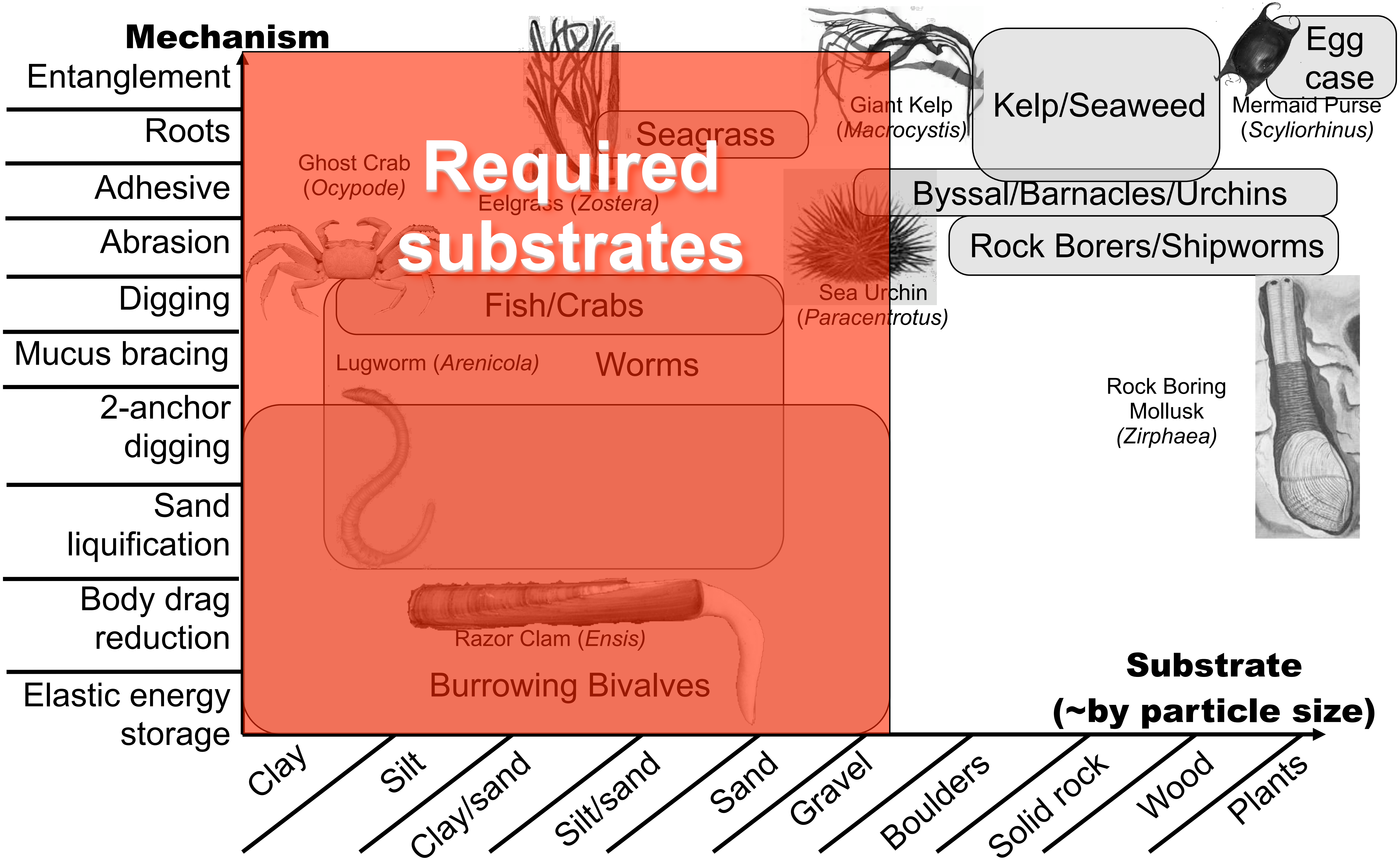

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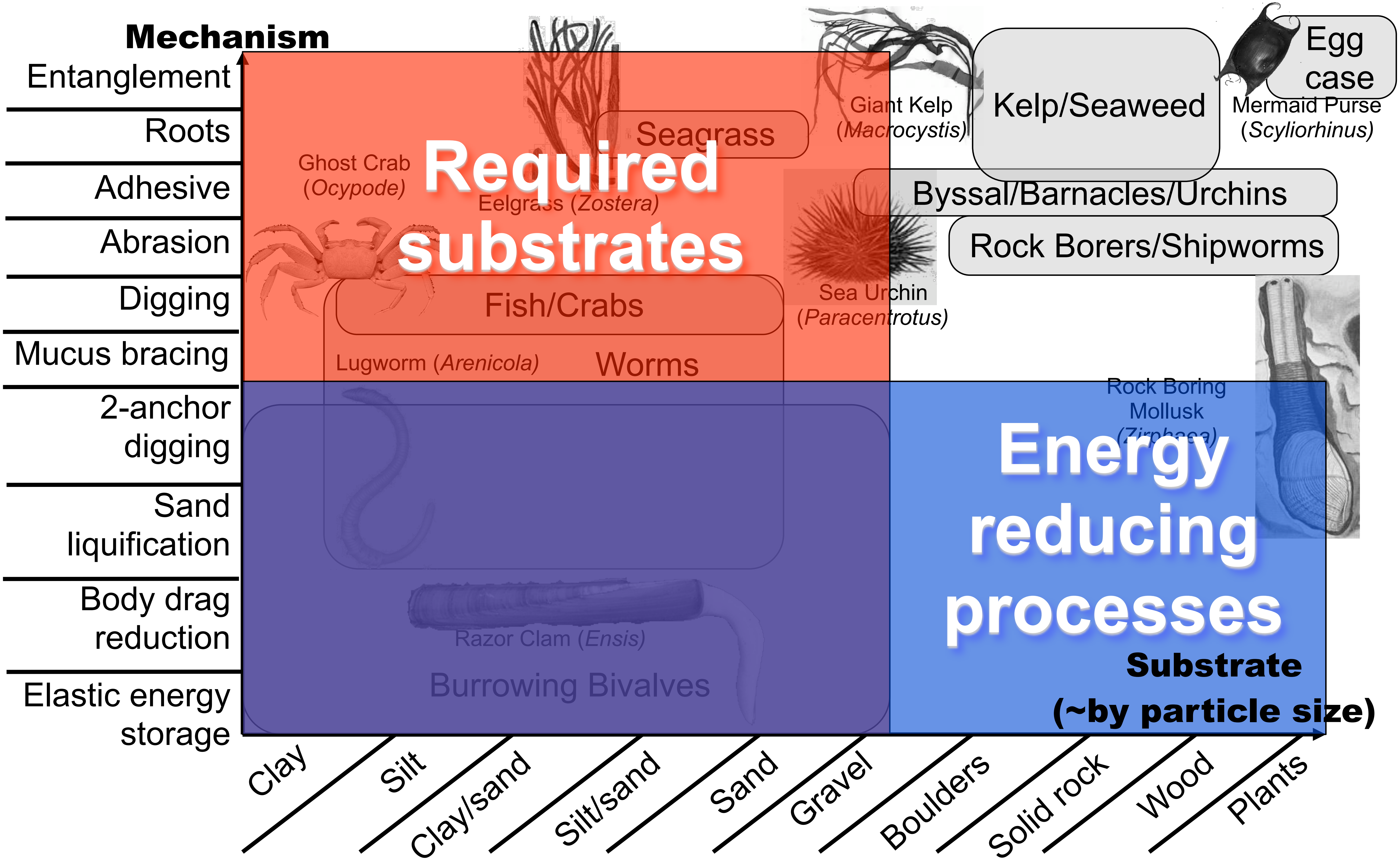

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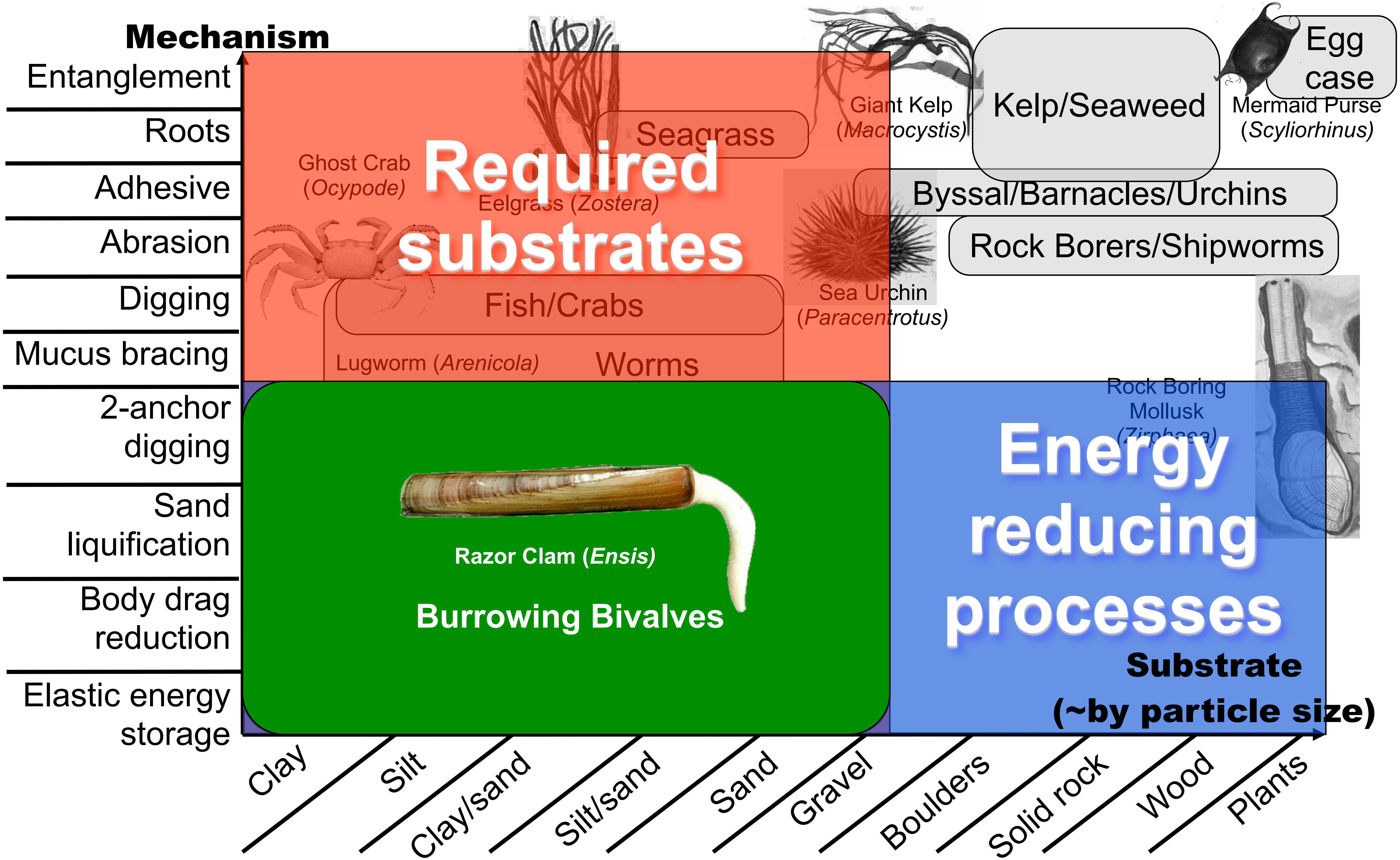


Ensis and biomimetics

Our aim: Generate low-power, compact, light weight, reversible burrowing technology

***Ensis*' engineering merits**

Fast
Burrows at nearly 1cm/s

Efficient
Uses approx 0.22J/cm

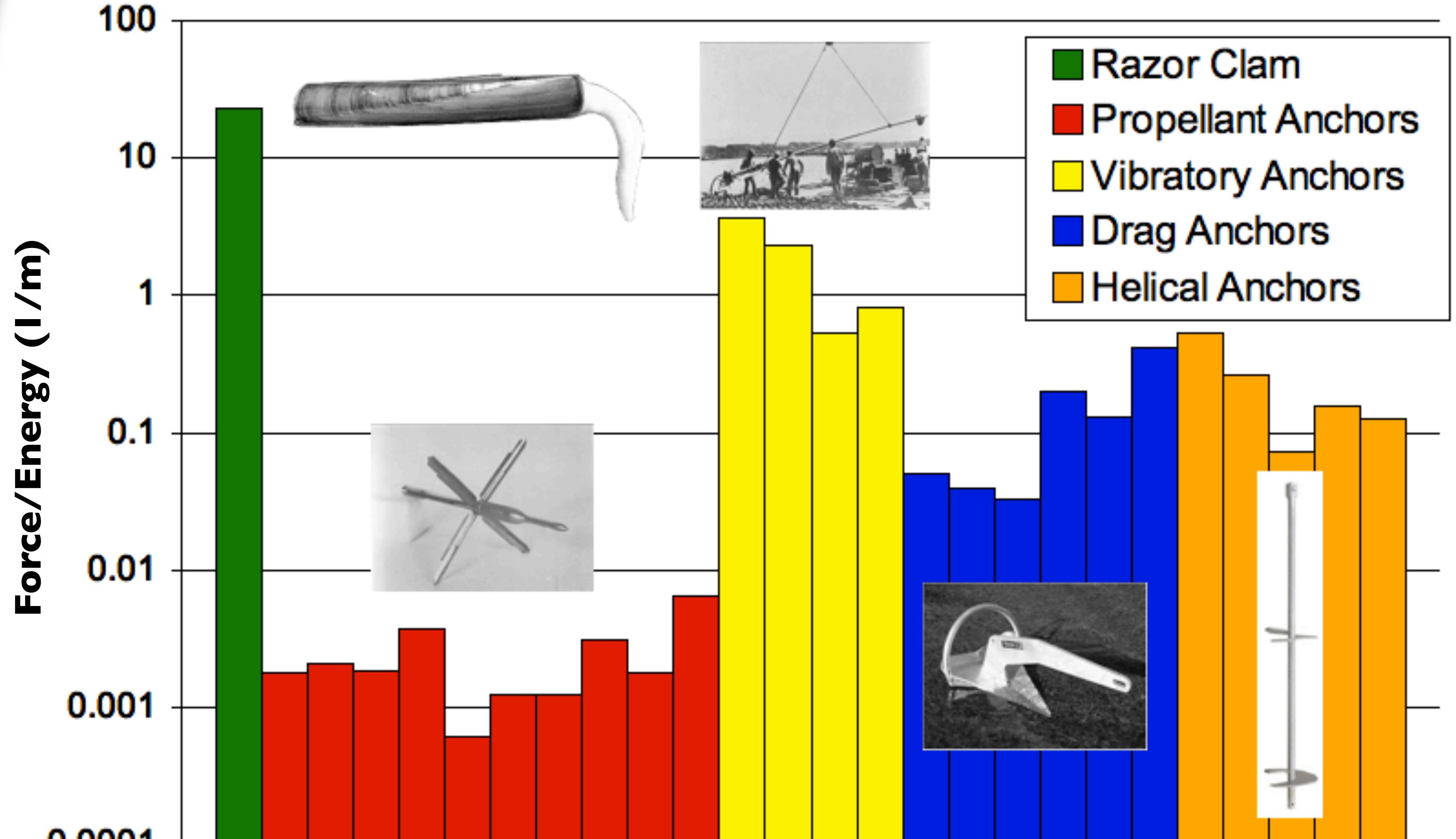
Large
Size scale of real engineering devices

Simple
No brain, 1DOF shell

Digs deep
Burrows to 70cm (5 body lengths)

E. R. Trueman, *Proc Roy Soc Lond B Biol Sci*, 1967
A. F. Holland, *Chesapeake Sci*, 1977

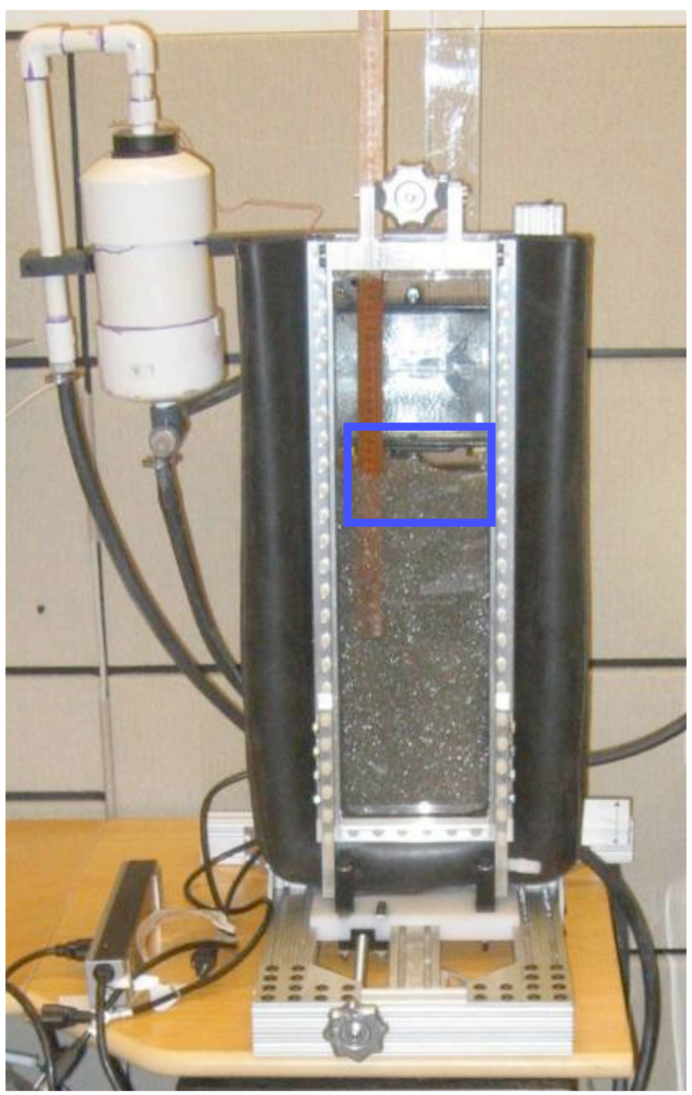
Anchoring force vs expended energy
(Note: log scale)



E. R. Hinz, *The Complete Book of Anchoring and Mooring*, 2001
B. Springer, *Sail*, 2006
R. J. Taylor, "Uplift-Resisting Anchors," *Anchoring Systems*, 1979
Technical Design Manual, Chance, 2007

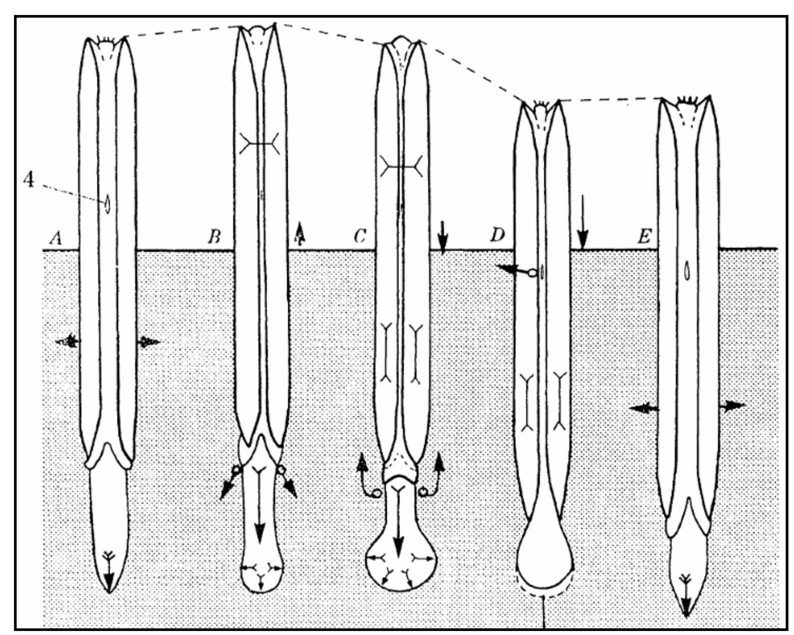
Burrowing *Ensis*

The Atlantic razor clam (*Ensis directus*)

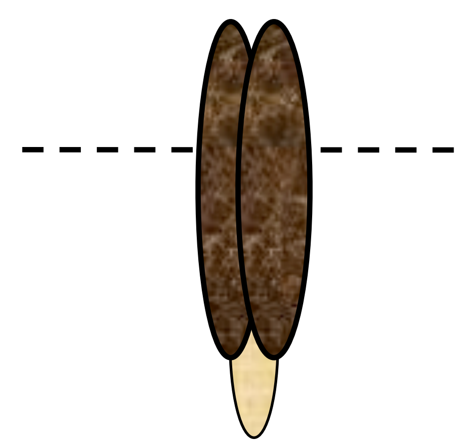


Clam visualizer

Burrowing kinematics



E. R. Trueman, *Proc Roy Soc Lond B Biol Sci*, 1967



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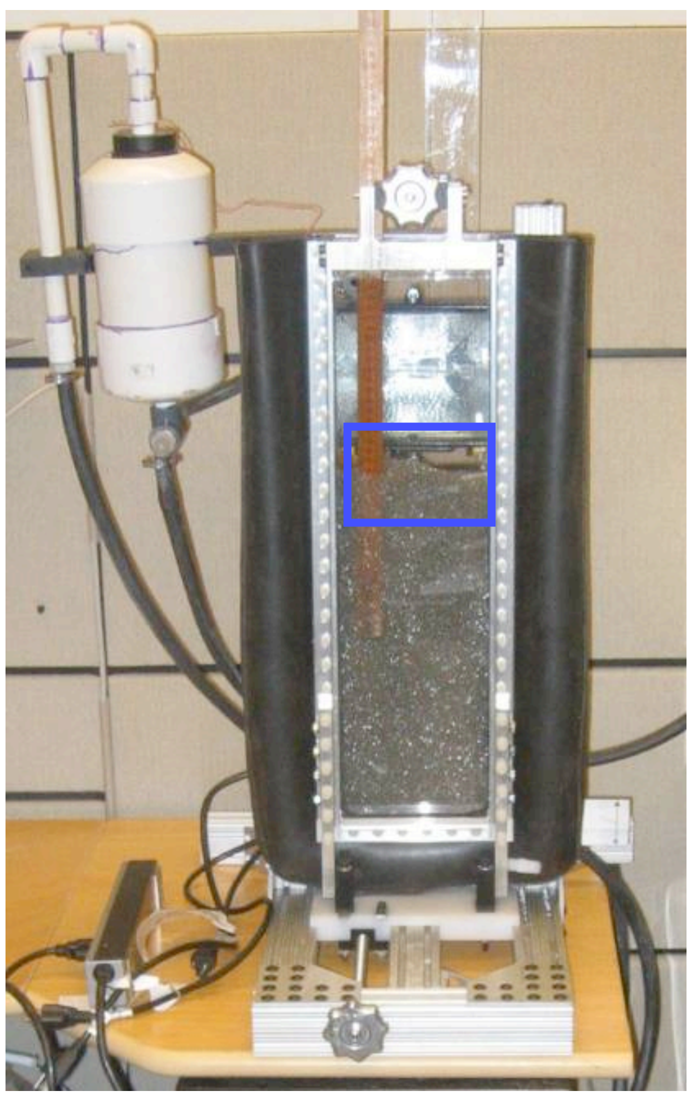

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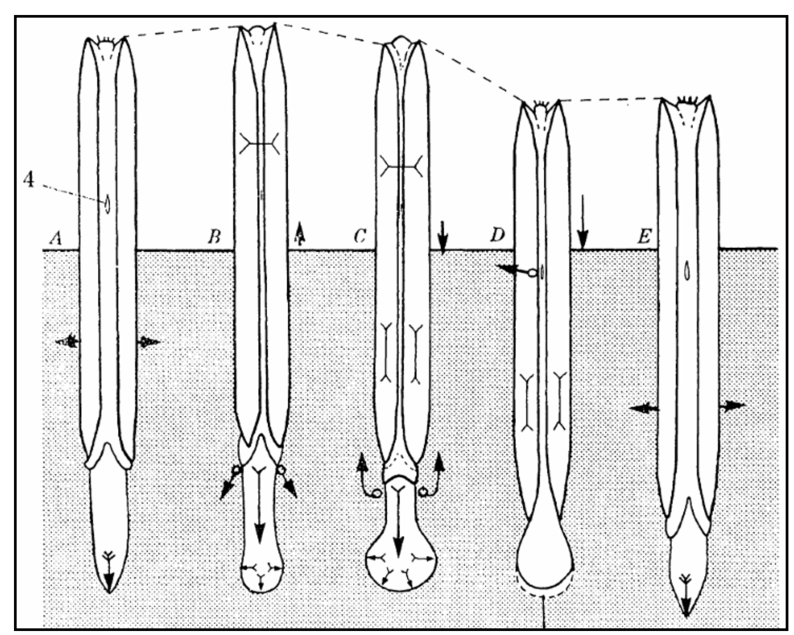

