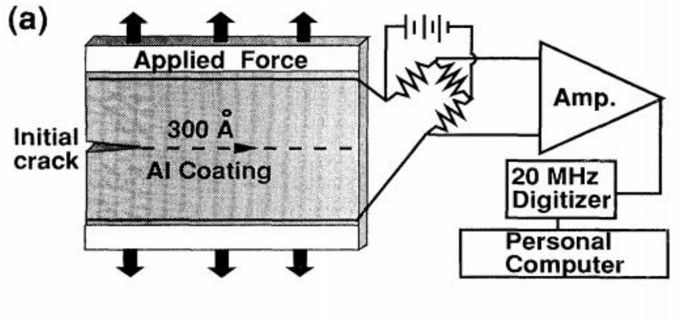
ME 412:

Experimental Methods in Engineering Mechanics

John M. Kolinski

PATT - EMSI

22.9.2021



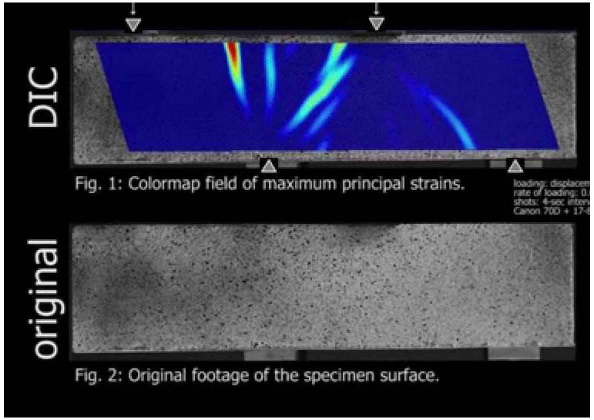
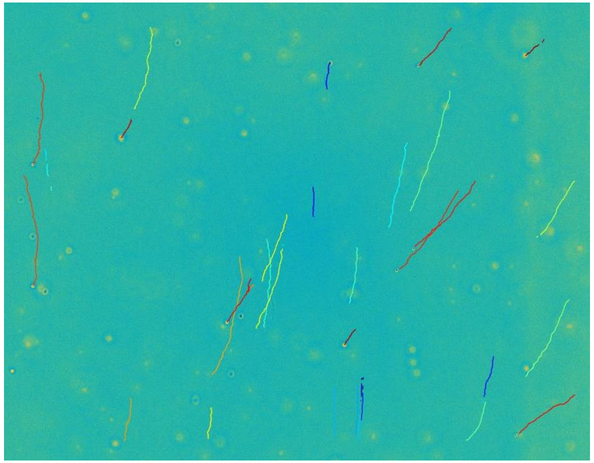


Fig. 1: Colormap field of maximum principal strains.

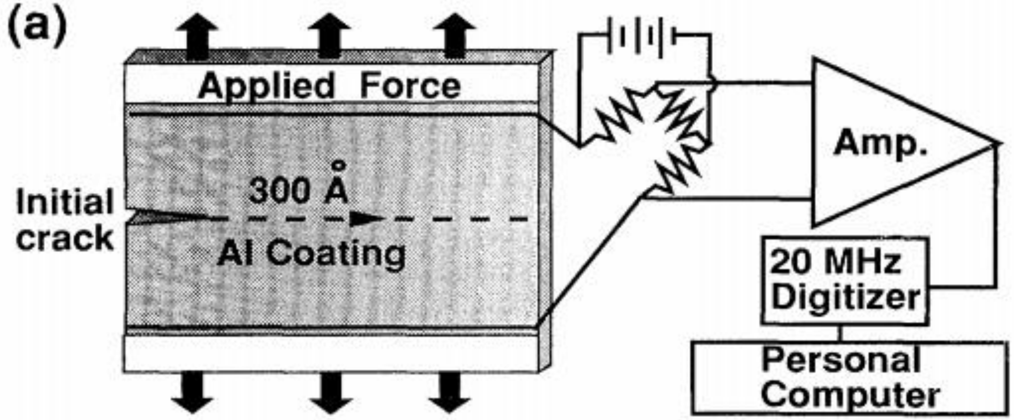
Fig. 2: Original footage of the specimen surface.



[Discussion of the syllabus]

Module 1 in brief – analog electronics

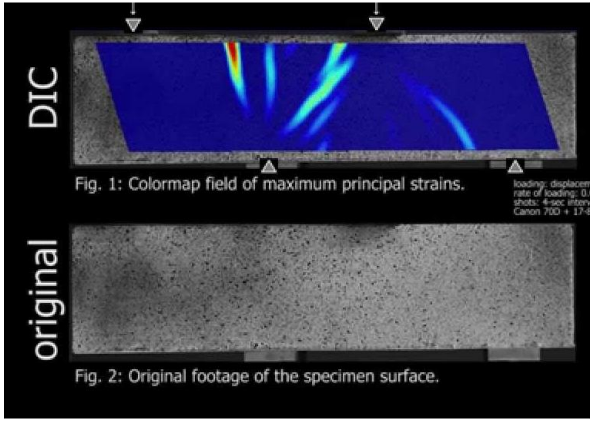
- We need an analog front-end to make sense of any quantity we wish to measure. The analog / digitized signal can then be used for quantifying or control. This is ***ubiquitous*** in mechanical sciences; thus the motivation to introduce the basics of analog circuitry.
- We will probe the speed of a dynamic crack in a brittle solid:



More on this later…

Modules 2 & 3

- Stretching of gels and bars: Use digital image correlation to measure constitutive law of hydrogel gel sample. UTMs in DLL will be used for the experiment. Process images with open-source NCORR software.
- Brownian motion & micro-rheology. Use Stokes-Einstein relation to measure viscosity from images of particles in solution. Become familiar with open-source particle tracking software package for Python / MATLAB



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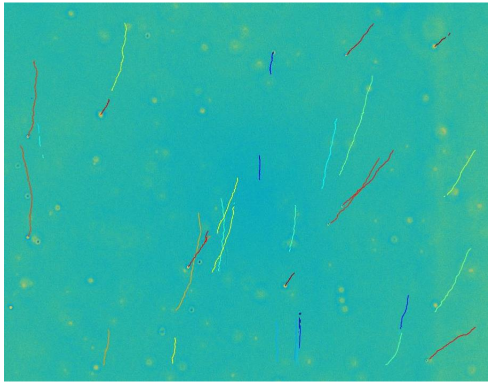


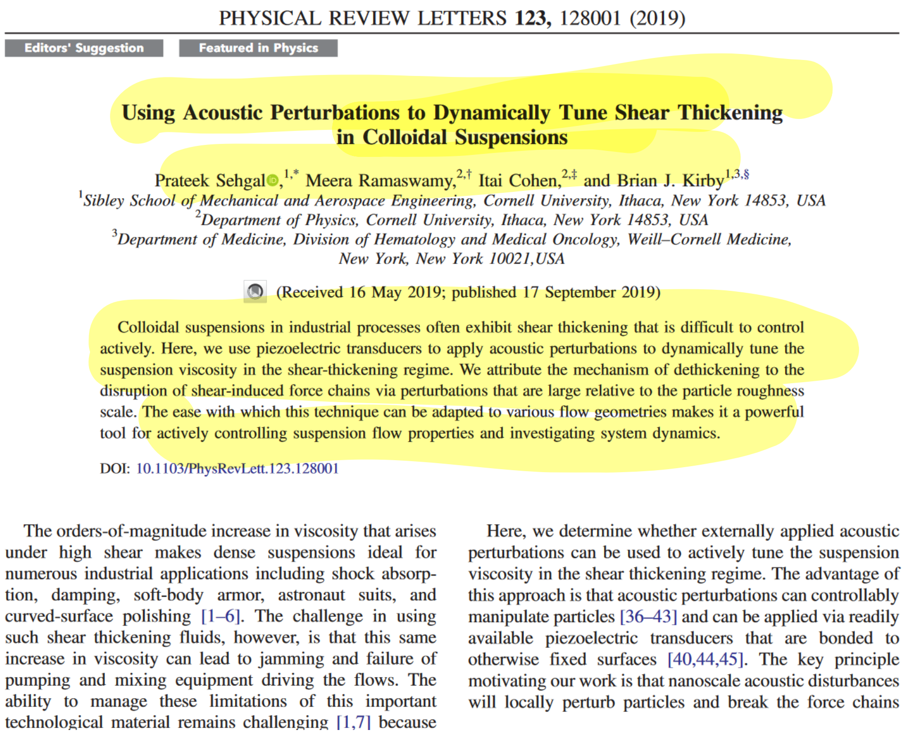
How will your grade be determined?

- For each of the 3 modules, your group will write a lab report within a group of 3-4 students; this will count for 80% of your grade. The peer assessment in modules 2 and 3 will be factored into this 80% for each module.
- Lab reports will be evaluated by other student groups as a team. The evaluation will count for 20% for modules 2 and 3; for module 1, the grading will be done by me
- Contributions to the wiki, or experimental “Je ne sais quoi” in a given module can add up to 5% to your grade. These should be included in the appendix to the report.
- Lab groups will rotate groupings in each module

Deliverables – lab reports for each module

- The lab reports will consist of a 4-5 page two-column document, with a focus on the scientific outcome of the experiment. Format should follow Physical Review Letters
- Figures and captions are an extremely important component to the report, and should be clear, legible, and concise.
- Writing should be clear and concise
- Exercises unrelated to the scientific results should be included in the appendix
- Wiki contributions should be included in the appendix and can receive additional credit toward the report grade

Lab report format



PHYSICAL REVIEW LETTERS **123,** 128001 (2019)

Editors' Suggestion **Featured in Physics**

Using Acoustic Perturbations to Dynamically Tune Shear Thickening in Colloidal Suspensions

Prateek Sehgal,[1,*] Meera Ramaswamy,[2,†] Itai Cohen,[2,‡] and Brian J. Kirby[1,3,§]
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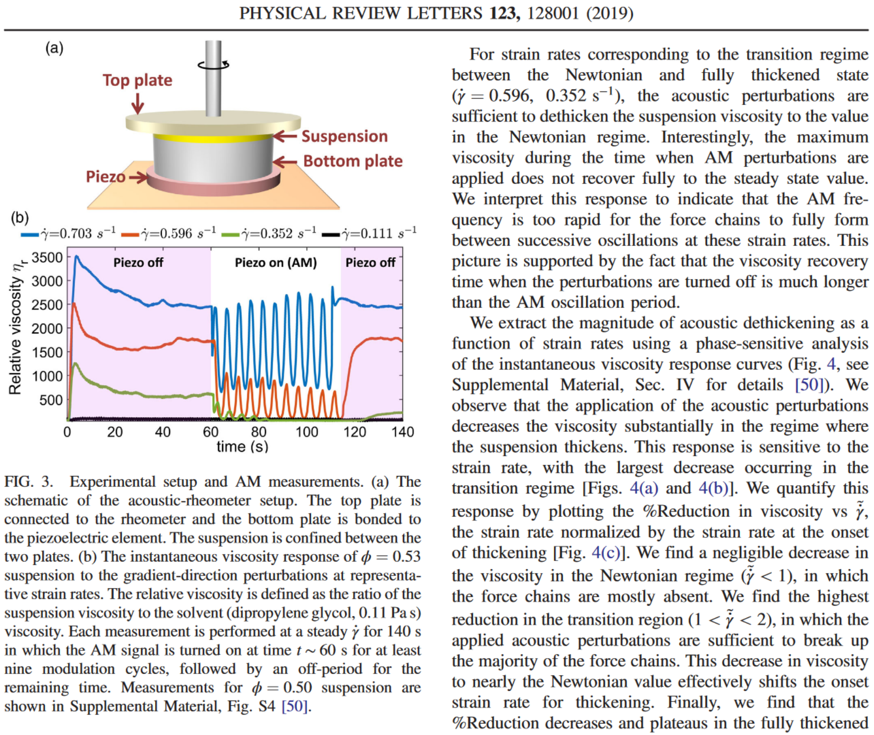
(Received 16 May 2019; published 17 September 2019)

Colloidal suspensions in industrial processes often exhibit shear thickening that is difficult to control actively. Here, we use piezoelectric transducers to apply acoustic perturbations to dynamically tune the suspension viscosity in the shear-thickening regime. We attribute the mechanism of dethickening to the disruption of shear-induced force chains via perturbations that are large relative to the particle roughness scale. The ease with which this technique can be adapted to various flow geometries makes it a powerful tool for actively controlling suspension flow properties and investigating system dynamics.

