**Tungsten Tip Resonance: Freq-ing Out**

**Problem**
Graphene is a material with many incredible application in the future. However, the nature of the one-atom thick material makes it very difficult to study. With the use of scanning tunneling microscopes (STM), images are captured but could the resonant frequencies found in tungsten tips cause enough noise to significantly lower the resolution of images?

**Abstract**
Waves and optics is one of the units that students often have the hardest time understanding as it is difficult for them to “see” what is happening at the atomic level. This lesson starts with an introductory discussion with demonstrations on the nature of science, measurement and uncertainty that introduces the students to the research in graphene. The second part of the lesson is intended for use during the waves and optics unit to emphasize wave properties, introduce resonance and lead into a study into atomic & nuclear physics through a discussion on resonance in the research done on graphene and connect with a lab on resonance using tuning forks.

**Alignment with Standards**

**National Standards: Advanced Placement Physics B**

IV. Waves and Optics - Wave Motion

1. Traveling waves – Students should understand the description of traveling waves, so they can:
   a) Sketch or identify graphs that represent traveling waves and determine the amplitude, wavelength, and frequency of a wave from such a graph.
   b) Apply the relation among wavelength, frequency, and velocity for a wave.
   d) Describe reflection of a wave from the fixed or free end of a string

2. Wave propagation
   b) Students should understand the inverse-square law, so they can calculate the intensity of waves at a given distance from a source of specified power and compare the intensities at different distances from the source.
3. Standing waves - Students should understand the physics of standing waves, so they can:
   a) Sketch possible standing wave modes for a stretched string that is fixed at both ends, and determine the amplitude, wavelength, and frequency of such standing waves.

4. Superposition - Students should understand the principle of superposition, so they can apply it to traveling waves moving in opposite directions, and describe how a standing wave may be formed by superposition.

V. Atomic and Nuclear Physics

A. Atomic physics and quantum effects

1. Photons, the photoelectric effect, Compton scattering, x-rays
   a) Students should know the properties of photons, so they can:
      (1) Relate the energy of a photon in joules or electron-volts to its wavelength or frequency.
      (2) Relate the linear momentum of a photon to its energy or wavelength, and apply linear momentum conservation to simple processes involving the emission, absorption, or reflection of photons.
      (3) Calculate the number of photons per second emitted by a monochromatic source of specific wavelength and power.
   b) Students should understand the photoelectric effect, so they can:
      (1) Describe a typical photoelectric-effect experiment, and explain what experimental observations provide evidence for the photon nature of light.
      (2) Describe qualitatively how the number of photoelectrons and their maximum kinetic energy depend on the wavelength and intensity of the light striking the surface, and account for this dependence in terms of a photon model of light.
      (3) Determine the maximum kinetic energy of photoelectrons ejected by photons of one energy or wavelength, when given the maximum kinetic energy of photoelectrons for a different photon energy or wavelength.
      (4) Sketch or identify a graph of stopping potential versus frequency for a photoelectric-effect experiment, determine from such a graph the threshold frequency and work function, and calculate an approximate value of h/e.
Wave-particle duality- Students should understand the concept of de Broglie wavelength, to

a) Calculate the wavelength of a particle as a function of its momentum.

b) Describe the Davisson-Germer experiment, and explain how it provides evidence for the wave nature of electrons.

1. Design experiments

2. Observe and measure real phenomena

**State Standards – Georgia Science Standards**

SCSh3. Students will identify and investigate problems scientifically.

a. Suggest reasonable hypotheses for identified problems.

b. Develop procedures for solving scientific problems.

c. Collect, organize and record appropriate data.

d. Graphically compare and analyze data points and/or summary statistics.

e. Develop reasonable conclusions based on data collected.

SCSh4. Students will use tools and instruments for observing, measuring, and manipulating scientific equipment and materials.

a. Develop and use systematic procedures for recording and organizing information.

b. Use technology to produce tables and graphs.

c. Use technology to develop, test, and revise experimental or mathematical models.

SP4. Students will analyze the properties and applications of waves.

a. Explain the processes that results in the production and energy transfer of electromagnetic waves.

b. Experimentally determine the behavior of waves in various media in terms of reflection, refraction, and diffraction of waves.

c. Explain the relationship between the phenomena of interference and the principle of superposition.