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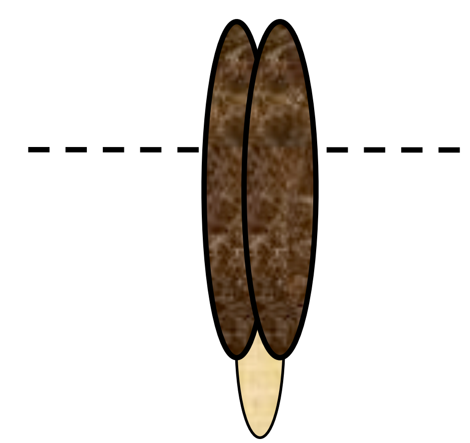

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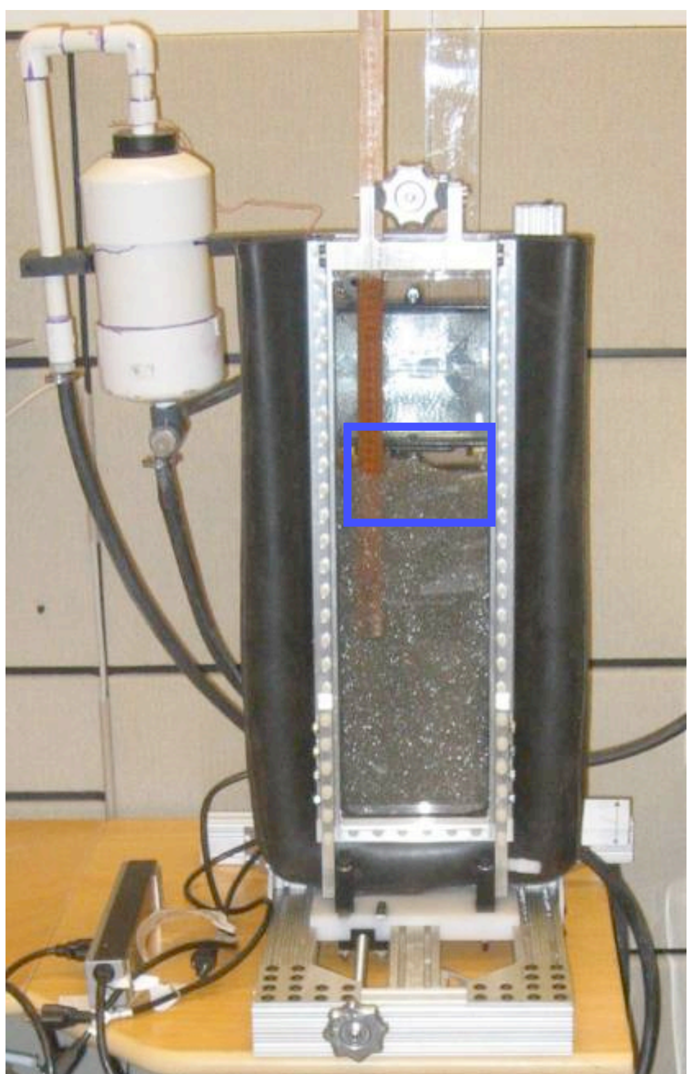

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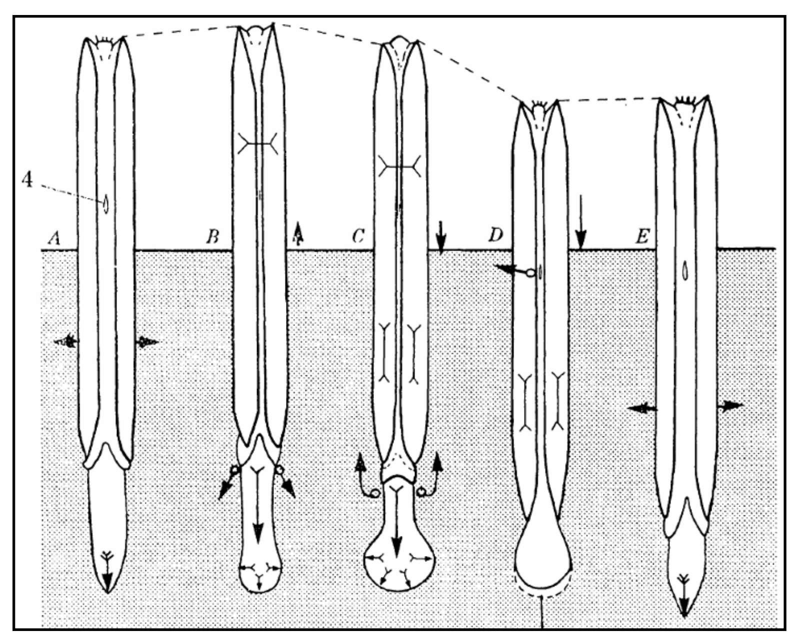

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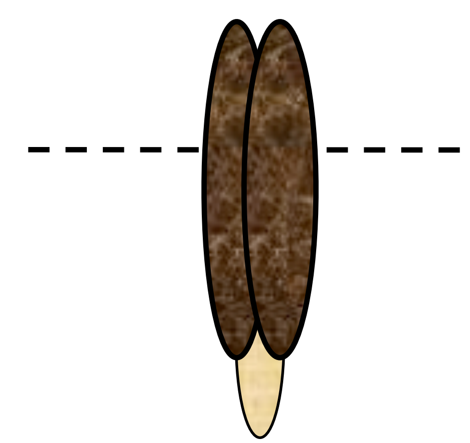

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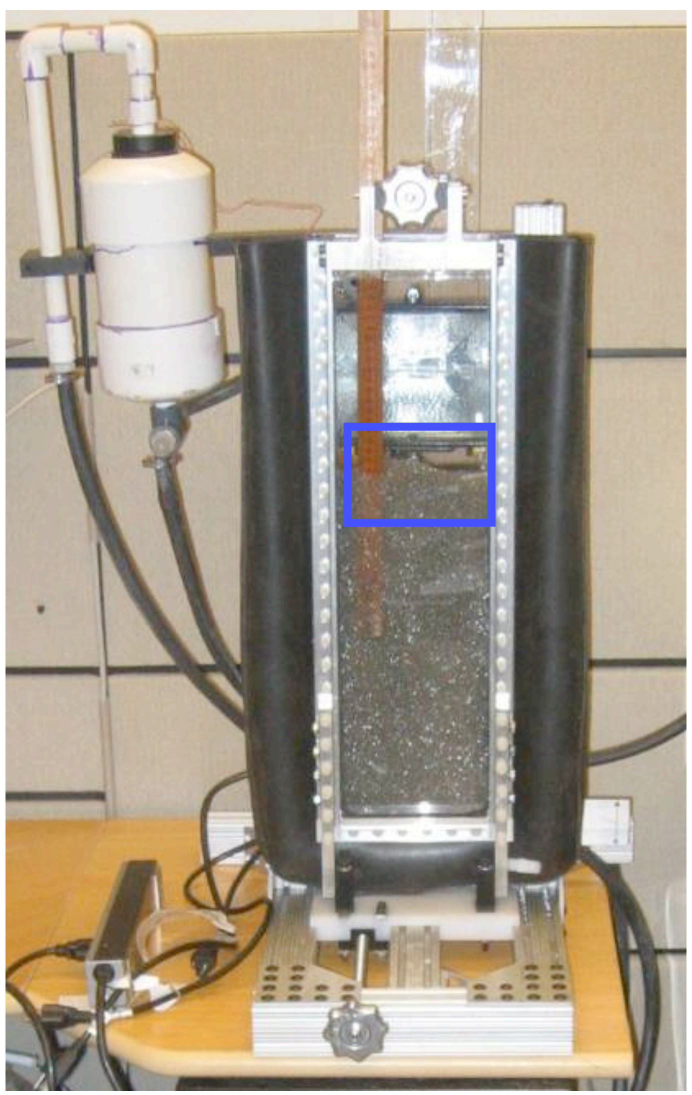

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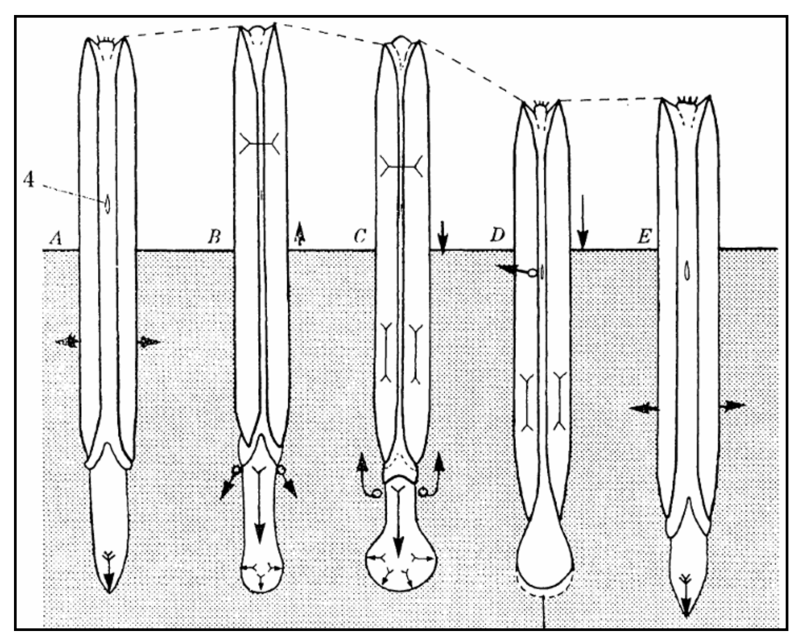

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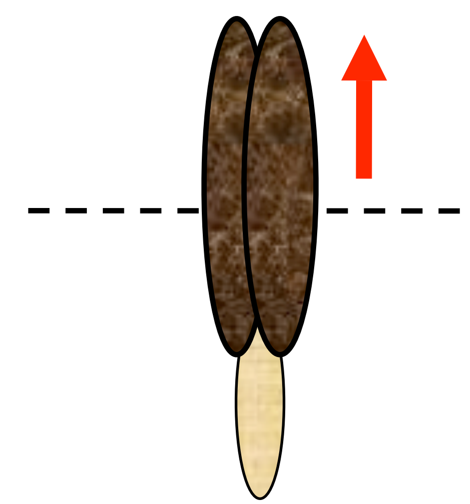

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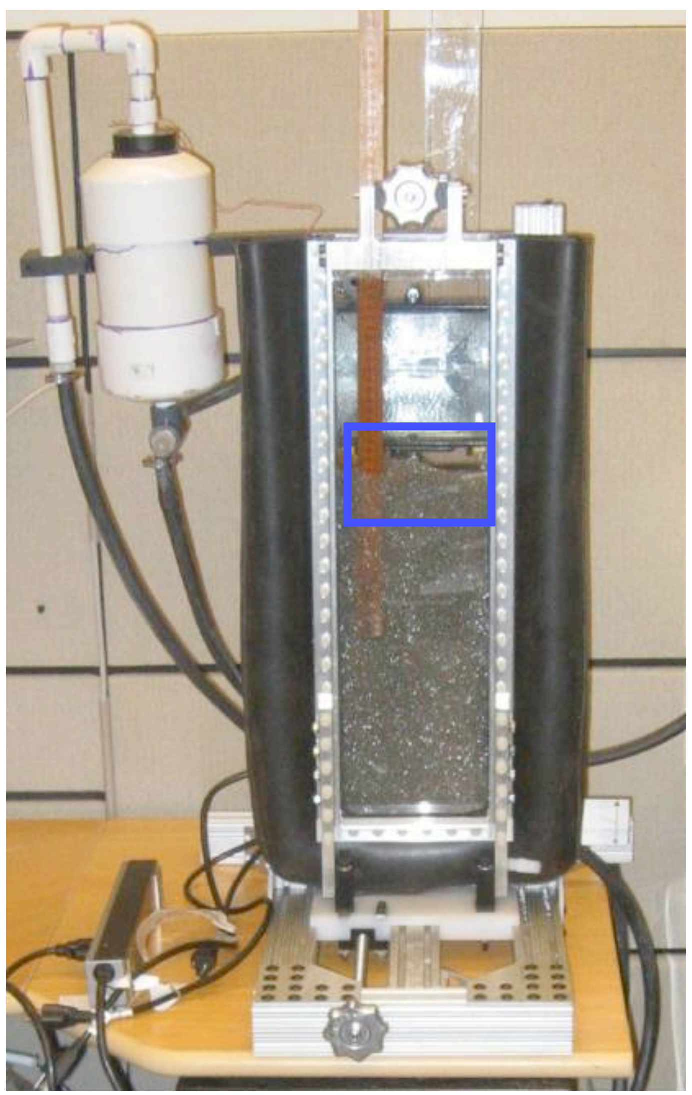

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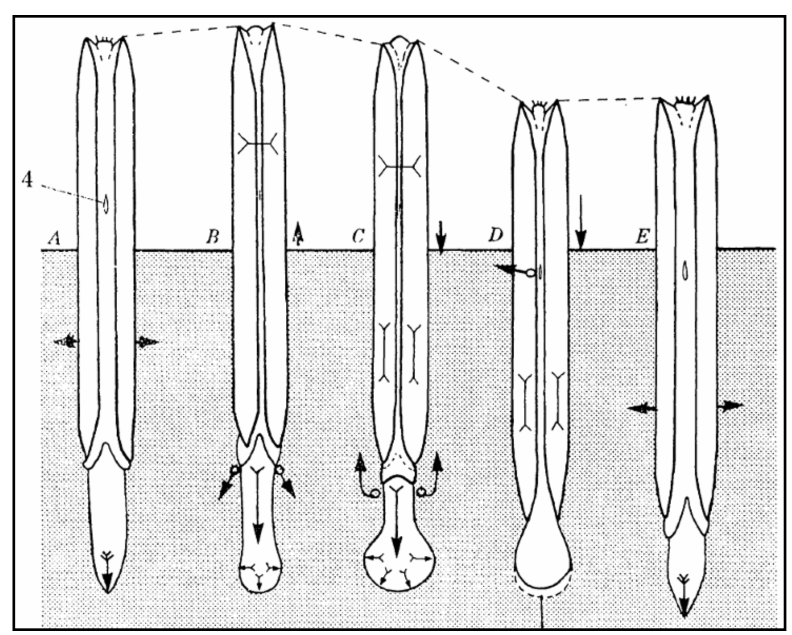

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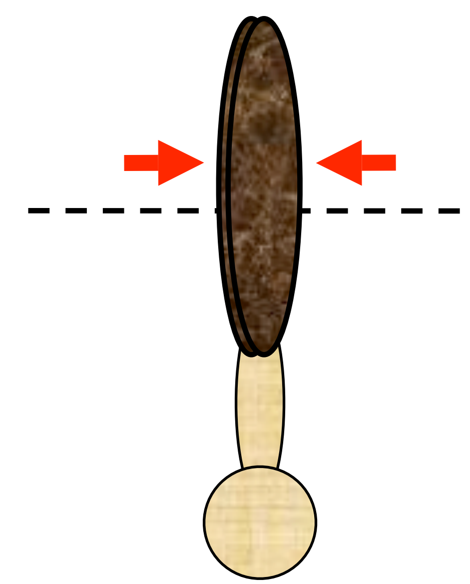

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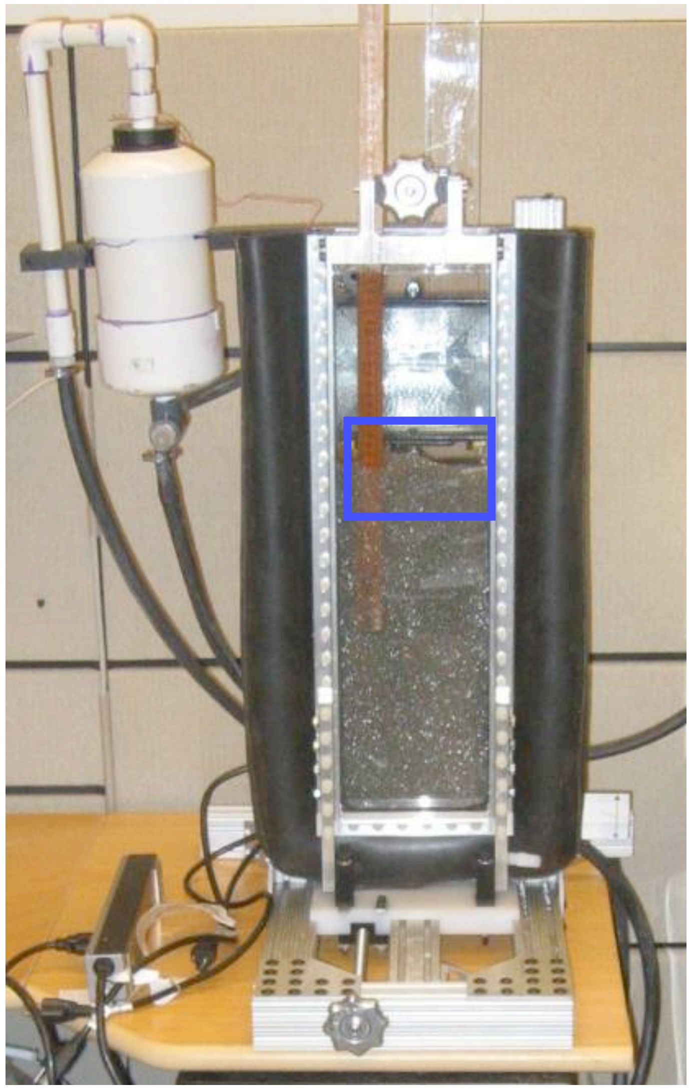

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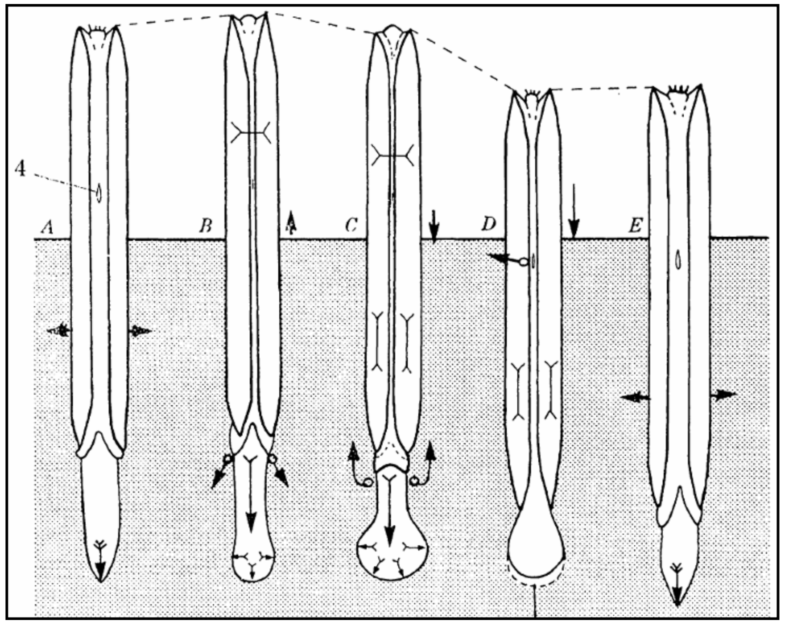
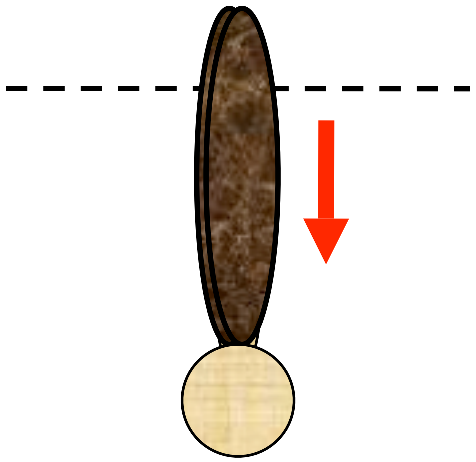


E. R. Trueman, *Proc Roy Soc Lond B Biol Sci*, 1967



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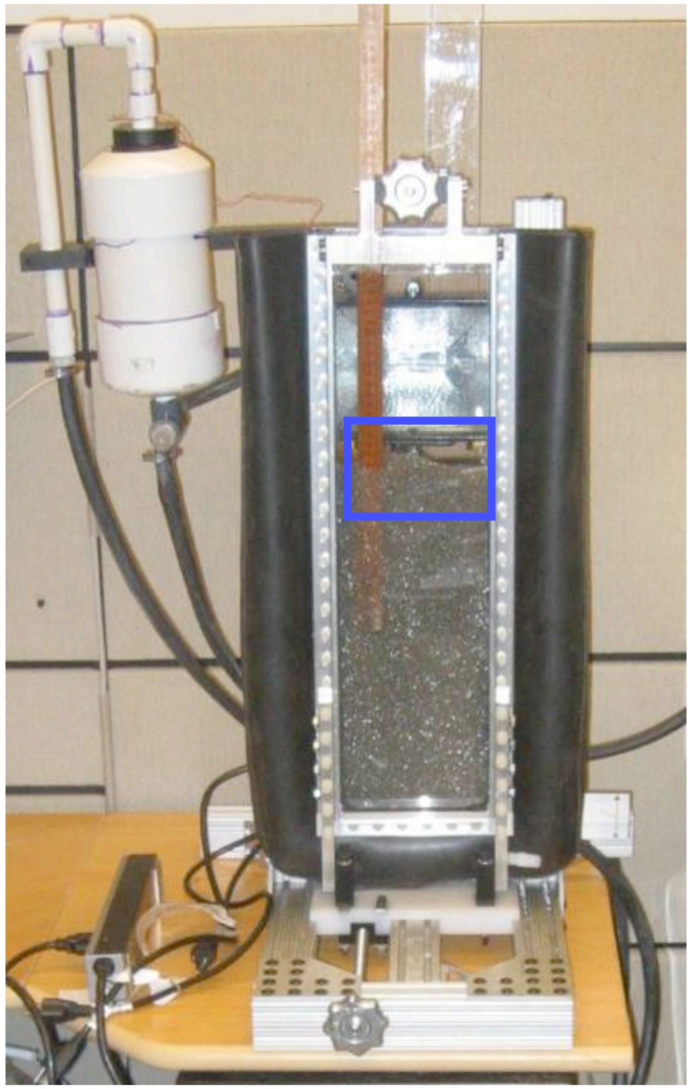

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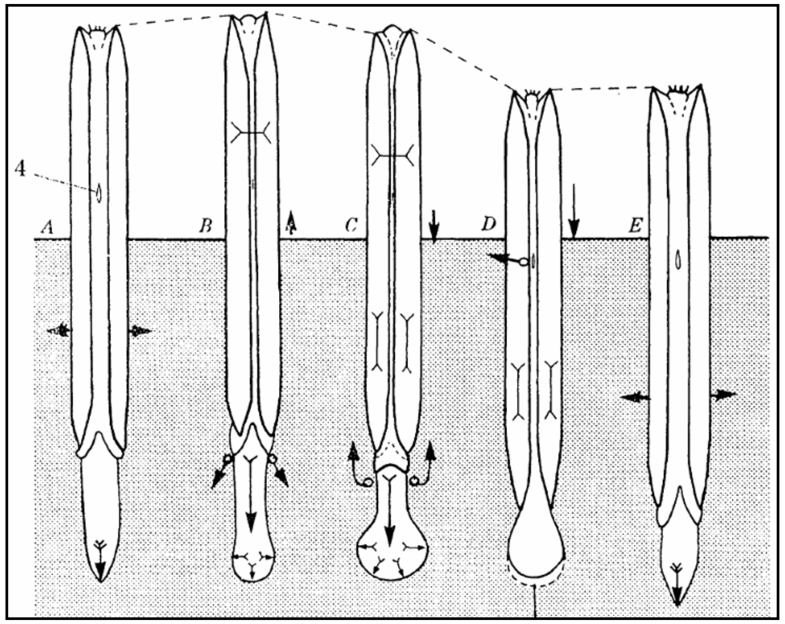