DOI: 10.1103/PhysRevLett.123.128001

The orders-of-magnitude increase in viscosity that arises under high shear makes dense suspensions ideal for numerous industrial applications including shock absorption, damping, soft-body armor, astronaut suits, and curved-surface polishing [1–6]. The challenge in using such shear thickening fluids, however, is that this same increase in viscosity can lead to jamming and failure of pumping and mixing equipment driving the flows. The ability to manage these limitations of this important technological material remains challenging [1,7] because

Here, we determine whether externally applied acoustic perturbations can be used to actively tune the suspension viscosity in the shear thickening regime. The advantage of this approach is that acoustic perturbations can controllably manipulate particles [36–43] and can be applied via readily available piezoelectric transducers that are bonded to otherwise fixed surfaces [40,44,45]. The key principle motivating our work is that nanoscale acoustic disturbances will locally perturb particles and break the force chains



PHYSICAL REVIEW LETTERS **123,** 128001 (2019)

FIG. 3. Experimental setup and AM measurements. (a) The schematic of the acoustic-rheometer setup. The top plate is connected to the rheometer and the bottom plate is bonded to the piezoelectric element. The suspension is confined between the two plates. (b) The instantaneous viscosity response of $\phi = 0.53$ suspension to the gradient-direction perturbations at representative strain rates. The relative viscosity is defined as the ratio of the suspension viscosity to the solvent (dipropylene glycol, 0.11 Pa s) viscosity. Each measurement is performed at a steady $\dot{\gamma}$ for 140 s in which the AM signal is turned on at time $t \sim 60$ s for at least nine modulation cycles, followed by an off-period for the remaining time. Measurements for $\phi = 0.50$ suspension are shown in Supplemental Material, Fig. S4 [50].

For strain rates corresponding to the transition regime between the Newtonian and fully thickened state ($\dot{\gamma} = 0.596$, 0.352 s^{-1}), the acoustic perturbations are sufficient to dethicken the suspension viscosity to the value in the Newtonian regime. Interestingly, the maximum viscosity during the time when AM perturbations are applied does not recover fully to the steady state value. We interpret this response to indicate that the AM frequency is too rapid for the force chains to fully form between successive oscillations at these strain rates. This picture is supported by the fact that the viscosity recovery time when the perturbations are turned off is much longer than the AM oscillation period.

We extract the magnitude of acoustic dethickening as a function of strain rates using a phase-sensitive analysis of the instantaneous viscosity response curves (Fig. 4, see Supplemental Material, Sec. IV for details [50]). We observe that the application of the acoustic perturbations decreases the viscosity substantially in the regime where the suspension thickens. This response is sensitive to the strain rate, with the largest decrease occurring in the transition regime [Figs. 4(a) and 4(b)]. We quantify this response by plotting the %Reduction in viscosity vs $\tilde{\dot{\gamma}}$, the strain rate normalized by the strain rate at the onset of thickening [Fig. 4(c)]. We find a negligible decrease in the viscosity in the Newtonian regime ($\tilde{\dot{\gamma}} < 1$), in which the force chains are mostly absent. We find the highest reduction in the transition region ($1 < \tilde{\dot{\gamma}} < 2$), in which the applied acoustic perturbations are sufficient to break up the majority of the force chains. This decrease in viscosity to nearly the Newtonian value effectively shifts the onset strain rate for thickening. Finally, we find that the %Reduction decreases and plateaus in the fully thickened

The format is simple: an abstract summarizes the results. The first paragraph is dedicated to relevant background information, and culminates in the unanswered question that the report will address. The next paragraph will then proceed to explain how the work contained in the report makes progress toward addressing the question. The remainder of the report is dedicated to presenting results. A brief discussion establishes context for the work.

A grading rubrick for grading the final reports:

1. Follows the PRL format (ca. 5 % of total).
    - Title, abstract, authors list using revtex template for PRL. No more than 5 pages for the main report, including figures, etc.
    - 1-2 paragraph introduction for background, going from general to specific.
    - Conclude introductory paragraph with the open question you will address with the report.
    - Next paragraph introduces your method to address the question - `In this letter, we will measure…. We simulate … This paragraph should consist of a concise summary of your results.
    - Specifics of the measurement / simulation approach should be provided, and supported with figures that validate the chosen approach. This portion should be anywhere from 2-5 paragraphs and 1-3 figures.
    - Results should follow – what did you find, and why are you confident in your conclusions? Support with data in figures!
    - Discussion / conclusion – 1-2 paragraphs. Review what you learned, and broaden the discussion to how your measurement / simulation advances the state of the art.
    - References, formatted appropriately.

A grading rubrick for grading the final reports:

2. Figures clear, legible and appropriately captioned (ca. 30 % of the grade)
    - I should be able to understand what you did by reviewing only the figures and captions. They should be clear, legibly labelled, and completely captioned in concise text.
    - All data should be presented with as quantitative a treatement of experimental / simulation error as you can provide.

A grading rubrick for grading the final reports:

3. Writing is clear and concise (ca. 30% of total grade)
   - 5 pages with figures is SHORT! Don’t waste words …
   - Good writing: the process of eliminating *unnecessary words!*
   - Style and clarity count

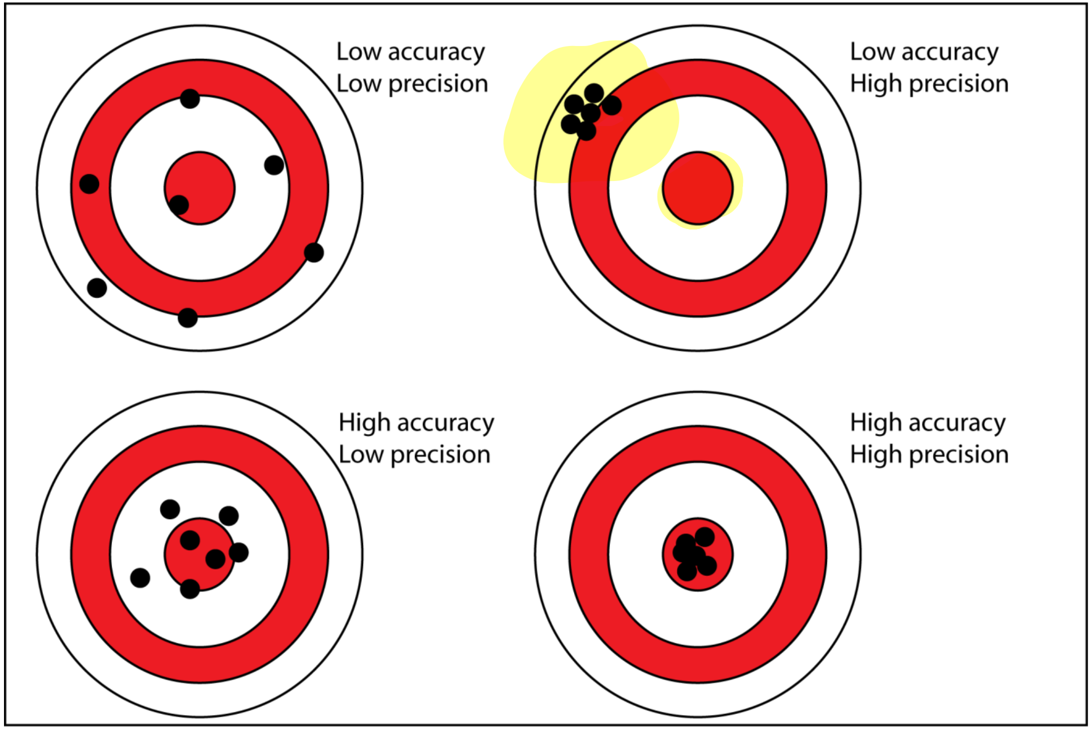
A grading rubrick for grading the final reports:

4. `Je ne sais quoi’ – the effort of the measurement & attempts to reduce noise, and provide excellent, reliable measurements. (ca. 20+5% of total grade)

- You’ve learned a lot of methods for reducing noise, and enhancing measurement precision.
- Here is your opportunity to show off – how precise are your measurements? How do they stand in comparison with the state of the art?
- How well have you understood and quantified the various sources of error in the measurement?
- Have you provided sufficient detail in the supplementary document for your report to support your error quantification & technical approach, including details of your simulation?
- You can also score points for identifying paths toward an improved measurement in the discussion – perhaps changing the actuator in some way, or enhancing the load cell’s precision, or changing the current range … however you might go about it, if you were given another chance, more time and unlimited equipment, what would you do to improve your measurement?

A grading rubrick for grading the final reports:

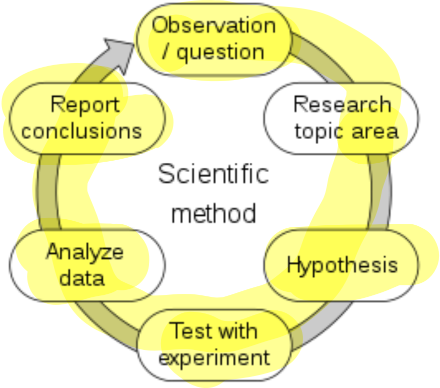
- 5. Appropriate use of statistics and error quantification (5%)
  - Use of error analysis where possible to generate error bars
  - Any discussion of error should distinguish between sources of error
  - Clear and consistent use of accuracy vs. precision
  - Clear and consistent recognition of experimental error and measured fluctuations of the physical phenomenon
  - Error propagation is carried out when relevant for derived quantities



A grading rubrick for grading the final reports:

5. Use of the scientific method (10%)

- Science is inherently hypothesis driven – the rationale for a given hypothesis is presented in the introduction, leading to the open question the experiment intends to address
- Confidence is built by hypothesis formulation and testing, which can rule out spurious / errant conclusions. This process should be described in the report or supplementary information.
- Conclusions are well-supported by data, within measurement error.
- Future prospects, prospective hypotheses suggested by the work and broad scientific outlook are presented in `discussion' or `conclusion' paragraph(s) in the report.



