Analyzing Space-Efficient Mixing in Microfluidic Devices

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Abstract
In order to perform complex laboratory procedures and deal with the evolving challenges of biomedical engineering, laboratories are now utilizing microfluidic devices. These devices possess micrometer scale channels that allow for precise and efficient mixing. In order to find the most commercial and scientific value for these devices, it is important that a device be as compact and space efficient as possible. In order to determine the optimal configuration of a dual-stream micromixer, different devices were run and imaged to find the diffusion gradient between multiple mixed fluids inside the devices. These images were then analyzed to determine the mixing indices at specific points within each micromixer. These values, as well as other parameters, were used to calculate the space efficiency of each of the devices using Fick’s laws of diffusion. This paper presents the study of the spatial efficiency of various micromixer designs. Analysis of several devices revealed that, although there were several advantages to using straight mixing channels, serpentine mixers used space on the device much more efficiently.

1. Introduction
Following the advent of microtechnology, scientists have begun to develop lab-on-a-chip technology with devices that integrate laboratory procedures into small, mass-producible chips [1]. A subset of this area of development encompasses the design and manufacture of microfluidic devices: micro-scale devices that use arrangements of micro-channels to transport, separate, and mix fluids in a specific order, much like the way microchips carry out a specific sequence of electronic operations [2]. By mixing at the microscale, many macro-scale fluid properties (such as surface tension, fluid resistance, and turbulent flow) that cause unfavorable conditions for precision laboratory work can be circumvented [3]. Working at the microscale also offers advantages such as reduced reaction times, reduced cost, and reduced power consumption [1]. Microfluidic devices can also be easily linked to other laboratory devices, reducing the demand for manual lab work and any experimental error that may occur in the process. Microfluidic technology has improved the efficiency of fluid mixing processes while also promoting
novel innovations in the field of biomedical technology [4].

In addition to their aforementioned advantages, microfluidic devices allow greater control over their intended functions and conserve space and resources [5]. They produce gradients that offer a novel way to approach many biological questions such as the interaction between biochemical signals [4]. As biomedical technology is used to research issues at more precise levels, microfluidics will be needed to better understand and manipulate medicine and molecules. Microfluidic devices need to become faster and more economical to meet the needs of these expanding fields, as they are capable of procedures that cannot be accomplished on the macro-scale.

Due to the fact that these devices typically operate at a very low Reynolds number (a quantity representing the pattern of flow), fluid behavior in microfluidic devices is somewhat different from behavior observed in macro-scale devices [6]. As a result, fluids in microfluidic devices typically follow a laminar flow pattern [7]. This, in turn, alters the behavior of fluid mixing. In macro-scale devices, turbulent flow causes eddies which greatly increase the rate of mixing. In microfluidic devices, almost all mixing occurs as a result of diffusion across parallel flows. This style of mixing has both benefits and drawbacks over conventional macro-scale mixing. On one hand, micromixing requires carefully designed and manufactured channels to provide precise and accurate mixing. On the other hand, these devices can be designed to achieve levels of mixing accuracy far greater than the level available with typical laboratory procedures.

Because of the aforementioned behavior of fluids at the microscale, it is very hard to induce turbulence into a microfluidic channel in order to thoroughly mix multiple solutions. As such, many microfluidic devices are designed to maximize the fluid interfaces between mixing flows. However, extending the channels in a linear fashion requires a large amount of space and is impractical from a manufacturing standpoint. Therefore, in order to maximize diffusion time while minimizing space used for mixing, it is important that mixing channels are designed with a high degree of understanding of the underlying dynamics of fluid systems. The purpose of this research is to empirically determine the optimal design for a dual-inlet micromixer using quantitative image analysis.

2. Materials and Methods

2.1 Fabrication of Microfluidic Devices
The microfluidic devices were fabricated using standard soft lithography techniques with a silicone elastomer called Polydimethylsiloxane (PDMS). PDMS was mixed with a curing agent in a 10:1 mass ratio and poured into pre-made silicon plate master templates. The templates were then placed in a vacuum to remove all pockets of air and then into an oven at 65° centigrade to cure for at least 2 hours. The devices were cut and peeled off and bonded with glass slides using a Tesla coil (corona discharger) to permanently bond the PDMS to the slides.
The devices were then put in the oven for 45 minutes to strengthen the bonding between the PDMS and glass layer in order to prevent leakage or failure of the devices.

