Microfluidic Mixing Using Microchannels in High School Science and Math

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Summary

This project explores groundbreaking research which is being developed in the mixing of microscopic quantities of fluids using microchannels. The research is being used to replace small pumps and other mechanical devices that are costly to produce with micro-pumps that use a small amount of voltage to perform the same function. The module will explore the difficulties and challenges associated with the microscale by using a slightly larger version in the classroom. Dyes will allow students to see visually how efficient the mixing can be using various styles of channel geometry. The class will also discuss the challenges of mixing fluids in a micro environment due to lack of turbulence (i.e. laminar flow), and how these issues relate to medical and commercial applications.

Intended Audience

This project is intended for use in high school math and science classrooms. It may be used in middle school science classrooms; however, students should have the prerequisite skills listed below.

Estimated Duration

This duration of this module should be about 3 days, with 55 minute classes. However this module can be expanded if other fluids are used in the channels.

Introduction

> "Biotechnology is increasingly about large numbers of experiments, such as analyses of DNA or of drugs, screening of patients, and combinatorial syntheses. All of these procedures require handling fluids. As the number of experiments has grown, the devices used to carry them out have shrunk, and the strategy of

‘smaller is better’ has begun to transform the world of fluidics as it has transformed the world of electronics.

The need in biotechnology applications to manipulate fluids moving in small channels--a process called microfluidics--has stimulated three new areas of research: development of new methods for fabricating fluidic systems, invention of components from which to assemble functionally complex fluidic devices, and examination of the fundamental behavior of fluids in small channels. Developments in microfluidic technology are also contributing to new experiments in fundamental biology, materials science, and physical chemistry.” (Physics Today. June, 2001)

Rationale for Module

One of the goals of the S.W.E.E.T. program is to expose middle and high school teachers to cutting edge engineering research. These experiences can then be summarized in a module, which can be taken back to the classroom. The end goal is to give students an idea of what engineering research is and to instill a curiosity in students about engineering.

Science

The basis of science is to further our knowledge of “why”. Why did something occur? Why does one chemical react to another? Science looks for the reason something happens. Science is based on a series of steps; observe the phenomenon, speculate on why it happens, and try to recreate it while explaining how.

Science can be driven by many forces. Society and culture can influence what science has highest priority for economic and moral support. Science can be performed for an unspecified amount of time and may never be completed. Science is a breaking down process. It takes the complex and tries to break it down to the base components.

Engineering

Engineering looks at a phenomenon and tries to find a practical use for it. Engineering can be used to develop something which does not currently have a use, but it will also be driven by societal and cultural issues to solve a current need. Although science may precede engineering, it is not a prerequisite. Engineering is more often concerned with the economic aspects of its endeavors than science, and therefore may be more influenced by commercialism. Engineering is a step up process that tries to take the base components of a phenomenon and create a use for the complex.

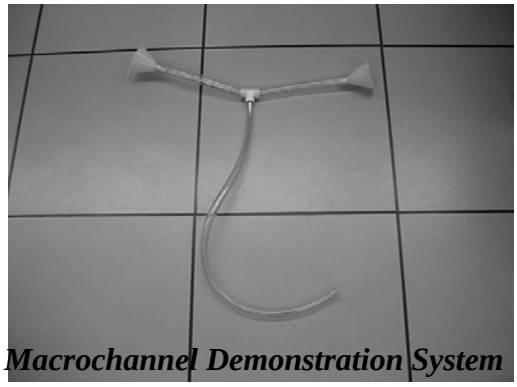
Goals

To expose students to cutting edge engineering research while in a classroom setting. Students will be able to gain an appreciation of the microscale that will be used in the lab. Students will use engineering research that is being developed in university labs to gain some understanding of its possible applications or ramifications in our world.

Equipment

Per lab Group:

- 1 – Straight channels *see Appendix G illustration 1.
- 1 – Y channels *see Appendix G illustration 2
- 1 – T channels *see Appendix G illustration 3
- 1 – Serpentine channel *see Appendix G illustration 4.
- 4 – Lab syringes with blunt tips
- Food coloring dye (at least two colors). Blue and yellow dyes were used in this setup. The concentration of blue dye was 3 drops per 4 ml of water. The concentration of yellow dye was 6 drops per 4 ml of water.
- 1 Box of copper BBs (6000 count)
- 3- 8 oz cups (Solo Style)
- 1 Science ring stand with 2 rings and 2 test tube holders
- Stopwatch
- Metric Ruler
- Scale (electronic preferred)
- Magnifying glasses



Macrochannel Demonstration System

Per Class:

- 1 Macrochannel Demonstration System:

  The Macrochannel is a T channel constructed using ¾” tubing and a PVC “T” fitting. Tubing at the T will have funnels attached to aid in pouring. Fluid will be poured in the T ends of the channel and run out through the single end to simulate mixing. **A catch bucket will be required.**

Prerequisite Knowledge

- Graphing procedures: independent vs. dependent variables
- Calculate ratios
- Curve fitting techniques
- Basic knowledge of SI unit for distance
- Understand what Mean is.
- Excel or graphing calculator experience helpful
- Calculate velocity.

Procedures

1. Complete "**How big is a micron worksheet**?"

   Appendix A, Teacher Notes Appendix B

2. Determine standard weight of a BB. (optional)

   a. Use electronic scale to determine the weight of one BB. Record on paper.

   b. Count out 10 BBs and weigh. Record on paper.

   c. Divide the weight obtained in step B and compare to the value in step A.

   d. Discuss variations in the weight of the BBs and standard deviation.

