

# CHEMICAL ENGINEERING ‘ON-A-CHIP’: Capturing the Integrated Scope of Chemical Engineering in STEM Outreach

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The U.S. Bureau of Labor Statistics predicts that the number of chemical engineering (ChE) jobs will increase by 8% from 2016–2026,<sup>[1]</sup> demanding a growth in the number of students studying ChE. The interest in Science, Technology, Engineering and Mathematics (STEM) is planted early in a student’s academic career and is reinforced during high school.<sup>[2–7]</sup> Whereas very few students change into STEM fields after entering college, the majority of students who enter college to pursue a STEM discipline tend to persist in that line of study.<sup>[2]</sup> High school teachers and guidance counselors, therefore, help set a student’s career path, but a lack of education in career trajectories in engineering, particularly in ChE, can hinder recruitment of students once they reach college.

Unlike other engineering disciplines, such as electrical or mechanical engineering, where the scope of study and career paths are clear, the skill sets, impact and contributions of ChEs and the broad spectrum of jobs that they hold tend to be poorly understood.<sup>[2,3,8]</sup> Specifically, there exists a persistent struggle to differentiate ChEs from chemists, and a failure to grasp how ChEs leverage all of the basic sciences for designing processes capable of transforming matter into new, valuable products.<sup>[8]</sup>

Beyond education of high school teachers and guidance counselors, student-faculty interactions in programs at universities, high schools, or even public venues boost understanding of and interest in ChE. Indeed, one of the most effective tools for recruiting students to ChE are laboratory experiences with faculty, undergraduates, and graduate students that combine fundamental principles with creative inquiry.<sup>[4–7,9]</sup> Successful outreach not only helps students answer the question “What does a chemical engineer do?”, it also encourages a more diverse set of students to engage in the discipline.<sup>[4,5,8,10,11]</sup>

## MOTIVATION

The same complexity that makes the ChE discipline and its impact difficult to grasp also challenges educational

initiatives aimed at conveying, in a single module, a sufficient representation of its scope. Indeed, in our own STEM outreach experiences, we have commonly employed independent experiments and demonstrations that illustrate disparate fundamental ChE concepts; for example experiments on chemical reactions, exploration of non-Newtonian fluids, illustrations of molecular separations, etc. What we commonly lack—and suspect similar ChE-focused STEM efforts by others do as well—is a clear platform for demonstrating the distinguishing skills of chemical engineers to rationally integrate processes across molecular, macroscopic, and system scales.

While chemical engineers often think about challenges associated with process scale-up, demonstration of large-scale process integration within the confines of the STEM outreach laboratory can be logistically challenging and costly. As a viable alternative, the involvement of chemical engineers in process scale-down—for example, in the design of molecular sensors,<sup>[12]</sup> miniaturized devices for health assays<sup>[13]</sup> and drug discovery,<sup>[14]</sup> or chemical plants on-a-chip<sup>[15]</sup>—provides an attractive basis for developing cost-effective, yet impactful ChE-based STEM modules.



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## MODULE OVERVIEW

Here, we describe a STEM module (Figure 1) that was first designed for the 2015 Pennsylvania Governor’s School and repeated at the 2016 and 2018 Lehigh University Summer Engineering Institute. These month-long residential programs were each designed to give a total of 50-100 high-achieving Pennsylvania high school students both classroom and hands-on experience in all of the engineering disciplines.

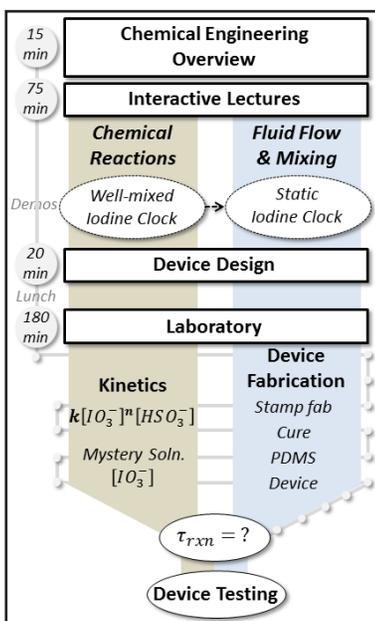


Figure 1. Integrated module schematic.

implications of mixing during the scale-up (e.g., bench-to-plant) and scale-down (e.g., plant-to-chip) of chemical processes.