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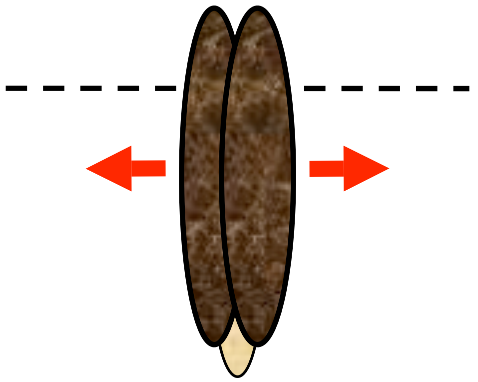
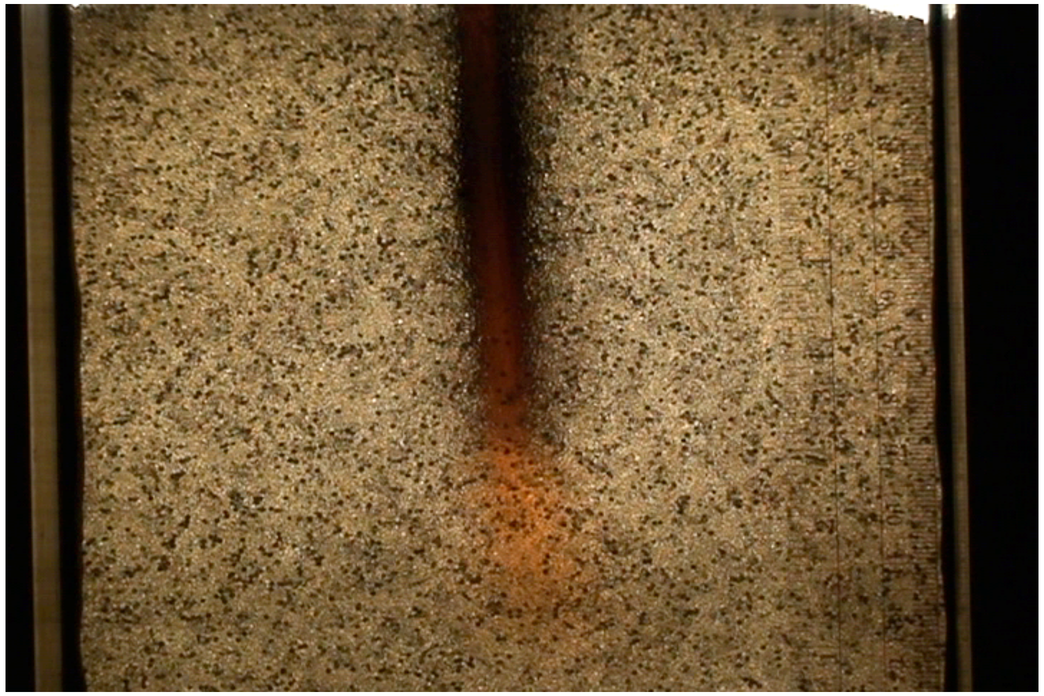
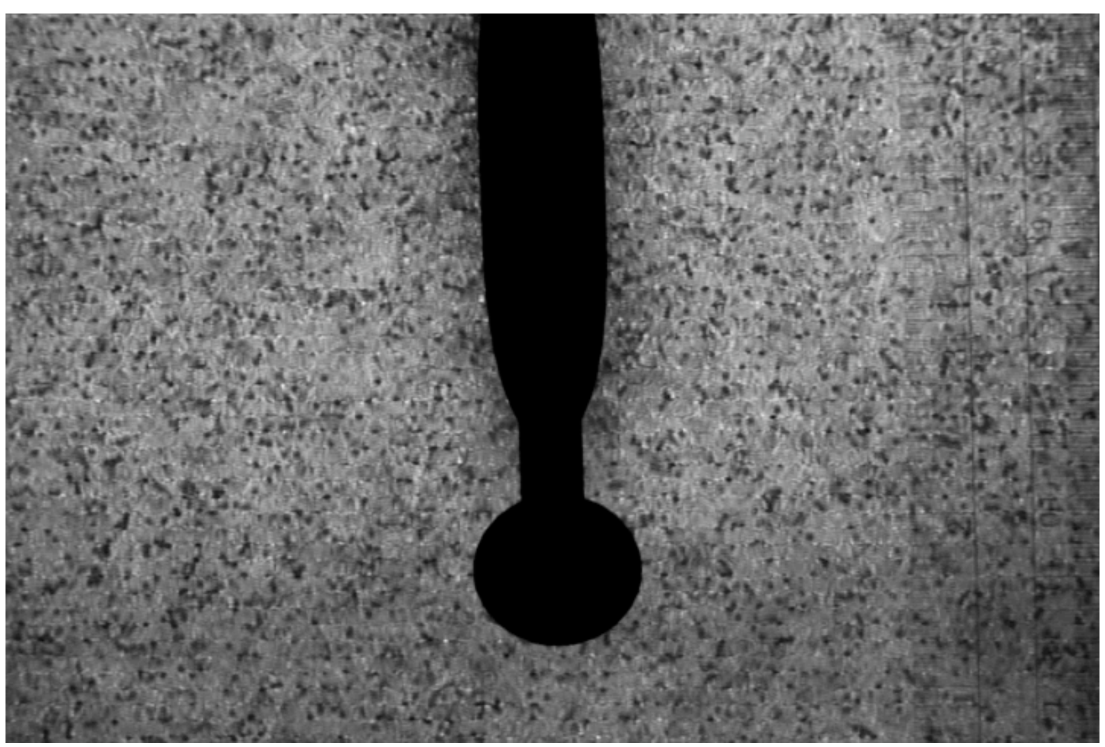


Visualizing soil deformation

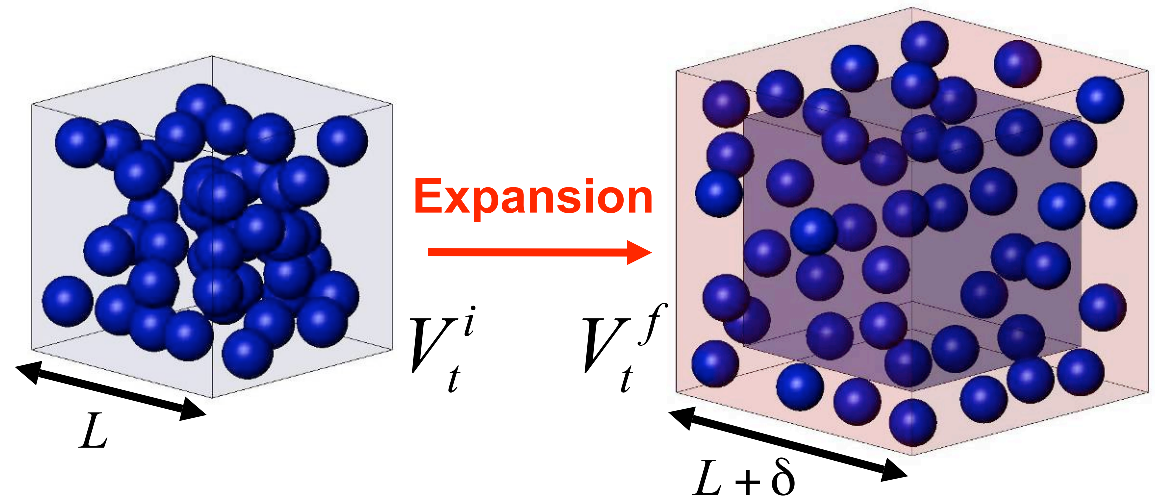


Original video frame



Masked and ready for PIV

Schematic of unpacking/porosity vs. volumetric strain



Initial solid volume in small cube : V_s^i

Final solid volume in small cube : $V_s^f = V_s^i \dfrac{V_t^i}{V_t^f}$

Initial porosity : $\phi^i = \dfrac{V_t^i - V_s^i}{V_t^i}$, final porosity : $\phi^f = \dfrac{V_t^f - V_s^f}{V_t^f}$

Displacement : $\partial\delta_i = \dfrac{\partial\delta_i}{\partial t} dt$, Strain : $\varepsilon_{ij} = \dfrac{1}{2}\left(\dfrac{\partial\delta_i}{\partial x_j} + \dfrac{\partial\delta_j}{\partial x_i}\right)$

Volumetric strain : $e = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} = \dfrac{V_t^f - V_t^i}{V_t^i}$

$$e = \frac{V_s^i - V_s^f}{V_s^f} = \frac{V_t^i(\phi^f - \phi^i)}{V_t^i(1 - \phi^f)} \Rightarrow \boxed{\frac{e + \phi^i}{1 + e} = \phi^f}$$

Localized fluidization

PIV of clam contraction

Original burrow video

$$\frac{\phi_f}{\phi_i}$$

Fluidization: ϕ >0.4
(>1.05 on colorbar)

C.Y. Wen, *Chem. Eng. Prog.*, 1966

Clam velocity vs. flow velocity required to fluidize

$$v_{clam} = 1.25 cm/s \ \ (\text{Trueman}, 1965)$$

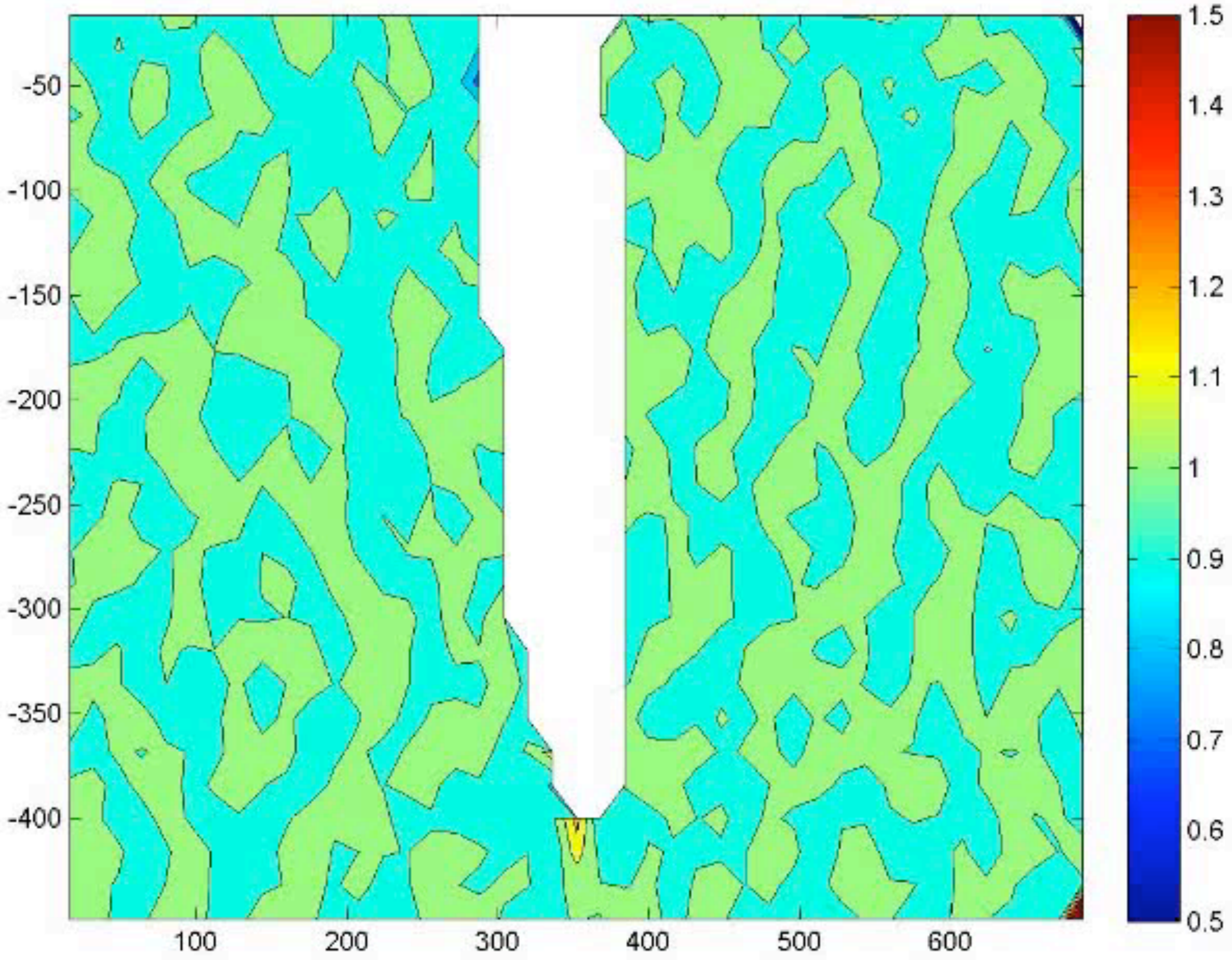
$$v_{clam} = 1.05 \pm 0.05 cm/s \ \ (\text{experiment})$$

$$v_{fluidize} = 1.35 cm/s \ (d = 1\text{mm}, \phi = 0.4)$$

L. G. Gibilaro, *Fluidization-dynamics*, 2001

Localized fluidization

PIV of clam contraction



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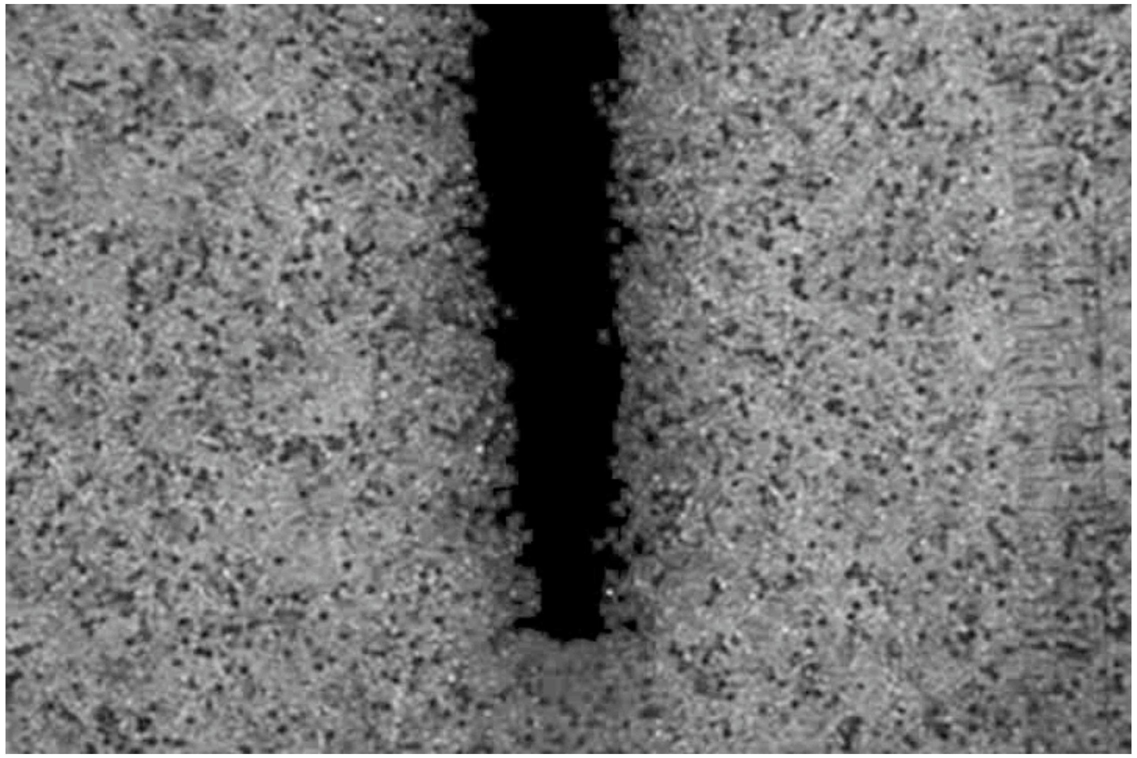

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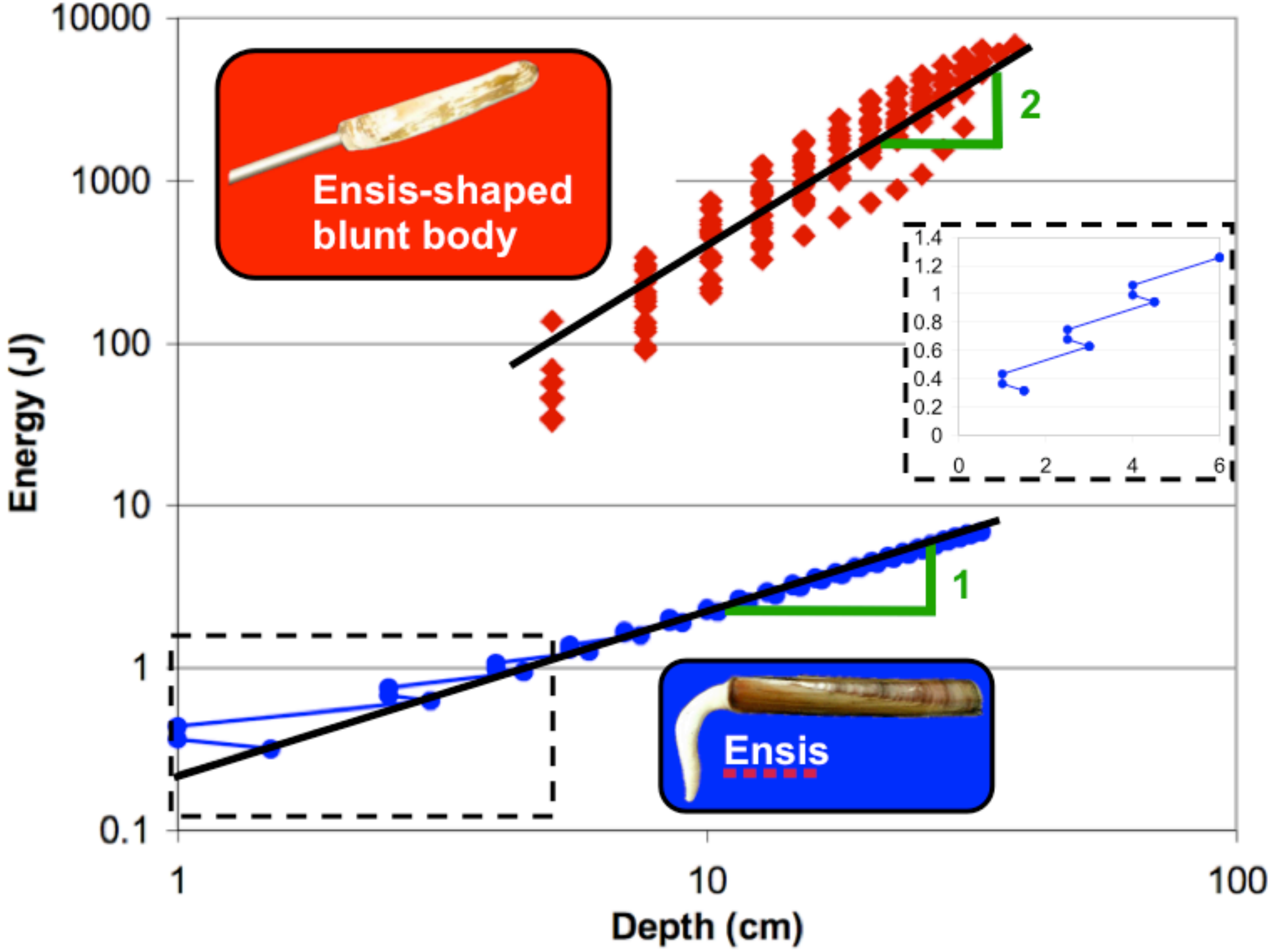
L. G. Gibilaro, *Fluidization-dynamics*, 2001