Straight Channel – Rate vs. Net Weight

Procedure / Data Collection
Use: Appendix C: "Straight Channel Lab Sheet" & "Data Analysis Graph Sheet"
Appendix D: "Graphical Data Analysis with EXCEL"
Appendix E: "Graphical Data Analysis with TI-83"

3. Complete Hypothesis section of Straight Channel Lab Sheet.

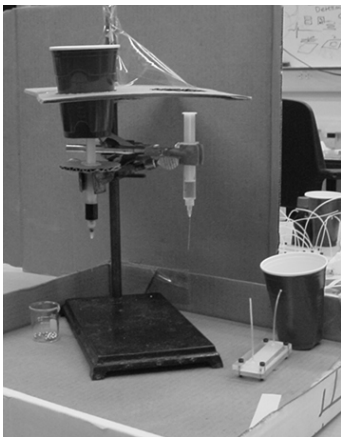
4. Measuring the friction within the syringe.

   a. Fill syringe to approximately 2 ml of blue-dyed water.

   b. With needle of syringe pointed up depress the syringe until you are certain that all air bubbles have been removed.

   c. Place syringe in clamp that is attached to ring stand so that it will not move down.

   d. Use empty cup to adjust the stabilizing sleeve so that the cup can be centered on the syringe but not tip over. (Warning – if the cup tips over when full of BBs you will not be happy)



Syringe Friction Setup

e. Remove cup and fill to approximately ¼ of the cup with BBs.

f. Carefully place the cup onto the syringe and observe the end of the needle to look for a drop to begin to form. If a drop forms immediately, then you have too much weight. Remove cup and remove some of the BBs.

g. Add BBs slowly until a drop begins to form at the end of the needle.

h. Remove cup and record its weight as the "Zero" weight in the Straight Channel Lab Sheet.

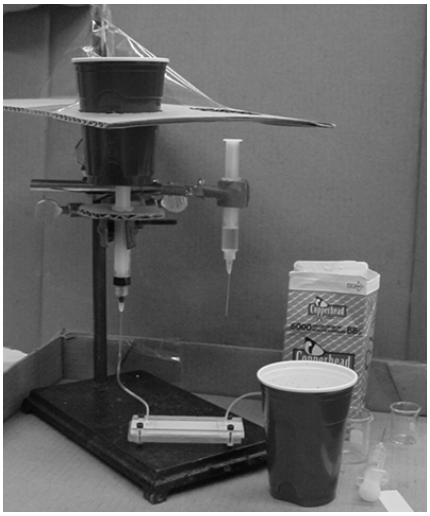
5. Measuring Flow Rates

a. Measure the distance between the lines on the top of the channel. Record this as the Channel Length on the Straight Channel Lab Sheet.

b. Attach a capillary from a straight channel to the syringe.

c. The capillary at the other end should be directed into a cup so you do not make a mess.

d. Add approximately 1/3 of the "zero" weight in BBs to the cup. Record its weight on Straight Channel Lab Sheet.



Straight Channel Lab Setup

e. Be sure to have stopwatch ready to record time.

f. Carefully place the cup onto the syringe. You should see flow in the capillary.

g. If flow rate is exceedingly slow carefully depress syringe by hand until fluid reaches a point just above the channel to save time.

h. When the fluid reaches the first line on the channel start recording time. Stop recording time when the fluid reaches the second line. Record time on Straight Channel Lab Sheet.

i. Remove cup.

j. Clean the channel.

   i. Remove the capillary from the syringe.

   ii. Attach syringe containing water to capillary and flush out dye.

   iii. Remove syringe.

   iv. Use compressed air or an air filled syringe to force water from channel. Do not be discouraged if you cannot **completely** clear the channel. **Caution: When using the dry syringe be sure not to retract the plunger while being attached to the capillary as you will draw fluid back into the syringe.**

k. Repeat steps d – j at least four more times using an additional 50 BBs each time rather than the 1/3 “zero” weight.

Analysis / Conclusions

6. Complete Straight Channel Lab Sheet.
7. Possible Class Discussion Questions
   - Why is it necessary to find the “zero” weight?
   - Why is the graph nonlinear?
   - Is there a terminal velocity of the fluid that can be achieved?
   - How can the lab be modified to increase accuracy and precision?
   - Would fluid viscosity affect the flow rate from what you measured?

Fluid Mixing using Macrochannels

1. Show video of fluids mixing through a microchannel.
2. Discuss fluid diffusion.
3. Macroscale demonstration:

    a. Prior to demonstration prepare two ½ gallon containers of water dyed blue and yellow. Concentration of dye for this demonstration is not critical.
    b. Ask students to hypothesize about the resulting mixture in the common tube when the blue and yellow solutions are poured into the funnels.
    c. Conduct demonstration and have class discussion about results.

Fluid Mixing using Microchannels

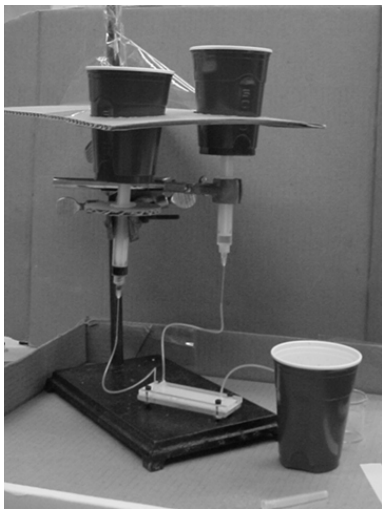
Procedure / Data Collection
Use: Appendix E: "Micromixing Lab Sheet"

1. Complete Hypothesis section of Micromixing Lab Sheet.
2. 1/3 of groups use T channel, 1/3 of groups use Y channel, 1/3 of groups use Serpentine channel to mix colors.
    a. Use two syringes with the same diameter and needle size.
    b. Fill the syringes with 3 ml of dye, one blue and one yellow. With needle of syringe pointed up depress the syringe until you are certain that all air bubbles have been removed.
    c. Place syringes in clamps attached to ring stand so that they will not move down.

d. Use empty cup to adjust the stabilizing sleeve so that the cup can be centered on the syringe but not tip over. (Warning – if the cup tips over when full of BBs you will not be happy)

e. Attach syringes to capillaries at the divided end (Y or T) of the channels.

f. The capillary at the single end should be directed into a cup so you do not make a mess.