The newly trained ChEs then work in teams to assess the kinetics of the Landolt-clock reaction<sup>[16-19]</sup> and to design and fabricate a plant-on-a-chip microfluidic device capable of enhancing the mixing of two reacting feeds despite laminar fluid flow conditions in order to continuously process reacting fluids at very small scales. This integrated platform enables assessment of the implications of process scale-down, specifically microscale mixing, on reaction.

## LEARNING OBJECTIVES

In addition to illustrating fundamental concepts underlying chemical process engineering, this module underscores how the scale-down (or by analogy scale-up) of a process requires chemical engineering insight beyond simple adjustment of system dimensions. This rationale contextualizes the problem by emphasizing its applicability to practicing chemical engineers. By the conclusion of the module, students should be able to do the following:

1. Apply knowledge of fluid flow and mixing to conceptualize, design, and fabricate a working microfluidic device
2. Determine governing kinetics of a chemical reaction through experiments and data analysis
3. Understand the effects of scale-down on fluid flow, mixing, and reaction
4. Apply the combined knowledge of residence time, reaction kinetics, and mixing to make predictions and interpret plant-on-a-chip data

The module specifically casts students as “ChEs for a day”, starting with “on-the-job training” that first aims to broadly familiarize them with their “responsibilities” as ChEs and thus introduce them to the general scope and impact of the discipline. The remainder of the training aims to build necessary technical skills for completing subsequent laboratory engineering tasks. These concepts include an introduction to elementary reaction engineering, fluid flow phenomena, and im-

## FOUNDATIONAL TECHNICAL CONCEPTS

The instructional components of the module introduce engineering concepts associated with chemical reactions and the fluid flow and mixing required for the hands-on laboratory.

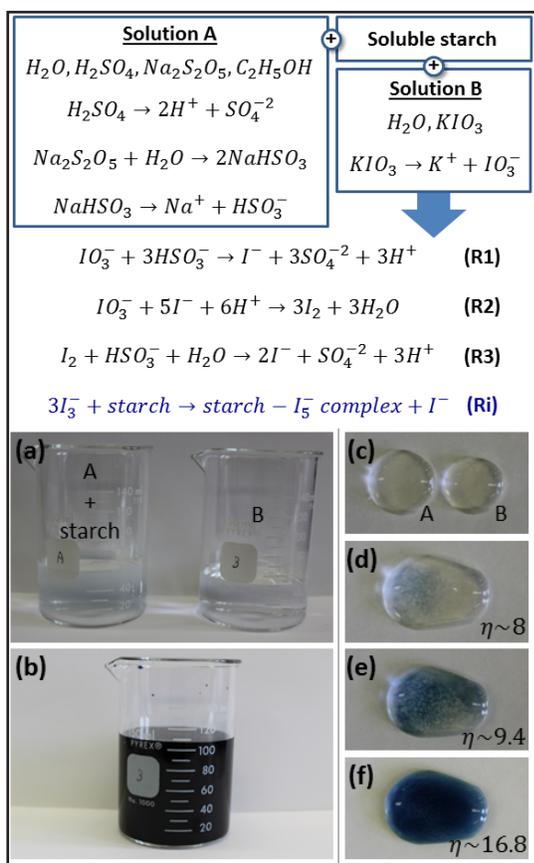
### Chemical Reaction Fundamentals

Following brainstorming of examples and associated signs of chemical reactions in their everyday lives, students learn about chemical reactions from thermodynamic and kinetic perspectives. Reactants and products are formally defined in terms of their associated energy states, with subsequent discussions defining heats of reaction, activation energy ( $E_a$ ), and the concept of endo-/exo-thermicity. We introduce the formal definition of the reaction rate constant ( $k_0 \exp(-E_a/RT)$ ) to highlight the influence of temperature ( $T$ ), and define and discuss how catalysts influence  $E_a$ . We discuss the concept of molar concentration by reminding students of Avogadro’s number, formally defining molarity, and working through simple examples of how to calculate molar concentrations of chemical species in solutions and mixtures thereof. By asking students to think probabilistically about what is required for reactions to occur between chemical species, we guide collective discovery of basic concepts of mass action kinetics, formalize differential rate laws, and discuss how graphical assessment of rate data relative to linearized integrated rate laws enables determination of reaction order and simplified estimation of kinetic parameters.