Fluidization energy savings



E. R. Trueman, *Proc Roy Soc Lond B Biol Sci*, 1967

The RoboClam

US patent application number 12455392

The RoboClam

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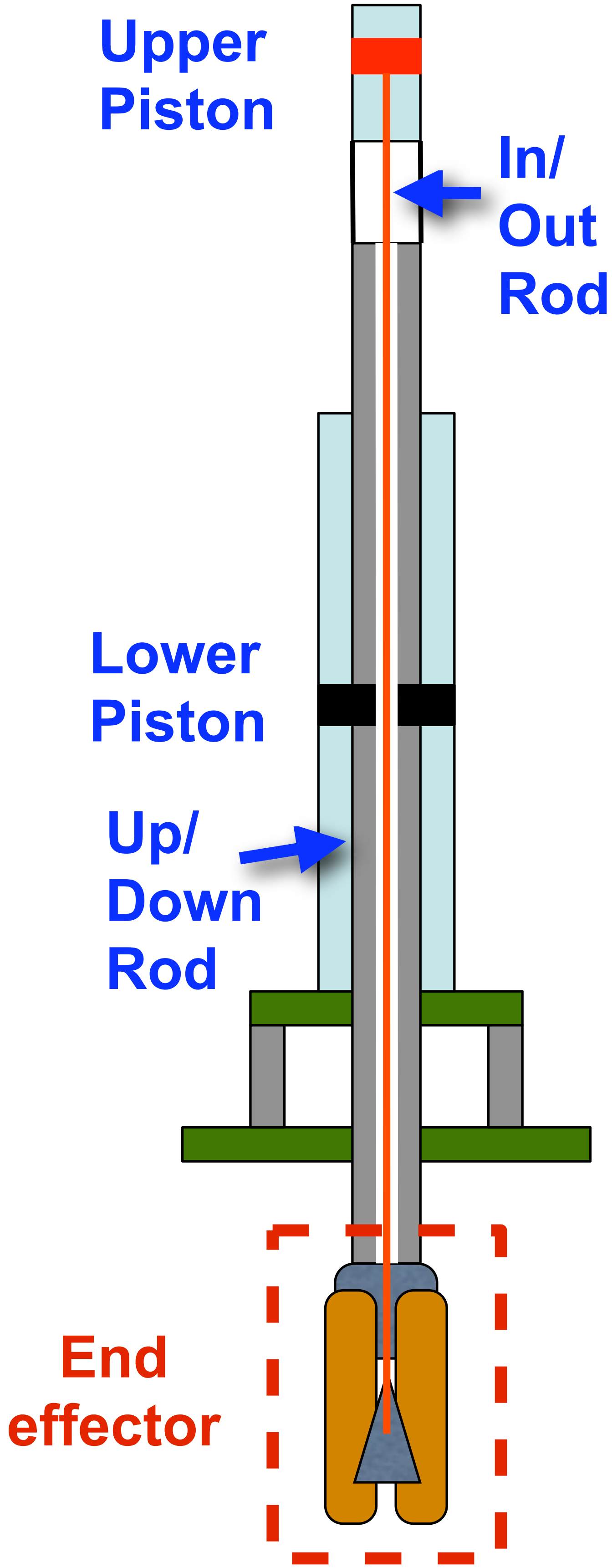
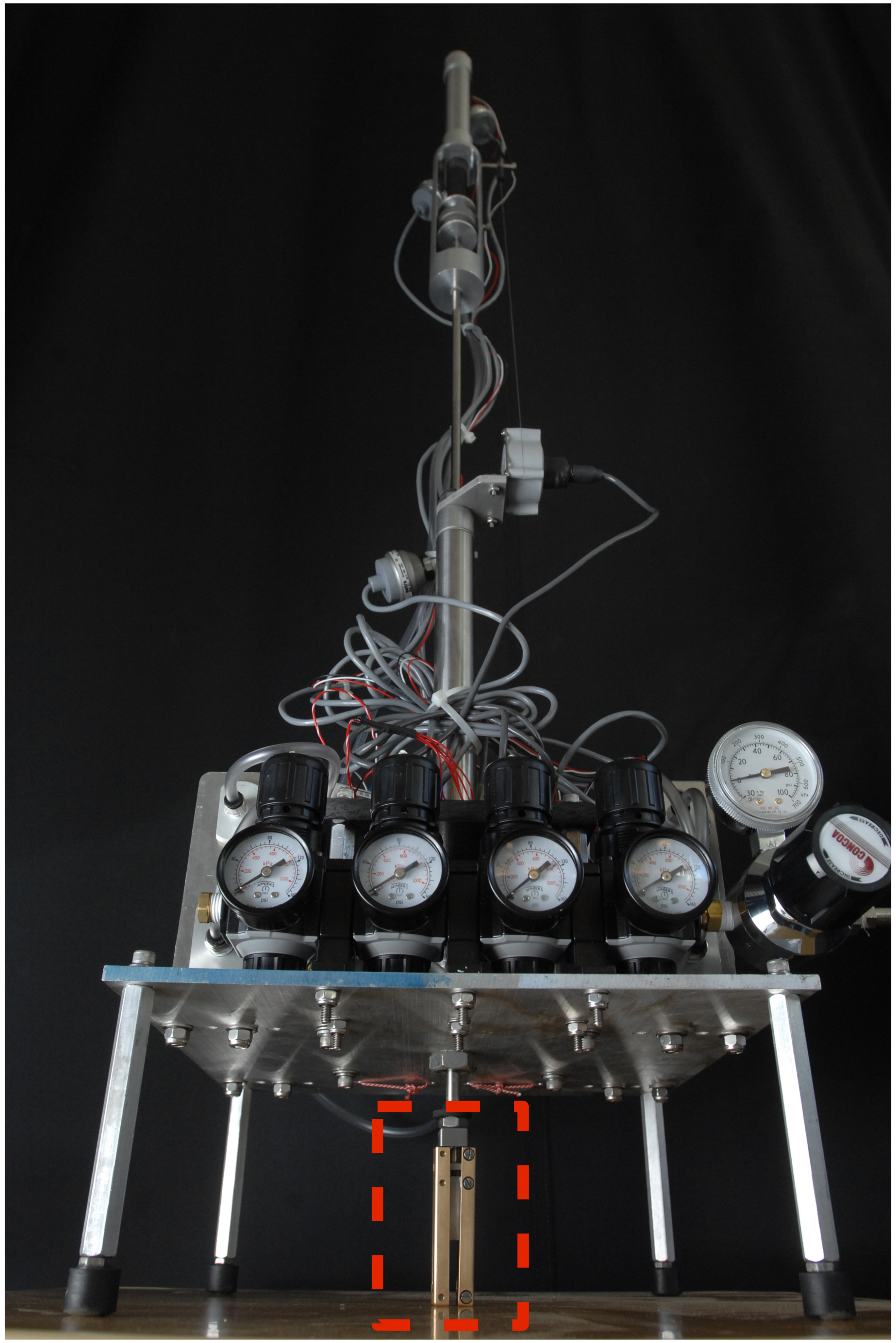
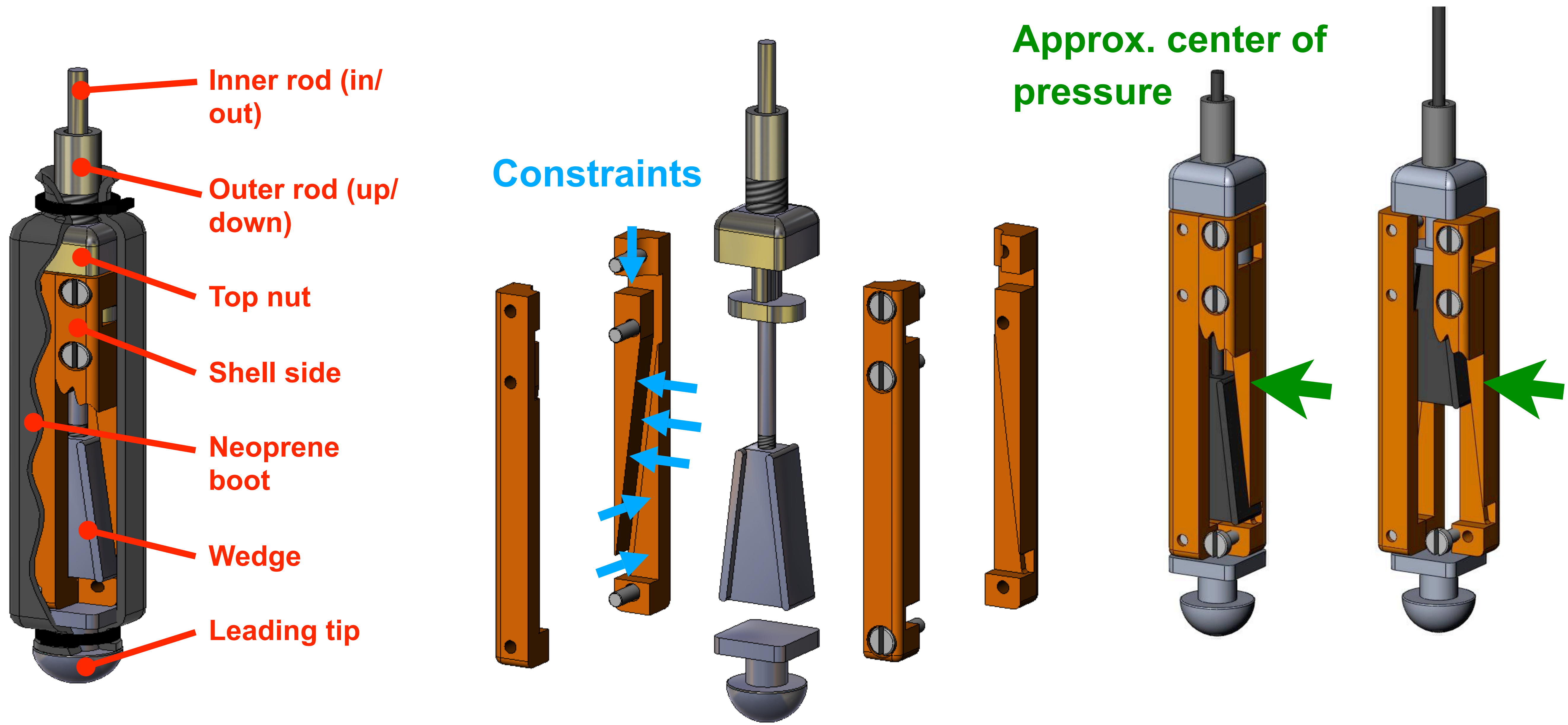
RoboClam layout





End effector

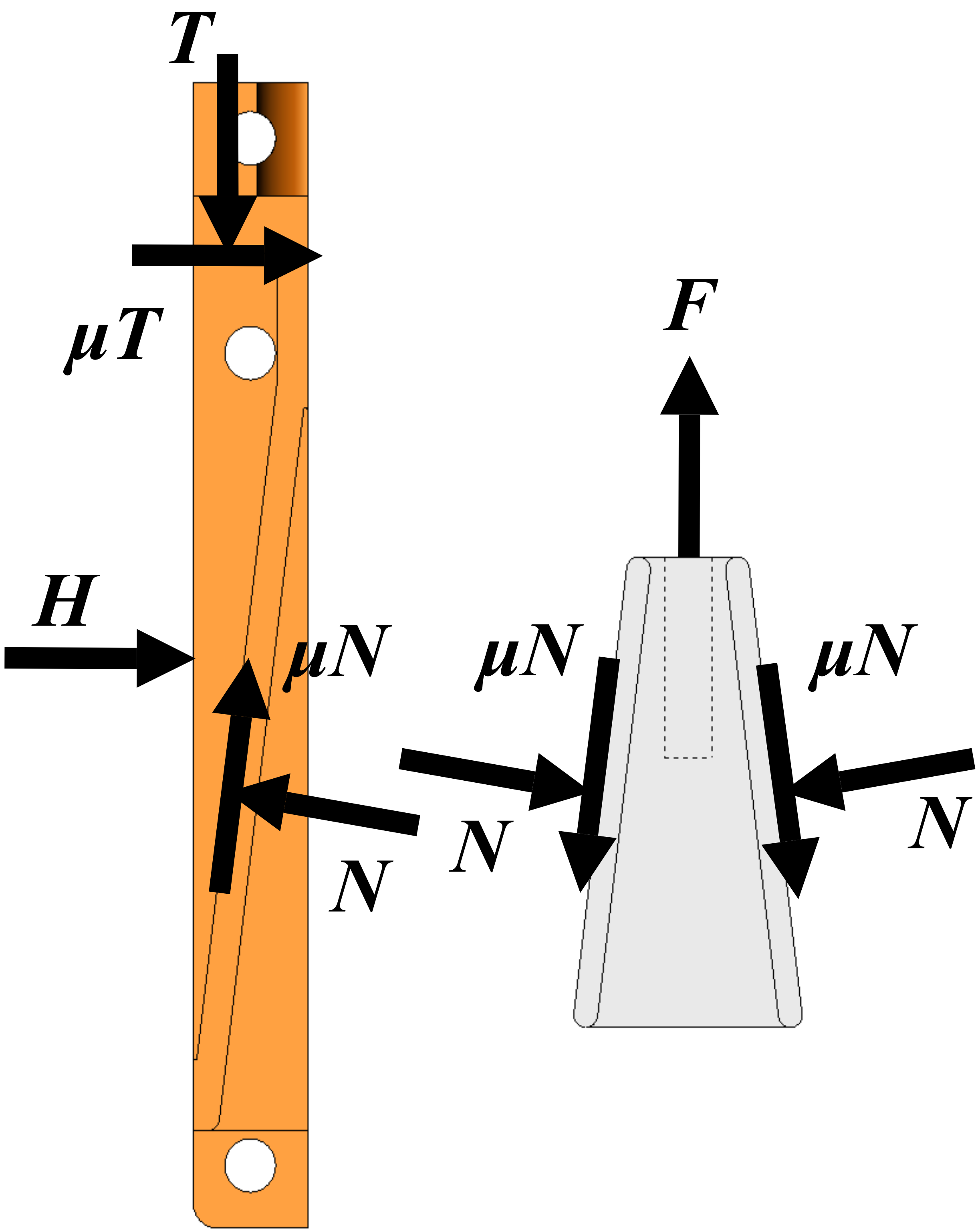
End effector design



Deterministic design

- Exact constraint design - jam prevention and predictable loading
- Wedge spans geometric center of shells

End effector performance



Transmission ratio

$$TR = \frac{H}{F} = \frac{1}{2}\left[\frac{\cos\theta - \mu\sin\theta}{\sin\theta + \mu\cos\theta} - \mu\right]$$

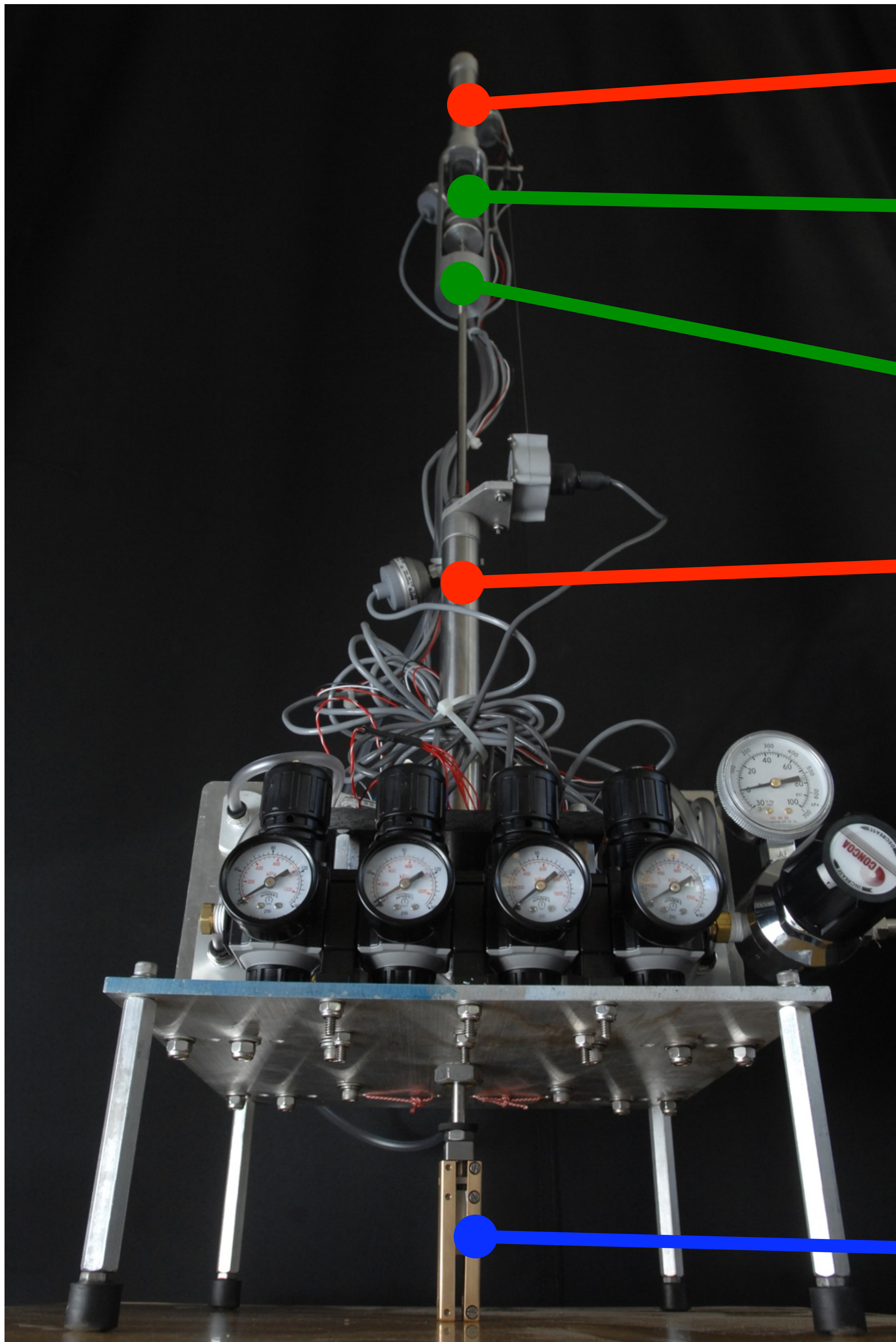
Mechanism efficiency

$$\eta = \frac{E_{in}}{E_{out}} = 2\frac{H\delta_x}{F\delta_y} = 2TR\sin\theta$$

μ was measured

Effector made from alloy 932 (SAE 660) bearing bronze and 440C stainless steel

Energy losses in RoboClam



Piston friction

Potential energy

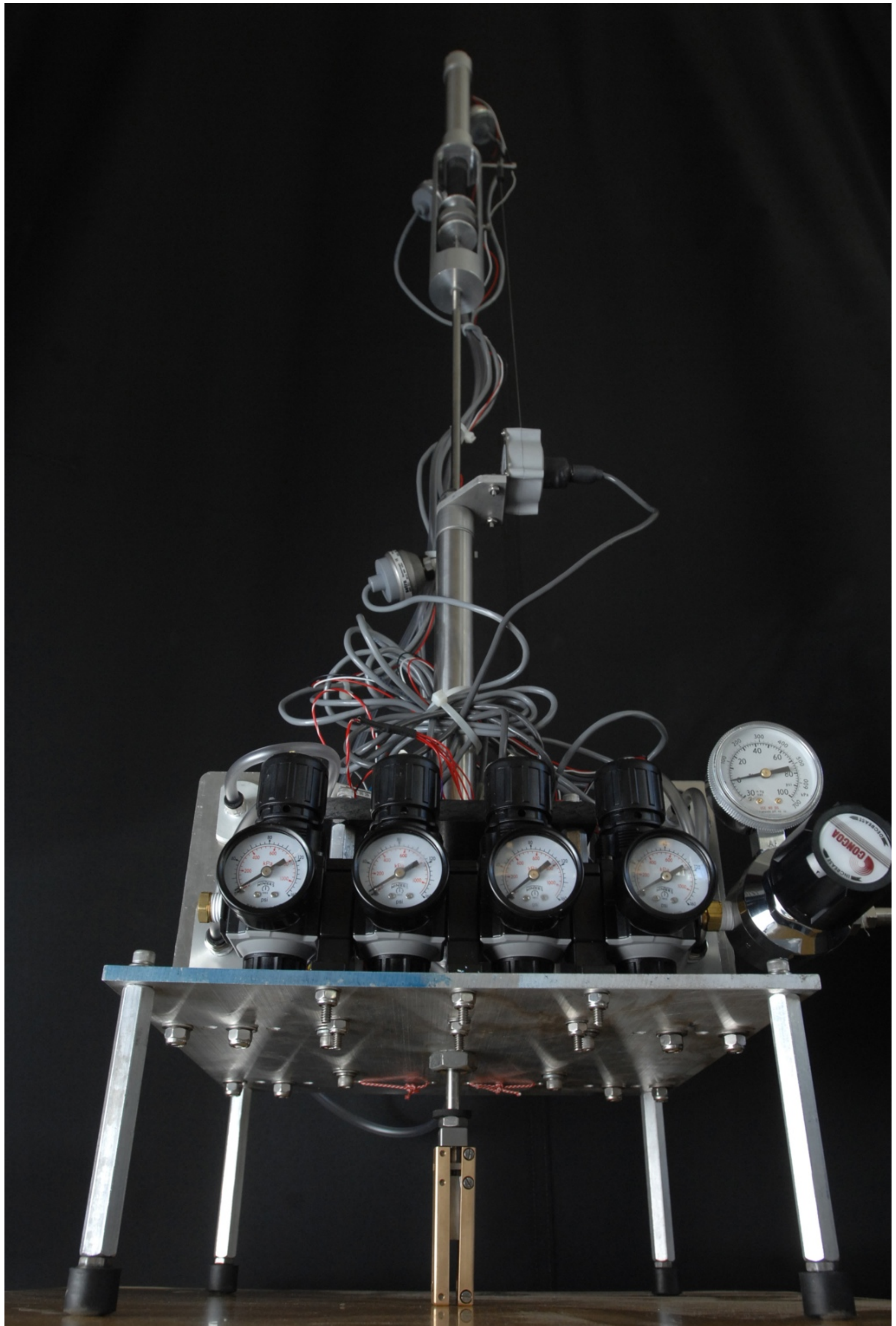
Potential energy

Piston friction

Goal:
Determine soil deformation energy

End effector mechanism efficiency

Energy losses in RoboClam



Up/down energy

$$E_{soil} = E_{in} - E_{friction} - E_{potential}$$

$$= \int_{\delta_1}^{\delta_2} \Delta p_u A_u dy - \left| F_{u,friction} (\delta_2 - \delta_1) \right|$$

$$- m_u g (\delta_2 - \delta_1)$$

In/out energy

$$E_{soil} = \eta \left(E_{in} - E_{friction} - E_{potential} \right) - E_{boot}$$

$$= \eta \left[\int_{\delta_1}^{\delta_2} \Delta p_i A_i dy - \left| F_{i,friction} (\delta_2 - \delta_1) \right| \right.$$

$$\left. - m_i g (\delta_2 - \delta_1) \right] - 0$$

Genetic algorithm (GA)

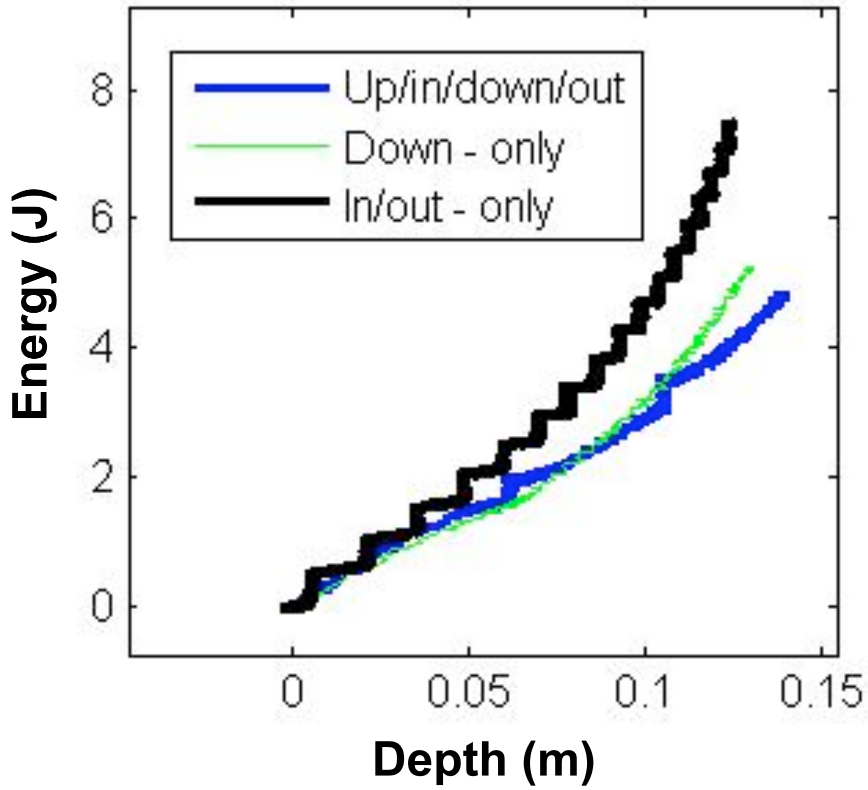
- GA: based on the idea of a competing population of organisms
- Each individual is a set of parameters to be used by the robot

  (i.e. pressures, timescales, displacements)
- Assigns a numerical "fitness" to each individual
- "Objective function" used to find the fitness of an individual:

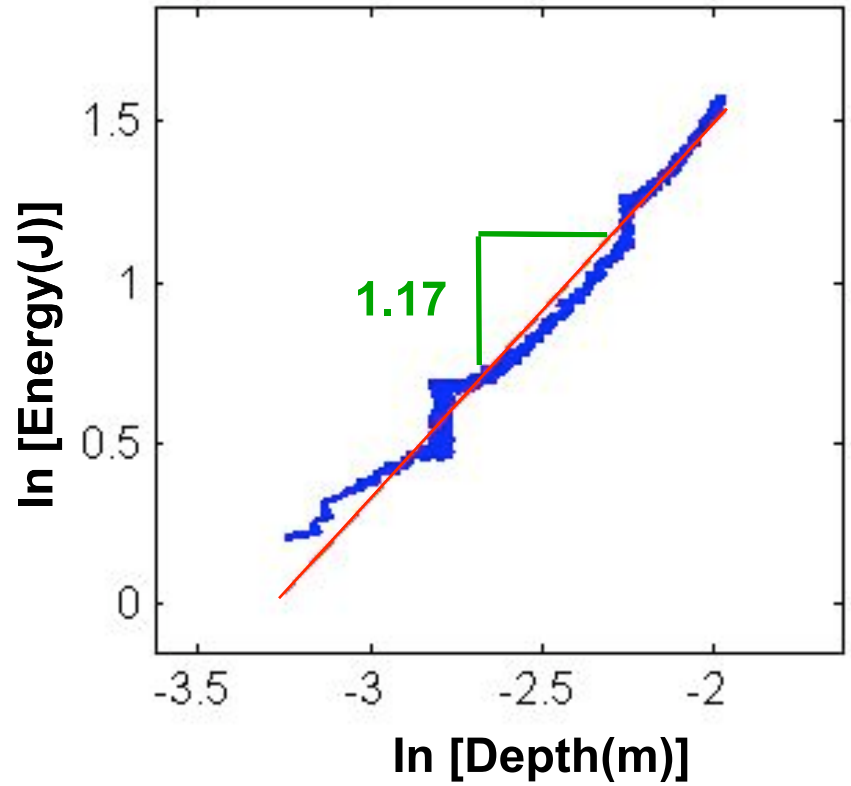
  Fitness = (energy/depth)*(power law exponent of energy vs. depth)