2.2 Preparation of Devices
Tygon tubings were cut and inserted into the input and output holes after the devices had been properly bonded. The input microtubes were connected to syringes that continuously pumped water and food coloring into the device. The different colored fluids were necessary to discern the diffusion length as well as the diffusion gradient at the fluid interface. The device was placed on the stage of the light microscope, which was set to a magnification of 20X. The syringes were put into syringe pumps and set at various flow rates. Both pumps were set to 5 microliters per minute for the first trial, then to 10 microliters per minute for the second trial. Output microtubes which removed fluid from the micromixer were positioned to drain into an empty beaker. The fluid was allowed to flush through the device before the images were taken.

2.3 Micromixing
Each device was allowed to run for several seconds in order to stabilize the flow of both streams. When both streams had stabilized, images of the devices were taken at regular length intervals by the microscope cameras.

2.3.1 Device 1: Straight Channel: 2 inlet 2 outlet, 3 cm Length, 300 µm Width

Fig. 1: A photograph of the straight channel device (Device 1)
This straight channel device was the control of the experiment. Diffusion was observed in its most basic form as fluids were run through two inlets and mixed within the 3 cm length channel. Two trials were run with different rates in order to observe their effects on diffusion. In the first trial, both syringe pumps were set to push at a rate of 5 µL/min; in the second, both were set to 10 µL/min. Images were captured at the inlets and outlets as well as along the straight channel, splitting it into fifths. The simplicity of this device was necessary to establish a foundation for comparison for all image analyses.

2.3.2 Device 2: Serpentine Channel: 2 inlet 2 outlet, 57 cm Length, 80 µm Width

Fig. 2: A photograph of the first serpentine device (Device 2)
This device was the logical next step in the experiment because it included the straight channel foundation as seen in Device 1 as well as the new serpentine element. Again, two trials were run with different rates, 5 and 10 μL/min, in order to observe their effects on diffusion. Pictures were taken in fifths of each row. The images were surveyed to see where the diffusion was completed in order to analyze the effects of the serpentine turns on the diffusion of the fluids.

2.3.3 Device 3: Serpentine Channel: 2 inlet 2 outlet, 10 cm Length, 80 μm Width

Images were captured in grayscale with the programs Camware and Turtle Beach under a 20X magnification light microscope.

2.4 Imaging of Device

Images of the diffusion gradient were taken at different points in the channels of each device. These images were used to analyze the level of diffusion throughout the course of the mixing as well as to compare differences in diffusion between devices. Images were captured in grayscale with the programs Camware and Turtle Beach under a 20X magnification light microscope.

2.5 Analysis of Images

Images of the microfluidic devices at various points along their channel lengths were analyzed using the program ImageJ. The images were either 8-bit or 16-bit black and white images. All images of a particular micromixer were calibrated using grayscale image values so that the unmixed food coloring had a value of 0 (black) and water a value of 1 (white). Rectangular areas roughly a quarter of the length of the imaged channels were selected and used to plot the profile of the gray-value vs. the distance in pixels across the width of the channel. This profile was plotted for each channel interval and graphed in comparison to one another (see Sec.3.3). All images were also analyzed to determine the standard deviations of gray-values in rectangular sections across each channel. These standard deviations represented the mixing indices at the points where the images were taken.

2.6 Calculations

Each image taken corresponds to a different point along the channel. In order to find the mixing index at each point in respect to time, two equations were utilized. First, the flow velocity was found by dividing flow rate (either 5 or 10 μL/min converted to m^3/s) by channel cross sectional area. This yielded flow velocity (m/s), which could then be utilized in the next equation: channel length divided by flow velocity yields time...
(s) for the fluid to reach this point in the channel. This value of time is then plotted in a graph of Mixing Index vs. Time to show the change of diffusion of the fluids in respect to time (See Sec. 3.3).