Micromixing Lab Setup

g. Place empty cups on each syringe.

h. Begin filling one cup with BBs until flow has started and filled the channel. Proceed to fill other cup until both colors are flowing equally in the channel. **Caution: a small amount of BBs can dramatically change the flow rate.**

i. Examine the flow in the common channel. If and when in the channel does mixing of the two fluids occur? Record you observations. Drawing with colored pencils may help explain what you see.

j. Remove cups and then syringes from capillaries.

k. Clean the channel.

    i. Remove the capillary from the syringe.

    ii. Attach syringe containing water to capillary and flush out dye.

    iii. Remove syringe.

    iv. Use compressed air or air filled syringe to force water from channel. Do not be discouraged if you cannot **completely** clear the

channel. **Caution: When using the dry syringe be sure not to retract the plunger while being attached to the capillary as you will draw fluid back into the syringe.**

l. Repeat steps e-m using an additional 50 BBs in each cup.

3. Time permitting, swap channels between groups and repeat.

Analysis / Conclusions

4. Class discussion on data and conclusions. May want to discuss turbulent and laminar flow characteristics.

Extension

Read one of the following articles and write a summary. Discuss laminar and turbulent flow.

http://faculty.washington.edu/yagerp/microfluidicstutorial/basicconcepts/basicconcepts.htm

http://www.math.hmc.edu/seniorthesis/archives/2003/dbeutel/dbeutel-2003-thesis.pdf

http://ieeexplore.ieee.org/iel5/84/18375/00846699.pdf

http://www.physicstoday.org/pt/vol-54/iss-6/p42.html

Safety Precautions

1. Small objects: The students will be handling BBs, syringes and other small objects. Care should be taken to ensure they are used over a container or box lid that will contain them in the event that they are spilled. BBs are not meant to be projectiles in this lab!
2. Liquids: The students will be handling food dye which will stain their hands as they work. Care should be taken if students are wearing nice clothing. The dyes may not come out in the wash. As with all liquids, if spilled on the floor, they may create a hazard and become slippery.
3. Sharp objects: although the syringe needles are blunt end, the potential for harm exists and therefore students should take care when handling.
4. Compressed air: Channels will be flushed with compressed air. Students should be wearing safety goggles or glasses to ensure dyes are not blown into the eyes. Care should be taken when channels are being flushed to ensure capillaries are pointed away from other students.

Waste Disposal – Dilute with water and pour down sink.

Instructional Strategies

This module was developed to give students an introduction to engineering research in the area of Microfluidics in Microchannels using the inquiry method. The success of student cooperative learning groups is a well established and accepted means for students to learn and explore difficult concepts. Student cooperative groups will be

utilized in the laboratory setting. The class will also employ the jigsaw strategy which entails students working in one group to learn a concept, then combining with members from other groups to share the information learned.

References

Whitesides G. & Stroock A. (2001). Flexible methods for microfluidics. Physics today, 54. Retrieved Jul 26, 2005, from http://www.physicstoday.org/pt/vol-54/iss-6/p42.html.

Appendix A

How Big Is A Micron?

The meter is the standard S. I. unit of measure for length. Since 1983 the meter has been officially defined to be the distance traveled by light in a vacuum in $1/299,792,458^{th}$ of a second. Now you probably cannot immediately interpret how far that is but you are certainly familiar with a meter stick. With your group come to consensus as to how long you believe a meter is by placing you hands a distance apart.

Without actually measuring estimate the following to the **nearest meter**.

Length of your table or desk _____ meters

Height of ceiling _____ meters

Distance from your seat to the door _____ meters

With a partner use a 'meter stick' and measure the following to the **nearest meter**.

Width and length of your table or desk _____ meters

Height of ceiling _____ meters

Distance from your seat to the door _____ meters

How close were your estimates to the measurements? Explain.

Precision of measurement is dependent upon how finely marked the measurement tool is divided. Accuracy is dependent on how well the user of the measurement tool uses the tool.

Do you think that your measurements from above are more precise, or more accurate? Explain.

List 3 things that you think are appropriately measured in meters.

List 3 things that you do **not** think are appropriately measured in meters.

A meter is a great unit of measure for many things but is not appropriate for others. As we start to look at things that are smaller than a meter we need to be more precise. Therefore we begin to divide the meter into smaller and smaller parts. The most common of these units are the centimeter and the millimeter. Each is defined as . . .

1 cm = $\frac{1}{100}^{\text{th}}$ meter = 10^{-2} meter

or 1 meter = 100 cm

1 mm = $\frac{1}{1000}^{\text{th}}$ meter = 10^{-3} meter

or 1 meter = 1000 mm

or 1 cm = 10 mm

Measure the following items to the nearest centimeter and then to the nearest millimeter.

Width of your desk or table	_____ cm	_____ mm
Length of your index finger	_____ cm	_____ mm
Thickness of this line ▬	_____ cm	_____ mm

Which of the measurements above are most precise, centimeters or millimeters? Explain.

But what about really small things like the width of a human hair or the thickness of a sheet of paper? Often precision is of utmost importance when measuring very small things so we need units that are even smaller. One of these units is the micron which is defined as . . .

1 micron = $\frac{1}{1,000,000}^{\text{th}}$ meter = 10^{-6} meter

or 1,000,000 microns = 1 meter

or 10,000 microns = 1 cm

or 1000 microns = 1 mm

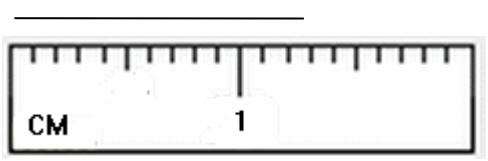
A micron is one one-thousandth of a millimeter! Imagine dividing a millimeter into 1000 equal parts! Now that's small.