Laboratory test results

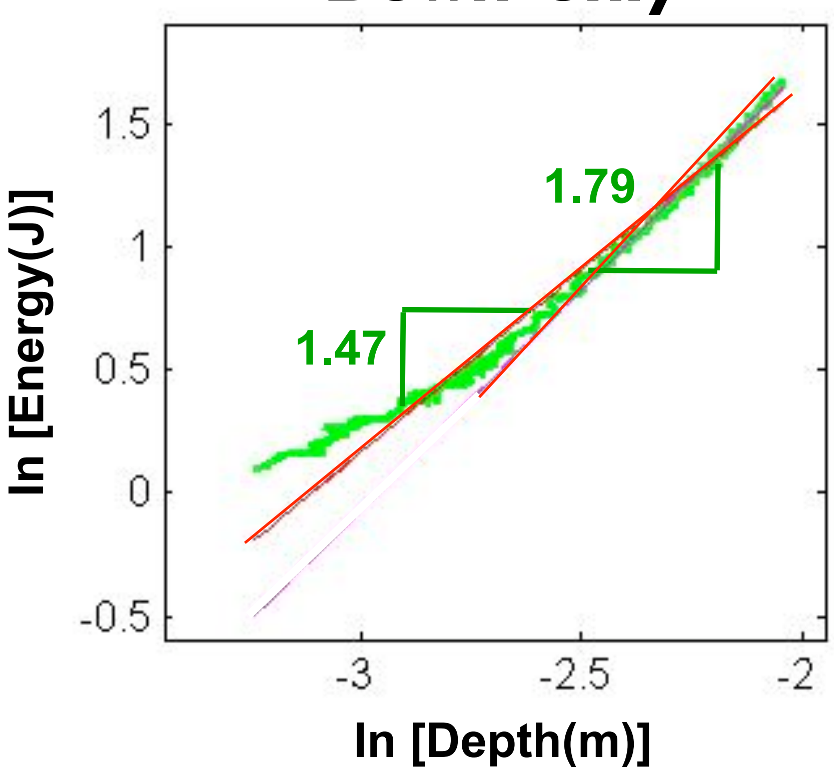
All motions



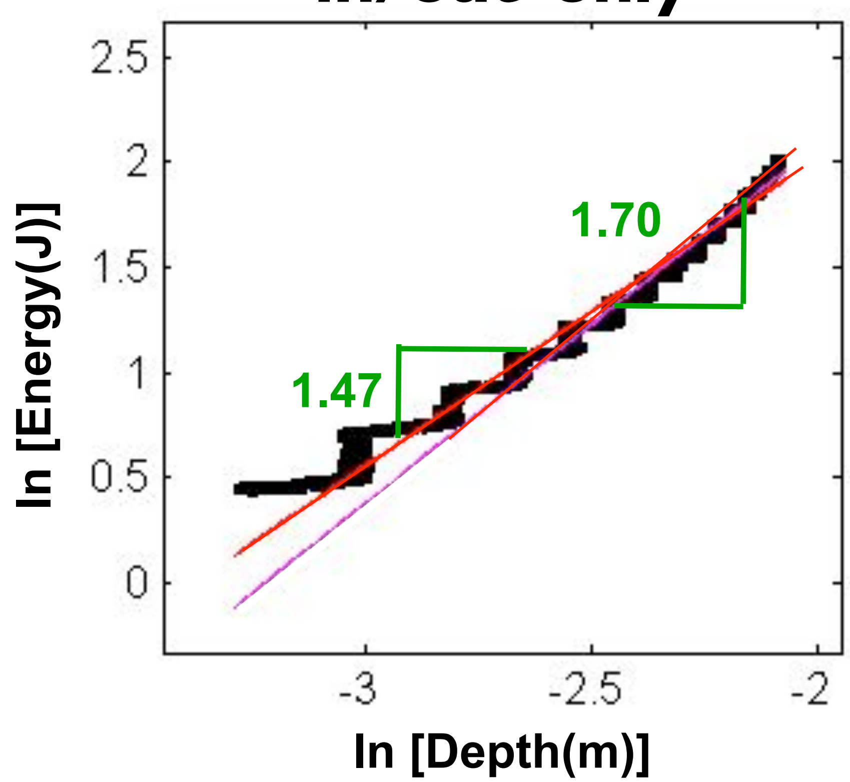
Full clam motion



Down-only



in/out-only



Movements at peak efficiency

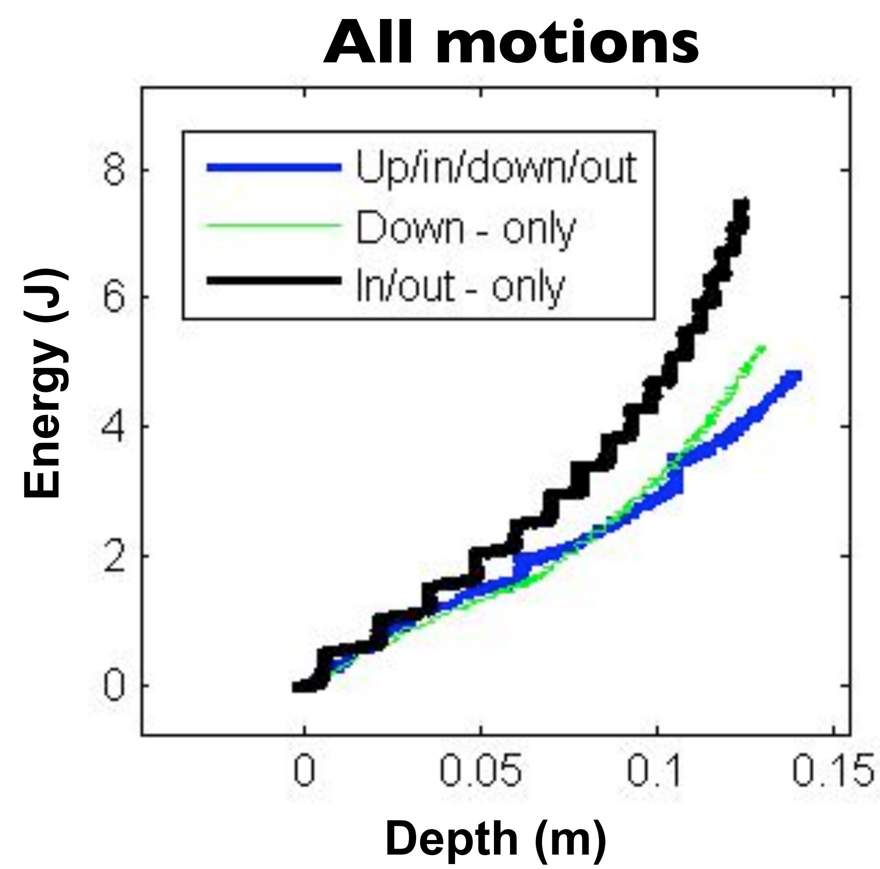
Up = 0.032s

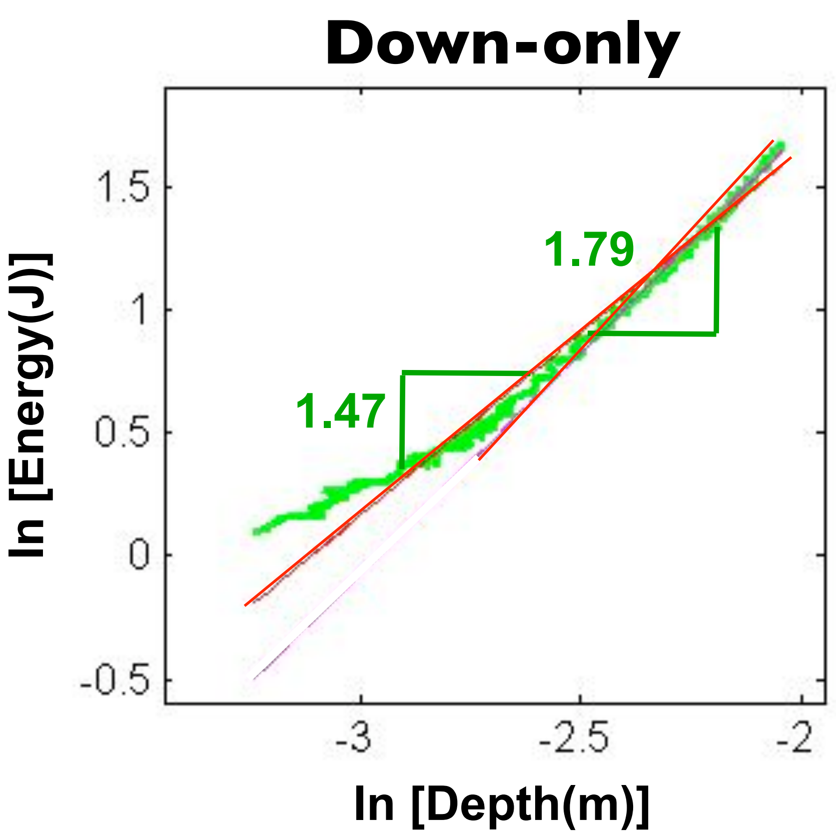
In = 6.5mm

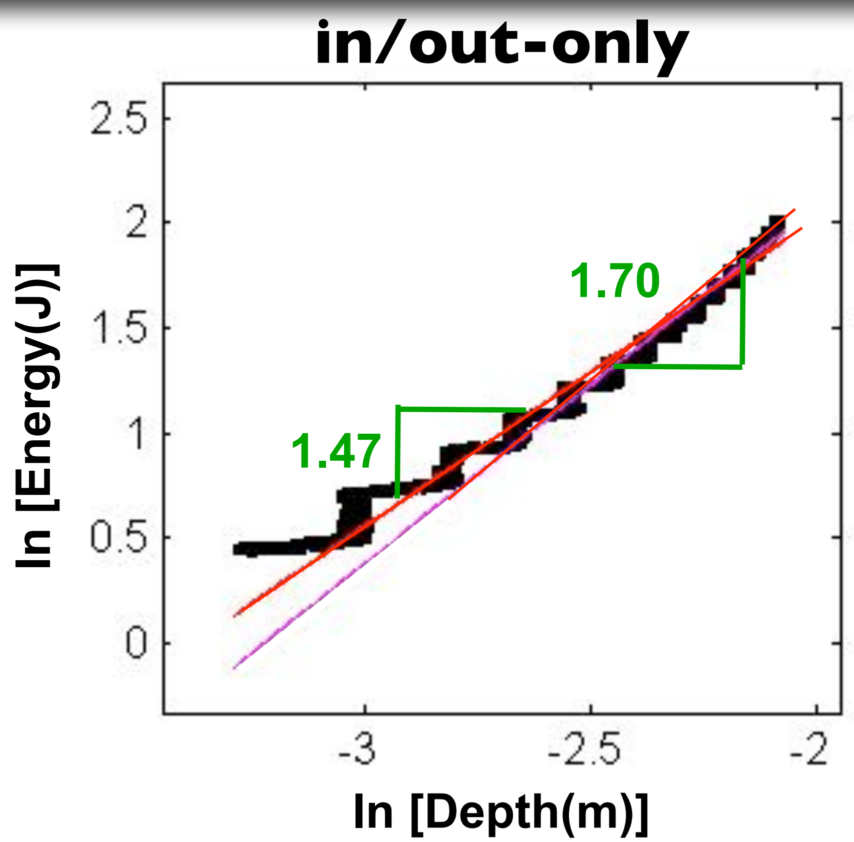
Down = 5cm

Out = 6.5mm

Laboratory test results







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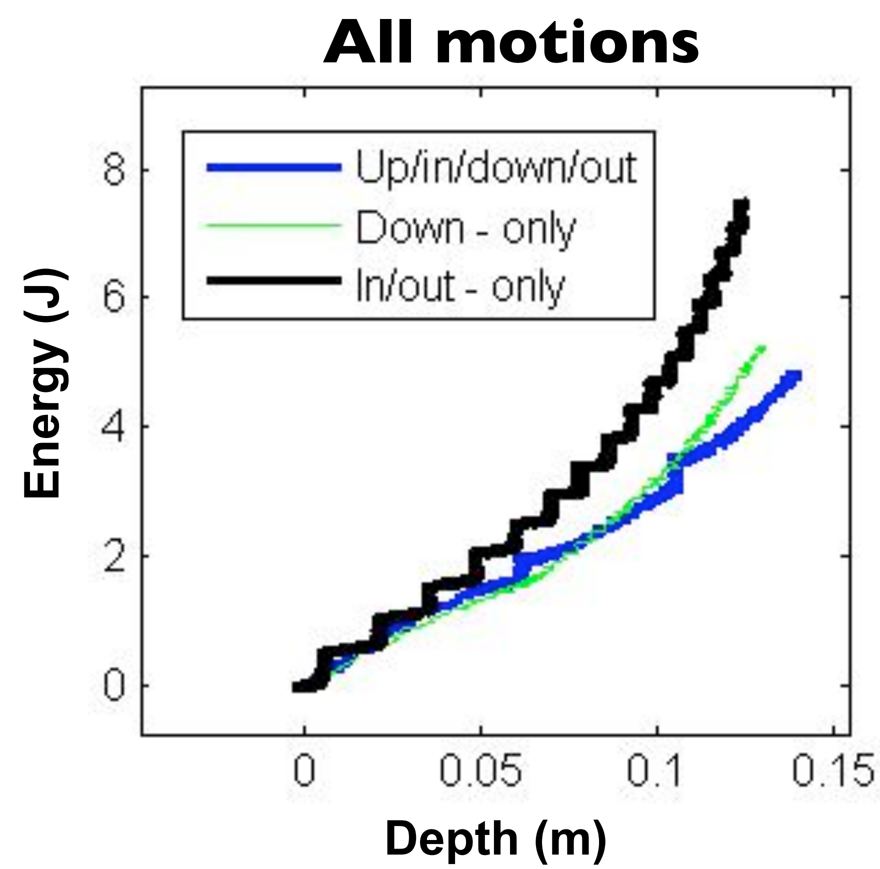

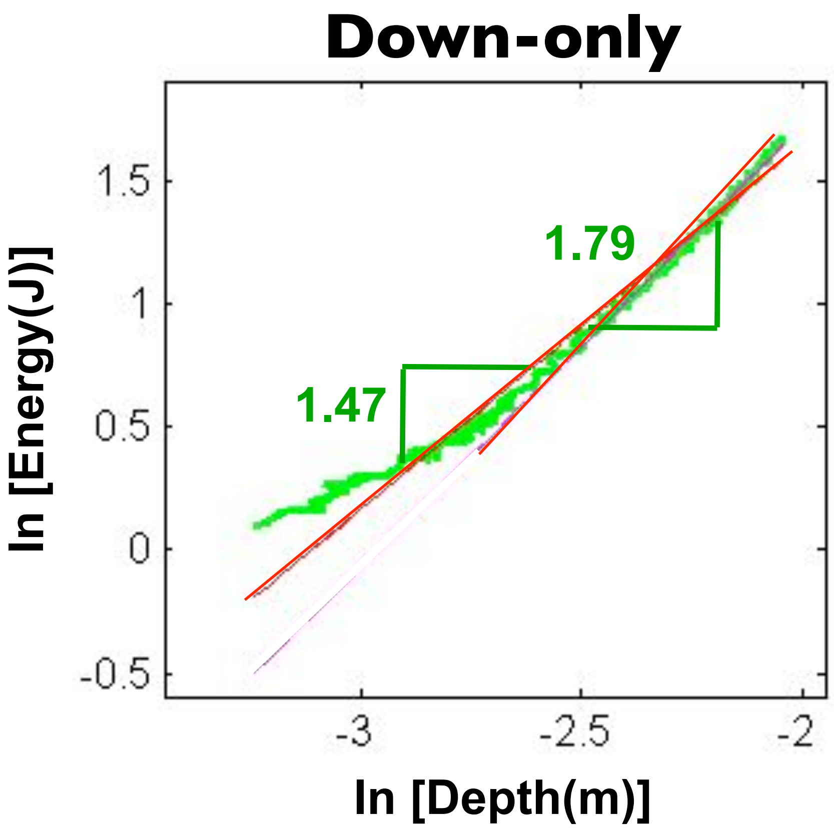

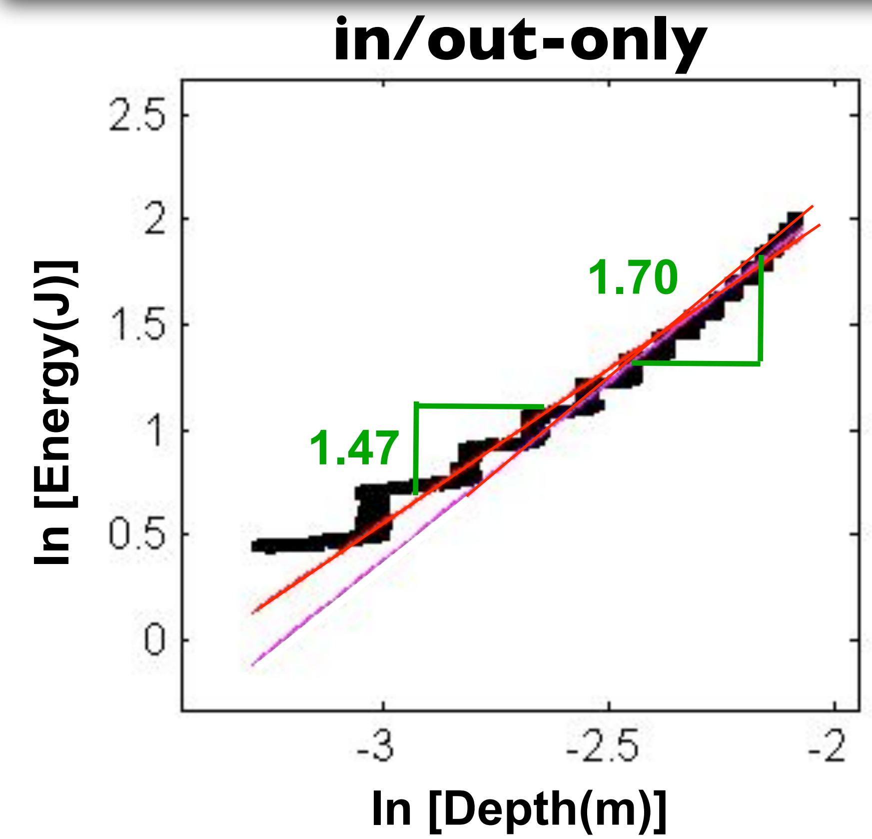

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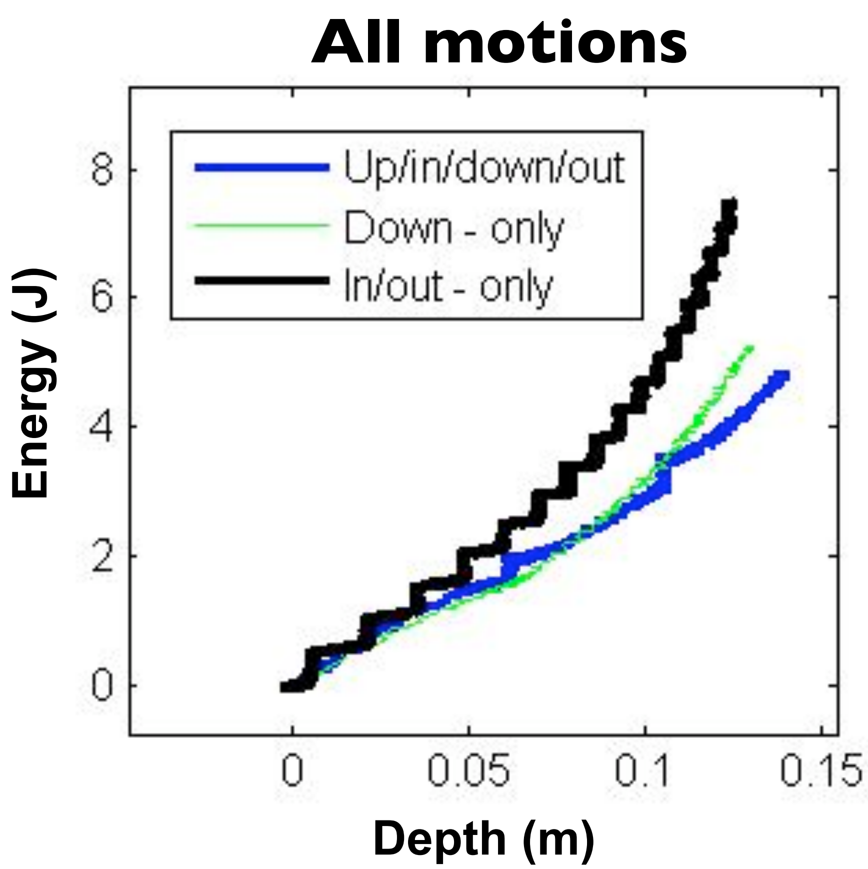