SP6. The student will describe the corrections to Newtonian physics given by quantum mechanics and relativity when matter is very small, moving fast compared to the speed of light, or very large.
a. Explain matter as a particle and as a wave.

b. Describe the Uncertainty Principle.

**Objectives**
The lesson acts as an introduction to the field of science and opens the door towards discussing current research in the field of science. Furthermore, the students will have the opportunity for hands-on learning in dealing with waves, particularly the aspect of resonance in materials.

**Anticipated Learner Outcomes**
Students should:

1. Inspired interest in the world of science research, particularly being exposed to graphene
2. Understand the nature of science and how scientific theories are developed and accepted
3. Understand orders of magnitude and how to approach new problems, particularly at the nano-scale
4. Discover the importance of uncertainty in measurements
5. Design an experiment to test a hypothesis to a real-world problem dealing with resonant frequencies
6. Analyze data from an experiment and draw conclusions on the relationship between frequency and various geometries
7. Calculate frequencies given different geometries from experiment conclusions

**Assessment & Rubrics**
A copy of the Powerpoint slides and the student handouts can be found in the Appendix of this document. A recommended rubric can be found based on the lab report.

Built in formative assessments can be done during the class discussion questions with the lab report acting as a summative assessment. Further homework, in-class assignments or test questions relating with waves and optics can and should relate to the Anticipated Learner Outcomes.
Background
In studying the physical properties of graphene, scanning tunneling microscopes (STM) were used for the purposes of producing high resolution images of graphenic samples. Graphene is described as being a single layer of graphite that is extremely light, highly conductive, transparent and incredibly strong. The material shows much potential with applications including integrated circuits, touch screens, solar cells, and ultracapacitors and high quality images are essential in gathering accurate data in characterizing graphene.

However, during the imaging process, a background frequency of approximately 400 Hz was observed, which if paired with the resonant frequencies of the tungsten tips could lead to increased oscillations. With the increased oscillations quantum tunneling from the tungsten tip to the surface of the graphene samples is spread to multiple atoms at different heights that will lead to low resolution images. This resonance could be a major cause for lower resolution images being produced for a given sample.

The research done over the summer led me to build and use COMSOL and Solidworks models to analyze various tip dimensions to determine the optimal dimensions and fixture options for tungsten tips to prevent adverse effects of resonance and minimize background noise in image production.

Materials & Supplies
- Graduated cylinder filled with water
- Open-ended PVC tube
- Meter stick
- Thermometer
- Tuning forks
Explained in more detail in the student handout

Plan
During the first week of school (55 minute class periods):

1. Start with the opening exercises and having students write question and show calculations (5 minutes)
2. Introduce the idea of the Nature of Science (5 minutes)
3. Discussion question (3 minutes in groups, 5 minutes as a class depending on how many research topics are brought up)
4. Discussion question on graphene (2 minutes as a class)
5. Introduce research experience at Georgia Tech and show video on graphene [http://www.youtube.com/watch?v=SXmVnHgwOZs](http://www.youtube.com/watch?v=SXmVnHgwOZs) (10 minutes)
6. Measurement Demo (10 minutes)
7. Finish with significant figures, units and standards lecture & discussion

During ‘Waves & Optics’ unit, preferably after introductory lessons on wave basics, including interference. This lesson should be on a block schedule (1.5 hours) or be a 2-day lesson:

1. Picking up from slide 13, start lesson with the blackbox activity (3 minutes to write down ideas, 5 minutes for volunteers)
2. Discuss measuring at the nano-scale using STM and the importance of tungsten tips for high-resolution images (5 minutes)
3. Resonance introduction with Tacoma Narrows bridge video [http://www.youtube.com/watch?v=j-zczJSxnxw](http://www.youtube.com/watch?v=j-zczJSxnxw) (10 minutes)
4. Resonance in tungsten tips (5 minutes)
5. Class discussion on experiment design for tuning forks lab (5 minutes)
6. Finalize procedures for lab and let students work on lab for remainder of class period (50 minutes)
7. Lab reports due 2 days after lab complete