### Landolt Reaction Demonstration

The final portion of the chemical reactions lecture is reserved for the demonstration of the classic chemistry reported by Landolt in 1886<sup>[16-19]</sup> and referred to commonly as the “iodine clock reaction”. This reaction is selected for its dramatic color change from a clear to deep blue solution as a distinct reaction indicator. The specific color change of the Landolt reaction (Figure 2a and b) is not shared with the students prior to its demonstration, but instead students are asked to recall signs of a chemical reaction and then to watch carefully for these during the demonstration.

Among possible chemical routes to the Landolt reaction,<sup>[16-19]</sup> this module employs mixing of an acidified (sulfuric acid,  $H_2SO_4$ ) aqueous solution of sodium metabisulfite



**Figure 2.** Landolt iodine clock reaction (mechanism, top) carried out in (a) well-mixed (WM) solutions of A and B, leading to (b) a rapid uniform color change at a time,  $t_{WM} \sim 20$  s. (c-f) Time series snapshots of the same chemistry carried out under transport-limited conditions in static droplets at times relative to the well-mixed condition,  $\eta \sim t/t_{WM}$ , as specified.

( $Na_2S_2O_5$ ) and ethanol (solution A) with soluble starch, and subsequent mixing with an aqueous solution of potassium iodate ( $KIO_3$ ) (solution B). Following its demonstration, description of the Landolt chemistry is tailored to the technical level of the students. For advanced high school students, the reaction mechanism (Figure 2, top) is briefly discussed, with emphasis on the following key concepts: 1) three key reactions, R1-R3, are critical for understanding the Landolt chemistry, 2) reaction R1 of bisulfite ( $HSO_3^-$ ) with iodate ( $IO_3^-$ ) to form iodide ( $I^-$ ) is the rate-limiting step and thus determines the effective kinetics of the reaction, 3) reaction R2 of the remaining iodate with iodide yielding iodine ( $I_2$ ) and R3 of iodine with the remaining bisulfite are much faster than R1 so that the iodine and thus triiodide ( $I_3^-$ ) concentration is minimized until all of the bisulfite ( $HSO_3^-$ ) reactant is consumed, 4) the first persistence of  $I_2$  in solution leads to an  $I_3^-$ -starch complex (Ri) exhibiting a distinct blue color, and 5) the time until onset of the associated color change can be tuned simply by controlling the concentrations of the re-

actants ( $IO_3^-$ ,  $HSO_3^-$ ) over a range where bisulfite remains as the limiting reagent and never exceeds by more than a factor of three the iodate concentration.

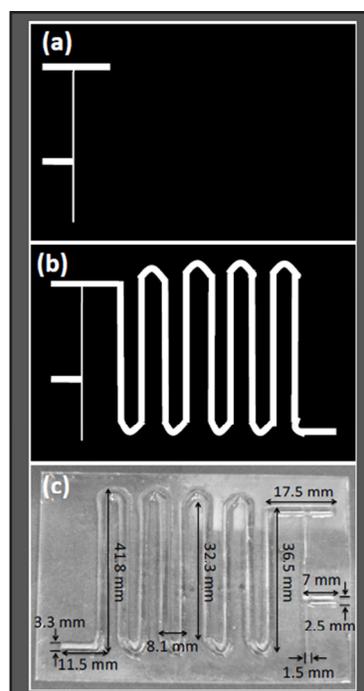
To assess student understanding, after its initial demonstration, we ask students to predict how the rate of the Landolt reaction would be impacted by factors like temperature as well as reactant and catalyst (i.e.,  $H^+$ ) concentration. Separate demonstrations are then carried out to illustrate the impact of these factors based, respectively, on decreasing the reactant temperature through use of an ice bath, increasing the concentration of  $Na_2S_2O_5$ , and doubling the catalyst concentration.

### Microfluidics and Mixing

During the fluids lecture, students are taught key concepts that enable them to design effective microfluidic devices. Fluid flow types (laminar, turbulent) and implications on mixing are described, using images of streamlines to illustrate the limited versus enhanced (i.e., by chaotic flow, eddies) mixing in laminar versus turbulent flow, respectively. The concept of Reynolds number,  $Re$ , is introduced to link physical fluid properties and flow rates to the flow type, and to frame discussions about process scale-up (i.e., chemical plant pipe flow) and scale-down (i.e., microfluidic devices). We specifically highlight flow limitations in microfluidic devices owing to the potential for device failure from increasing microchannel pressures at high flow rates, and conclude

by introducing the key engineering challenge of the module: to design a device that enhances mixing in laminar flow.