En.Wikipedia: Scientific_method

A summary of the rubrick for grading the final reports:

Grading Category	% of report grade
PRL format (title, abstract, technical layout, etc.)	5
Figures clear, well-annotated and captioned	30
Clear, concise writing	30
Proper use of any statistical analysis / error quantification	5
Use of scientific method	10
Experimental “Je ne sais quoi” / wiki / etc.	20 + 5 (5 bonus)
Total	105 / 100

Good vs. Bad captions:

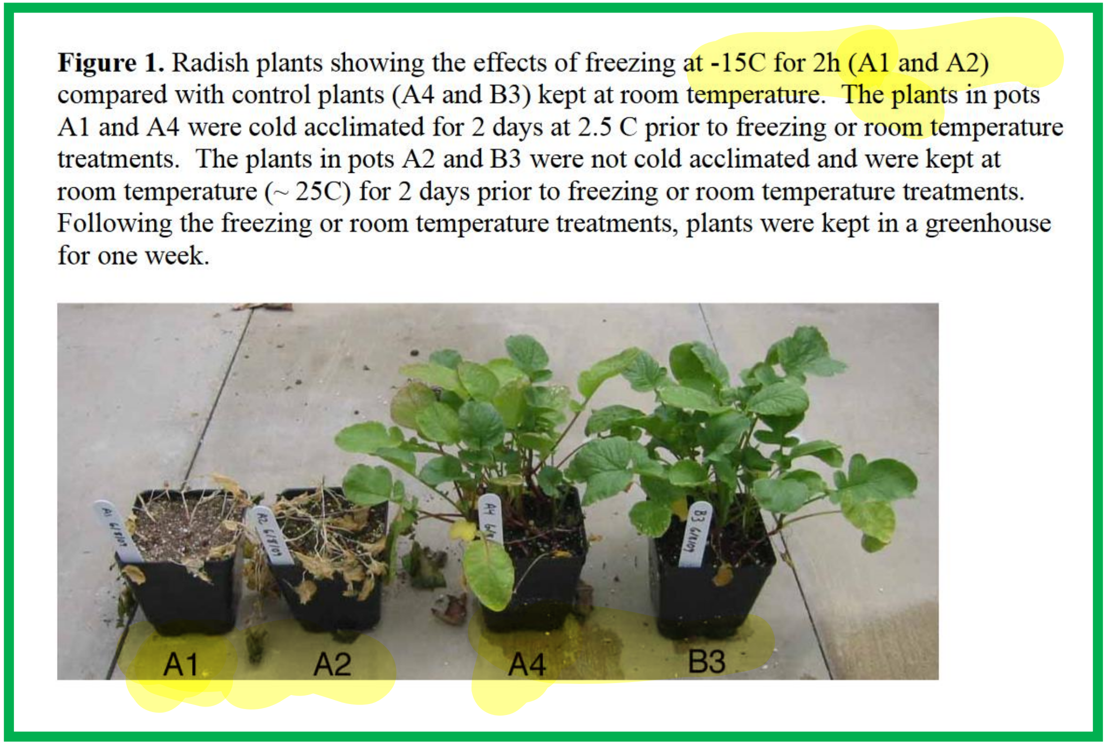


Figure 1. Radish plants showing the effects of freezing at -15C for 2h (A1 and A2) compared with control plants (A4 and B3) kept at room temperature. The plants in pots A1 and A4 were cold acclimated for 2 days at 2.5 C prior to freezing or room temperature treatments. The plants in pots A2 and B3 were not cold acclimated and were kept at room temperature (~ 25C) for 2 days prior to freezing or room temperature treatments. Following the freezing or room temperature treatments, plants were kept in a greenhouse for one week.

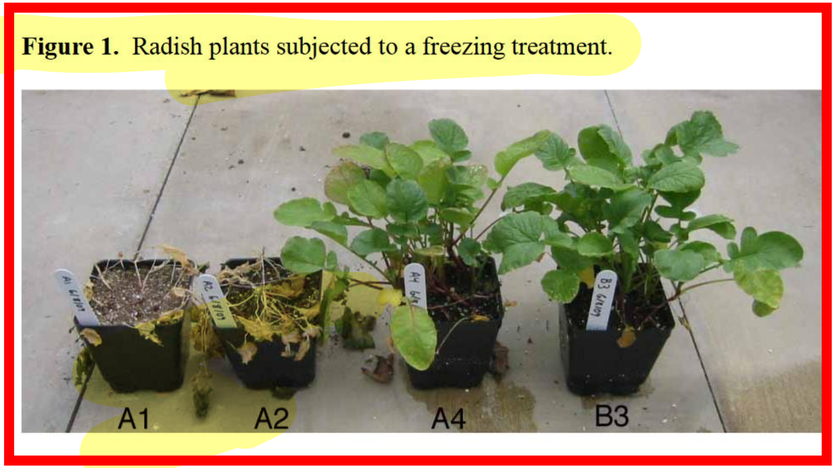


Figure 1. Radish plants subjected to a freezing treatment.

Contact hours & teaching staff

- The course is a 4 hour class. This means that you should budget 4 hours for lab activities on Wednesday morning, and an ***additional 4 hours*** off campus to complete the readings, and complete module reports.
- Ramin Kaviani will help help to teach the class & attend ad-hoc office hours on Tuesday afternoons.

Schedule for the class

Week	Module	Plan for contact hours	Outside of class – readings prior to lecture
1	I	Intro to course – grading, expectations; intro to module; intro to exercises & background – passives and filters	Reading on Oscilloscopes, review syllabus
2	I	Transistors and amplifiers	Assigned readings
3	I	Wheatstone Bridge & driving circuitry	Assigned readings
4	I	Calibrate samples with 4-wire measurement, debug / calibrate bridge circuit	Assigned readings
5	I	Measurements, report preparation and writing	Work on report
6	I	Measurements, report writing	Work on report
7	II	Intro. To instrumentation & experimental prep – DIC lab	Assigned readings
8	II	Prepare samples for measurement; first measurements	
9	II	Conclude experiments & process data	Assigned readings & software preparation for DIC
10	II	Conclude processing & write lab report	
11	III	Lecture, discussion & exercises – Brownian motion	Prepare reading; evaluate report of alt. group from Mod II
12	III	Experimental set-up & preparation	Assigned readings & software preparation for particle tracking
13	III	Conclude experiments & process data	
14	III	Complete data processing & write reports	

Crack speed – dynamic fracture testing using analog electronics

Reference: Fineberg, Gross, Marder and Swinney. *Instability in dynamic fracture.* PRL 67, 4, 1991

ME 412

John M. Kolinski

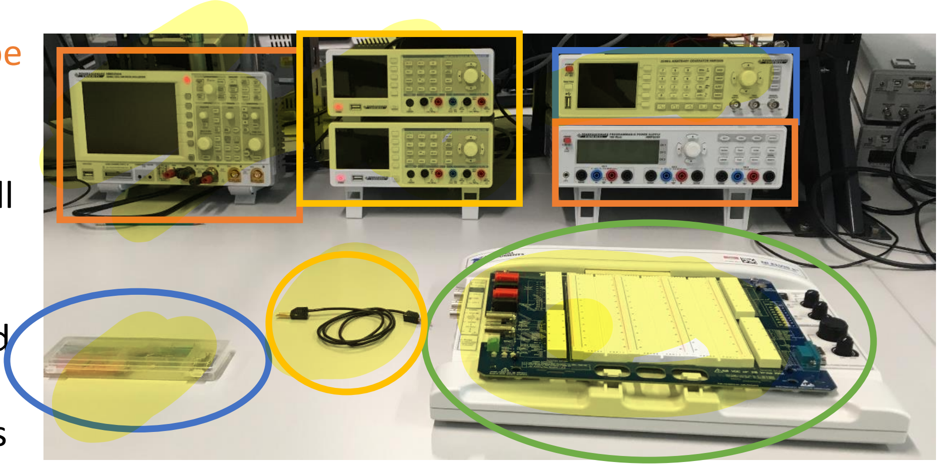
Equipment for analog electronics module

You'll be using the lab benches in MED 2 2419. The lab bench layout is standard at each desk, and includes a 3-channel power supply, a function generator, two multi-meters and an oscilloscope (see the layout at right).

Also available are a standard breadboard and jumper wire, as well as BNC connectors (not shown) and banana plug connectors.

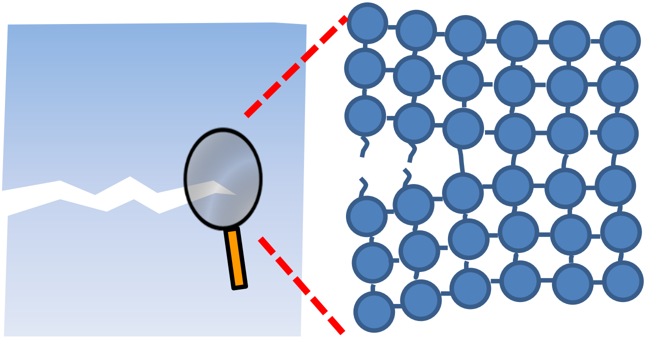
Circuit components are found near the entrance to the room, and include all components from passives (resistors, capacitors, inductors and diodes) to actives, up to and including the op-amps and precision voltage references.

On day one of your on campus presence, you'll form your group for the semester by our algorithm. Groups are formed at random.



How do things Break?

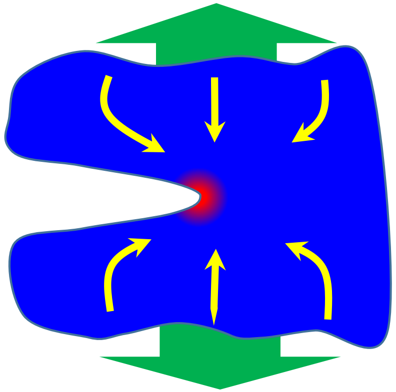
The Griffith approach (1922) –



Materials break when there is enough *elastic energy* (J/m^2) to drive a crack

Number of bonds per unit area (~10^{20} m^{-2}) × Bond energy (~10^{-19} J) = Fracture energy (1-10 J/m^2)

The energy supply comes from the elastic energy stored in the solid – due to the applied stress



➔ Fracture is a matter of energy balance

Elastic energy stored in the sample = dissipation / surface energy

$$G = \Gamma$$

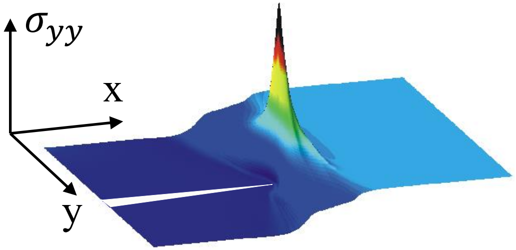
How do things Break?

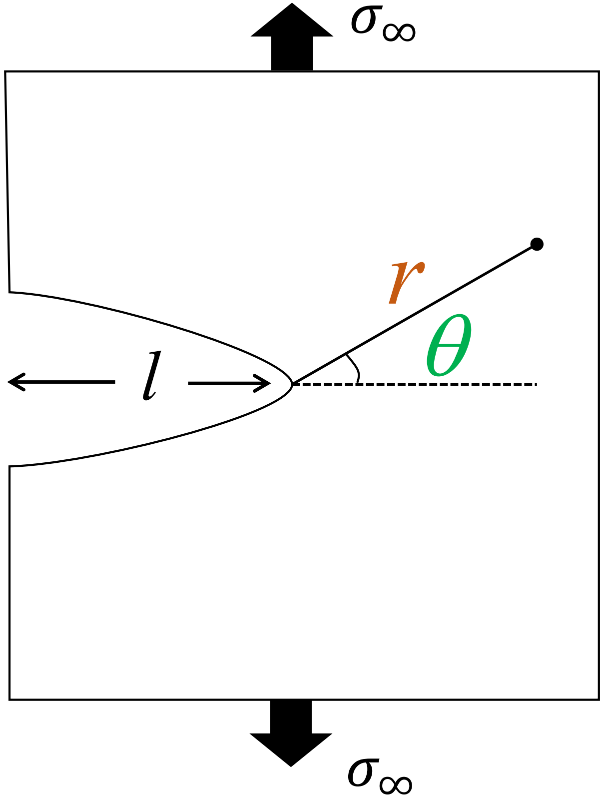
Linear Elastic Fracture Mechanics (LEFM) 1950's -

Cracks create ***singular stresses*** at their tip

As $r \to 0$, the stress ***diverges*** (Freund, 1990)

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta, \mathrm{v}) + \mathcal{O}(1)$$





K = stress intensity factor ($\sim \sigma_\infty \sqrt{l}$)