A further note on precision

You can estimate one degree of precision beyond the precision of the tool being used. For example, when you were using the unmarked meter stick to measure the height of the ceiling you might have been tempted to say that it was 2.8 meters rather than 3 meters. You would be "guessing" at the 0.8 but it was probably closer to the actual measurement than 3 meters.

So if your scale is marked in millimeters you can estimate to the nearest $\frac{1}{10}$ th of a millimeter. You might want to use a magnifying glass to get a closer look.

Find the length of the line using the magnified scale below. Be as precise as possible.



As precisely as you can find the length and width of the line below.

Length _____

Width _____

Thickness of a sheet of paper

It would be very difficult to find the thickness of a single sheet of paper using a scale divided into millimeters but we can find the thickness of many sheets of paper.

Use a textbook and precisely measure the thickness of the indicated number of sheets. Be sure to measure each of the thickness. Do not use a previous measurement to calculate another measurement. Then calculate the thickness of a single sheet of paper by dividing the measurement by the number of sheets.

10 sheets	_____ mm	1 sheet	_____ mm
25 sheets	_____ mm	1 sheet	_____ mm
50 sheets	_____ mm	1 sheet	_____ mm
100 sheets	_____ mm	1 sheet	_____ mm

From what you have found how many microns thick is an average sheet of paper from your textbook? Show how you arrived at your conclusion.

Extension

What about even smaller measurements such as the size of a molecule or what about very large measurements such as the distance between stars. Investigate more units for both smaller and much larger measurements. Give examples of how these are used.

Appendix B

Teacher Notes

How Big Is A Micron?

The meter is the standard S. I. unit of measure for length. Since 1983 the meter has been officially defined to be the distance traveled by light in a vacuum in $1/299,792,458^{th}$ of a second. Now you probably cannot immediately interpret how far that is but you are certainly familiar with a meter stick. With your group come to consensus as to how long you believe a meter is by placing your hands a distance apart.

Without actually measuring estimate the following to the **nearest meter**.

Length of your table or desk _____ meters

Height of ceiling _____ meters

Distance from your seat to the door _____ meters

You will need to have unmarked meter sticks for each group. These are easily cut from inexpensive lumber such as 1 x 2s.

With your group use a 'meter stick' and measure the following to the **nearest meter**.

Width and length of your table or desk _____ meters

Height of ceiling _____ meters

Distance from your seat to the door _____ meters

How close were your estimates to the measurements? Explain.

After this ask the groups who got their estimates exact to the nearest meter. You will probably have groups that are coming up with decimal values and it should be noted that even though their measurements are more precise they are not using the nearest meter.

Precision of measurement is dependent upon how finely marked the measurement tool is divided. **Accuracy** is dependent on how well the user of the measurement tool uses the tool.

Do you think that your measurements from above are more precise, or more accurate? Explain.

A short discussion about the difference between precision and accuracy would be appropriate at this time.

List 3 things that you think are appropriately measured in meters.

List these on the board. Discuss if necessary.

List 3 things that you do **not** think are appropriately measured in meters.

List these on the board. Discuss if necessary.

A meter is a great unit of measure for many things but is not appropriate for others. As we start to look at things that are smaller than a meter we need to be more precise. Therefore we begin to divide the meter into smaller and smaller parts. The most common of these units are the centimeter and the millimeter. Each is defined as . . .

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or 1 meter = 1000 mm

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Length of your index finger	_____ cm	_____ mm
Thickness of this line ▬	_____ cm	_____ mm

Which of the measurements above are most precise, centimeters or millimeters? Explain.

This again would be a good opportunity to discuss precision.

But what about really small things like the width of a human hair, the diameter of a capillary, the length of a circuit on a microchip, or the thickness of a sheet of paper? Often precision is of utmost importance when measuring very small things so we need units that are even smaller. One of these units is the micron which is defined as . . .

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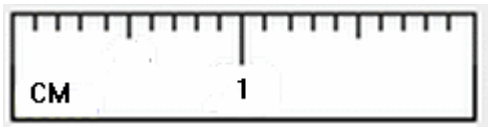
A further note on precision

You can estimate one degree of precision beyond the precision of the tool being used. For example, when you were using the unmarked meter stick to measure the height of the ceiling you might have been tempted to say that it was 2.8 meters rather than 3 meters. You would be "guessing" at the 0.8 but it was probably closer to the actual measurement than 3 meters.

So if your scale is marked in millimeters you can estimate to the nearest $\frac{1}{10}$ th of a millimeter. You might want to use a magnifying glass to get a closer look.

Find the length of the line using the magnified scale below. Be as precise as possible.



As precisely as you can find the length and width of the line below using your metric ruler.

Length _____

Width _____

Here you might want to bring the class together to make sure all groups are getting the same results.

Thickness of a sheet of paper

It would be very difficult to find the thickness of a single sheet of paper using a scale divided into millimeters but we can find the thickness of many sheets of paper.

Use a textbook and precisely measure the thickness of the indicated number of sheets. Be sure to measure each of the thickness. Do not use a previous measurement to calculate another measurement. Then calculate the thickness of a single sheet of paper by dividing the measurement by the number of sheets.

10 sheets	_____ mm	1 sheet	_____ mm
25 sheets	_____ mm	1 sheet	_____ mm
50 sheets	_____ mm	1 sheet	_____ mm
100 sheets	_____ mm	1 sheet	_____ mm

From what you have found how many microns thick is an average sheet of paper from your textbook? Show how you arrived at your conclusion.

Have a member of each group share how they arrived at their conclusion.

Extension

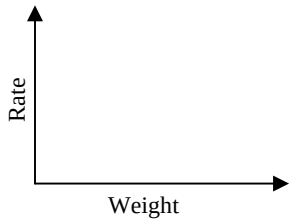
What about even smaller measurements such as the size of a molecule or what about very large measurements such as the distance between stars. Investigate more units for both smaller and much larger measurements. Give examples of how these are used.

Appendix C - I

Straight Channel Lab Sheet

HYPOTHESIS

Before performing the experiment hypothesize on the relationship between the weight on the syringe and the rate of flow along the channel. Accompany your statement with a sketch of the graph of the relationship.