The remainder of the lecture is devoted to introducing concepts that are key to making a functioning microfluidic device (Figure 3) capable of contacting two reactant streams as a train of droplets isolated by a third continuous flowing fluid. Using the principles outlined by Garstecki et al.,<sup>[20]</sup> we discuss the design of the device (i.e., droplet breakup in a T-junction) and the properties of the fluids that enable droplets to be formed in a continuous



**Figure 3.** Template of microfluidic device (a) provided to students and (b) for the instructor-designed device. (c) Instructor-designed microfluidic device with dimensions.

fluid.<sup>[20-22]</sup> Specific to device design, the microchannels feeding reactant fluids to the T-junction must be half the width of the main channel through which the continuous fluid flows. The capillary number,  $Ca$ , is introduced and its significance for droplet formation is explained in terms of the properties of the continuous fluid and interfacial tension with the droplet-forming fluids. We discuss the requirement of  $Ca \sim O(10^{-2})$  to ensure droplet breakup,<sup>[20]</sup> and collectively calculate  $Ca$  for the specific fluids to be processed in the students' microfluidic devices.

### Conceptualizing Scale-Down (Scale-Up) Challenges

We help students conceptualize challenges that chemical engineers face when scaling reactive processes by demonstrating the Landolt iodine clock reaction under static (diffusion limited) conditions. Following solicitation of student predictions for the impact of suppressed mixing on the reaction, we contact droplets of each of the reactant solutions, and encourage students to make observations of how the absence of mixing leads to the slowed onset and inhomogeneity of the clear-to-blue color change (Figure 2c-f) relative to the well-mixed case (Figure 2a and b). We exploit this simple example to discuss scale-up and scale-down challenges in general and as a way of integrating chemical reaction and fluid flow design principles. Mixing implications are then discussed using pictures of common reactor configurations. Successful strategies for microfluidic mixing are shown, including herringbone patterns and the use of sharp corners to cause mixing due to fluid tumbling.<sup>[21,23,24]</sup> Finally, the concept of residence time,  $\tau$ , is introduced and calculations are demonstrated for a tubular reactor and microfluidic channel as the basis for discussing impacts of non-uniform mixing at each scale.

## LABORATORY DESCRIPTION

Table 1 summarizes the supplies and equipment required for this module.

Students are divided into groups of 5 for the hands-on portion of the module aimed at the design of a microfluidic device capable of predictively controlling the Landolt reaction under continuous flow conditions. The laboratory is coordinated between microfluidic device design and fabrication, collaborative benchtop elucidation of the reaction kinetics of the Landolt iodine clock reaction, and collective device testing as schematized in Figure 1.

### Microfluidic Device Design

Each group is given 20 minutes to use their creativity and knowledge of fluids to design devices (i.e., channel geometry) that they feel will best allow them to 1) carry out a well-mixed Landolt reaction and 2)

accurately predict the location in the microfluidic channel where progressing droplets will first display the clear-to-blue color change. Templates for the main channel in the microfluidic devices are designed in Microsoft PowerPoint by drawing channel geometries on a black background using white lines of a sufficient width (4 pt) (Figure 3), which translates to devices with 2.5 mm wide channels. PowerPoint templates containing the T-junction geometry (Figure 3a, line width 1 pt  $\approx$  1.5 mm channels) for separately feeding reactant solutions A and B to the continuous fluid, are provided to each student group to ensure that all devices form droplets. Throughout the design process, groups are advised on the mixing effectiveness and fabricability of channel features they include. Due to the fabrication method used, small features ( $< 100 \mu\text{m}$ ) will not effectively be patterned onto the microfluidic stamp. Duplicates of the patterns are then