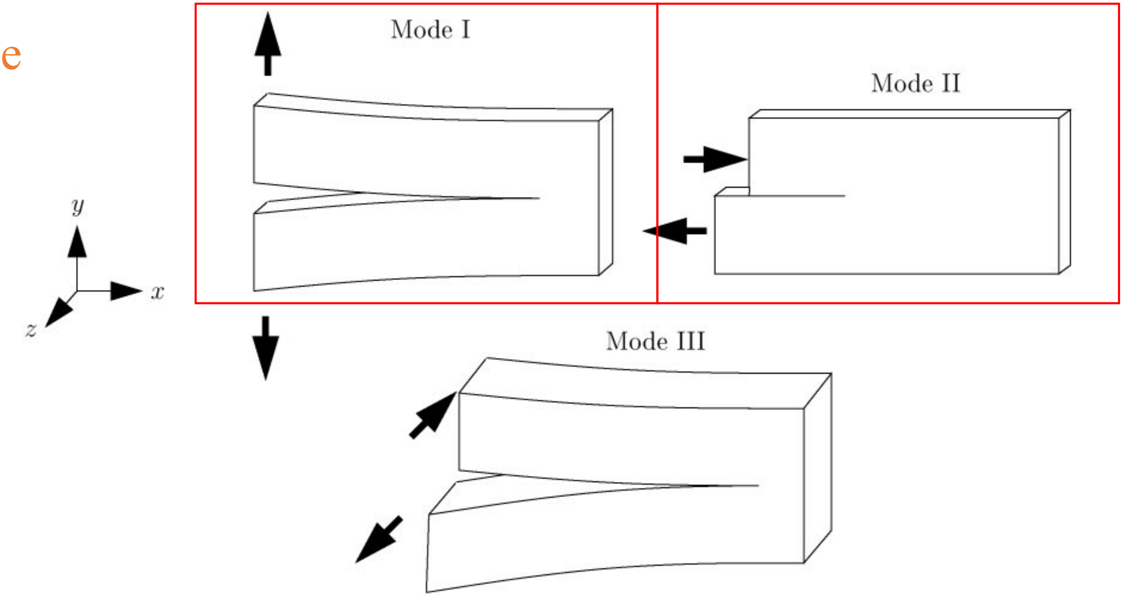
$f_{ij}(\theta, \mathrm{v})$ - dimensionless functions of ***angle*** and ***crack speed***

How do things Break?

LEFM – path selection and crack plane loading

There are ***3 fracture modes***: characterized by the **symmetry of the loading** on the crack plane.

$$\sigma_{ij} = \sum_{\alpha=\mathrm{I}}^{\mathrm{III}} \frac{\boldsymbol{K}_{\alpha}}{\sqrt{2\pi r}} f_{ij}^{\alpha}(\mathrm{v}, \theta)$$



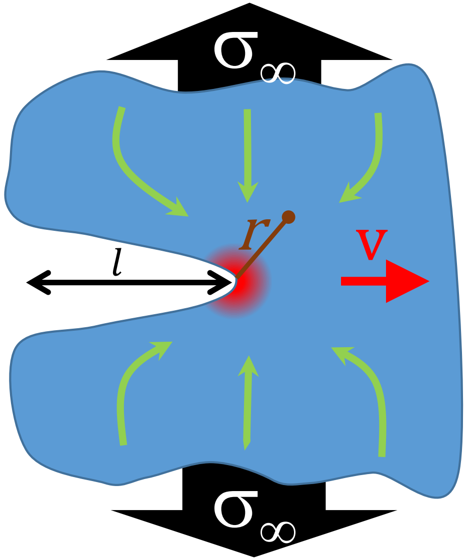
Because the ***stress is singular,*** there is ***no a-priori path selected*** for a crack

Our ***applied loading*** is ***tensile*** loading → Mode I

But remember …. Mode II

How do things Break?

LEFM predictions for dynamic cracks



- Stresses diverge asymptotically close to the crack tip

$$\sigma \sim \frac{K}{\sqrt{r}}$$

Irwin '56

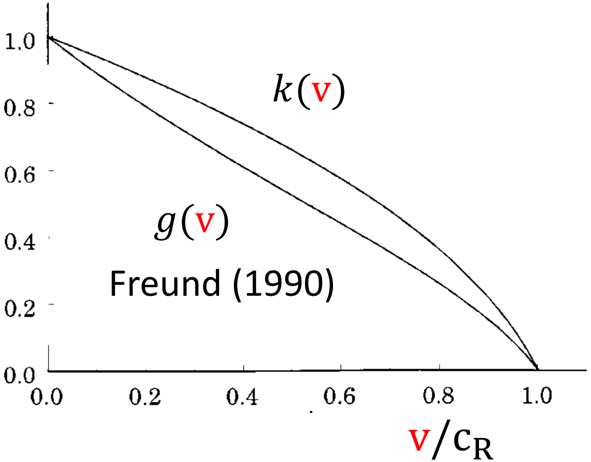
- The "stress intensity factor" ***K*** can be ***computed*** or ***measured***

$$K \sim k(\mathrm{v})\sigma_\infty\sqrt{l}$$

- The elastic energy flux ***G*** is related to ***K*** by:

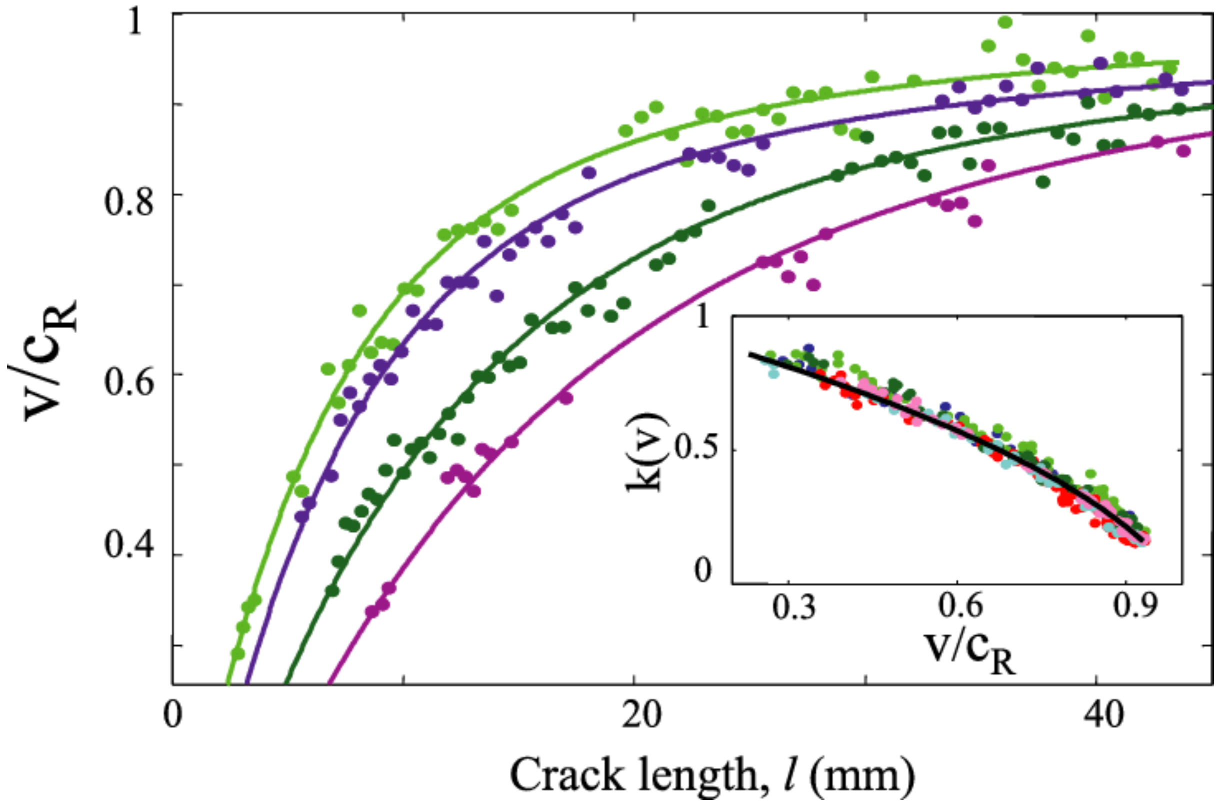
Freund
Eshelby'72
Kostrov '75

$$G \sim \frac{A(\mathrm{v})K^2}{\mathrm{E}} \sim \frac{g(\mathrm{v})\sigma_\infty^2 l}{E}$$



c_R - Rayleigh wave velocity – the speed of elastic shear waves at a free surface

The background: LEFM predicts a crack tip equation of motion - ℓ(v)

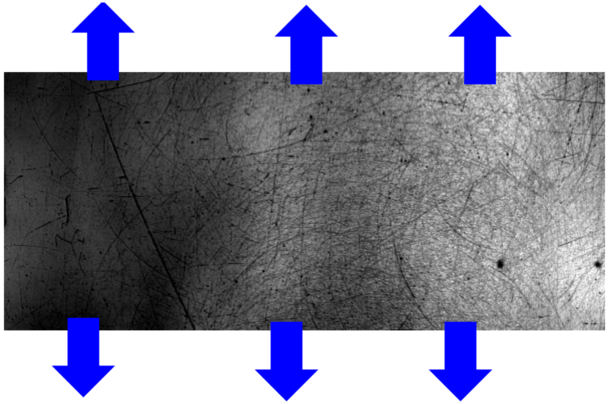


The crack tip’s velocity increases as it propagates into the sample.

This is a consequence of more elastic energy flowing to the crack tip as it propagates.

Such behavior is predicted by Linear Elastic Fracture Mechanics Theory

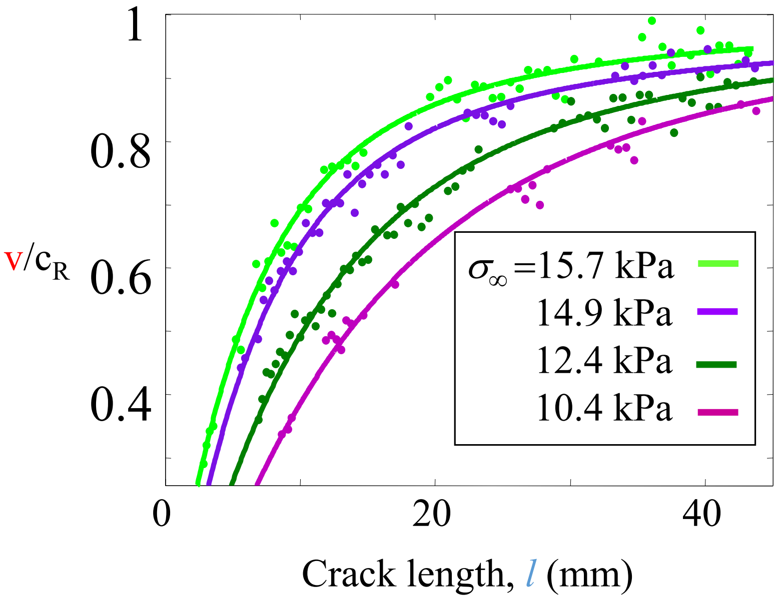
Testing dynamic fracture mechanics
using gels



A **simple** crack in an ***infinite medium*** and constant stress, σ_∞ , using $\boldsymbol{G} = \boldsymbol{\Gamma}$:

$$\Gamma = G(\mathrm{v}, l) \simeq \frac{6}{E}\frac{l}{\pi}\sigma_\infty^2\left(1-\frac{\mathrm{v}}{\mathrm{c_R}}\right)$$

L.B. Freund, Dynamic Fracture Mechanics (1990)



T. Goldman, A. Livne, J. Fineberg, Phys. Rev. Lett. **104**, 1144301(2010).

Linear Elastic Fracture mechanics works!