**Summary**

The purpose of these lessons is to introduce students to current ideas in research, particularly dealing with graphene and to emphasize the concept of resonance and its affect in every material. With the introductory lesson, the nature of science discussion will set the stage for the year as students learn to think critically and discuss the importance of science research and to take into account uncertainty when dealing with research. The topic of graphene will be introduced and incorporated throughout various lessons as an example of its relation to a number of topics, including atomic physics, waves & optics and electricity & magnetism. The lesson plan here focuses on waves and the principle of resonance with a lab activity where students are challenged to design an experiment to find the natural frequency of unmarked tuning forks and relate that with the research I participated in during the summer in finding the resonant frequencies of tungsten tips in scanning tunneling microscopes.
Appendix
Resonance Lab: Student Handout

**OBJECTIVE:** To determine the fundamental frequency and wavelength of 4 tuning forks

**MATERIALS:** Graduated cylinder filled with water, open ended PVC tube, meter stick, thermometer, 4 tuning forks

**PROCEDURE:**
1. Fill the graduated cylinder with water.
2. Hold a vibrating tuning fork over the open end of the tube while changing the water level. Locate a fundamental resonance (loudest sound) by manipulating the water level and reactivating the fork.
3. Read the water levels $X_1$ and $X_2$ at two successive resonance points (loudest sound) and record them in the data table.
4. Calculate the wavelength from Eq 1
   \[ \lambda = 2 |X_1 - X_2| \]  
   (Eq 1)
5. Record the room temperature in Celsius with a thermometer. Calculate the accepted speed of sound using Eq 2 and record in the data table.
   \[ v = 332 + 0.6T \]  
   (Eq 2)
6. Calculate the frequency of the tuning fork used using Eq 3
   \[ v = f \lambda \]  
   (Eq 3)
7. Repeat the above steps for a total of FOUR different frequencies of tuning forks
8. Compare with actual frequencies of tuning forks to calculate for % error

**DATA TABLE:**

<table>
<thead>
<tr>
<th>Fork Length</th>
<th>A = _______</th>
<th>B = _______</th>
<th>C = _______</th>
<th>D = _______</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
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<td></td>
<td></td>
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<tr>
<td>$X_2$</td>
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<tr>
<td>Wavelength</td>
<td></td>
<td></td>
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<tr>
<td>Velocity of Sound ($T = _______$)</td>
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</tr>
<tr>
<td>Frequency</td>
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<tr>
<td>% Error</td>
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</tbody>
</table>
ANALYSIS:

1. On a sheet of graph paper, graph $f$ vs. $L$ and $\lambda$ v. $L$

2. As the length of the resonant air column gets bigger, the **frequency** of the tuning fork gets (check one)

   Higher ___________  Lower ___________

3. As the length of the resonant air column gets bigger, the **wavelength** of the tuning fork gets (check one)

   Longer ___________  Shorter ___________

4. What can you predict about the frequency of shorter tuning fork compared to a longer one?

5. How (if at all) does the diameter of the PVC tube affect the resonance?

6. Looking at the percent error, where would you expect the error to originate from and how could we minimize error in our experimentation?

CONCLUSION:

In addition to a discussion of the results from the lab, include a statement on the effects of resonance for scanning tunneling microscope (STM) tips and what your recommendation would be in appropriate dimensions for the tungsten tips used for imaging graphene.
## Physics Lab Rubric

Lab Report Rubric – All laboratory investigations will use the following rubrics for grading.