**TABLE 1**  
Supplies and equipment for microfluidic and reaction demonstrations and experiments.

Item [Source]	Quantity	Estimated Unit Cost	Estimated Total Cost
<b>Microfluidic device supplies</b>			
Clear acetate sheet (transparencies) [Staples]	50	\$17.29	\$17.29
Polydimethylsiloxane (PDMS) [Robert McKeown Company, Inc.]	500 g	\$50.00	\$50.00
UV curing glue (NOA 81) [Norland Products Inc.]	1 oz.	\$19.00	\$19.00
Ethanol [Fisher]	4 L	\$180.28	\$180.28
Acetone [Fisher]	4 L	\$105.95	\$105.95
Isopropyl myristate [Fisher]	500 mL	\$77.20	\$77.20
Glass microscope slides (75 X 25 mm) [Fisher]	144	\$59.60	\$59.60
Glass microscope slides (75 X 50 mm) [Fisher]	144	\$115.50	\$115.50
Tubing (OD 3/32 inch) [McMaster Carr]	50 ft	\$11.00	\$11.00
Stainless steel connectors (ID 0.023 in, L 0.35 in) [New England Small Tube]	100	\$ 0.45	\$45.00
Isopropyl myristate [Fisher]	1 kg	\$131.50	\$131.50
Syringes (3 mL, pack of 200) [Fisher]	1	\$31.69	\$31.69
Petri dishes (100x15 mm, case of 500) [Fisher]	1	\$285.11	\$285.11
<b>Total cost</b>			<b>\$1,129.12</b>
<b>Reaction supplies</b>			
Distilled water	--	--	--
Sodium metabisulfite ( $\text{Na}_2\text{S}_2\text{O}_5$ , 250 g) [Fisher]	1	\$33.20	\$33.20
Potassium iodate ( $\text{KIO}_3$ , 100 g) [Fisher]	1	\$55.37	\$55.37
Sulfuric acid ( $\text{H}_2\text{SO}_4$ , 100 mL) [Fisher]	1	\$88.69	\$88.69
Ethanol	--	--	--
Starch (soluble, 250 g) [VWR]	1	\$46.66	\$46.66
Sample tubes (50 mL, case of 500) [VWR]	1	\$288.98	\$288.98
Sample tubes (15 mL, case of 500) [VWR]	1	\$267.08	\$267.08
Transfer pipettes (7.5 mL, case of 500) [VWR]	2	\$58.81	\$117.62
Gloves (Nitrile, pack of 100, size M) [VWR]	2	\$29.15	\$58.30
Gloves (Nitrile, pack of 100, size L) [VWR]	2	\$29.15	\$29.15
Polypropylene bottles (250 mL, Pk of 12) [VWR]	1	\$84.59	\$84.59
Polypropylene bottles (500 mL, Pk of 12) [VWR]	1	\$115.57	\$115.57
<b>Total cost</b>			<b>\$1,185.21</b>
<b>Equipment required</b>			
Furnace, plasma cleaner, syringe pumps (3), UV lamp, balance, stopwatch, safety and UV glasses			

printed onto clear acetate sheets (transparencies).

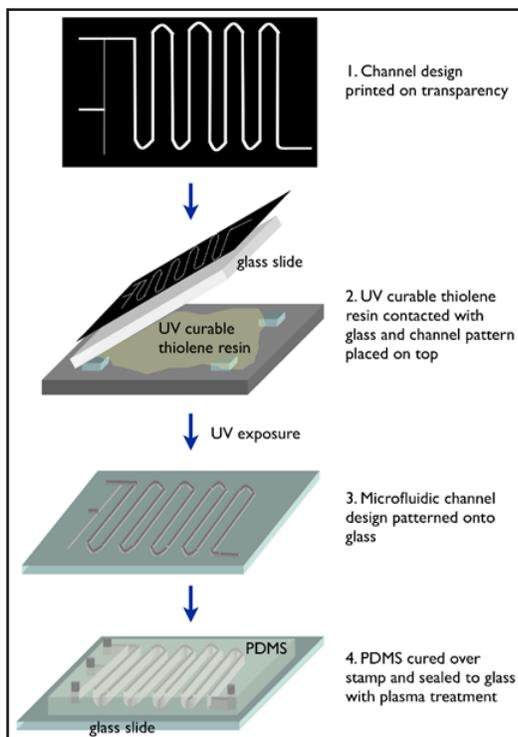
### Microfluidic Device Fabrication

With help from the instructors and while abiding by safety precautions (i.e., chemical fume hood, gloves, safety/UV goggles), the students fabricate stamps for templating microfluidic channels via a simple, previously developed method (Figure 4).<sup>[22]</sup> Briefly, duplicate printouts of the microfluidic design on transparencies are overlaid and aligned to ensure that UV light is blocked by black areas and transmitted through clear areas. The corners of a large microscope slide (75 mm × 50 mm) are traced onto a sheet of clear acetate, glass spacers (previously cut ca. 15 cm × 15 cm microscope slides) are placed at the traced corners, and a large droplet of UV curable thiolene resin is placed in the center. The large microscope slide is placed on the glass spacers, ensuring that the resin fills the void and no bubbles appear. The microfluidic stamp is then formed by placing the printed channel pattern on top of the large glass slide, followed by exposure to UV light for approximately 30 seconds, cleaning with acetone, ethanol and water, and post-curing under UV light for an additional 30 minutes.