The experimental set-up:

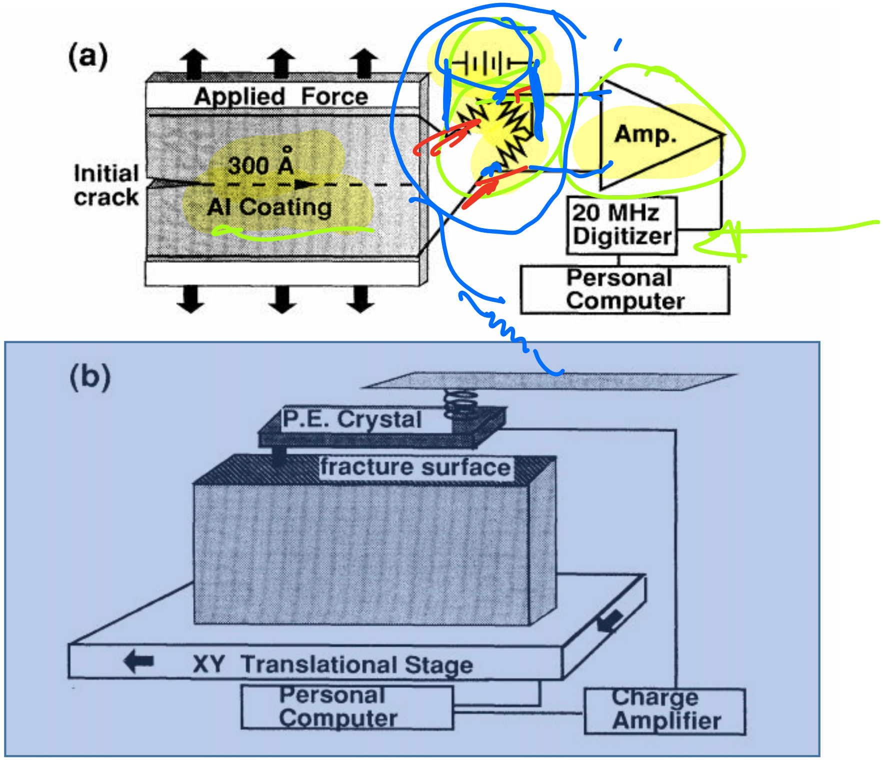


FIG. 1. Schematic representation of the experimental apparatus: (a) velocity measurements; the path of the crack (dotted line) and its direction of propagation are indicated. (b) Surface profile measurements.

Here we see a Wheatstone bridge configuration that is used with a high-speed digitizer to record at 20 MHz the resistance of a thin coating of aluminum applied to brittle plastic.

As the crack propagates, the cross-section of the aluminum coating *reduces,* increasing the resistance measured across the sample – recall our expression for resistivity, where R = ρ ℓ/A. Here, A reduces as the crack propagates. However, the coating thickness and guage of the resistor are held constant; thus, the measured resistance is inversely proportional to the coating's unruptured length.

Profilometry indicates a non-smooth crack surface

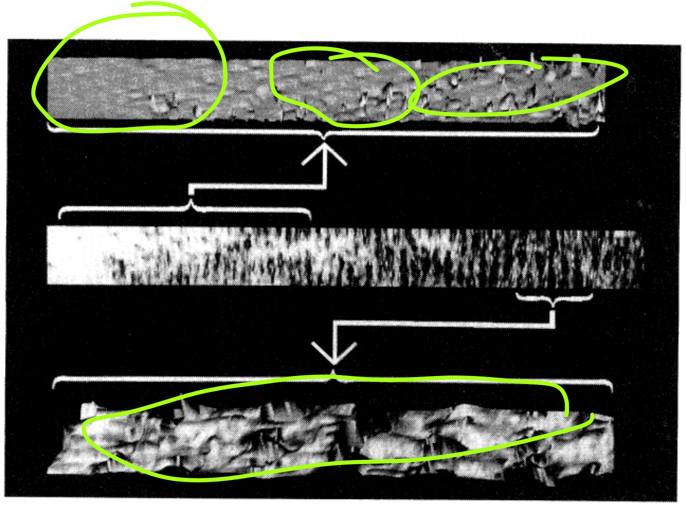


FIG. 2. Computer visualizations of the profilometer data for a crack that propagated from left to right. The central image shows an overview of a portion of the fracture surface, 62 mm × 1.5 mm. Lighting models are used, so that the image is nearly identical to illuminated photographs of the surface. Note the ripple pattern with wavelength on the order of 1 mm. Two subregions have been magnified and are shown in perspective. The onset of the instability appears in the upper image; the highest peaks are about 20 μm. The lower image contains a magnified view of the ripples created by the instability once it develops more fully; the highest peaks are about 50 μm.

Using the mechanical profilometer, a 3D representation of the crack's surface is obtained. It is clear that whereas the crack initially propagates smoothly, ***sharp features emerge*** as the crack progresses further.

These features could be important in understanding the observations of crack tip velocity …

Crack tip speeds: the measurement and the prediction

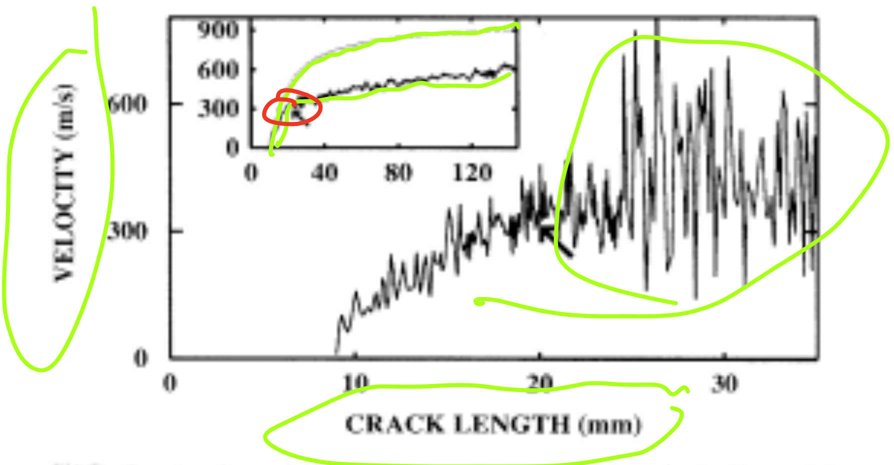


FIG. 3. At the critical velocity of 330 ± 20 m/s, indicated by an arrow, the mean acceleration of a crack slows, and the velocity begins to oscillate. These oscillations are much larger than the resolution. Inset: The measured velocity of the crack, averaged on the scale of 1 mm (solid line), compared with the theory of Freund (dotted line), Ref. [2]. The theory should apply strictly up to 30 mm, and predicts an asymptotic velocity of 975 m/s.

Here we see a huge departure between theory and experiment: In the inset, the predicted v(ℓ) curve is plotted.

The experimental data, however, look nothing like this (!) There are all sorts of spikes, and acceleration that is observed. Nevertheless, we see the crack accelerate on average.

Cross-correlation of velocity with surface profilometry indicates that the surface roughness features occur in tandem with velocity fluctuations

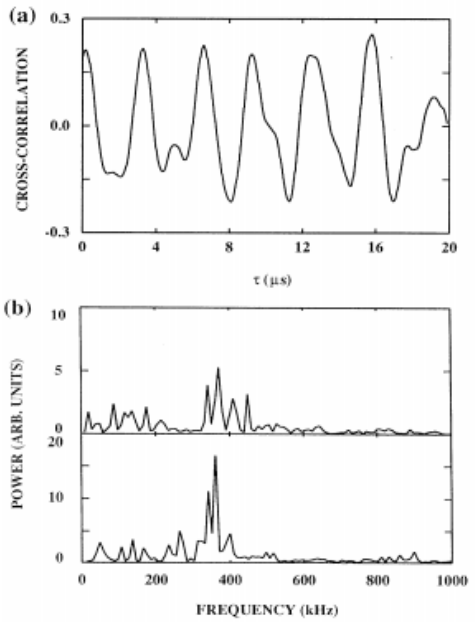


FIG. 4. (a) The correlation of the velocity oscillations with surface profile in a region well beyond transition is shown in this graph of the cross-correlation function, $\sum_t A(t)V(t+\tau)$, where τ is the delay time and A and V are, respectively, the surface height and fluctuating part of the velocity, normalized by their rms values. (b) Power spectra of surface height. Upper: Surface created in the 100 μs immediately following the onset of oscillations. Lower: Surface created in the subsequent 100 μs. Although the mean velocity of the crack increases by over 60%, the frequency of oscillation remains constant.

In (a), we see the correlation of the velocity with the surface profile in the `noisy’ region. Clearly the surface features and velocity are well-correlated at a timescale of a few microseconds.

The frequency spectrum of the surface features at two different velocity windows. At top, the mean velocity is 3/5 what it is at the bottom, indicating that the frequency of the observed surface features is velocity-independent.

The velocity at the onset of oscillations is singly-valued, indicating a critical transition.

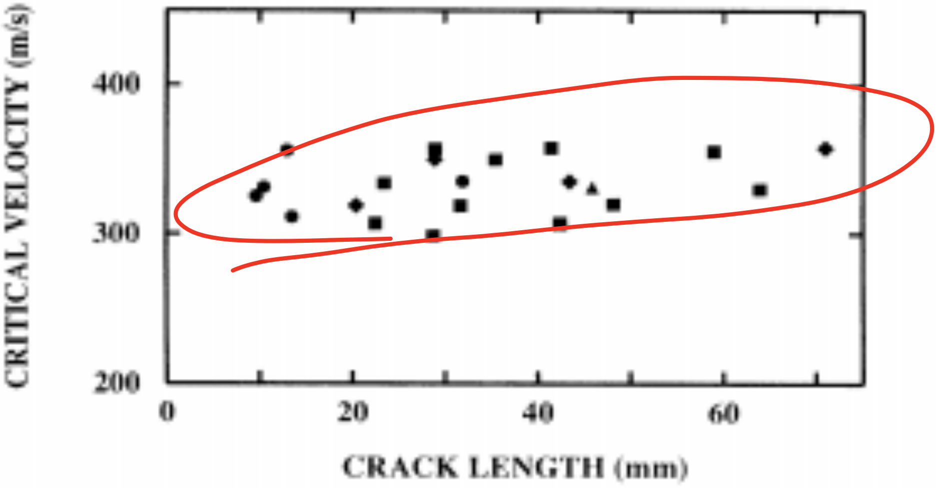


FIG. 5. Critical velocity as a function of crack length at the time of transition. Circles, 1.6-mm extruded PMMA in air; squares, 3.2-mm cell-cast PMMA in air; diamonds, 3.2-mm cell-cast PMMA in helium; and triangle, 3.2-mm cell-cast PMMA in nitrogen. All measurements were at room temperature.

Here we see that the velocity immediately prior to the onset of ***v*** fluctuations is nearly constant, around 320 m/sec, as the applied stress is varied (a longer run-out to reach a given velocity)

This suggests that the transitional velocity is a uniquely valued, and indicates a critical transition to unstable crack propagation.

Analog Electronics I: resistors & V-dividers

Tuesday, September 15, 2020 8:18 PM

pg. 1-44 in Horowitz & Hill, The Art of Electronics.

2 Fundamental laws:

Ohm's law we're using this for our measurement.

Kirchoffs laws

$$\boxed{V = I R}$$

Resistance to e⁻ flow.