<table>
<thead>
<tr>
<th></th>
<th>(5 pts)</th>
<th>(3 pts)</th>
<th>(2 pts)</th>
<th>(1 pt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>• Name, Date, Lab Partner</td>
<td>One of the &quot;excellent&quot; conditions is not met</td>
<td>Two of the &quot;excellent&quot; conditions is not met</td>
<td>Three of the &quot;excellent&quot; conditions is not met</td>
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<td></td>
<td>• Writes a statement of the purpose of the lab.</td>
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<td>• States a hypothesis that is based on research and/or sound reasoning</td>
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<td>• Title is relevant.</td>
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<td></td>
<td>• Hypothesis (prediction) is testable.</td>
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<tr>
<td>Procedure</td>
<td></td>
<td>A description or step-by-step list of how the experiment was performed</td>
<td>Description unclear, couldn't be repeated</td>
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</tr>
<tr>
<td>Observations / Results (data)</td>
<td>• Graphs and tables are present</td>
<td>Results are clear and labeled, trends are not obvious,</td>
<td>Results are unclear, missing labels, trends are not obvious at all</td>
<td>Results are present, though too disorganized or poorly recorded to make sense of</td>
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<tr>
<td></td>
<td>• Labeled correctly</td>
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<td></td>
<td>• Results and data are clearly recorded, organized so it is easy for the reader to see trends.</td>
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<td></td>
<td>• Written description present</td>
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<tr>
<td>Analysis / Questions</td>
<td>• All questions have been answered completely and thoroughly.</td>
<td>Analysis somewhat lacking in insight, enough data, though additional data would be more powerful</td>
<td>Analysis lacking in insight, not enough data was gathered to establish trends, OR analysis does not follow data</td>
<td>Analysis poor, not enough data, inaccurate analysis</td>
</tr>
<tr>
<td>Sample Calculation</td>
<td>• Lab reports must contain at least one sample calculation of each type you are required to do.</td>
<td>One of the &quot;excellent&quot; conditions is not met</td>
<td>Two of the &quot;excellent&quot; conditions is not met</td>
<td>Three of the &quot;excellent&quot; conditions is not met</td>
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<td></td>
<td>• You should have the general formula used in the calculation.</td>
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<td>• You should have the formula with the correct numbers &amp; units included.</td>
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<td>• Your answer should include the correct units and the correct number of significant figures.</td>
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<td>• If there are no sample calculations write NONE</td>
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<tr>
<td>Conclusions</td>
<td>• Summarizes the essential data used to draw conclusions</td>
<td>One of the &quot;excellent&quot; conditions is not met</td>
<td>Two of the &quot;excellent&quot; conditions is not met</td>
<td>Three of the &quot;excellent&quot; conditions is not met</td>
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<tr>
<td></td>
<td>• Conclusions follow data (not wild guesses or leaps of logic),</td>
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<td></td>
<td>• Discusses applications of experiment (&quot;real world&quot; connections)</td>
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<tr>
<td></td>
<td>• Hypothesis is restated and rejected or accepted based on the data.</td>
<td></td>
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</tr>
<tr>
<td>Format</td>
<td>• Followed instructions</td>
<td>Neat, organized with headings, few spelling/grammar errors</td>
<td>Somewhat lacking in organization, multiple spelling/grammar errors, not neat</td>
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<tr>
<td></td>
<td>• Proofread</td>
<td></td>
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<tr>
<td></td>
<td>• Neat/legible</td>
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<tr>
<td>Total (/30)</td>
<td></td>
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</tbody>
</table>

Please note, if any section is missing from the lab report, the grade earned cannot be higher than 60%.
COMSOL Tutorial

Upon opening COMSOL, the following screen appears:

Choosing Physics (click the next arrow button or finish flag as marked in red above)

Select 3D >> Add Physics, Choose Structural Mechanics >> Solid Mechanics (solid)

Select Study Type >> Choose Eigenfrequency >> Length unit [mm]

Right Click on ‘Global Definitions’ >> Choose ‘Parameters’ >> Name your variables (in this case, BeamL, Beam W)
Define the ‘Geometry’ by right clicking and selecting a preset (in this case ‘Cylinder’) >> Set your parameters using variables from previous step >> ‘Build All’

Define Materials by right clicking and selecting ‘Open Material Browser’ >> Under the search bar type in the material you are looking for (in this case ‘Tungsten’) >> if material is not ‘Built-In’ then you can add your own material if you know the material properties >> Click the ‘+’ button to add material to the model
Setting up the Physics >> Right click ‘Solid Mechanics’ and select ‘Fixed constraint’ (left click and right click area on model)

If you click on the ‘Free’ menu under ‘Solid Mechanics’ you should now see that boundary or part selected as being ‘overridden’
Right click on ‘Mesh’ and select ‘Free Tetrahedral’ >> Select ‘Size’ and set Calibration in the drop-down menu (in this case we will use ‘Normal’) >> Click ‘Build All’ to apply to model