While the stamp is post-curing, students prepare polydimethylsiloxane (PDMS), the polymer that will be patterned over the microfluidic stamp, in a 10:1 silicone elastomer base to cross-linker ratio. Due to the high viscosity of the pre-cured mixture, air trapped as bubbles must be removed through degassing (vacuum, 30–60 min) to avoid impacting the channel geometry in the cured PDMS. Degassed PDMS is then poured over the post-cured microfluidic stamp and cured at 75°C for one hour. The students cut out their microfluidic devices using an X-Acto knife, and exploit condensation of plasma-induced<sup>[25]</sup> polar silanol groups on the surfaces of the PDMS and glass to strongly seal them to a large glass slide. Final sealing of the device is completed by application and curing (3–5 min) of resin along the outer edge.

### Bench-Scale Reaction Kinetics

Students are tasked with elucidating the kinetics of the Landolt iodine clock reaction, namely the order,  $n$ , with respect to the reactant  $KIO_3$  and reaction rate constant,  $k$ , given by the description based on mass action kinetics of the rate limiting step (R1, Figure 2),  $rate = k[IO_3^-]^n[HSO_3^-]$ . Groups



**Figure 4.** Fabrication steps to make a microfluidic stamp from thiolene resin. Reproduced from Ref. [22] with permission from The Royal Society of Chemistry.

are provided with two stock reactant solutions (A and B, Figure 2) and the specific concentrations of each, as well as a solution of soluble starch, access to distilled water, and sample tubes and transfer pipettes equipped with volumetric gradations. Each group is assigned a set of four  $KIO_3$  concentrations to test with the Landolt chemistry in small volumes (e.g., 5 mL of solution A with 2 mL of the starch solution combined with a 5 mL variant of solution B). Students are asked to determine the appropriate dilution of the stock solution B to yield new 5 mL solutions with the desired  $KIO_3$  concentrations and to employ volumetric gradations on the transfer pipettes and sample tubes to prepare those solutions. Duplicate data points are included as a basis for discussing and quantifying experimental error and confidence limits.

Each group is responsible for calculating and recording in a shared spreadsheet the  $KIO_3$  concentration in each reaction solution and the experimentally determined time to the clear-to-blue color change. Graphical analysis of the linearity of pooled data sets in terms of 1)  $[KIO_3 [M]]$ , 2)  $\ln ([KIO_3 [M]])$ , and 3)  $1/[KIO_3 [M]]$  vs. time, is used to assess whether  $[KIO_3 [M]]$  obeys 1) zeroth-, 2) first-, or 3) second-order kinetics and to estimate  $k$ .

In order to assess understanding, the reaction kinetics laboratory is concluded by providing each group with a solution B containing an unspecified concentration of  $KIO_3$ . Each group is tasked with developing a strategy for estimating the concentration of  $KIO_3$ . With guidance from the instructor provided as needed, each group reacts the mystery solution B with solution A in the presence of soluble starch, and uses the rate law determined from the collective data analysis to calculate the  $KIO_3$  concentration. Once each group has estimated the  $KIO_3$  concentration in their “mystery” solution, the instructor provides the actual concentration for comparison, and leads brainstorming of factors that may influence any measured deviations.

### Plant-on-a-Chip Testing

How effectively the microfluidic devices mix the reacting solutions is tested using the Landolt iodine clock reaction with nominal (i.e., demonstrated) reactant concentrations. Prior to testing, students employ knowledge of reaction kinetics, residence time, and mixing phenomena to predict

where, along the channels of an instructor-designed device (Figure 3c), the clear-to-blue color change will occur. This device incorporates sharp corners to facilitate mixing. Students mark their predicted location on an image of the device included in a handout. The Landolt reaction is then demonstrated in this device (projected using a document camera) by forming droplets containing solutions A and B in isopropyl myristate (IM) via balanced pumping of each solution with separate syringe pumps (Figure 5). Despite incorporation of mixing features, solution interfaces and gradients in the eventual blue color of the droplet can still be observed (Figure 5, inset 1).

Based on observations of mixing in the instructor-designed device, each group assesses their own device, calculates residence times, and predicts and marks the position of the color change on their device. Nominated group representatives give a brief presentation (maximum of 2 minutes) about their microfluidic design, articulating their thought process and rationale for both their design and reaction positioning predictions. Students vote for the design they think will have the most effective mixing and most accurate prediction of the color change location. The design garnering the most votes is tested collectively for accuracy of the reaction position prediction.