Equation 1: The flow velocity, the rate at which the fluids travel through the channel length, is equal to the flow rate, the volume passing through a point in the channel per second, over the cross sectional area of the channel.

\[ U(m/s) = \frac{\text{Flow Rate}(m^3/s)}{\text{Channel Cross sectional Area}(m^2)} \]

Equation 2: The time taken to reach the imaged point in the channel is equal to the channel’s distance from the inlet divided by the flow velocity.

\[ t = \frac{\text{Channel Length}}{U} \]

Trendlines were added based on the data points from which the mixing index decreased to a value of 0.1. A perfect mixing index of 0 is impossible (See Sec. 4.5) and all of the mixing indices decreased until about 0.1.

2.7 Calculation of Spatial Efficiency
Space efficiency was calculated with a simple ratio.

Space Efficiency Ratio = \[ \frac{\text{di}}{\text{dx}} \]

Equation 3: The space efficiency was determined by taking a ratio. This ratio is the derivative of the mixing index vs. distance traveled trendline divided by the area of the device taken up on the PDMS mold. The ratio is multiplied by a negative one in order to counteract the negative slope of the mixing index vs. distance trendline.

A higher ratio means that the device should theoretically have better space efficiency. Due to the inconsistency of pixel intensity in the images, complete mixing is defined as a mixing index of .1, which was the average measured mixing index of two equally mixed fluids.

3. Results
3.1 Prepared Microfluidic Devices
Fig. 3.1-1: Device 1 (See Fig. 1)
Fig. 3.1-2: Device 2 (See Fig. 2)
Fig. 3.1-3: Device 3 (See Fig. 3)

3.2 Microscope Images of Devices
3.2.1 Device 1: Straight: 2 inlet 2 outlet, 3 cm Length, 300 µm Width

Fig. 4: Device 1 Inlet

This is the inlet of Device 1 at the 5 µL/min rate. The diffusion line is very distinct at this initial interface.

Fig. 5: Device 1 Outlet

This is the outlet of Device 1 at the 5 µL/min rate. The fluids have mixed such
that the diffusion line is already blurred, even after the 3 cm length.

3.2.2 Device 2: Serpentine: 2 inlet 2 outlet, 57 cm Length, 80 μm Width

![Device 2 Inlet](image)

**Fig. 6:** Device 2 Inlet

The inlet of Device 2 shows the steady and distinct streams of the two fluids at 5 μL/min.

![Device 2 Outlet](image)

**Fig. 7:** Device 2 Outlet

By the end of the channel, the fluids have mixed to the point that no diffusion line is visible.

3.2.3 Device 3: Serpentine: 2 inlet 2 outlet, 10 cm Length, 80 μm Width

![Device 3 Inlet](image)

**Fig. 8:** Device 3 Inlet

This is the point in the channel right after the inlet for Device 3 at 5 µL/min. It shows a clear diffusion line.

![Device 3 Outlet](image)

**Fig. 9:** Device 3 Outlet

By the end of the channel at the outlet, no diffusion line is visible, which shows complete mixing.

3.3 Mixing Index Calculation

These graphs show the changes in mixing indices in respect to time, pixel intensities in respect to channel width, and mixing indices in respect to time for both the 5-5 uL/min and 10-10 uL/min flow rates.

3.3.1 Device 1: Straight: 2 inlet 2 outlet, 3 cm Length, 300 μm Width
This graph demonstrates the relationship between mixing index and the length of the channel when both fluids traveled at a flow rate of 5 μL/min. As the fluids flow through the device, the mixing index decreases and the fluids become more uniform. The mixing index in this graph decreases to 0.3, because it did not have enough time to diffuse farther.

This graph demonstrates the relationship between pixel intensity across the width of the channel at different points along the channel length when both fluids traveled at a flow rate of 5 μL/min. Letters A, B, C, D, and E each represent 1/5 of the channel length. As the fluids flow through the channels, from point A to E, the pixel intensity across the width of the channel becomes more uniform. Because the fluids are traveling down a straight channel, they are not mixed; they passively diffuse up until the outlet.