Voltage / potential

flow of e⁻

Analogy to hydrodynamics:

$$H = J \cdot R$$

hydrostatic pressure

fluid flux

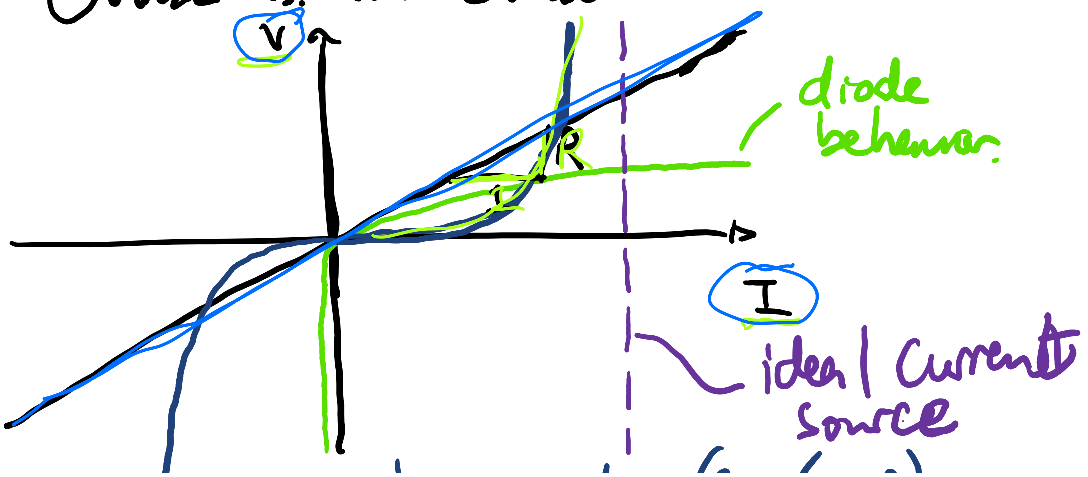
Hydrodynamic resistance

"A Volt pushes an Amp through an Ohm."

= potential energy / unit charge.

*Voltage is measured relative to a reference potential.

"Ohmic" vs. "non-Ohmic" behavior



source

non-linear resistor (e.g. lamp)

Power: $P = IV = \boxed{I^2R}$

Ohm's law.

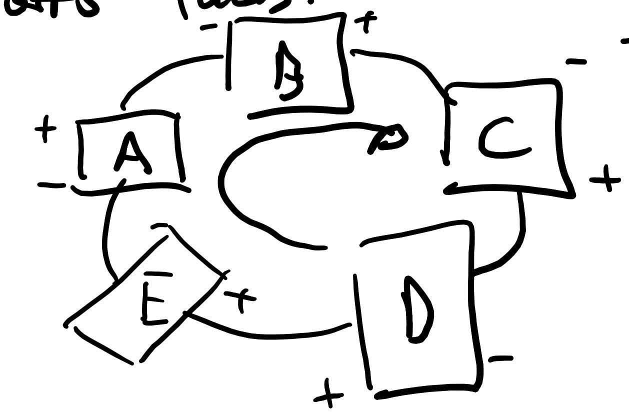
I : current, charge/time

V : work or energy/charge

$[IV]$ $\frac{\text{work}}{\text{time}} = \frac{\text{energy}}{\text{time}} = [P]$.

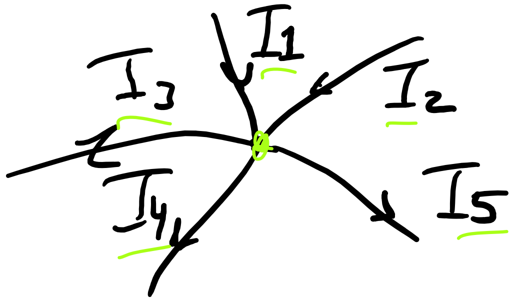
Kirchoff's laws:

I:



* Sum of voltages around a closed loop is 0.

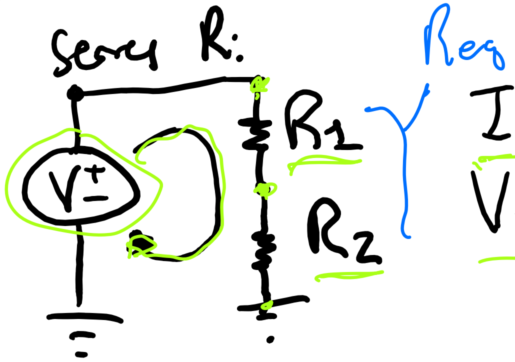
II



* Sum of the currents at a node is 0.

$I_1 + I_2 + I_5 + I_4 + I_3 = 0$

Examples: Series R:

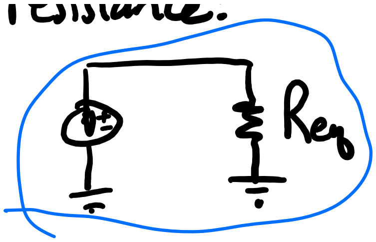


$I_{tot} = I_1 = I_2$ by K2.

$V_{tot} = V_1 + V_2$ (K I)

An eq. resistance: $V_{tot} = I_t R_{eq} = I_t R_1 + I_t R_2$

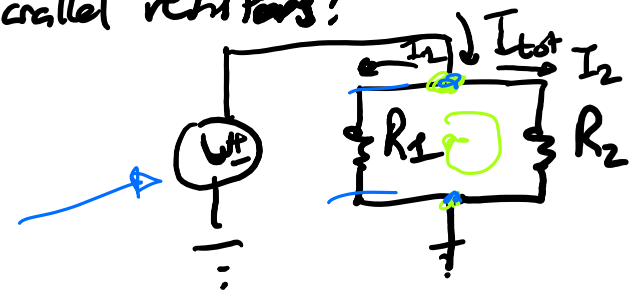
Thn eq. resistance:



$V_{tot} = I_t R_{eq} = I_t R_1 + I_t R_2$ $= I_t(R_1+R_2)$

$$\boxed{\Rightarrow R_{eq} = R_1 + R_2}$$

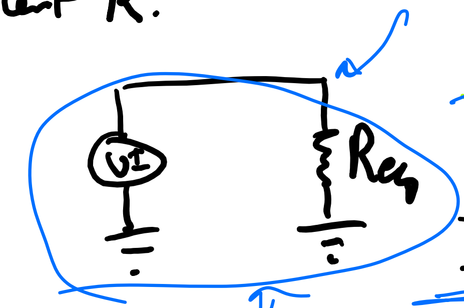
parallel resistors:



$I_{tot} = I_1 + I_2$. (K2)

$V_{tot} = V_1 = V_2$ (K1).

equivalent R:



$V_{tot} = I_{tot} \cdot R_{eq} = V_1 = V_2$

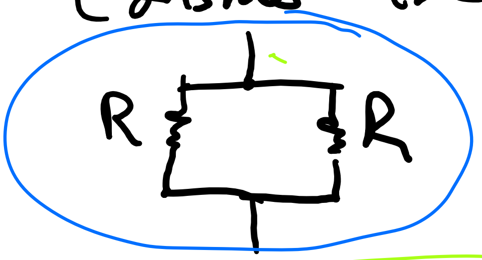
$I_{tot} R_{eq} = I_1 R_1 = I_2 R_2$

$I_{tot} = I_1 + I_2$; $I_1 = \frac{V}{R_1}$, $I_2 = \frac{V}{R_2}$

$I_{tot} = \frac{V}{R_{eq}}$

$$\boxed{\frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2}} \Rightarrow \boxed{R_{eq} = \frac{R_1 R_2}{R_1 + R_2}}.$$

Consider these cases:



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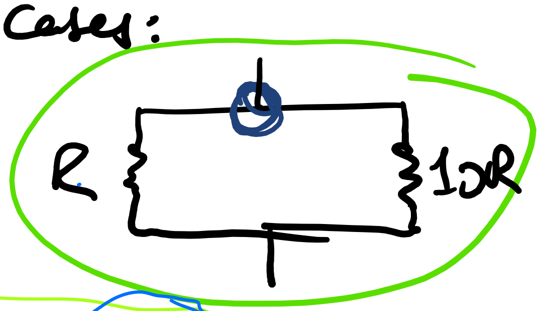

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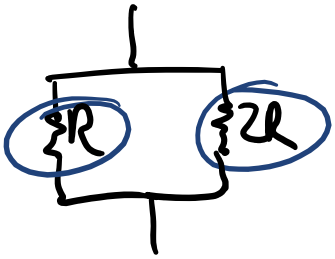
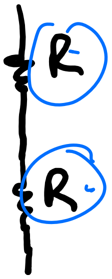


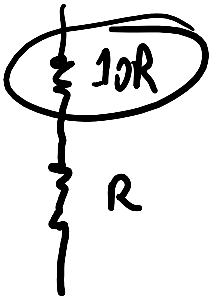
$$\boxed{R \| R \Rightarrow R_{eq} = \frac{R^2}{2R} = \frac{R}{2}}.$$

$$R \| 10R \Rightarrow R_{eq} = \frac{10R^2}{R+10R} = \frac{10R^2}{11R} \simeq R$$

$\overline{R+10R}$ $\quad \overline{11R} \simeq R.$

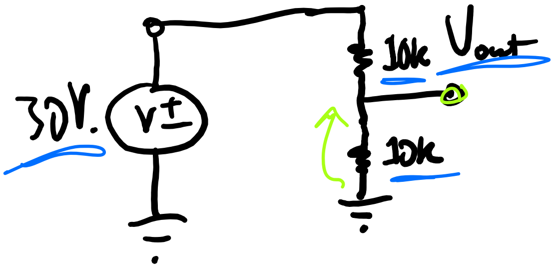
$R_{eq} = 2R$





$R_{eq} = 11R \simeq 10R.$

V - divider (a device)

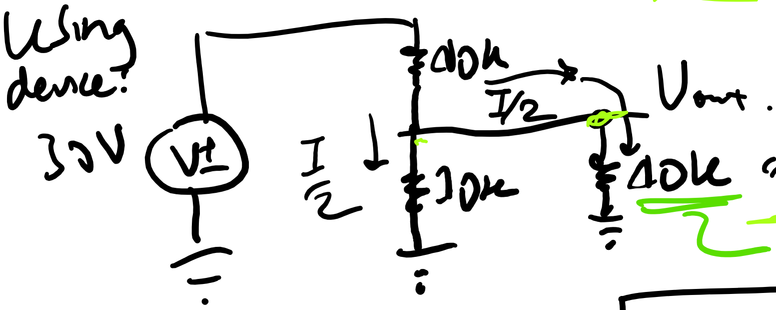


Solve for V_{out}:

$$I = \frac{V_{in}}{(R_1+R_2)} \; ; \quad \boxed{V_{out} = IR_2}$$

$$V_{out} = \frac{V_{in} R_2}{R_1+R_2} = \boxed{\frac{V_{in}}{2}}$$

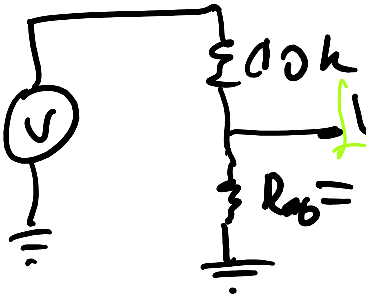
Using device?



"Resistive load."

100k.

$\equiv$



$$\boxed{V_{out} = \frac{V}{3}}$$

$R_{eq} = 10k \| 100k = \cancel{5k}\ 10k.$

Thevenin equivalent circuits

- For any two nodes in a circuit, irrespective of the circuit's complexity (only linear circuit elements @ steady-state):

An equivalent circuit composed of a voltage source U_{TH} and a resistance R_{TH} can be found.