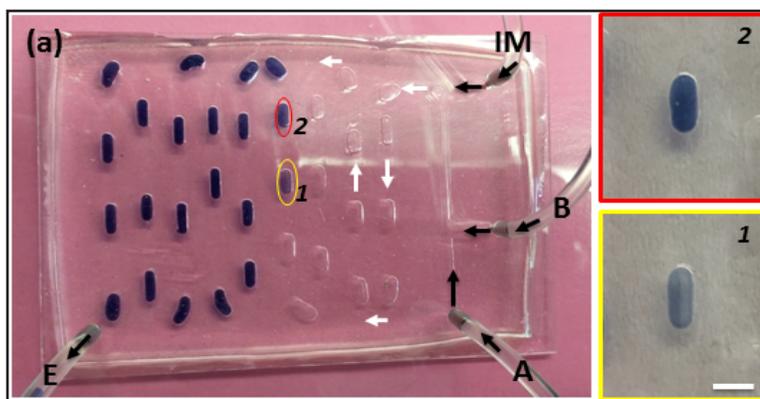
## MODULE ASSESSMENTS

This multi-faceted educational module was delivered over the course of three summers to a total of approximately 200 students. Various modes of assessment were employed to understand how well specific learning objectives were met.

### Formative Assessment

Formative assessments were embedded within the lecture and laboratory components of the module and are briefly enumerated below. The outcome of each assessment is presented in italics.

- Students were asked to brainstorm how the rate of the Landolt reaction could be measured, and to hypothesize how factors like decreasing temperature (i.e., ice bath) and changing reactant and catalyst concentrations would influence reaction rate. *Students were uniformly able to successfully conclude that the rate of the Landolt reaction could be quantified by simply timing from the start of reagent mixing until the dramatic color change. Students successfully predicted qualitative trends of the reaction rate relative to changes in the reaction variables. In some cases, however, a point of confusion arose in translating the reaction rate to the timing of the color change. For example, while students would correctly predict an increase in reaction rate for a given scenario, they would sometimes suggest that this would be manifested as a lengthening rather than shortening of the time until color change.*



**Figure 5.** (a) Mixing in the instructor-designed microfluidic device of solutions A and B in bubbles flowing in a continuous fluid, isopropyl myristate (IM), highlighting the (1) gradient in color due to unmixed reactants and (2) a completely mixed sample. Scale bar represents 2 mm.

- Students were tasked with formulating and executing the experimental plan to estimate the concentration of a reactant ( $KIO_3$ ) in a “mystery” solution, which assessed students’ understanding of previously extracted kinetics and the ability to calculate concentrations. *Students successfully determined that they could mix a known composition and volume of Solution A with a quantified volume of the mystery Solution B, and then back-calculate the concentration of  $KIO_3$  from the measured reaction time on the basis of the determined rate law. Students were uniformly able to accurately predict the concentration of their “mystery” solution.*
- Students described the rationale for their device design and mixing features, with instructor feedback provided to reinforce mixing concepts in addition to ensuring device fabricability. *The students successfully developed designs that were creative from both an aesthetic and functional standpoint, but commonly required instructor feedback on how best to balance these two design constraints to ensure successful fabrication. Students were generally able to express a scientific rationale for each feature in the device.*
- Students were tasked with demonstrating their ability to calculate total volume and residence time in their device and an instructor-designed device. *Through individual help from the instructors and their fellow classmates, students were able to perform these calculations.*
- Students integrated their knowledge of reaction kinetics and residence time calculations to predict the channel position where color change of the Landolt reaction would occur, with subsequent testing enabling quantitative comparison of experimental results with theoretical predictions (e.g., enhanced or poor mixing, confidence in kinetics, etc.) and collective discussion of deviations and ChE scale-down concepts. *The predictions in the instructor-designed device were generally accurate within reasonable experimental error. The students were able to apply the calculation method used to predict the reaction*

position in their own device. Of the devices tested, these predictions were relatively accurate.

### Summative Assessment

Each group was asked to make a brief oral presentation on the design of their microfluidic device, emphasizing design features engineered to enhance mixing under laminar flow conditions. The groups also discussed the results of their analysis of the mystery solution, quantified the total residence time in their microfluidic device, and identified the channel position where they predicted completion of the reaction. Peer and instructor feedback were provided at the conclusion of each presentation regarding technical features of the device design and reaction predictions.