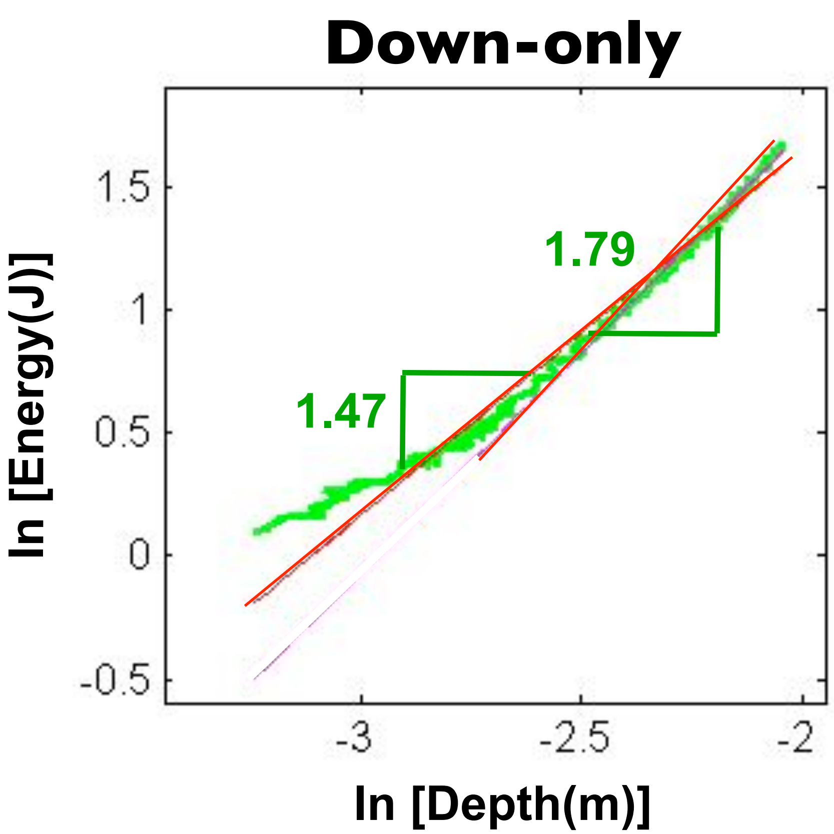

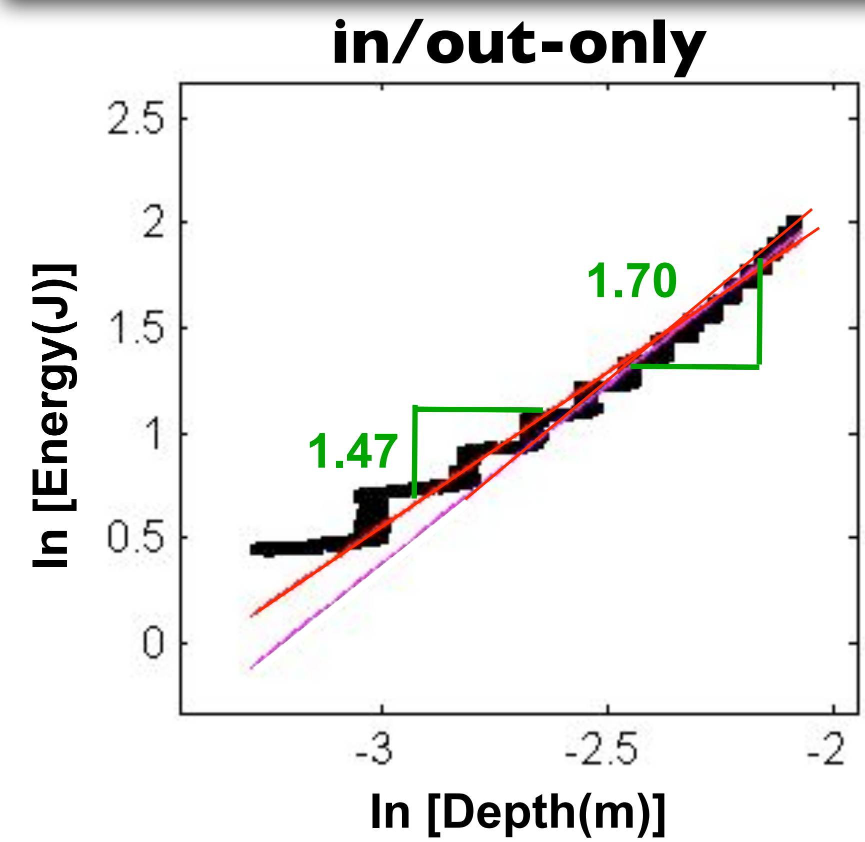

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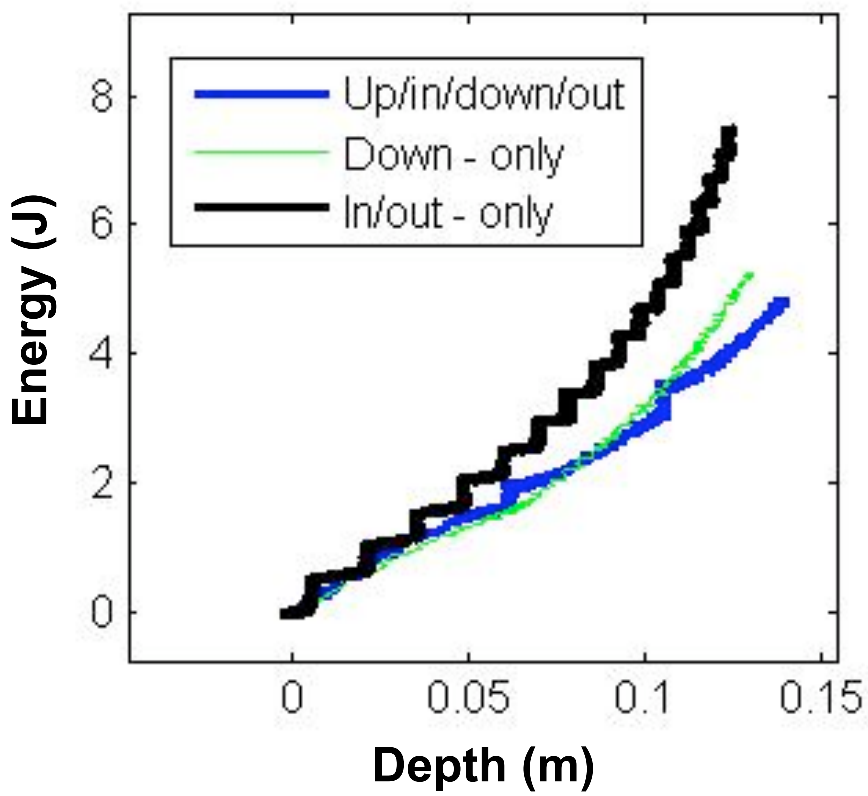
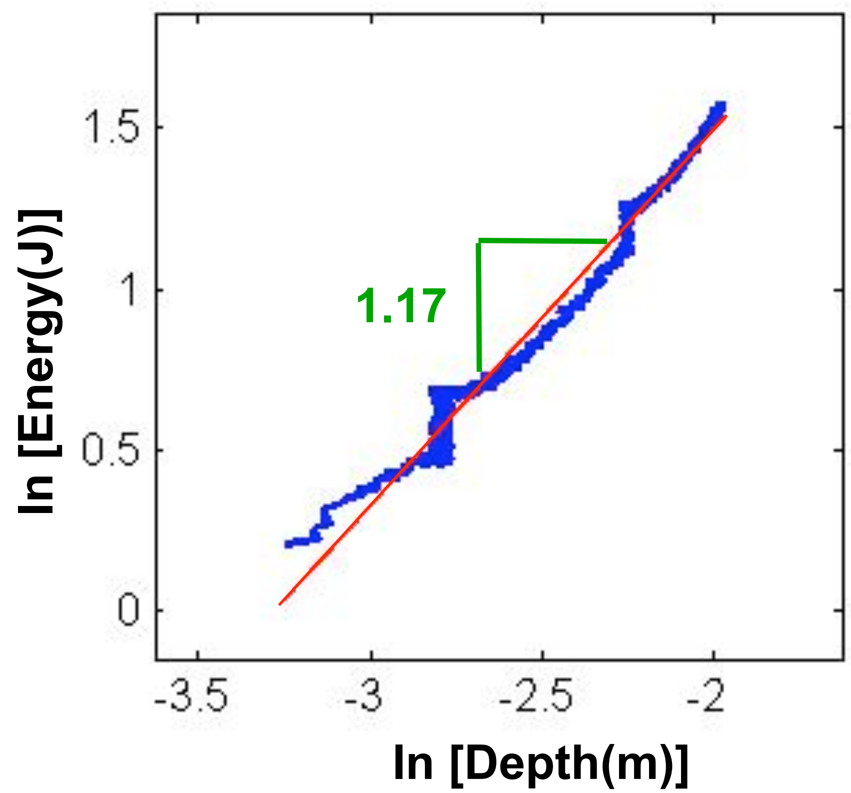
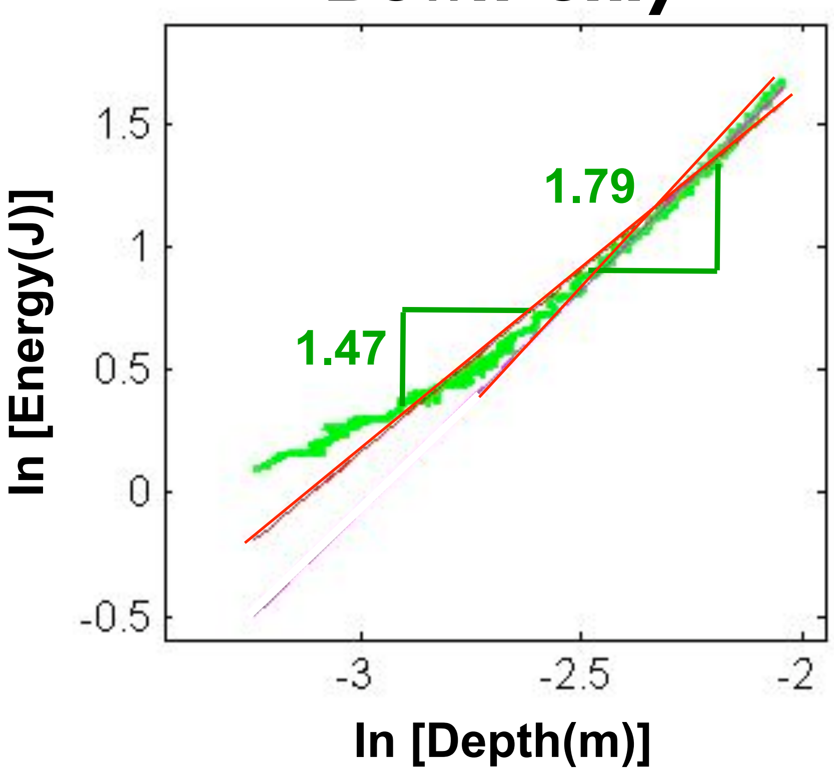


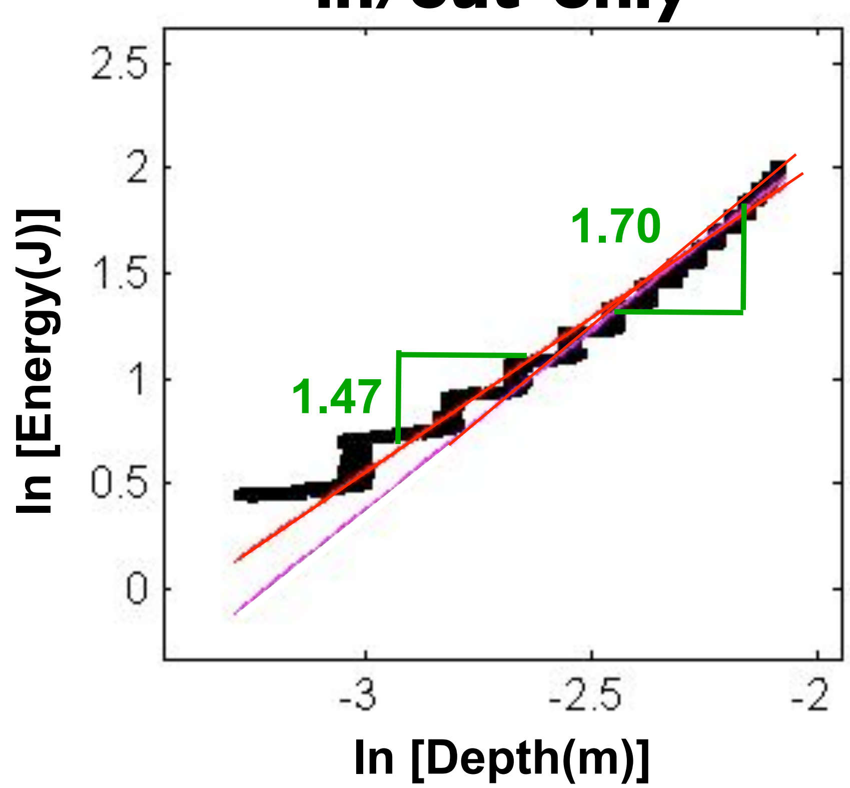
Full clam motion



Down-only



in/out-only



Movements at peak efficiency

Up = 0.032s

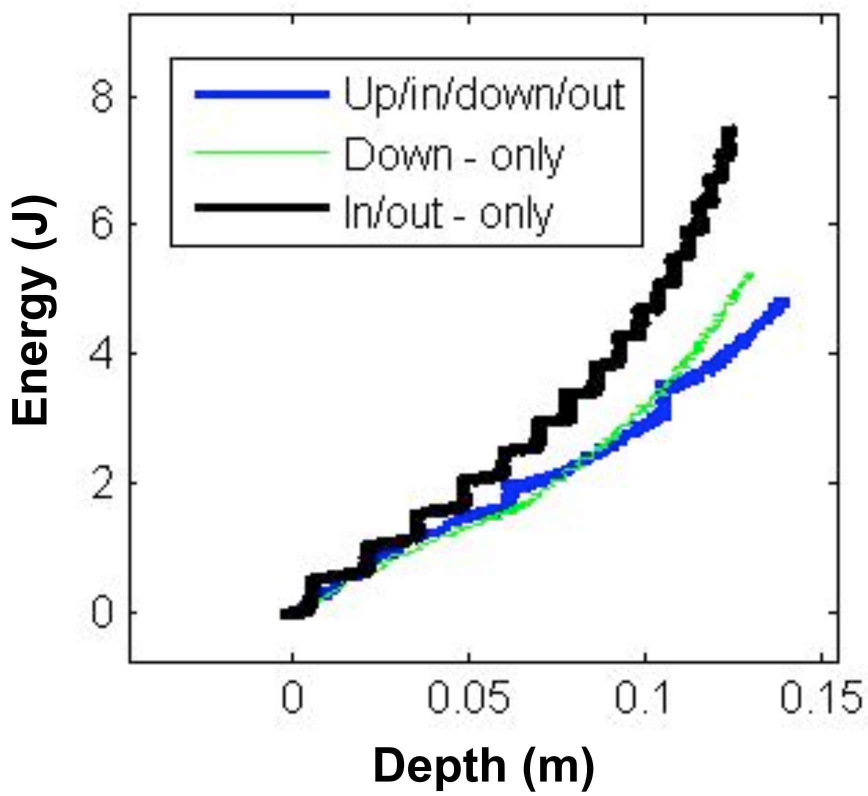
In = 6.5mm

Down = 5cm

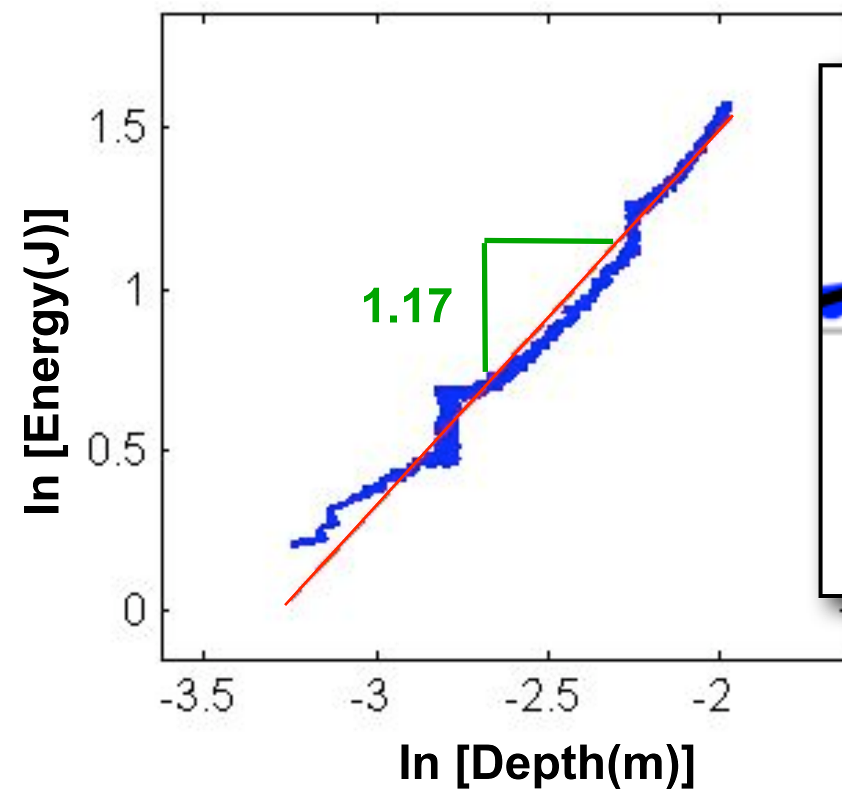
Out = 6.5mm

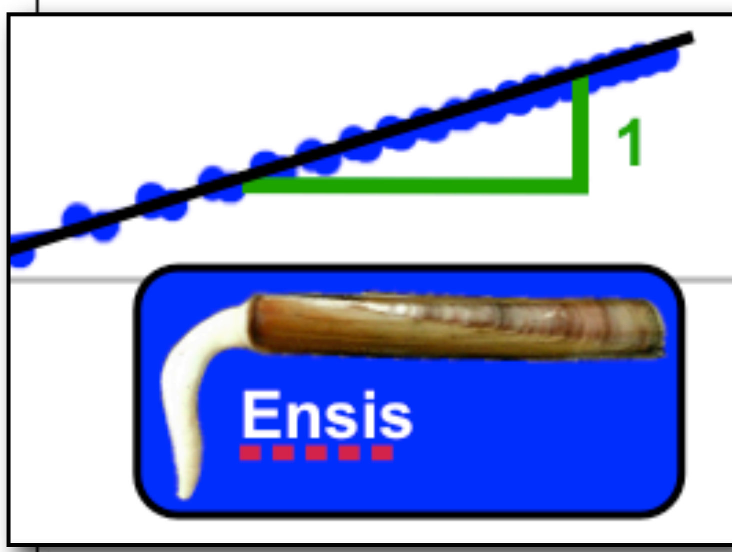
Laboratory test results

All motions



Full clam motion





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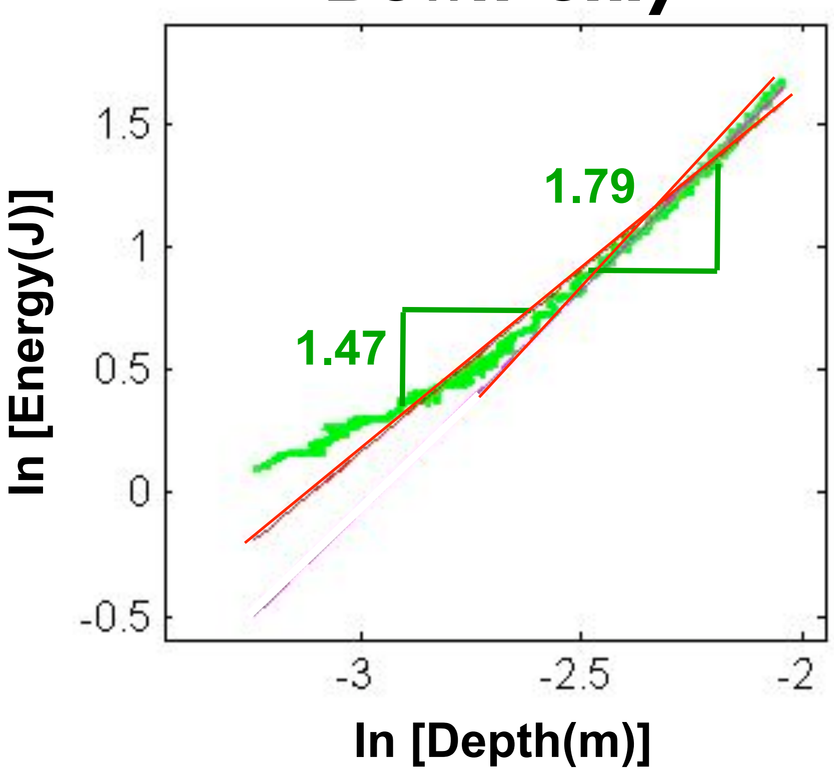

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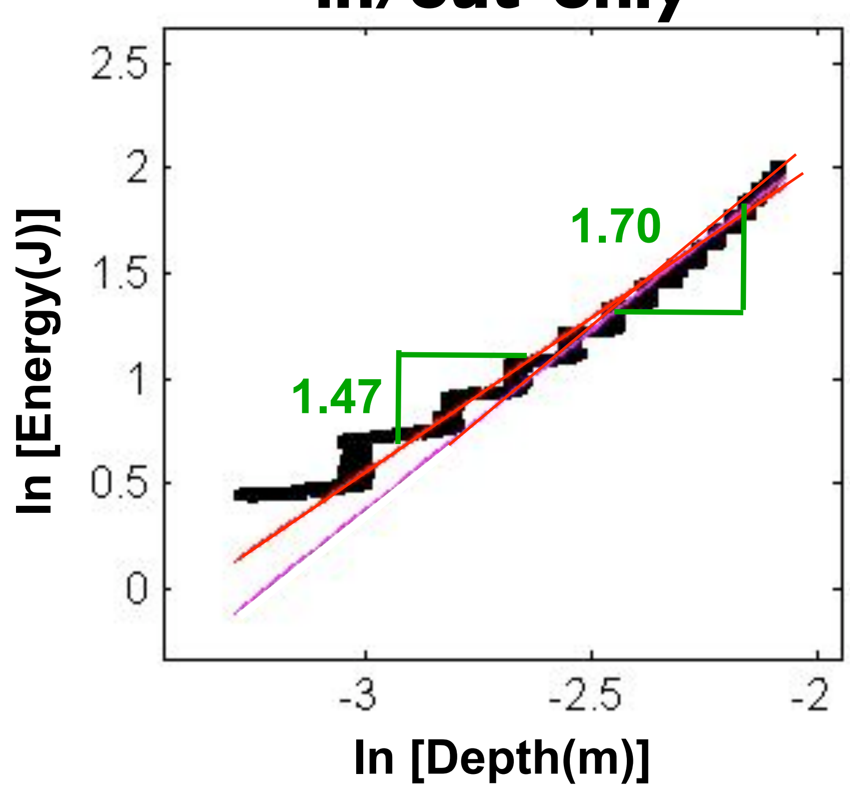

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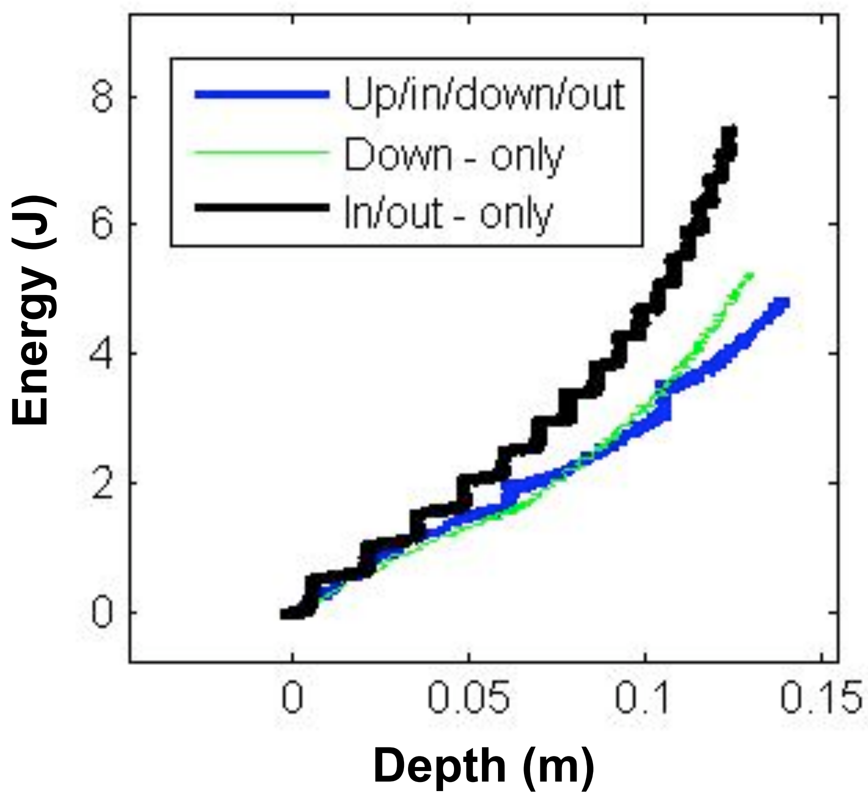

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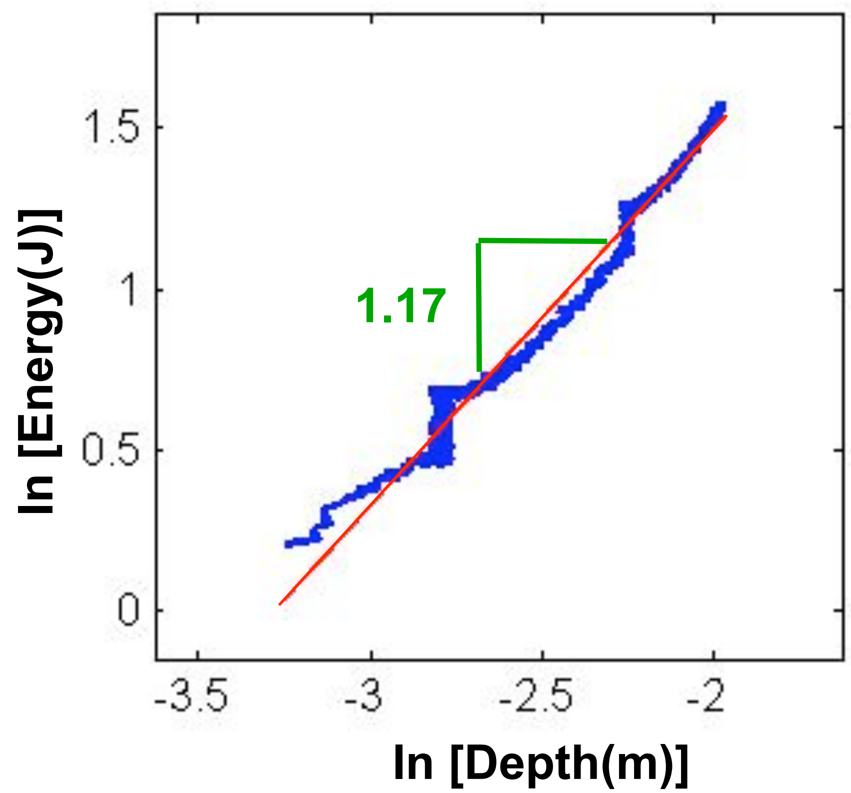