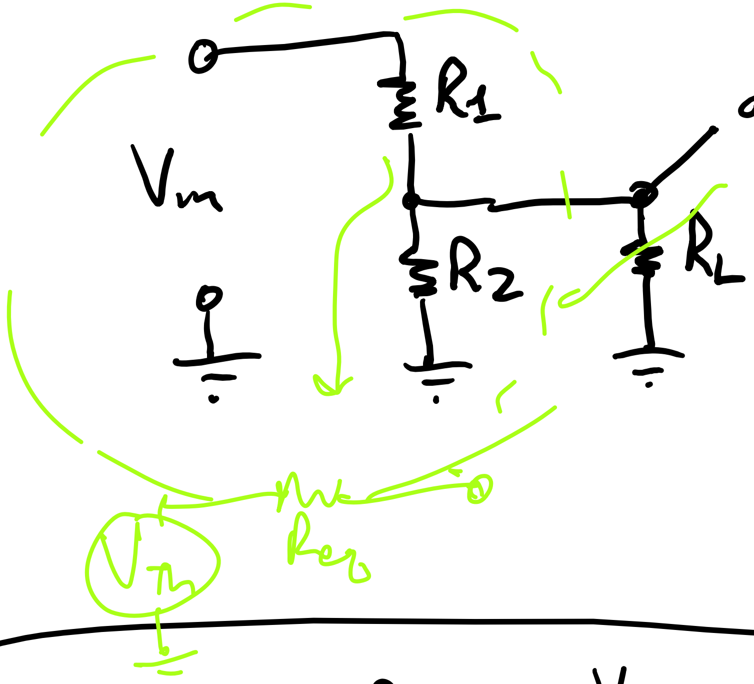
* V_{TH} & R_{TH} can be found in 2 steps:

1. $V_{TH} = V$ (open circuit) – no load!
2. $R_{TH} = \frac{V_{TH}}{I\text{ (short circuit)}}$

R_{TH} is the output impedance of such a circuit

The voltage divider revisited: the Thevenin equivalent circuit and output impedance

Let's revisit the humble voltage divider circuit from last week:



1. V open circuit: $V_a = \frac{V_{in} R_2}{R_1+R_2} = \boxed{V_{Th}.}$

2. $R_{Th} = \frac{V_{Th}}{I(\text{short})}$! If $R_L = 0\,\Omega$, a short circuit is achieved.

If this circuit is shorted, we find:

$$I = \frac{V_{in}}{R_1}.$$

Thus, $R_{Th} = \frac{V_{Th}}{I} = \frac{R_1 R_2}{R_1+R_2}$. Note, this is $R_1 \| R_2$!

Reactive circuit elements & transient circuit response: capacitors

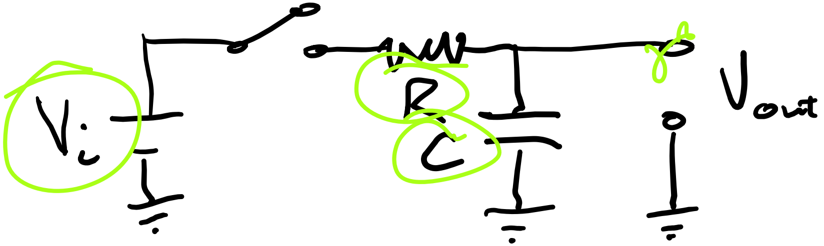
A ***capacitor with capacitance*** *C* stores charge (*Q*) in proportion to the applied voltage *V*. This can be expressed with an equation as:

$$\boxed{Q = CV}$$

Q is hard to quantify or measure in practice; instead, we reformulate this expression for current *I* to make it more manageable, by taking the time derivative of both sides:

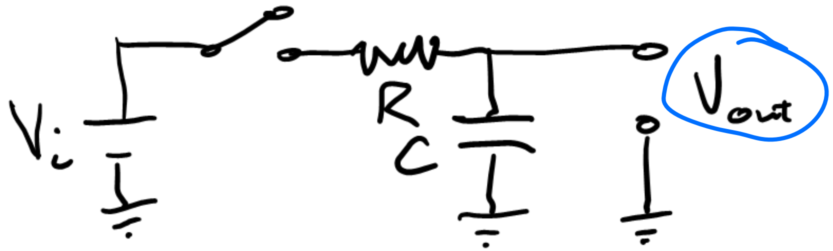
$$\frac{dQ}{dt} = C\frac{dV}{dt} \rightarrow \boxed{I = C\frac{dV}{dt}}$$

Since *I* now depends on the *temporal behavior* of *V,* we call capacitance a `reactive’ circuit element -> current `reacts’ to changes in voltage. A natural question is how this manifests itself with a simple circuit: let us look at the transient response of a simple circuit:



here, $I = \boxed{\frac{V_i - V(t)}{R} = \boxed{C\frac{dV}{dt}}}$.

solving this ODE: $\boxed{V(t) = V_i + Ae^{-t/RC}}$.

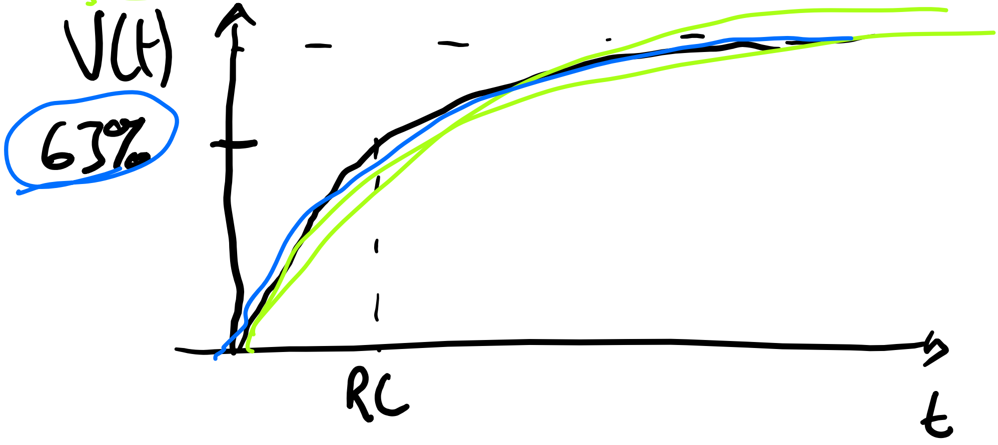


solving this ODE: $\boxed{V(t)=V_i+Ae^{-t/RC}}$

We can find A by considering the initial condition:

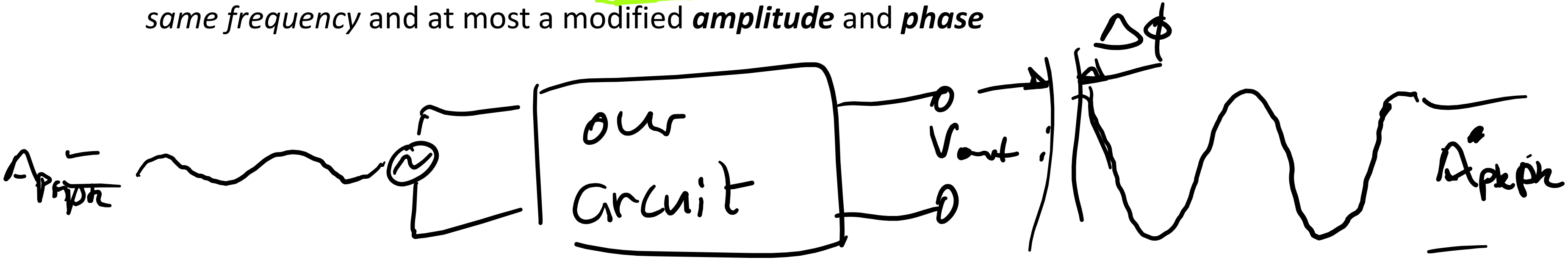
$$V(0)=0=V_i+Ae^{0} \Rightarrow \boxed{A=-V_i.}$$

Thus, $\boxed{V(t)=V_i\left(1-e^{-t/RC}\right):}$



A/C circuit analysis – looking at sinusoidal* signals

Since our circuits at this stage are *Linear*, the output of a sinusoidally driven circuit is itself a sinusoid with the *same frequency* and at most a modified ***amplitude*** and ***phase***

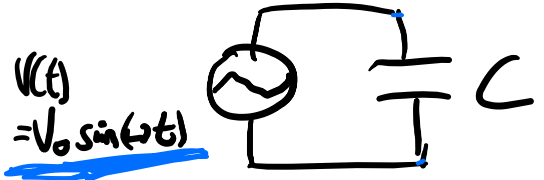


Sinusoids are parameterized by an ***amplitude*** and a ***phase*** **–** this structure lends itself well to a description with complex variables, which also have two quantities of merit – the ***real*** and ***imaginary*** part. The phasor description, with e.g. $V = V_0 e^{j\varphi} = V_0\,(\cos\varphi + j\sin\varphi)$; for a signal oscillating with frequency ω, the phase of this signal is ωt

* For the math experts, the Fourier series is a sum of sinusoids, and with appropriate weights can approximate any periodic function over an interval. Thus analyzing the response to an arbitrary sinusoid, and the linear property of RLC circuits means we can describe the circuits response to an *arbitrary* forcing.

Generalizing resistance: Impedance and the transfer function for `forcing’ (V) to `response’ (I)

Let's first consider a sinusoidal voltage applied to a capacitor:



Here, $\underline{I} = \underline{C}\frac{dV}{\underline{dt}} = \underline{C\omega V_0 \cos}(\omega t)$

Neglecting the phase, we can obtain the current as:

$\boxed{I} = \frac{\boxed{V}}{\boxed{1/\omega C}}$; thus the capacitor behaves like an ω-dependent resistor!

RECALL: $I = \frac{V}{R}$

To account for phase correctly, we'll write $V = \mathrm{Re}(V_0 e^{j\omega t})$.

Since $I = C\frac{dV}{dt}$, $\Rightarrow I(t) = \mathrm{Re}(j\omega C V_0 e^{j\omega t}) = \mathrm{Re}\left(\frac{V_0 e^{j\omega t}}{-j/\omega C}\right)$.

Thus, we define a reactance X_c for the capaci:.

$$\boxed{X_c = \frac{V}{I} = \frac{-j}{\omega C}}$$

(n.b. this is structurally similar to R from Ohm's law! $R = \frac{V}{I}$.)

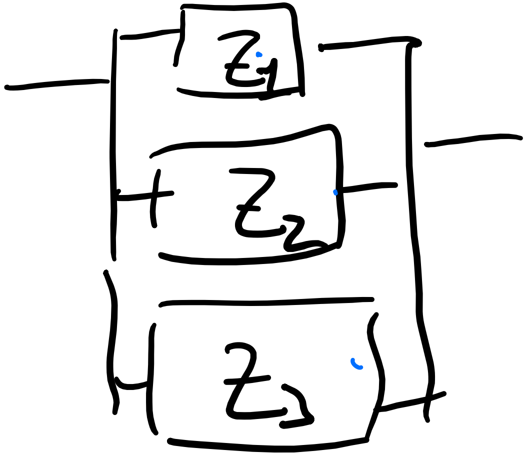
We can now define a generalized Impedance, Z, which in general is complex:

$$\boxed{I = \frac{V}{Z}} \Longleftrightarrow \boxed{V = IZ}.$$

Z's follow R's rules for addition in || & series:

: $\boxed{Z_{eq} = Z_1 + Z_2 + Z_3}$.