This graph demonstrates the relationship between mixing index and time when both fluids traveled at a flow rate of 5 μL/min. As the fluids spend time in the device, the fluids diffuse and become more uniform, resulting in a lower mixing index value. The geometry of Device 1 (a straight line) reduces the time the fluids spend inside the micromixer.
channel when both fluids traveled at a flow rate of 10 μL/min. As the fluids flow through the device, the mixing index decreases and the fluids become more uniform. The mixing index in this graph decreases to 0.4, because it did not have enough time to diffuse farther. At a faster flow rate, the fluids did not diffuse to the same extent as the 5 flow μL/min rate fluids did.

**Fig. 14**: Device 1, 10-10 μL/min: Pixel Intensity vs. Channel Width

This graph demonstrates the relationship between pixel intensity across the width of the channel at different points along the channel length when both fluids traveled at a flow rate of 10 μL/min. Letters A, B, C, D, and E each represent ⅕ of the channel length. As the fluids flow through the channels, from point A to outlet, the pixel intensity across the width of the channel becomes more uniform.

**Fig. 15**: Device 1, 10-10 μL/min: Mixing Index vs. Time

This graph demonstrates the relationship between mixing index and time when both fluids traveled at a flow rate of 10 μL/min. As the fluids spend time in the device, the fluids diffuse and become more uniform, resulting in a lower mixing index value. At a flow rate of 10 μL/min, the fluids spend less time in the device and cannot diffuse fast enough.

### 3.3.2 Device 2: Serpentine: 2 inlet 2 outlet, 57 cm Length, 80 μm Width

**Fig. 16**: Device 2, 5-5 μL/min: Mixing Index vs. Channel Length

This graph demonstrates the relationship between mixing index and the length of the channel when both fluids traveled at a flow rate of 5 μL/min. As the fluids flow through the device, the mixing index decreases and the fluids become more uniform. The mixing index in this graph approaches 0, because the micromixer incorporated some
turns and had a longer overall channel length.

This graph demonstrates the relationship between mixing index and time when both fluids traveled at a flow rate of 5 μL/min. As the fluids spend time in the device, the fluids diffuse and become more uniform, resulting in a lower mixing index value. The geometry of Device 2 (long rows compacted together with less turns) allows the fluid to spend a much longer time inside the device to diffuse. As a result, the mixing index is able to approach 0. A linear regression was taken of the data points, because the mixing index ceased decreasing significantly, a trendline of only the first few points was plotted to provide a more accurate relationship between decrease in mixing index over time.

This graph demonstrates the relationship between mixing index and the length of the channel when both fluids traveled at a flow rate of 10 μL/min. As the fluids flow through the device, the mixing index decreases and the fluids become more uniform. A linear regression was taken of the data points, because the mixing index ceased decreasing significantly, a trendline of only the first few points was plotted to provide a more accurate relationship between decrease in mixing index over time.
Fig. 20: Device 2, 10-10 μL/min: Pixel Intensity vs. Channel Width

This graph demonstrates the relationship between pixel intensity across the width of the channel at different points along the channel length when both fluids traveled at a flow rate of 10 μL/min. Letters A1, A2, and A3 each represent a different row of the total channel length. As the fluids flow through the channels, from point T1 to the outlet, the pixel intensity across the width of the channel becomes more uniform.

Fig. 21: Device 2, 10-10 μL/min: Mixing Index vs. Time

This graph demonstrates the relationship between mixing index and time when both fluids traveled at a flow rate of 10 μL/min. As the fluids spend time in the device, the fluids diffuse and become more uniform, resulting in a lower mixing index value. At a flow rate of 10 μL/min, the fluids spend less time in the device and cannot diffuse fast enough. A linear regression was taken of the data points. because the mixing index ceased decreasing significantly, a trendline of only the first few points was plotted to provide a more accurate relationship between decrease in mixing index over time.

3.3.3 Device 3: Serpentine: 2 inlet 2 outlet, 10 cm Length, 80 μm Width

Fig. 22: Device 3, 5-5 μL/min: Mixing Index vs. Channel Length

This graph demonstrates the relationship between mixing index and the length of the channel when both fluids traveled at a flow rate of 5 μL/min. As the fluids flow through the device, the mixing index decreases and the fluids become more uniform. The mixing index in this graph decreases to 0.1. Device 3 has more turns, and each turn helps to mix the fluids.