The aim of this module was ultimately to effectively link ChE fundamentals with hands-on laboratory activities and for students to tackle real ChE challenges. The unique setup of the program, with two lectures in the morning and a laboratory after lunch, enables immediate experimental reinforcement of the concepts taught. Quantitative summative assessment of the effectiveness of this educational module was achieved through student surveys, the results of which are tabulated in Table 2.

### Student Reflections

Students were also asked to reflect on the following question: "What was the most helpful/beneficial portion of the session and/or the most relevant material presented?" The responses, summarized here, underscore the effectiveness of the integrated module format in teaching, illustrating, and reinforcing ChE fundamentals.

*"I enjoyed the connection between the information presented in the powerpoint and the experimentation. I like applying the knowledge. I found that designing our own microfluidic device was fascinating, because we thought about the information in greater depth and were able to look at the viewpoints of our classmates."*

*"The review of chemistry at the beginning was very helpful and informative, and provided much of the information needed to complete the lab. The experiments and the building of the microfluidic device were also very interesting and relevant."*

Questions from Summative Survey	Rating (out of 5)
Value to you of the information presented?	4.1
Audience interaction, time for questions?	4.2
Overall, how satisfied were you with this session?	4.0

The open-ended device design component of the module leads to unique designs that may present unanticipated fabrication challenges or device failure. We exploit this uncertainty as the basis for discussing associated risks, and for allowing students to choose to take known risks, which some did, or to reconsider their design. Overall, this collaborative process helped the students use their creativity, anchored by their knowledge of successful mixing strategies, to design unique microfluidic devices.

*"I really appreciated that we were allowed to design and produce our own microfluidic devices based on the information that was provided. It was hands on engineering."*

This experiential learning pushed the students to put new concepts into practice, reinforcing the idea that fundamental concepts do apply to real world problems.

Reaction kinetics experiments in which students collected, pooled, and analyzed experimental data offered first-hand reinforcement of lecture concepts, instances for instruction on basic laboratory skills, and opportunities for quantification and thinking about experimental error, its root causes, and its propagation to the final results. The greatest sources of error in the data were contamination, due to reuse of disposable transfer pipettes on more than one reaction experiment, volumetric measurement errors in preparing specific variants of solution B, and errors in the accuracy of timing of the reaction. Despite these errors, the students were successfully able to collectively and collaboratively determine the reaction order and to improve their understanding of the fundamentals of chemical reactions.

*"I thought the entire lab was very well presented and was a lot of fun to be in. The information provided was very helpful. Overall I learned some new things that I never saw before in Chemistry."*

*"I liked being able to actually get hands on with the chemistry and do some math. I wish there were more actual classes like this in the program."*

The overall goal of this module was to use the lecture and laboratory to educate students about the field of chemical engineering. We aimed to present real challenges to students that chemical engineers face and to give them tools to solve these problems during the laboratory period. Overall, this module was successful in educating students about chemical engineering, in some cases increasing excitement about the discipline:

*"The most beneficial part for me was just learning about what exactly a chemical engineer does and what goes on in a chemical plant."*

while, in other cases, clarifying disinterest in the field:

*"I realized that I am not interested in chemical engineering, though I enjoy chemistry. I liked performing the reactions and finding the concentrations-this was a good refresher."*

## SUMMARY

This module teaches students about the complexity and impact of the field of chemical engineering. The students become “ChEs for a day” where they are taught chemical engineering fundamentals during their “on-the-job training” and immediately apply these new skills in a creative laboratory experience designing a ‘plant-on-a-chip’. They are challenged to scale-down the Landolt iodine clock reaction to the microliter scale by applying their new training in fluids, elementary reaction engineering, and knowledge of transport limitations in reacting and laminar fluid flow systems. The multi-faceted module provides a range of experiences for students, including the design and fabrication of microfluidic devices to meet reactant mixing design criteria, experimental assessment of kinetics through pooling and analysis of collective data, quantification of residence times, and opportunities for device testing and engineering analysis, predictions and refinement. This integration of ChE fundamentals offers insight into chemical engineering process design principles that are commonly challenging to capture in ChE-based STEM outreach events. The active nature of this learning module teaches students about real challenges faced by chemical engineers in their work environment, effectively educating students about the vastness and impact of the discipline and aiding in the recruitment of students prior to entering college.

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