**Simulation**

Right click ‘Study 1’ and click ‘Compute’ for a simple and relatively quick solver calculation >> Under the ‘Eigenfrequency’ drop down menu provides the first 6 modes of eigenfrequencies
Parametric sweep

Right click Study >> Select ‘Parametric sweep’ >> Define parameter and steps (in this case, the ‘BeamL’ parameter set from the beginning is used with a range of 1 [mm] to 10 [mm] with a step of 1 [mm])

Right click on ‘Study 1’ and click ‘Compute’ (depending on the Mesh set, the solver can take several minutes) >> After the solver has finished running, the ‘Parameter value’ drop-down menu can be selected to view the frequency for the given parameter value >> Under the Export menu you can export the data, video files of the animation, etc.
SolidWorks Modeling

The opening screen for SolidWorks is as follows after selecting ‘New Document’. Start by choosing ‘Part’ to create a desired geometry and click ‘OK’.

Depending on what geometry you want to model, you will use various sketch tools to create a model. For the purposes of the example, we will create a thin dimpled membrane sample as shown below.
To run the Solidworks simulation, click on the top menu with the checklist icon and select ‘Add-Ins’ and the following menu will be appear >> Select ‘SolidWorks Simulation’ and click ‘OK’

Now you should see a ‘Simulation’ tab option in the top left bar >> Click the tab and click on ‘Study Advisor’ and ‘New Study’
In this case, we will run the ‘Frequency’ solver >> The menu along the top gives you various options including ‘Apply Material’ (Silicon Carbide), ‘Fixtures Advisor’ (fixed along the edge) and ‘External Loads’ (gravity) >> Under the ‘Run’ menu create a mesh and then you can select ‘Run’

The final result gives a resonant frequency value of 26,570 Hz and deformation gradient as shown below
Opening exercises

- Answer the following Question of the Day (QotD) in your class notebook:
  - How many seconds will you spend in this classroom?
- Nature of Science discussion
The Nature of Science

Observation: important first step toward scientific theory; requires IMAGINATION to tell what is important.

Theories: created to explain observations; should make predictions.

Observations will tell if the prediction is accurate, and the cycle goes on.
The Nature of Science

How does a new theory get accepted?

• Predictions agree better with data
• Explains a greater range of phenomena
What are some current theories and topics in science that are being researched today?
How could you use the three items shown above to get a Nobel Prize in Physics?
Graphene

One-atom thick layer of graphite, which is extremely light ($1 \text{ m}^2 = .77 \text{ mg}$), highly conductive, transparent and incredibly strong

Potential applications include:
- integrated circuits
- solar cells
- ultracapacitors
Graphene
Measurement Demo

One volunteer each to measure the width of the Promethean screen in:

1.) m
2.) cm.
3.) mm.

Whose measurement is the most precise?
Measurement and Uncertainty

No measurement is exact; there is always some uncertainty due to limited instrument accuracy and difficulty reading results.
Significant Figures

The number of significant figures is the number of reliably known digits in a number.

23.21 cm has 4 significant figures

0.062 nm has 2 significant figures (the initial zeroes don’t count)

80 km is ambiguous – it could have 1 or 2 significant figures. If it has 3, it should be written 80.0 km.
Significant Figures

Your turn: How many significant figures do each of the following numbers have:

(a) 214,
(b) 81.60
(c) 7.03
(d) 0.03
These are the standard SI prefixes for indicating powers of 10.

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Abbreviation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>yotta</td>
<td>Y</td>
<td>$10^{24}$</td>
</tr>
<tr>
<td>zetta</td>
<td>Z</td>
<td>$10^{21}$</td>
</tr>
<tr>
<td>exa</td>
<td>E</td>
<td>$10^{18}$</td>
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<tr>
<td>peta</td>
<td>P</td>
<td>$10^{15}$</td>
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<tr>
<td>tera</td>
<td>T</td>
<td>$10^{12}$</td>
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<tr>
<td>giga</td>
<td>G</td>
<td>$10^{9}$</td>
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<tr>
<td>mega</td>
<td>M</td>
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<td>kilo</td>
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<td>deci</td>
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<td>$10^{-1}$</td>
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<td>milli</td>
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<td>micro</td>
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<tr>
<td>yocto</td>
<td>y</td>
<td>$10^{-24}$</td>
</tr>
</tbody>
</table>

† µ is the Greek letter “mu.”