Fig. 23: Device 3, 5-5 μL/min: Pixel Intensity vs. Channel Width
This graph demonstrates the relationship between pixel intensity across the width of the channel at different points along the channel length when both fluids traveled at a flow rate of 10 μL/min. Letters T1, T2, T3, and T4 each represent a different serpentine interval of the channel length (there are seven intervals, but the fluids were diffused by the fifth interval). As the fluids flow through the channels, from point T1 to the outlet, the pixel intensity across the width of the channel becomes more uniform.

Fig. 24: Device 3, 5-5 μL/min: Mixing Index vs. Time

This graph demonstrates the relationship between mixing index and time when both fluids traveled at a flow rate of 5 μL/min. As the fluids spend time in the device, the fluids diffuse and become more uniform, resulting in a lower mixing index value. The geometry of Device 3 (more turns with less channels) increases the time spent in the micromixer.

Fig. 25: Device 3, 10-10 μL/min: Mixing Index vs. Channel Length

This graph demonstrates the relationship between mixing index and the length of the channel when both fluids traveled at a flow rate of 10 μL/min. As the fluids flow through the device, the mixing index decreases and the fluids become more uniform. The mixing index in this graph decreases to 0.1. The mixing index decreases quickly for the first interval of the channel (the first serpentine interval), and then begins to decrease more steadily.

Fig. 26: Device 3, 10-10 μL/min: Pixel Intensity vs. Channel Width

This graph demonstrates the relationship between pixel intensity across the width of the channel at different points along the channel length when both fluids traveled at a flow rate of 10 μL/min. Letters T1, T2, T3, and T4 each represent a different serpentine interval of the channel length. As the fluids
flow through the channels, from point T1 to the outlet, the pixel intensity across the width of the channel becomes more uniform.

**Fig. 27**: Device 3, 10-10 μL/min: Mixing Index vs. Time

This graph demonstrates the relationship between mixing index and time when both fluids traveled at a flow rate of 10 μL/min. As the fluids spend time in the device, the fluids diffuse and become more uniform, resulting in a lower mixing index value. The geometry of Device 3 (more turns with less channels) increases the time spent in the micromixer. However, the greater flow rate caused the fluid to pass through the micromixer more quickly.

### 3.4 Space Efficiency Calculations

<table>
<thead>
<tr>
<th>Device Trial</th>
<th>$\frac{dl}{dx}$</th>
<th>Device Area (mm$^2$)</th>
<th>Space Efficiency Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device 1 5 μL/min</td>
<td>-0.0079</td>
<td>.9</td>
<td>0.0087</td>
</tr>
<tr>
<td>Device 1 10 μL/min</td>
<td>-0.004</td>
<td>.9</td>
<td>0.0044</td>
</tr>
<tr>
<td>Device 2 5 μL/min</td>
<td>-0.0081</td>
<td>185</td>
<td>0.0000437</td>
</tr>
</tbody>
</table>

See section 2.7 for calculations.