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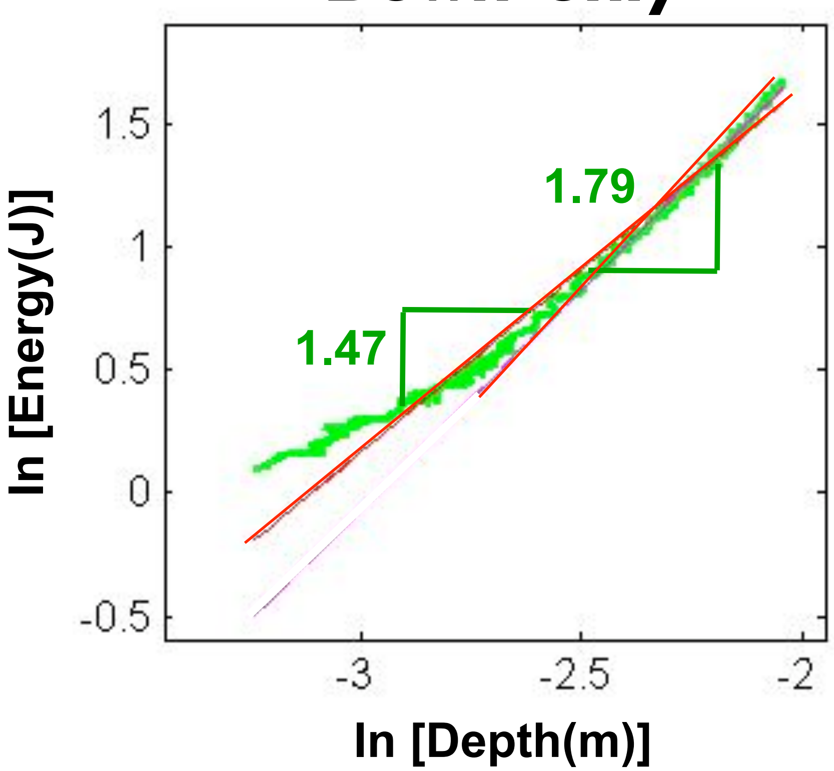

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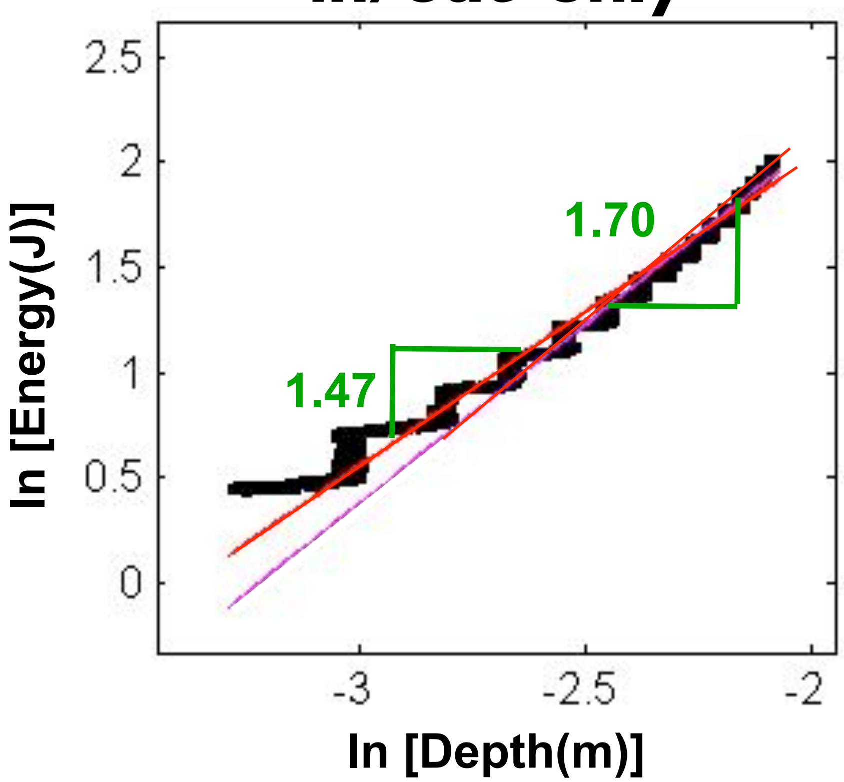

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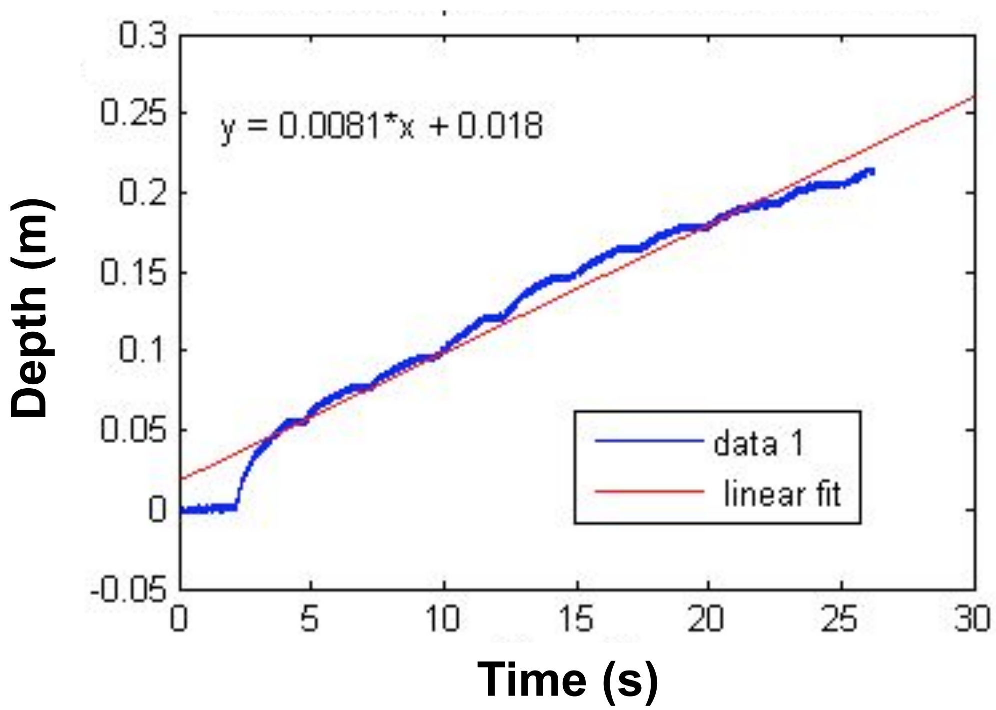
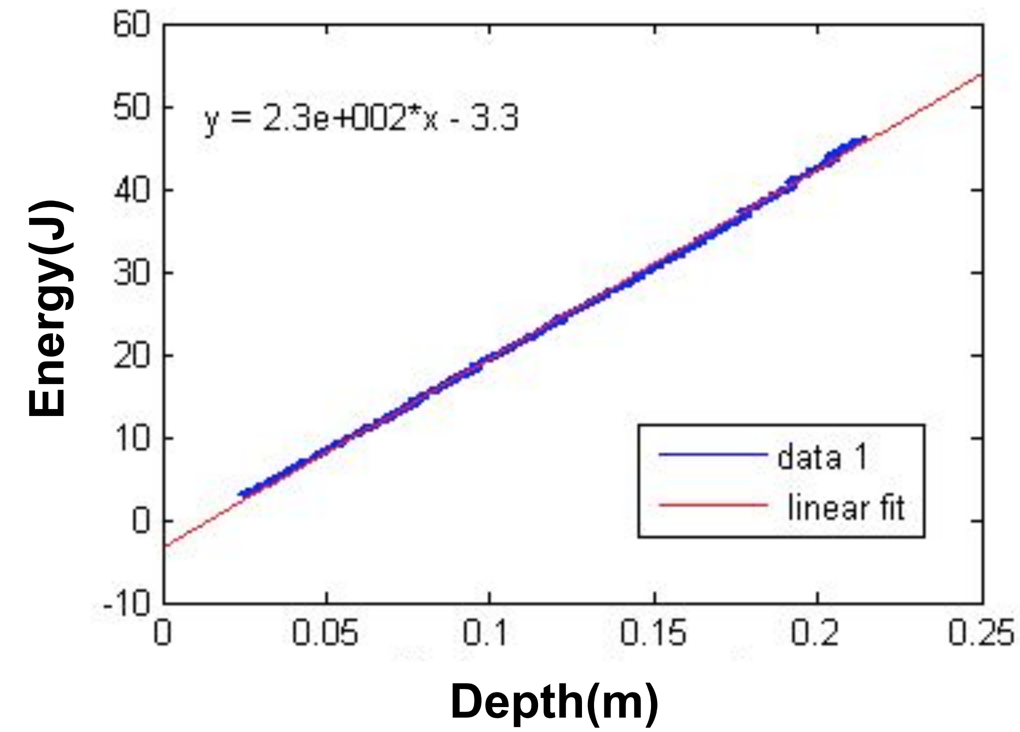
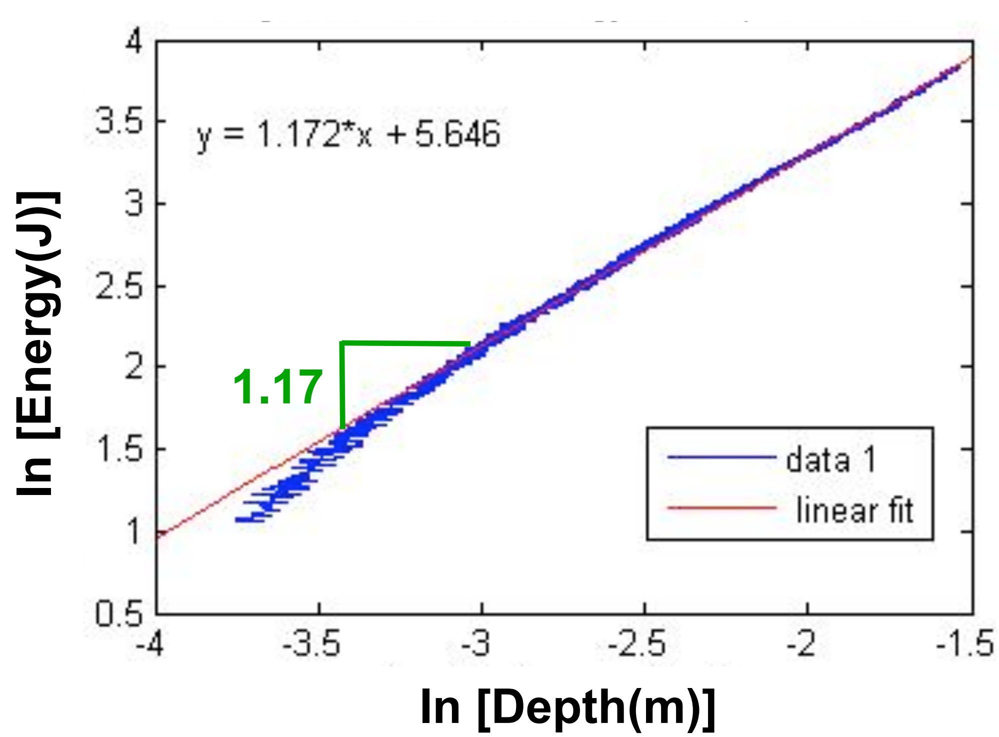
RoboClam ocean test results



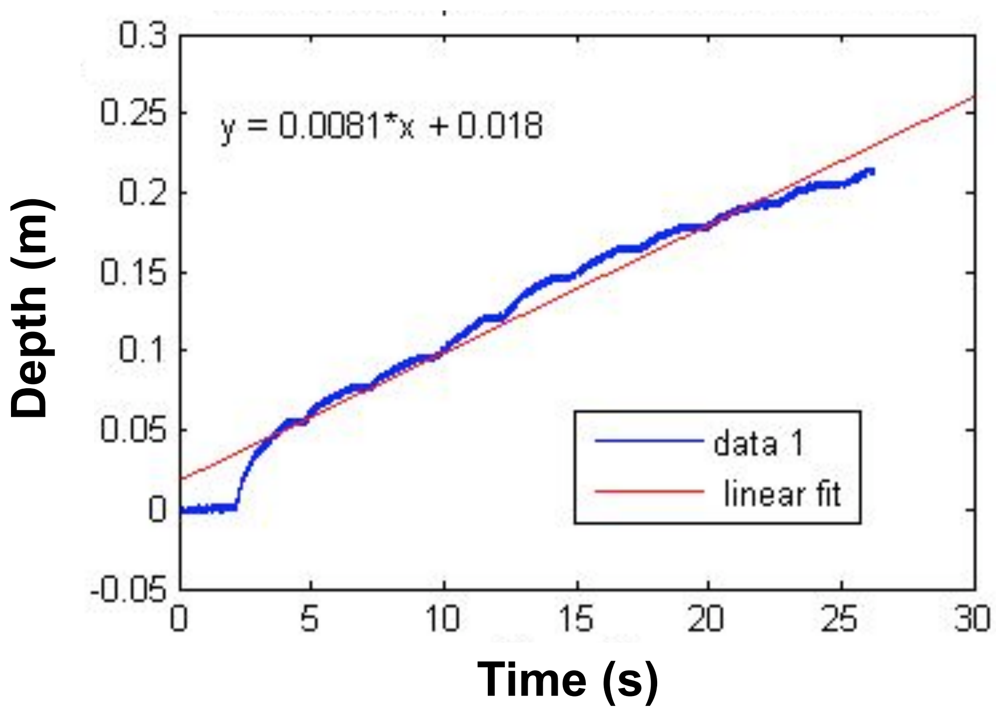


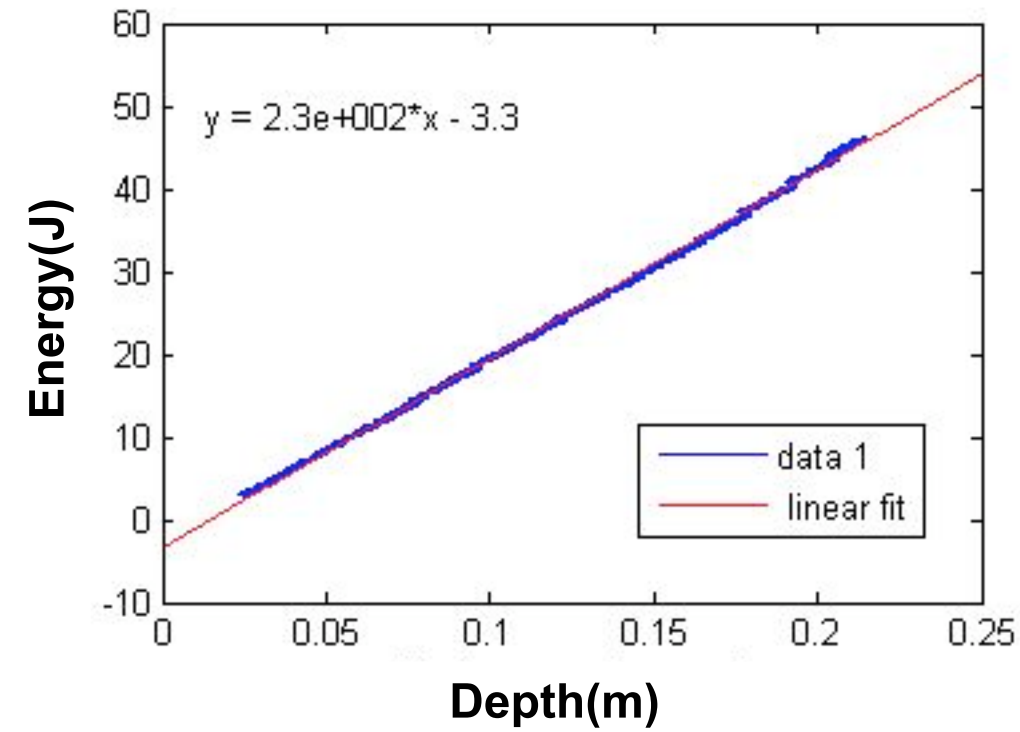


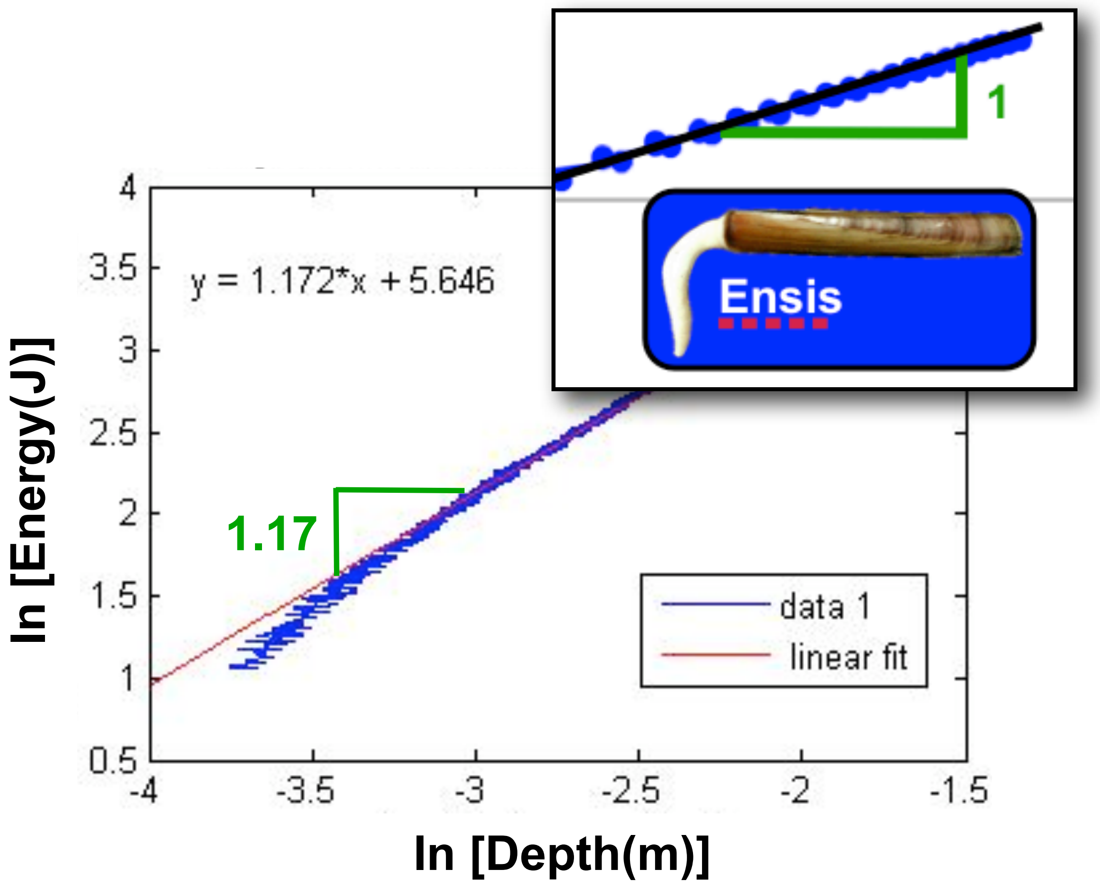
- Plots shown are lowest fitness test out of 119 burrowing trials with 1/2X end effector

- Parameters of best test:
  Up time = 0.0854s
  Down time = 2.00s
  In/out disp = 0.286cm
  Up press = 43.4psi
  In press = 40.6psi
  Down press = 90psi
  Out press = 90psi

RoboClam ocean test results







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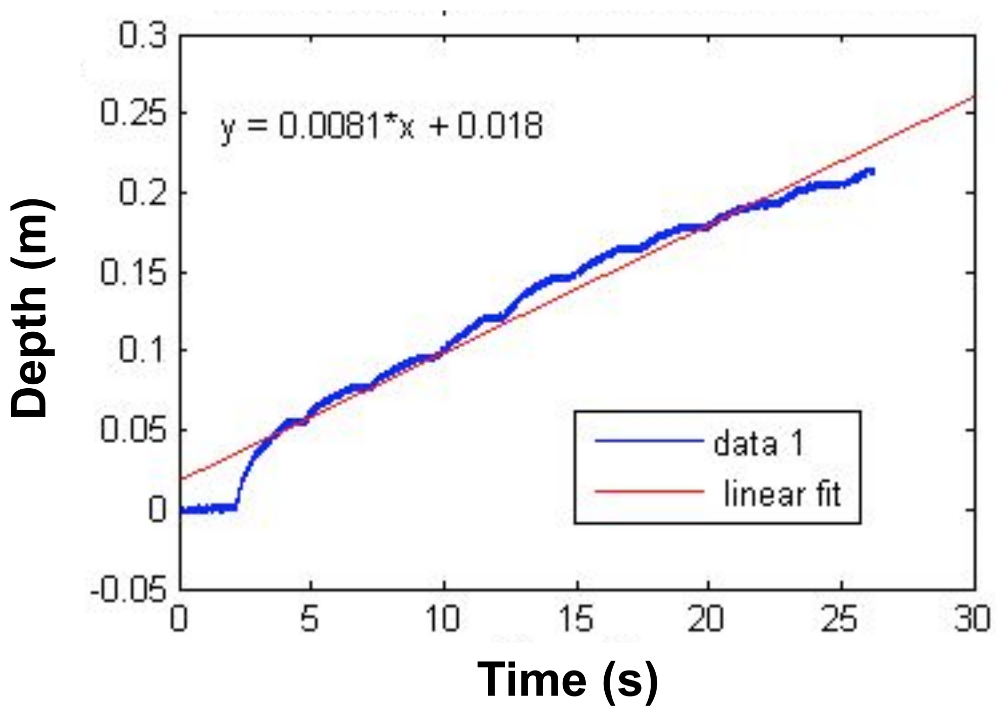
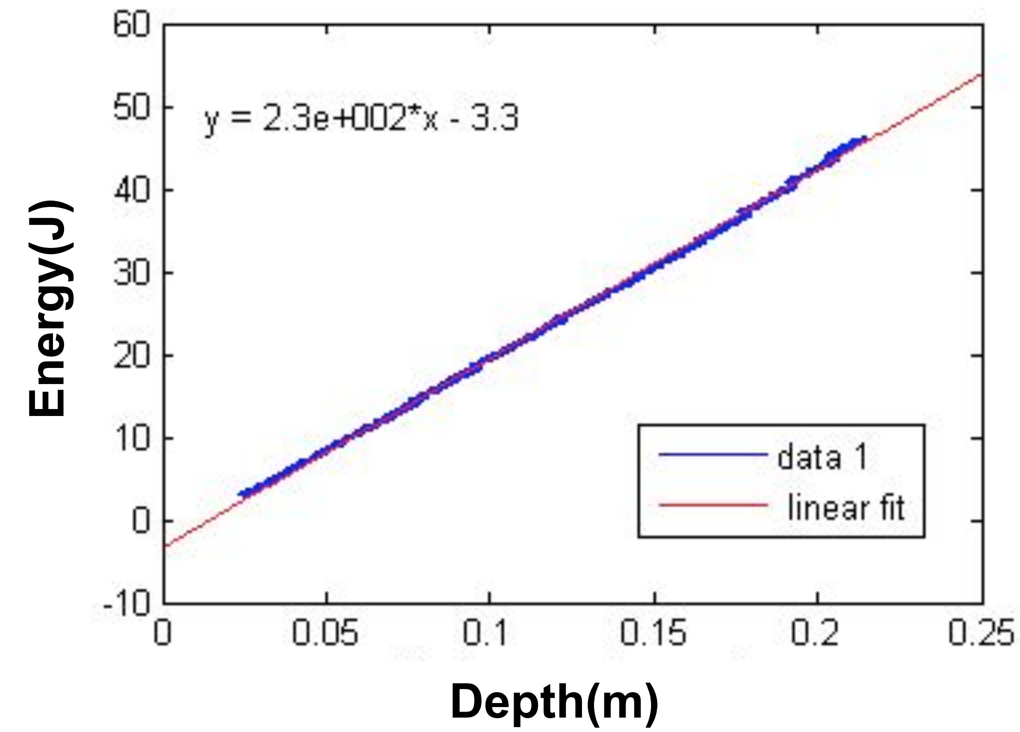
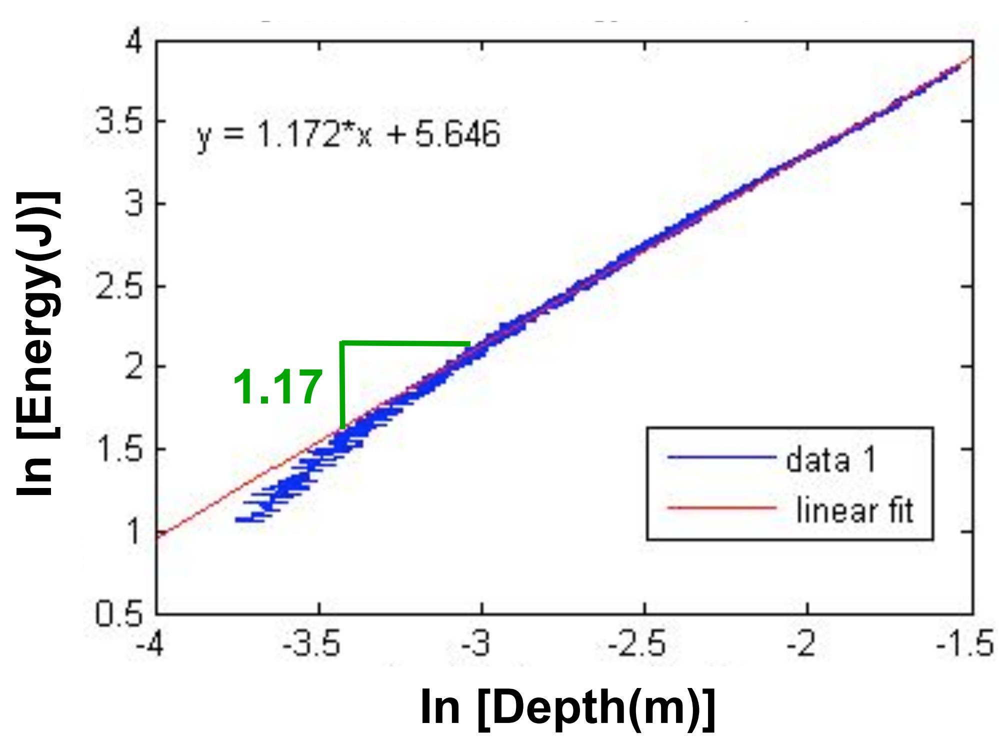
RoboClam ocean test results