In ||:



$$: \boxed{Z_{eq} = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}}}.$$

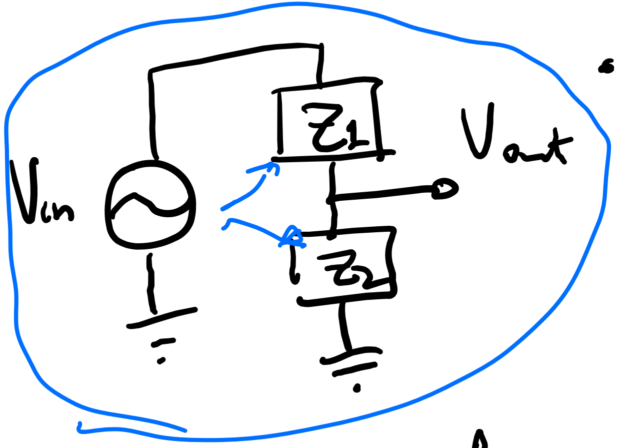
Generalized impedance for passive circuit elements:

$\underline{Z_R} = \underline{R}$ (resistors)

$\underline{Z_I} = \underline{j\omega L}$ (inductors)

$\underline{Z_c} = \underline{-j/\omega C}$ (capacitors).

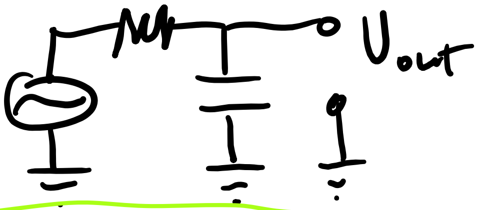
Generalizing the V-divider: frequency dependent response and filter devices



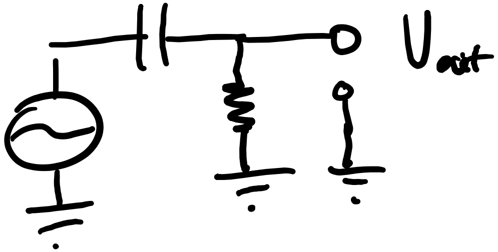
- The analysis is essentially the same as before:
  - $I = \frac{V_{in}}{Z_{tot}}$, $Z_{tot} = Z_1 + Z_2$.
  - $V_{out} = I Z_2 = \frac{V_{in} Z_2}{Z_1 + Z_2}$.

But now, Z is in general complex – and thus ω-dependent!

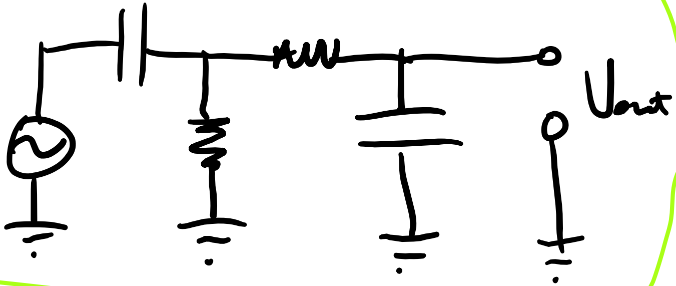
Low-pass filter:



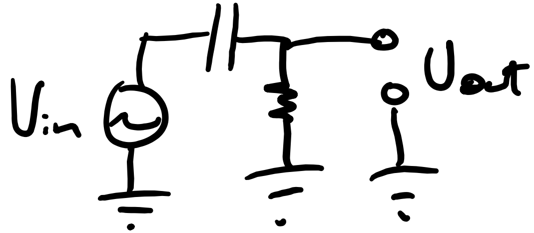
high-pass filter:



band-pass filter:



Analysis of the high-pass filter



By generalized Ohm's law: $I = \frac{V_{in}}{Z_{tot}} = \frac{V_{in}}{R - j/\omega C}$

$$= \frac{V_{in}(R + j/\omega C)}{R^2 + (1/\omega C)^2}$$

$$\Rightarrow V_{out} = I Z_R = \frac{V_{in}(R + j/\omega C)R}{R^2 + \left(\frac{1}{\omega C}\right)^2}$$

Since we'll focus on amplitude, not phase, we'll work w/

$$|V_{out}| = (V_{out}^* V_{out})^{1/2} = \frac{R V_{in}}{\left[R^2 + \left(\frac{1}{\omega C}\right)^2\right]^{1/2}} = \frac{R\omega C}{(1 + (R\omega C)^2)^{1/2}} V_{in}$$

SGM

Experimental Methods in Engineering Mechanics – ME 412

Fall semester 2022
Lab / lecture: Wednesdays MED 2 2419 (module 1, weeks 1-6), other locations to be announced
Office hour: Tuesday afternoon, MED 2 2419, typ. 3-5 p.m.

Professor:	John M. Kolinski (john.kolinski@epfl.ch), +41 21 693 0270
Teaching associates:	Chenzhuo Li
Wiki:	**https://wiki.epfl.ch/me412-emem-2021**
Grading:	A lab report will be prepared by each group at the end of the module, for a total of 3 reports; these will be used to calculated your grade. More information on grading can be found below in **Format and Procedures**.

I. Rationale:

Experimental measurement is the cornerstone of all scientific progress. Being able to design, construct apparatus, carry out measurements and interpret data is essential to scientific and engineering endeavors. In the field of mechanics, there are some experimental methods that have proved their utility, including the use of electronics in experiment, and imaging. This class provides a broad introduction to these methods with specific classical examples in three modules. Through these examples, students will develop a foundation for future research and development in applied mechanics.

II. Course Aims and Outcomes:

Aims

At the end of this class, you should be comfortable identifying an experimental method to measure a given mechanical quantity. Furthermore, you will become familiar with the three experiments and the science behind them. You will be required to seek out information in the course of each module, and this should prepare you to face challenging, open-ended experimental problems in engineering or science.

Specific Learning Outcomes:

Students who have taken this class can expect

- to understand enough analog electronics to build simple circuits using passive and active components with minimal assistance from e.g. Google
- to read a manual or data sheet and then successfully use the IC or apparatus
- to understand the basics of imaging and geometric optics
- to understand the construction and essential elements of a microscope
- to use image processing to extract data from digitally recorded images
- to learn about the mechanics of fracture and Brownian motion
- to be familiar with particle tracking and image correlation methods

III. Format and Procedures:

The course structure is unconventional, so please ask questions if you do not understand something. Warning: this is not a lab class where I provide you with a recipe. You will be required to identify problems, and take the appropriate actions to address them, often without substantial input from the teaching staff. Part of the process of science and engineering is collaborative effort to solve open-ended problems. Not all students appreciate this course structure – if you don't think you will like this course structure, I encourage you to consider the other great course offerings at EPFL instead of EMEM.

Each module will be introduced with a preliminary lecture, where the scientific motivation for the measurement and experimental approach are introduced. Some guided laboratory exercises will provide a platform for engagement with the necessary experimental apparatus. Following these preliminary lab exercises, each experimental group will proceed to construct some components of the experiment, calibrate the constructed components, record data and compile the laboratory procedure and results into a report.

Experimental groups will comprise three to four students each, for a total of approximately 10 groups. Groups will prepare a report to be assessed after the module. Contributions to the course wiki should be included in the appendix, and will be assessed with the report. Wiki contributions can only enhance the grade of the report, and will not detract from it.

I will grade the first reports to provide an example of the standards expected in a report, and the two subsequent modules will be graded by other groups, whose assessment I will use in determining the grade. As long as the assessment is not capricious, the peer assessment will be used to determine the grade for the report. The assessment of the other group's report will comprise a portion of your grade for the report on the respective module.

In each module, groups must rotate so that each individual student is working with students they have not worked with in a previous module.

Grading: lab reports form the bulk of the grade, with each module weighted equally. For modules 2 and 3, the grade will consist of 80% of the composite assessment (mine and the evaluation of another group), and 20% of your grade will be based on your group's *assessment* of the peer report. Contributions to the wiki can add up to 5% toward the report grade.

The format for the lab reports should follow the 2-column APS letter format (see https://journals.aps.org/prl/authors for technical formatting guidelines), with a focus on concise explanations, and an intense focus on the results of the experiment. All technical details concerning the lab exercises and contributions to the wiki can be submitted as an appendix, or as a second document. Close attention must be paid to **figure presentation and captioning**, as this is a critical aspect of clearly communicating your results from the experiment. Bullet points describing expectations are as follows:

- Figures should be clear, with legible axis labels and legends.
- Figure captions should be complete and concise – all aspects of the figure should be explained, but excess verbiage is to be avoided.
- Writing style should be focused in concise and clear exposition.
- Rigor in the scientific approach, including hypothesis formulation, hypothesis testing, development of results with data to support the conclusions drawn from the experiment, and contextualization of the result in a brief discussion convey the rigor of the scientific approach to each experiment.

Expectations of group reports for each module:

- The report on the final measurement will follow the format of a PRL paper. Some rough guidelines on this writing style can be found here: https://www.asc.ohio-state.edu/wilkins.5/onepage/prl.html . I would encourage more a focus on the overall spirit of the guidelines (points 1, 2, 8 and 9) are the most important. Having a precise line count is less important, but any text on page 5 is too much text. A supplementary document or appendix including technical details, materials and methods and calibration experiments is allowed, but should only be used to fill in the gaps in the paper.
- The grading breakdown, briefly, is:

Grading Category	**% of report grade**
PRL format (title, abstract, technical layout, etc.)	5
Figures clear, well-annotated and captioned	30
Clear, concise writing	30
Proper use of any statistical analysis / error quantification	5
Use of scientific method	10
Experimental "Je ne sais quoi" / wiki / etc.	25 (5 bonus)
Total	**105 / 100**

IV. Background for the class:

This course assumes a strong background in fluid and solid mechanics, as well as familiarity with electronics and associated apparatus.

V. Course Resources: I encourage you to take good notes during introductory lecture for each module, and maintain a running lab book with figures and illustrations. These will make the preparation of the lab reports much easier.

Selected readings will be provided each week on the wiki

The wiki forms a core component of the class. Here, explanations of a particularly helpful procedure, or extra information that you found useful should be posted. Contributions to the wiki should be carefully documented and presented to increase their utility. Wiki contributions should be included with lab reports in the appendix, and can be counted as additional credit for the lab report.

- An incomplete list of course readings:
    The art of electronics by Horowitz and Hill
    Theory of Elasticity by Landau and Lifshitz
    Fluid Mechanics by Landau and Lifshitz
    Dynamic Fracture Mechanics by L.B. Freund
    …. Selected papers to be posted to the Moodle
    …. Data sheets for pertinent op-amps, etc.

VI. Academic Integrity

As laboratory reports constitute the bulk of the assessment, a high standard for proper citation practice is essential. Any deliberate plagiarism will result in a failing grade for the report. You will not lose credit for proper attribution; on the contrary, proper attribution will enhance the clarity of the report and likely increase your grade.

VII. Students with disabilities

In compliance with the EPFL LEX 2.6.5, I am available to discuss appropriate academic accommodations that may be required for student with disabilities.

IX. Tentative Course Schedule: (*Subject to change*)

Week	Module	Plan for contact hours	Outside of class – readings prior to lecture
1	I	Intro to course – grading, expectations; intro to module; intro to exercises & background – passives and filters	Reading on Oscilloscopes, review syllabus
2	I	Transistors and amplifiers	Assigned readings
3	I	Wheatstone Bridge & driving circuitry	Assigned readings
4	I	Calibrate samples with 4-wire measurement, debug / calibrate bridge circuit	Assigned readings
5	I	Measurements, report preparation and writing	Work on report
6	I	Measurements, report writing	Work on report

7	II	Intro. To instrumentation & experimental prep – DIC lab	Assigned readings
8	II	Prepare samples for measurement; first measurements	
9	II	Conclude experiments & process data	Assigned readings & software preparation for DIC
10	II	Conclude processing & write lab report	
11	III	Lecture, discussion & exercises – Brownian motion	Prepare reading; evaluate report of alt. group from Mod II
12	III	Experimental set-up & preparation	Assigned readings & software preparation for particle tracking
13	III	Conclude experiments & process data	
14	III	Complete data processing & write reports	