DATA

Channel Length _____ cm

"Zero" Weight _____ gm

Flow Rate Data

Weight (gm)	Time (sec)	Net Weight (gm)	Rate (cm/sec)

DATA ANALYSIS

1. Calculate the net weight being used to cause the flow by finding the difference between the recorded weight and the "Zero" weight for each flow. Record in table above.
2. Calculate the rate for each flow by finding the ratio of the Channel Length and the time. Record in the table above.
3. Appropriately scale the attached graph below and plot Rate vs. Net Weight Optional: Use graphing calculator or Excel to graph data points and find the function which best fits the data. See attachments for specific instructions.

CONCLUSIONS (Answer on space provided on Data Analysis Graph)

1. Does your analysis of the data support your hypothesis? Why or why not?
2. Where do you think the "Zero" weight plays a role in your graph?

Appendix C - II

Straight Channel Lab Sheet - Data Analysis Graph

Be sure to scale your graph appropriately.

3. Does your analysis of the data support your hypothesis? Why or why not?

4. Where do you think the “Zero” weight plays a role in your graph?

Appendix D

Graphical Data Analysis with EXCEL

Enter Data

Enter NET WEIGHT data into column A and RATE data into column B.

Graph Data

Highlight data in column A and B. Click on Insert pop-down menu and select CHART. Choose XY (Scatter). Press Finish.

Curve Fitting

Click on Chart pop-down menu and select Add Trendline. Select Exponential type. Click OK.

Finding Function

Double-click on the trendline that is on the graph. Select the Options tab. Check Display equation on chart. Click OK.

A**ppendix E**

Graphical Data Analysis with TI-83

Enter Data

Press STAT. Highlight EDIT and press ENTER. If lists contain data you can clear them by highlighting the title of the list, for example L1, and press CLEAR. Enter NET WEIGHT data into list L1 and RATE date into L2.

Graph Data

Press STAT PLOT. Highlight Plot1 and press ENTER. Highlight ON. For TYPE highlight the first option as this is the scatter plot. Xlist and Ylist must be L1 and L2, respectively. Mark can be of your own preference.

Press ZOOM and scroll to ZOOMSTAT. Press ENTER.

Curve Fitting

Press STAT. Highlight CALC. Scroll to ExpReg. Press ENTER. You are now at the home screen and need to tell the calculator where to find the data. Type L1,L2 (These are the 2^{nd} function options for the keys 1 and 2). Press ENTER

Graphing Function

Write down values for the values of a and b. Also take note of the structure of the function y = a*b^x. Press Y=. Enter the function substituting the values for a and b. Press GRAPH.

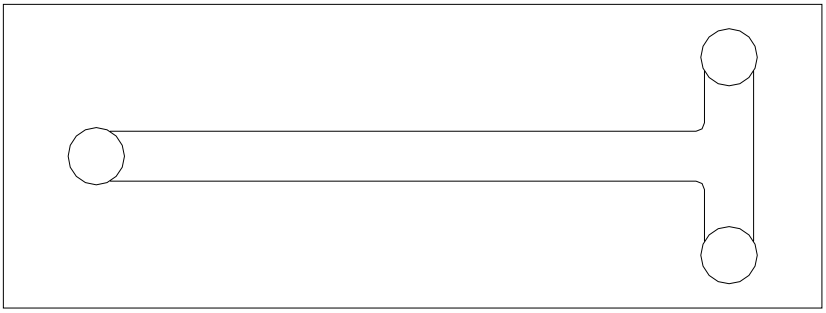
Appendix F

Micromixing Lab Sheet

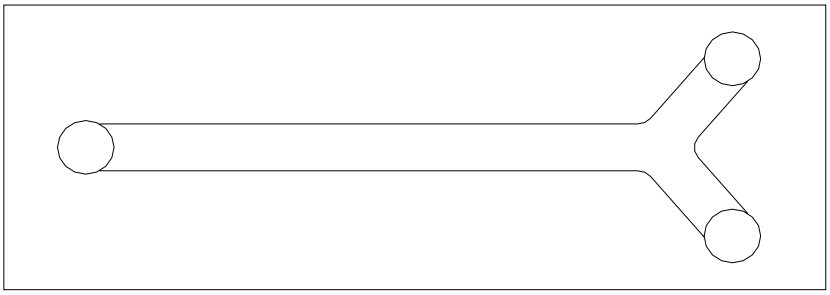
HYPOTHESIS

Before performing the experiment hypothesize in writing where in the channel mixing of the colors will occur. Use the diagrams below to draw and label your hypothesis.