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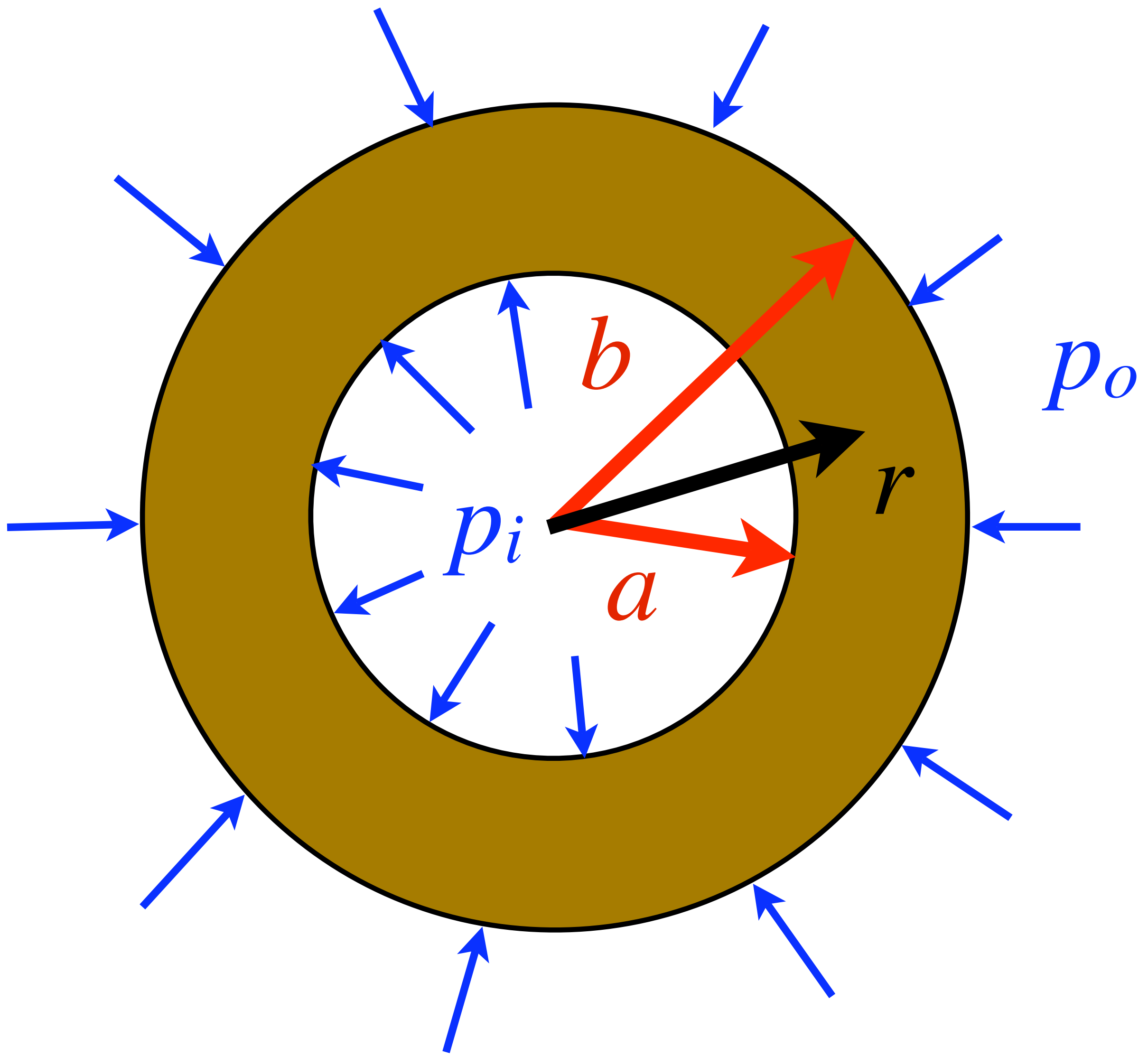
Stress field around cylinder



Thick-walled pressure vessel stresses

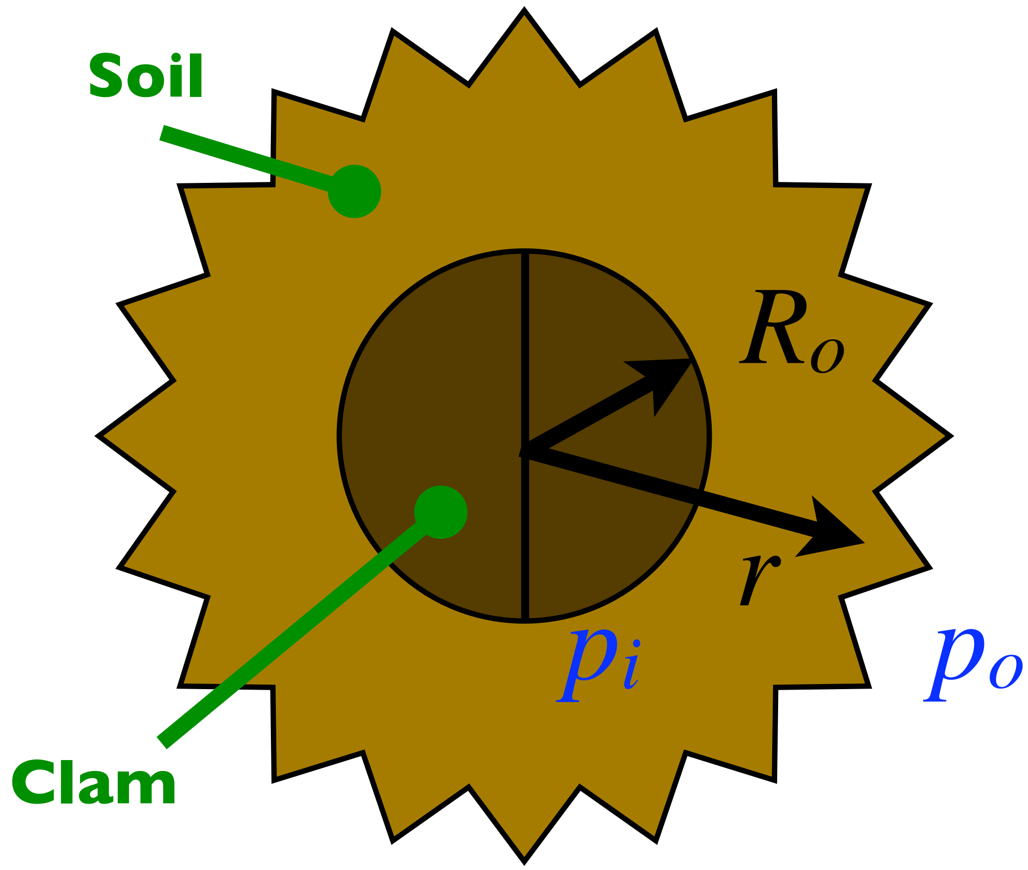
$$\sigma_r = \frac{a^2b^2(p_o - p_i)}{b^2 - a^2}\frac{1}{r^2} + \frac{p_i a^2 - p_o b^2}{b^2 - a^2}$$

$$\sigma_\theta = -\frac{a^2b^2(p_o - p_i)}{b^2 - a^2}\frac{1}{r^2} + \frac{p_i a^2 - p_o b^2}{b^2 - a^2}$$

S. P. Timoshenko , *Theory of Elasticity*, 1970

Stress field around clam

Top view on clam



Simplifications for stress around clam:

- *b* goes to infinity for infinite soil bed
- reverse signs for geotech conventions
- Consider infinitely long clam

$$\sigma_r = \frac{R_o^2(p_i - p_o)}{r^2} + p_o$$

$$\sigma_\theta = -\frac{R_o^2(p_i - p_o)}{r^2} + p_o$$

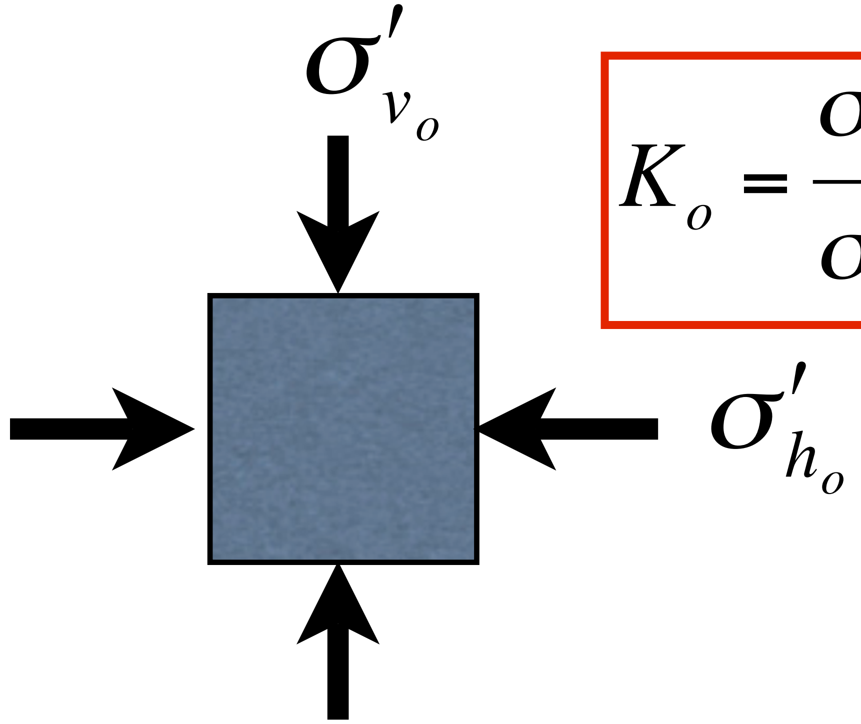
$$\sigma_z = \rho_t g h$$

$$\tau_{r\theta} = \tau_{\theta z} = 0 \text{ because of symmetry}$$

$$\tau_{rz} = 0 \text{ because of infinitly long clam}$$

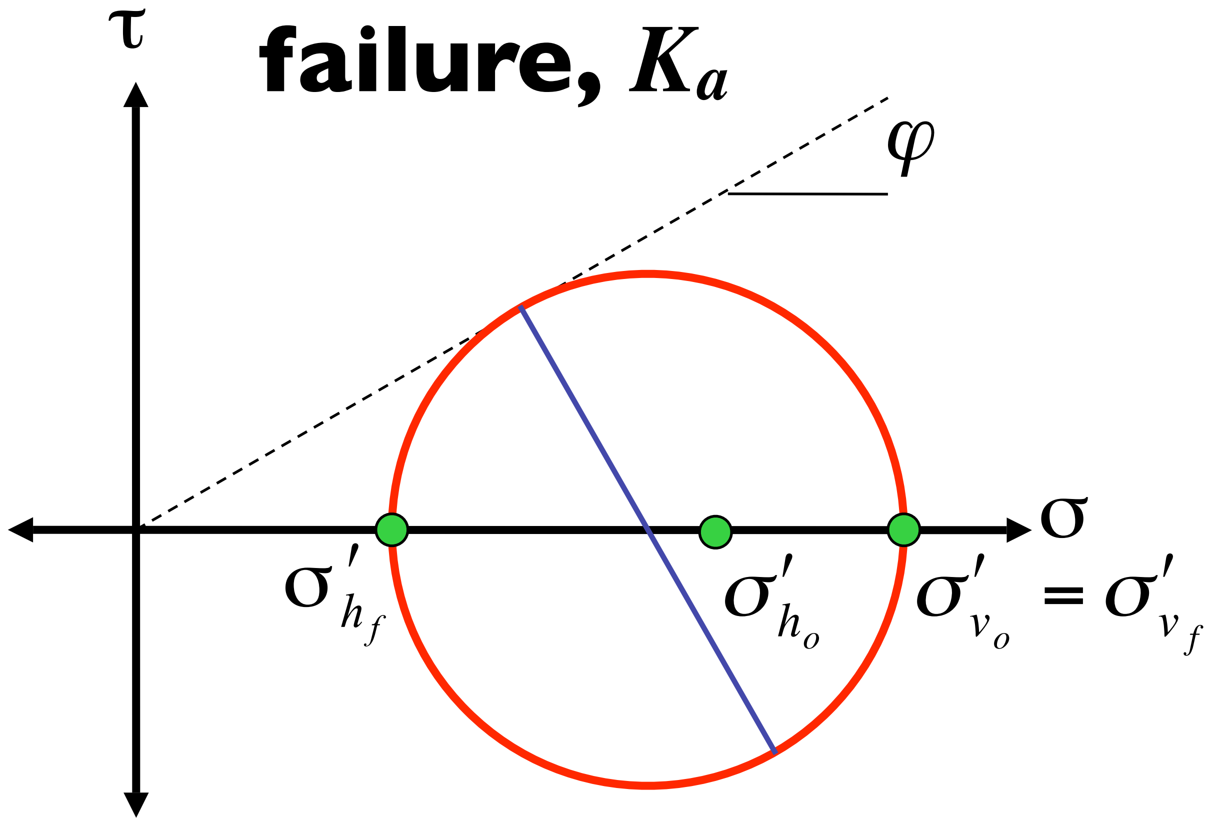
Soil stresses and failure

Coefficient of lateral earth pressure, K_o



$$K_o = \frac{\sigma'_{h_o}}{\sigma'_{v_o}}$$

Coefficient of active failure, K_a



$$\sigma'_{h_f} = \sigma'_{v_f}\left(\frac{1-\sin\varphi}{1+\sin\varphi}\right) = K_a\sigma'_{v_f}$$

Correlation between total horizontal stress at infinity and undisturbed soil stresses

$$p_o = \sigma'_{h_o} + u$$

$$p_o = K_o\sigma'_{v_o} + u$$

$$p_o = K_o gh(1-\phi)\left(\rho_p - \rho_f\right) + \rho_f gh$$

Soil failure criterion

Failure when: $\sigma'_h = \sigma'_{h_f}$

$$\sigma'_h = \sigma_r - u = \sigma'_{v_o} K_a = \sigma'_{h_f}$$

$$\frac{R_o^2 (p_i - p_o)}{r^2} + p_o - \rho_f g h = gh(1-\phi)(\rho_p - \rho_f) K_a$$

$$\Rightarrow \frac{r_f}{R_o} = \left(\frac{(p_i - p_o)}{gh(1-\phi)(\rho_p - \rho_f)[K_a - K_o]} \right)^{1/2}$$

Assumptions

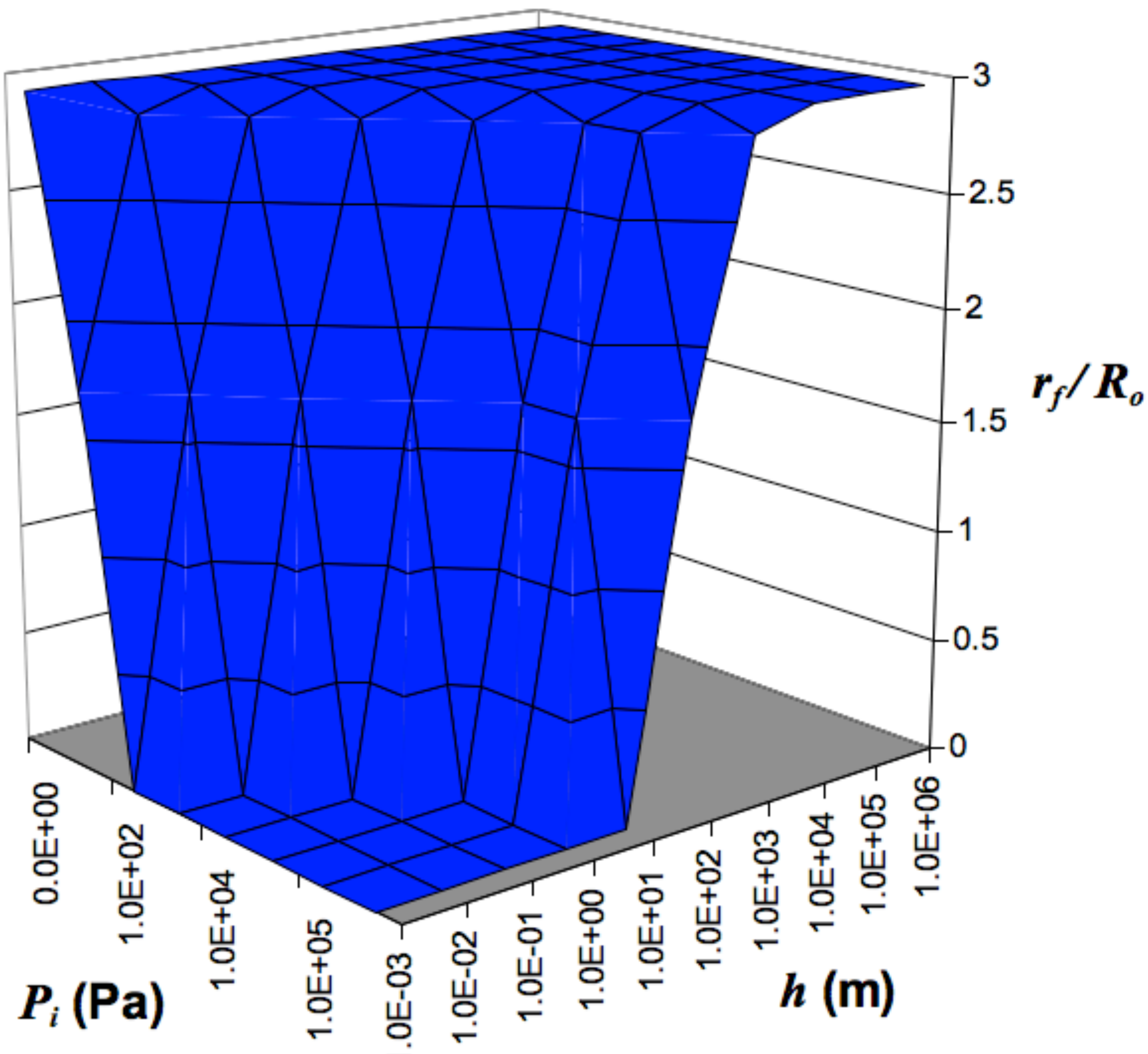
At failure, no soil has moved, pore pressure has not changed, and there are no inertial effects

Scaling

If $p_i = 0$

$$\frac{r_f}{R_o} \approx (K_a - K_o)^{-0.5}$$

Location of failure surface

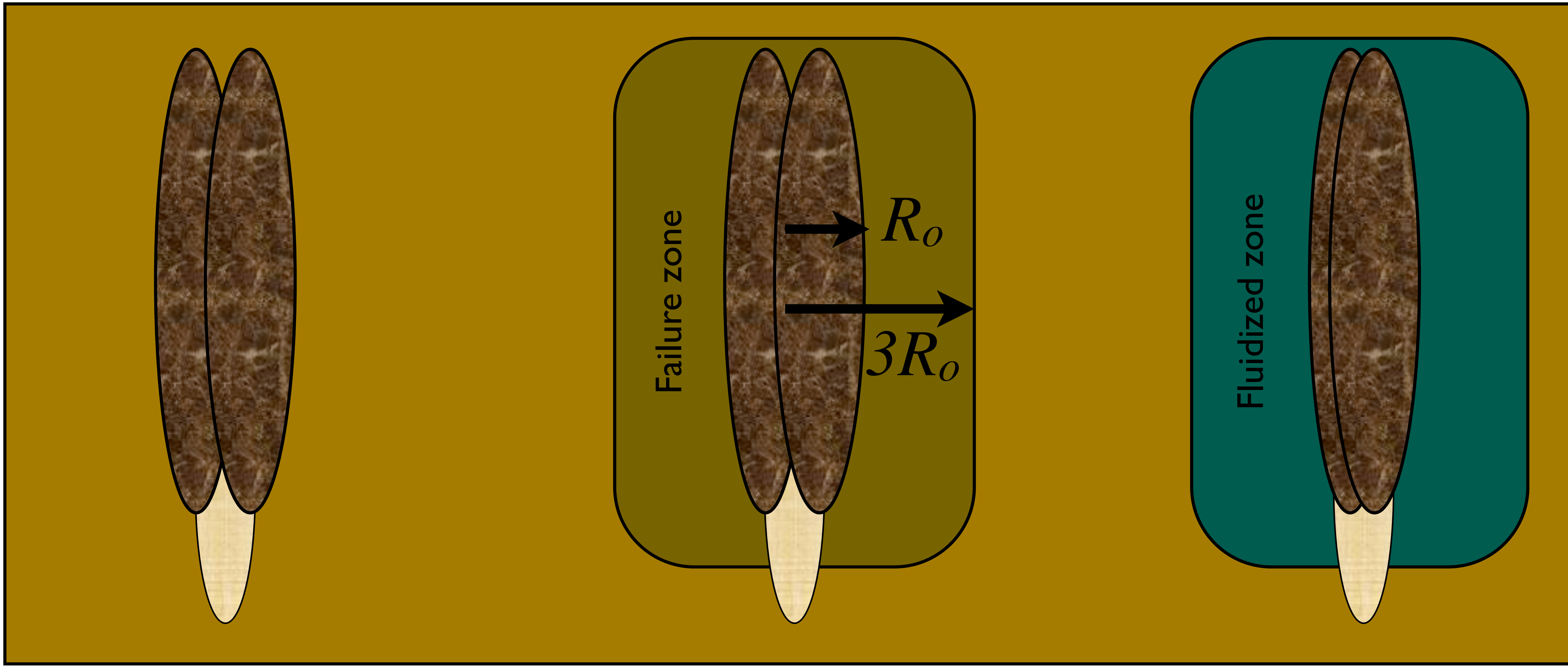


Important points

- Failure surface plateaus at $r_f/R_o \approx 3$ over a large range in pressures, depths, and soil properties
- Model works for both plastic and granular soils
- Failure zone should be largely independent of depth

$$\frac{r_f}{R_o} \approx \left(K_a - K_o\right)^{-0.5}$$

Review of failure hypothesis



Shell exerting equal and opposite pressure on soil

Shell relaxes stress on soil and causes failure zone

Shell contracts to mix failed soil with surrounding water

Conclusions and ongoing work

- Through *Ensis*-inspired burrowing, RoboClam offers an exponential decrease in digging energy (n = 2 to n = 1.17) over penetrating a static soil
- RoboClam has achieved energy reduction in significantly different substrates

Ongoing work

- Test 1X and 2X end effectors in lab and real soils
- Verify soil failure/fluidization model
- Form design rules from RoboClam testing and fluidization model to predict burrowing device performance
- Construct a self-contained case study burrowing device

Thank you

Research sponsors

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