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How could we figure out what is in the black box if we can’t see it with our eyes?

What theories could we develop and how could we test these theories?
Measuring at the Nano-Scale

Scanning tunneling microscope (STM) is an instrument used for imaging surfaces at atomic level.

Varying a voltage to keep a constant current, the tungsten tip alters the height to map the surface of a sample.
Measuring at the Nano-Scale
Sharp tungsten tip plays a key role in high-resolution images
Forced Vibrations; Resonance

Forced vibrations occur when there is a periodic driving force.

If the frequency is the same as the natural frequency, the amplitude becomes quite large. This is called resonance.
Forced Vibrations; Resonance

Energy transferred and amplified as shown in the Tacoma Narrows Bridge.
Question asked by Professor First:

Does resonance affect the resolution in STM images? If so, how could we alter the tip to minimize resonance effects?
Resonance Lab

Given a set of unmarked tuning forks, how could we figure the frequency of each tuning fork using the principle of resonance?
Resonance Lab

To study the affects of resonance, we will use a set up as follows:

- For the open end, the wavelength $\lambda$ is $\frac{1}{4}$ of the length of the tube.
- For the closed end, the wavelength $\lambda$ is the length of the tube itself.

The equation $v = f \lambda$ is also shown to relate the speed $v$, frequency $f$, and wavelength $\lambda$. 

$$v = f \lambda$$
# Resonance Lab

In your lab notebooks, write out your objective, hypothesis, materials, procedure and data table

<table>
<thead>
<tr>
<th>Fork Length</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2</td>
<td></td>
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<tr>
<td>Wavelength</td>
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<tr>
<td>Velocity of Sound</td>
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</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
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<tr>
<td>% Error</td>
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</tbody>
</table>
OBJECTIVE: To determine the fundamental frequency and wavelength of 4 tuning forks

MATERIALS: Graduated cylinder filled with water, open ended PVC tube, meter stick, thermometer, 4 tuning forks

PROCEDURE:
1. Fill the graduated cylinder with water.
2. Hold a vibrating tuning fork over the open end of the tube while changing the water level. Locate a fundamental resonance (loudest sound) by manipulating the water level and reactivating the fork.
3. Read the water levels $X_1$ and $X_2$ at two successive resonance points (loudest sound) and record them in the data table.
4. Calculate the wavelength from Eq 1
   \[ \lambda = 2 |X_1 - X_2| \]
   (Eq 1)
5. Record the room temperature in Celsius with a thermometer. Calculate the accepted speed of sound using Eq 2 and record in the data table.
   \[ v = 332 + 0.6T \]
   (Eq 2)
6. Calculate the frequency of the tuning fork used using Eq 3
   \[ v = \frac{f}{\lambda} \]
   (Eq 3)
7. Repeat the above steps for a total of FOUR different frequencies of tuning forks
8. Compare with actual frequencies of tuning forks to calculate for % error

DATA TABLE:

<table>
<thead>
<tr>
<th>Fork Length</th>
<th>A = ______</th>
<th>B = ______</th>
<th>C = ______</th>
<th>D = ______</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Velocity of Sound (T = ______)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Error</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ANALYSIS:

1. On a sheet of graph paper, graph $f$ vs. L and $\lambda$ v. L
2. As the length of the resonant air column gets bigger, the frequency of the tuning fork gets (check one)
   
   Higher _________    Lower _________
3. As the length of the resonant air column gets bigger, the wavelength of the tuning fork gets (check one)
   
   Longer _________    Shorter _________
4. What can you predict about the frequency of shorter tuning fork compared to a longer one?
5. How (if at all) does the diameter of the PVC tube affect the resonance?
6. Looking at the percent error, where would you expect the error to originate from and how could we minimize error in our experimentation?

CONCLUSION:
In addition to a discussion of the results from the lab, include a statement on the effects of resonance for scanning tunneling microscope (STM) tips and what your recommendation would be in appropriate dimensions for the tungsten tips used for imaging graphene.