### 4. Discussion/Analysis

#### 4.1 Flow Rates

Two flow rates were observed in the three devices used in this experiment. The first trial used the flow rate of 5 μL/min for both inlets and the second trial used the flow rate of 10 μL/min for both inlets. The Mixing Index vs. Time graphs (See Figs. 12, 15, 18, 21, 24, and 27) for all devices showed that as time progressed, mixing index decreased; therefore, diffusion increased with time. Devices showed that the 5 μL/min rate trials reached lower mixing indices than 10 μL/min rate trials did given more time. For Device 1, the 5 μL/min rate trial reached a mixing index of 0.3, whereas the 10 μL/min rate trial only reached a mixing index of 0.4 (See Figs. 12, 15). However, the 5 μL/min rate trial had more time to diffuse; if the 10 μL/min rate trial was extrapolated to the same time as the 5 μL/min rate trial, then it would have reached the same value. In Device 2, the 5 μL/min rate trial reached its lowest mixing index earlier in the channel than the 10 μL/min trial did; it reached mixing index of 0.1 at point E2 while the 10 μL/min trial reached 0.1 at point C2, which is approximately 2.85 cm earlier in the channel (See Figs. 18, 21). For Device 3, the 5μL/min trial reached...
complete diffusion at point M3, about ½ the length that the 10μL/min trial took to diffuse. Because it takes fluids longer to completely progress through a device at a slower rate than at a faster rate, more time is available for diffusion. Faster flow rates restrict the change in mixing index if the micromixer does not have enough channel length to allow for complete diffusion. Given enough channel length, both flow rates will diffuse at approximately the same rate and have similar relationships between mixing indices and distance or time. Interestingly, a higher number of turns over short channel length also seems to increase the effect higher flow rate has on mixing performance. Continued research is needed in order to determine the ideal speed at which fluids can flow through the device and simultaneously diffuse as fast as possible.

4.2 Mixing Indices
The mixing index is the standard deviation of the grayscale value of the pixels in the images of the channels. As the two fluids diffuse and become more uniform, the mixing index decreases. A mixing index value of 0 indicates perfect mixing and uniformity. However, the quality of the images and the noise from the background causes the measured mixing index to never equal 0. In this case, the minimum mixing index used is 0.1. The mixing index decreases proportionally with time and distance along the channel. The mixing indices in Device 3 decrease steeply, and then begin to level off (See Fig. 22). The mixing index of Device 3 (as calculated by linear regression of the data) has the steepest slope at 5μL/min but has a slope less than half as large at 10 μL/min, suggesting flow rate has a significant impact in the change in mixing index per millimeter. Device 1 also mirrors this behavior, although it does not have enough length to allow complete diffusion. The mixing index of Device 2, on the other hand, is not nearly as affected by flow rate, with only a minor decrease in slope magnitude at 10μL/min compared to the 5μL/min trial. Examining mixing indices provides insight on the distance and length required to mix two fluids uniformly.

4.3 Geometry Analysis
Device 1 was a straight channel. Device 2 had long channels with fewer turns, whereas Device 3 had shorter channels but more turns. Device 1 and Device 3 had similar rates of change of mixing index vs. time and channel length, but Device 3 changed more quickly over the same distance than Device 1 did (See Figs. 10 and 22). The turns of Device 3 allowed for greater mixing, but also increased the effect higher flow rate had on mixing performance. This trend can also be seen in the graphs of pixel intensity vs. channel width: the rates of change of the pixel intensity over channel width approach zero more quickly after each turn than the rates of change for Device 1 along a straight channel do (See Figs. 11 and 23). Turning caused the fluid on the inner radius of the channel to have a shorter path than the fluid on the outside radius [8]. These different paths caused dispersion of the molecules in the fluid, increasing the rate at which the fluids diffused [9]. Diffusion between fluids can be optimized by incorporating more turns, or varying the path the fluids take with respect to each other. Device 2 had a large amount of channel length: greater channel length allows the fluids more time to diffuse. A superior microfluidic device would utilize not only turns, but also the long and compact channels to provide more mixing and longer diffusion time.

4.4 Spatial Efficiency
Device 1 did not diffuse to the extent that Device 2 and 3 did. Device 1 was only 3 cm
long compared to 10 cm (Device 3) and 57 cm (Device 2). By incorporating turns, Device 2 and 3 were able to compact more channel length into an area similar to that of Device 1. Even though there was not much diffusion in channel 1, it had a high space efficiency ratio because there was no “wasted area” in the straight channel. In real microfluidic devices, there would be a significant amount of wasted area due to the need to have walls between channels, as well as the fact that a straight line would need to turn at some point to stay on the device. Device 3, on the other hand, has a comparatively small space efficiency ratio due to larger size of the channels. The device achieves complete mixing much faster than the straight channel in the first of the trials and only slightly slower on the 10μL/min trials, indicating that the turns of the serpentine channel have a significant effect on diffusion. The space efficiency ratio directly varies with flow rate, indicating that the flow rate has a significant effect on achieving complete mixing.