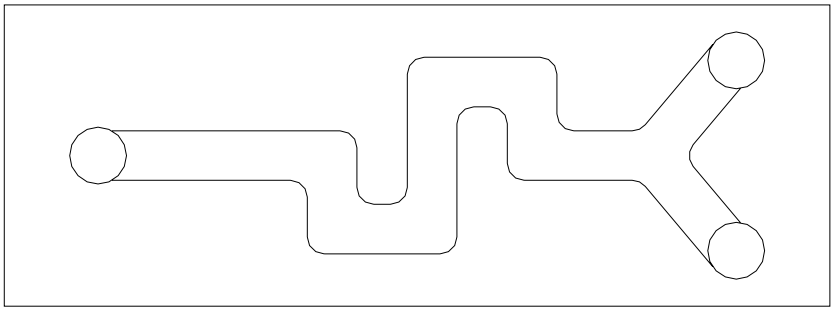
T channel



Y channel

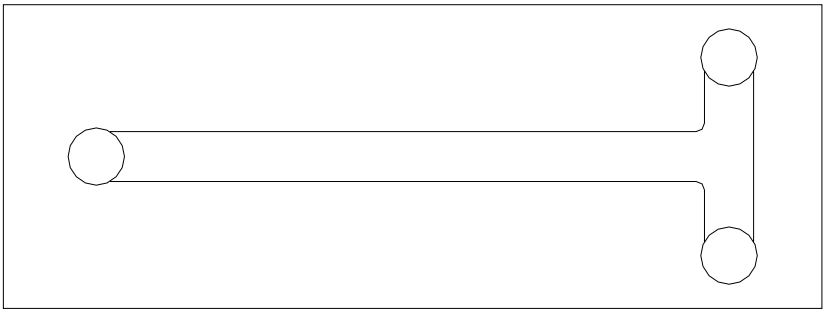


Serpentine Channel

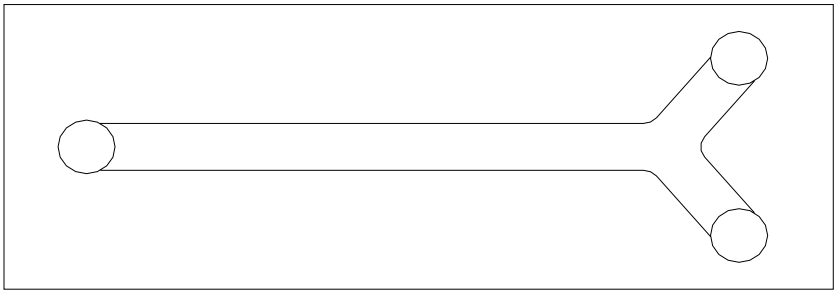


EXPERIMENTAL DATA / OBSERVATIONS: Using the diagrams below draw what you observed during your initial investigation.

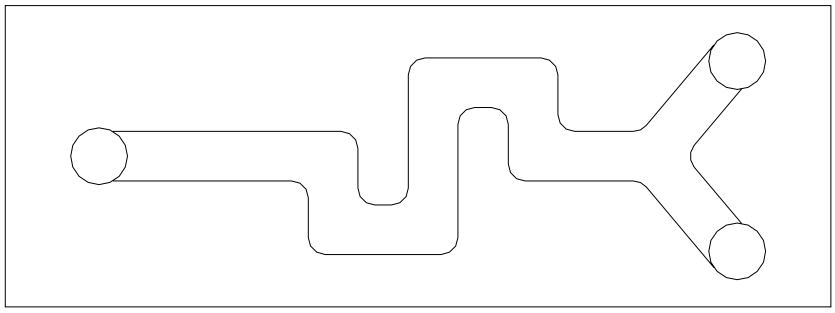
T channel



Y channel

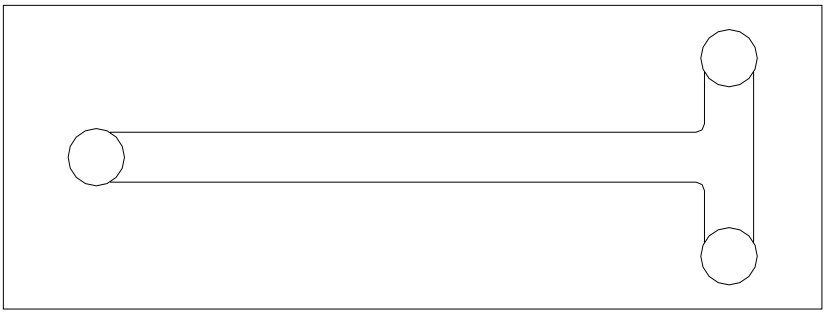


Serpentine Channel

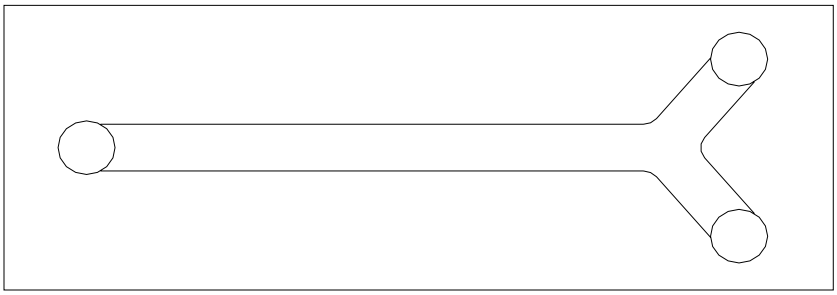


Using the diagrams below to draw what you observed after adding 50 BBs to the cups.

