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Development of a software tool to improve educational outcomes in a time constant measurement experiment

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Abstract:

In a junior level mechanical engineering experimental measurements laboratory course, students perform an experiment in which they determine time constants of various electronic temperature sensors, based on a lumped capacitance heat transfer model. In the past, many students have struggled with the mechanics of calculating the time constant using Microsoft Excel, often spending excess time on it and/or generating erroneous results. While such deficiencies are correctable with additional feedback and instruction, the additional time would come with an opportunity cost of other potential lab activities. It is preferable instead to spend available lab time on other tasks, such as interpreting the meaning of the time constants, and hypothesizing and testing different aspects of the experiment that can affect the calculated time constants. Since these preferred activities necessarily rely on the correct calculation of time constants, a software tool was developed which can be used to more quickly and easily calculate time constants. It is a graphical program which runs on GNU Octave, and it has the capability to import raw data, select subsets of the data to analyze, and calculate the time constant based on the user's selections. The new tool is designed for use during the laboratory period, so that students can receive feedback on their analysis and correct common mistakes before leaving the laboratory. The tool also calculates time constants several times faster than could be accomplished using Excel, thus reducing the amount of time students must spend calculating time constants and allowing students to collect and analyze many more data sets than they did previously. The new tool also incorporates more graphical interaction and feedback than students experienced with Excel. The ease of use, speed, and new feedback provided by the software tool allows additional improvements to be made to the experiment. These include obtaining a larger number of time constant values, on which to perform better statistical analyses, as well as facilitating additional inquiries into the experimental data on multiple cognitive levels. This paper discusses the purpose, function, and effectiveness of the tool, including estimates of time saved. It also discusses how the additional experimental analysis improvements, made possible by the new software tool, impact student understanding and course learning outcomes.

Introduction:

One of the experiments in the junior level experimental methods laboratory course at Mercer University's mechanical engineering program involves characterizing the time response of temperature sensors. Briefly summarized, the sensor response is characterized by a time constant τ based on the lumped capacitance method of evaluating conduction (a standard topic in heat transfer textbooks, *e.g.*, [1]). In this model, the time response of the mass (*i.e.*, the sensor) is governed by the equation

$$\frac{\theta}{\theta_i} = \exp\left(-\frac{t}{\tau}\right) \tag{1}$$

where θ represents the difference between the sensor and ambient temperatures, θ_i is the initial temperature difference, and t is time. Time constant τ is considered to be a function of the sensor's density, volume, surface area, and heat capacity, as well as of the convection coefficient at its surface.

Over the past several years, the author has observed various difficulties encountered by students, including errors resulting from incorrect assumptions, and excess time being spent analyzing experimental data. Additionally, there is an effort currently underway to update the course objectives and realign the various experiments with those objectives. To address both the student difficulties and better align the experiment with educational objectives, the author has undertaken to modify the experiment requirements and methodologies. As part of improving the methodologies, the author has created a software time constant tool (TC Tool) to be used in determining time constants. The focus of this paper is the motivation behind the tool development, capabilities of the tool, and how the tool can facilitate expanding the learning objectives in this experiment.

Educational Objectives:

The laboratory course here discussed, like many of its kind, has multiple educational objectives. It helps to satisfy the ABET engineering program accreditation Criterion 3, Outcome 6 regarding experimentation [2]. There is also the matter of topics covered, which is briefly described in the course catalog [3] under the course number MAE 301L. In addition to these explicit requirements, it can be helpful to consider course outcomes in terms of broad cognitive outcomes such as Bloom's (revised) Taxonomy [4], or the laboratory focused Fundamental Objectives of Engineering Instructional Laboratories, as described in the 2002 San Diego colloquy [5]. Other identified goals for the course update process include a greater utilization of statistical analyses, more effective use of technology, and better alignment with modern engineering practice.

Individual experiments in the laboratory course tend to focus on a subset of the overall educational objectives. The recent changes to the experiment described above, facilitated in no small part by the introduction of the TC Tool, are meant to: focus on the "identification of experimental objectives" as described in the course catalog [3]; emphasize the Models objective from the Fundamental Objectives, particularly by a more in-depth analysis of "the strengths and limitation of theoretical models as predictors of real-world behaviors" [5]; and, by freeing students from some of the tedious details of data formatting and regression implementation, allow for more effort to be spent on the "higher levels" of Bloom's Taxonomy [4]. It should be noted that the prior version of the experiment, which had a primary focus on calculation of time constants, was not without pedagogical merit; but relegation of the time constant calculation to a tool allows for greater student productivity and a focus on other learning objectives that better fulfill the course's overall goals.

Motivation:

One of the original motivations for the TC Tool was to reduce analysis errors committed by students, as well as time spent determining time constants from experimental data. To help explain this motivation, the previous experimental methodology is described below, along with common mistakes and issues.

In the earlier version of this experiment, students transfer various temperature sensors between two water baths maintained at different temperatures. Temperature data is collected electronically using a Keysight 34972A data acquisition/switch unit (DAQ). The DAQ writes data files to a USB drive in comma separated value (CSV) format. Files are then transferred to a computer where students perform further analysis on Microsoft Excel. Students plot their data and find the time constant using the "percent change method," *i.e.* the time at which $\frac{\theta}{\theta_i} = 0.368$ based on Equation (1) at time $t = \tau$. This method is often described to students as finding the time at which 63.2% of the temperature change has been recorded. This analysis is performed for each experimental trial.