Interestingly, the mixing indices of Device 2 are relatively unaffected by flow rate, and maintain a consistent space efficiency ratio across both trials. These are offset by its massive size, which gives it a much lower ratio than the other two devices. However, most of the device is unused, as the fluids achieve complete mixing around ¼ of the way through the device. If a shorter device (¼ of the current length and area) was used and assuming a consistent mixing profile, than the results would be slightly different:

<table>
<thead>
<tr>
<th>Device Trial</th>
<th>(\frac{df}{dx})</th>
<th>Area (mm²)</th>
<th>Space Efficiency Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device 2 5 μL/min</td>
<td>-0.0081</td>
<td>37</td>
<td>0.000219</td>
</tr>
<tr>
<td>Device 2 10 μL/min</td>
<td>-0.0079</td>
<td>37</td>
<td>0.000214</td>
</tr>
</tbody>
</table>

This means that the pattern for Device 2, appropriately scaled for the diffusivity of the solutions inside, would be far more space efficient than Device 3. This also makes sense, given that there is a much higher channel density in Device 2 compared to Device 3.

4.5 Error Analysis

Figure 28: Air Bubble

Figure 29: Leakage
Figure 30: Debris

In the trial with the original Device 2 (a horizontal serpentine micromixer, length 6.48 cm), there was an air bubble near the 3rd fifth of the first row. This did not affect the results of the 5 μL/min flow rate, but when the flow rate was increased to 10 μL/min the channel burst into an air bubble (See Fig. 28). This created a leak which leaked out the clear water fluid, leaving only green dye after this point within the channel (See Fig. 29). Air bubbles were one of the major issues in working with the micromixing devices, along with improper bonding and debris (See Fig. 30).

Another error was the slight slant on the PDMS so that the horizontal plane of the device was not level. Because of this, the microscope focus had to be constantly adjusted, which led to minor inconsistencies in the image. Adjusting the focus may lead to differences in shading due to human error, which could have affected the results when analyzing the image through ImageJ.

There were also errors introduced by the handling of data. Because the mixing index vs. channel length and mixing index vs. time were modeled with linear regression, the estimation of the complete diffusion length may have been inaccurate. In fact, the rate of change in the mixing index was often very high at the beginning of the device and fell off relatively quickly.

5. Conclusion
Microfluidic devices have already been used for many functions in biomedical technology, from chemical analyses to the tagging of antigens. These microfluidic devices need to be faster and more efficient in order to keep pace with the growing demands of biomedical experiments. Diffusion occurs between two fluids in microfluidic devices; this diffusion can be measured quantitatively by the mixing index. The slower the fluids travel through the device, the more time the fluid molecules have to diffuse. However, the flow rate can have a very small or very large effect on the relationship between mixing index and time or distance, depending on the geometry of the channels. The design of the microfluidic devices affects how well fluids mix inside the device: incorporating turns causes dispersion between molecules of each fluid, encouraging diffusion over the diffusion line.

The potential uses for microfluidic devices will grow as the micromixers become both more efficient at spacing and mixing. Different combinations of fluids will require different times and distances in order to completely diffuse due to their different diffusivity constants. Future experiments would investigate the relationship between the time and distance needed to achieve complete diffusion for different diffusivity constants, calculated using Fick’s laws once again. In addition, a comparison between active and passive micromixers could be conducted to further understand microfluidics. Microfluidics is continually becoming more adopted among biomedical scientists and engineers. There is still potential to improve the efficiency and optimize the design of these devices to better serve doctors and patients.
References

Acknowledgements
We would like to thank our mentor, Dr. Jeffrey Zahn, as well as the people who assisted us during this project, Rohit Gupte and Jean Lo. We are also grateful to the Rutgers Department of Biomedical Engineering for generously allowing us to use their resources and lab. We would also like to acknowledge the Governor’s School of Engineering and Technology, Jean Patrick Antoine, and all of the counselors for their guidance. Thanks to Rutgers University, the State of New Jersey, Morgan Stanley, Lockheed Martin, South Jersey Industries, Inc., and PSE&G.