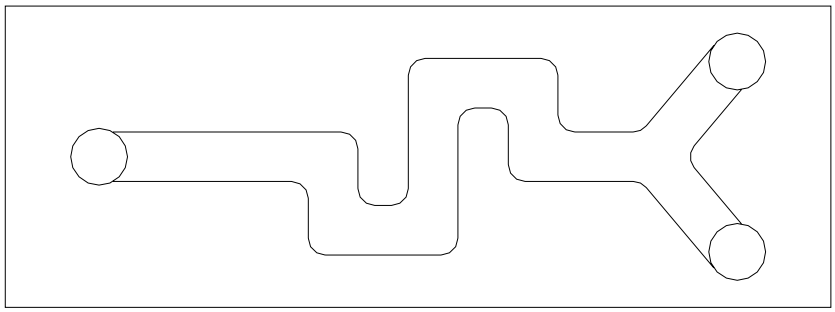
T channel



Y channel

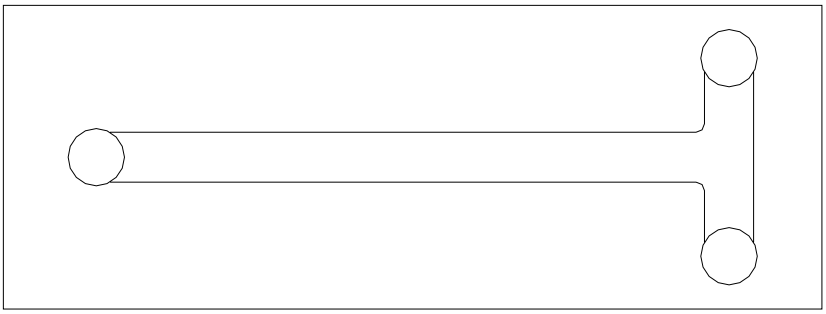


Serpentine Channel

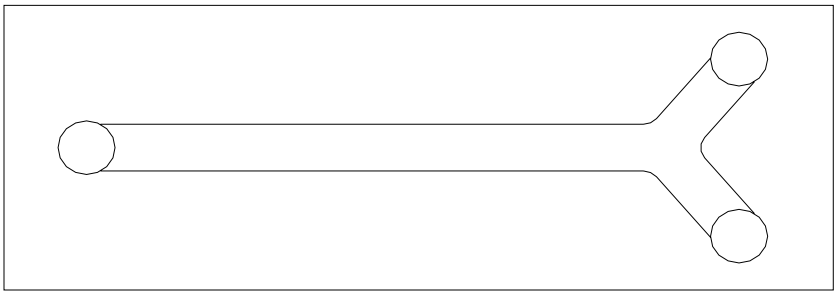


Using the diagrams below to draw what you observed after adding 100 BBs to the cups.

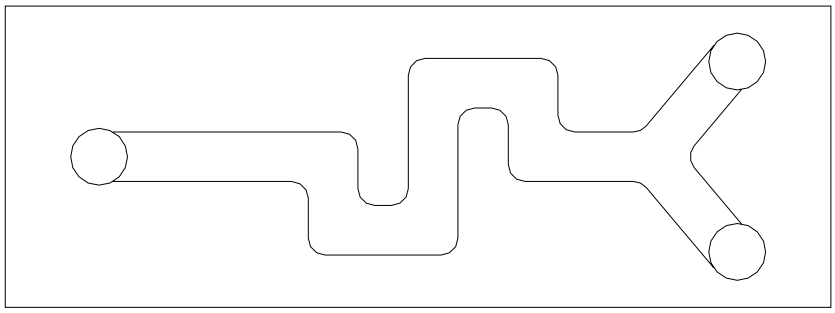
T channel



Y channel



Serpentine Channel



DATA ANALYSIS

1. Explain in your own words the differences between what you observed and your hypothesis.

2. Since the fluid is water and food color could it be causing your results? What other factors could be responsible?

CONCLUSIONS

Write a conclusion discussing these questions:

- What is the key difference between the first teacher demonstration using the large tubes and the channels you worked with?
- Does size matter in relation to the mixing?
- Does color of dye matter in relation to mixing?
- Does the rate of fluid flow through the channel have an effect on mixing?

Extension

What would happen if a more viscous fluid like olive oil was used in the channel? Would mixing occur if two dissimilar fluids like motor oil and olive oil were used? Could the viscosity of the fluids be a factor in the rate mixing occurs? Repeat the experiment using several types of fluids, thick and runny, water and oil based, colored or not.

Appendix F

Channel Construction

Channels for this module were created using a CNC (computer numeric control) machine. Other methods may be used; however the CNC allows for a uniform channel in depth and geometry.

- The channels were cut from Plexiglas acrylic pieces 1-1/2” wide x 5” long.
- White electrical tape was used to create a seal between the top layer of acrylic and the base piece. The tape was applied to the acrylic face that had the channels. The glue from the electrical tape assisted in creating the seal created when pressure is applied.
- The top acrylic was mechanically fastened with four 6-32 bolts and nuts to the bottom base piece with the channel and electrical tape in between.
- Capillary was glued with super glue (to hold in place temporarily) and then epoxy into the reservoir holes at the ends of the channels. The diameter of the capillary is not critical however it must fit snuggly onto the end of the syringe.
- All channels were created using a 1/16” end mill bit and were approximately 100 microns deep. The specific dimensions of the geometry are not critical but the shape illustrated is. (i.e. a T must have a T, a Y must have a Y on one end)

If you would like to order a set of channels for your class you can contact Henry Ruff at Palouse Precision Inc. (509) 432-3684

Illustration 1: Straight Channel

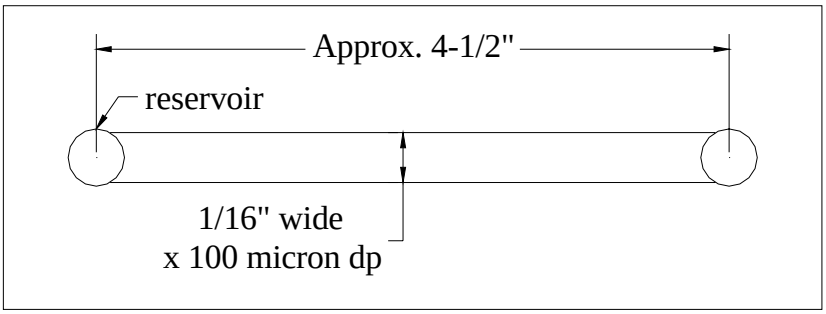


Illustration 2: Y channel

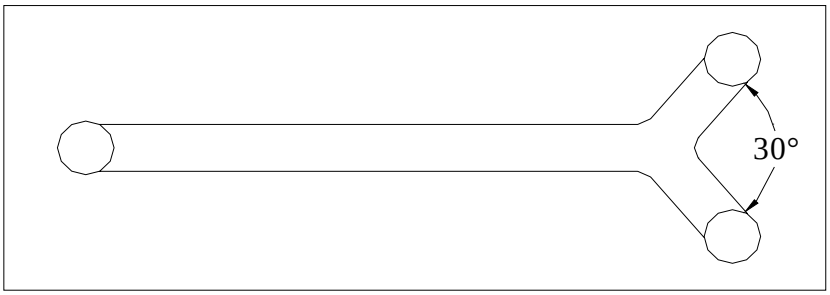


Illustration 3: T channel

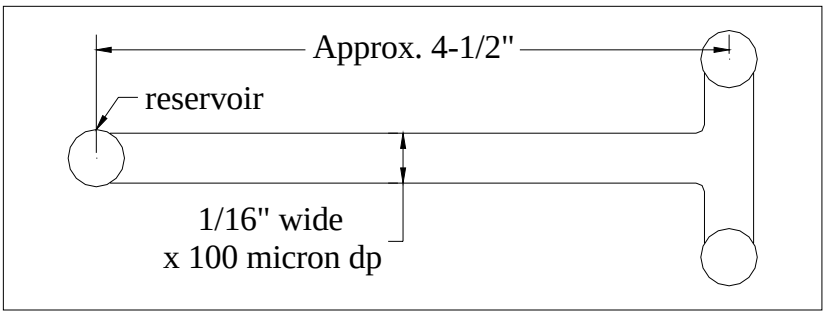
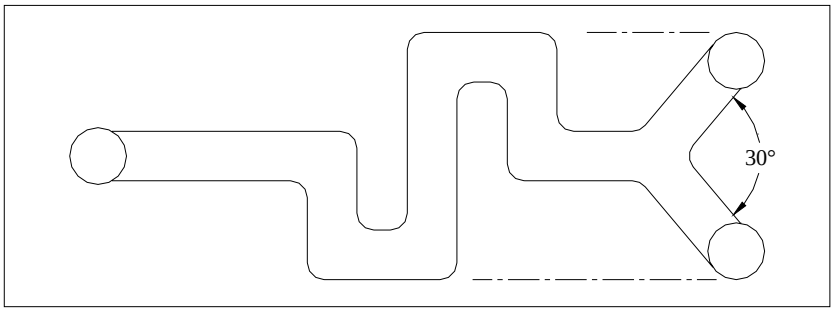
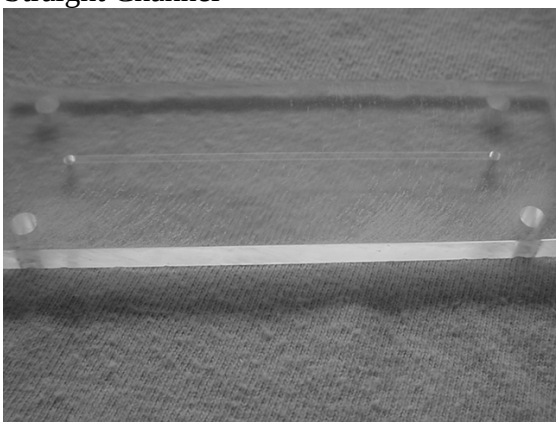


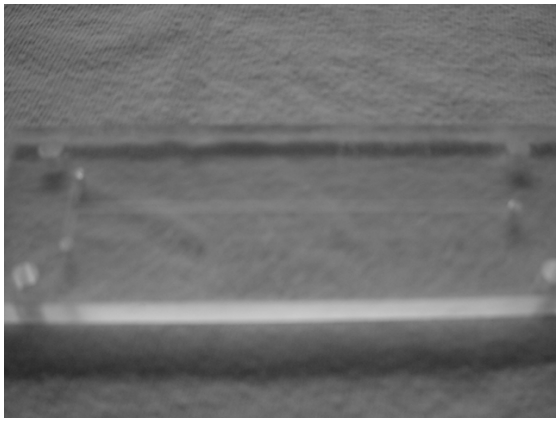
Illustration 4: Serpentine Channel



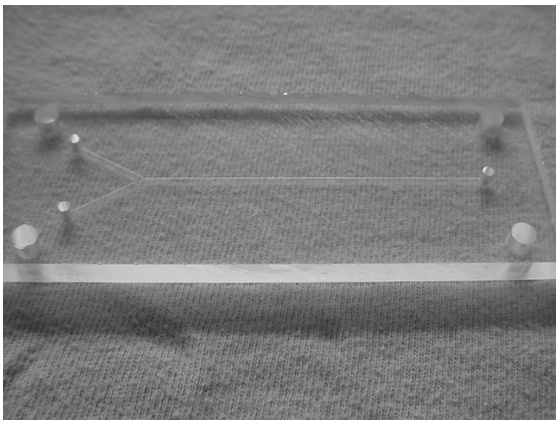
Straight Channel



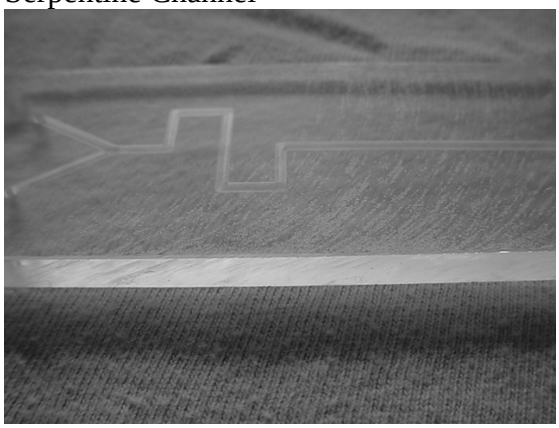
T Channel



Y Channel

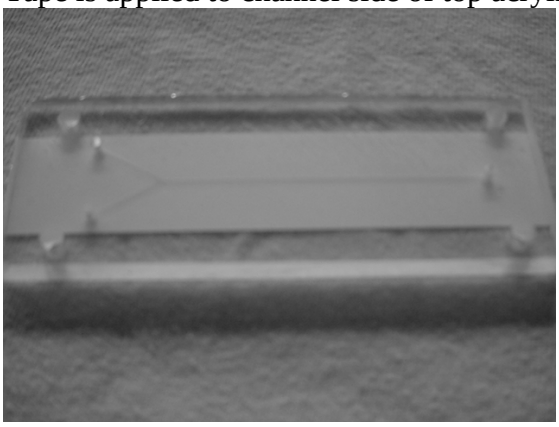


Serpentine Channel



Channel Assembly

Tape is applied to channel side of top acrylic.



Bottom acrylic plate bolted to top with capillaries attached.