The author is aware of several recurring issues related to data analysis. First, the DAQ creates a timestamp that Excel does not recognize as a time format. (Note: Software products are always evolving; this assertion was true at the time of the TC Tool development, and the author is not aware that it has ceased to be so.) Students are given information with which to develop a workaround, but this takes time and effort that could be spent elsewhere.

After students have obtained usable time values, they may then plot their data. An example data set is shown in Figure 1. Students should then set a zero time value, determine the initial and final temperature values, and calculate the temperature corresponding to 63.2% of the temperature change. They can then find the time constant by performing a linear interpolation between the two nearest data points to find the time value associated with the target temperature.

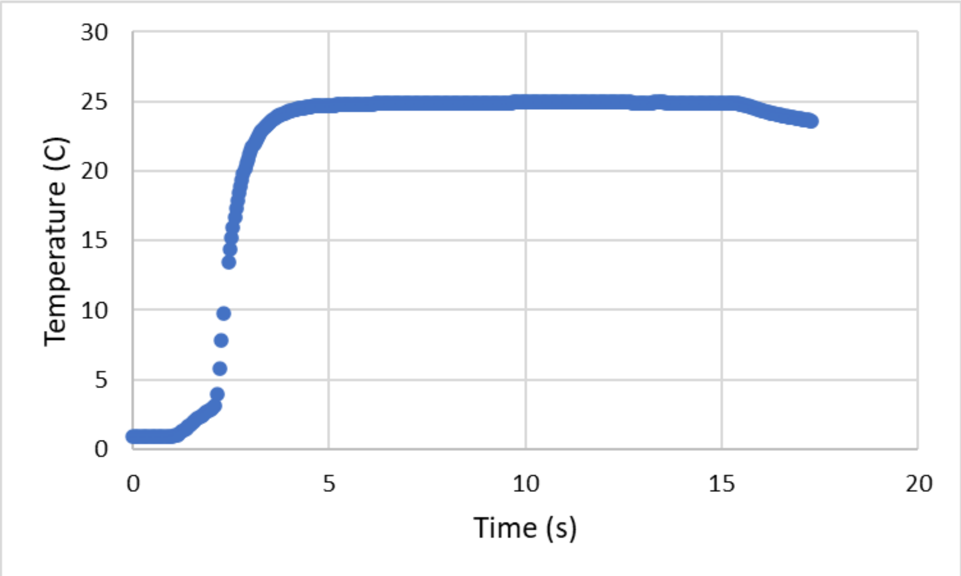

Figure 1: Raw temperature transition data using a thermistor.

During this analysis process, students often incorrectly identify the experiment start time as the first collected data point (0s in Figure 1), or as the data point corresponding to taking the sensor out of the first water bath (about 1.1s in Figure 1), rather than the correct data point corresponding to placing the sensor in the second water bath (about 2.2s in Figure 1). Students should therefore subtract a time offset in this example of about 2.2s, so that time zero on the plot corresponds to the experiment start time. Because data analysis takes considerable time, most students do the analysis after lab time, and there is no chance to correct their analysis before they turn in their reports. The author has tried requiring students to analyze one data set in advance, and has corrected any analysis issues during the laboratory period; but many students have nevertheless forgotten how to correctly analyze the data, and still submitted incorrect results in their reports.

Once time is correctly represented, students often spend considerable time performing the rest of the analysis: determining initial and final temperatures from the plot (in particular, the initial temperature will change for each data set, depending on how long the sensor was in the air before being inserted into the second water bath); calculating the percent change temperature; finding the two data points immediately bounding that temperature; and performing a linear interpolation to calculate the time constant. All the above analysis steps must be repeated for each collected data set.

As discussed in the procedure above, the main student difficulties under consideration are therefore: time and effort required to convert timestamps into usable time values; correct identification of zero time and offsetting time values; and time and effort required to calculate time constants from all data sets. By improving the use of technology and automated data collection and processing, the student experience can be better aligned with modern engineering practice, and the time saved can be spent to achieve other desired educational objectives as listed previously.

Analysis Modification:

In addition to (or as part of) the TC Tool being presented, other changes to the analysis procedures for this experiment are desirable. One way to help students recognize errors in their time constant calculations would be to graph the theoretical measurement response (based on the calculated time constant) along with the experimental data. This could make incorrect zero time choices more obvious, and might induce students to redo their calculations. Additionally, even if time constants are calculated correctly, plotting the theoretical response can provide students with visual evidence of how closely the experimental system resembles the lumped capacitance model. However, this additional graphing would also impose an additional time burden on students, multiplied by the number of data sets to be analyzed.

Rather than creating their own graph based on their calculated time constant, students might instead perform an exponential regression on their data in order to both find the time constant and graphically show how well it fits their data. The regression solution method could also be considered an improved alignment with technology use and engineering practice, per the stated goals. Exponential trendlines are a built-in feature in Excel, so this might seem like an easy solution. However, this solution also requires additional work. Excel's regression of a negative exponential requires the *y* asymptote to be zero, so students will have to convert their explicit temperature data to a difference form similar to Equation (1). Additionally, Excel's formulation uses a linearized regression, meaning the function

$$y = a\, e^{bx} \tag{2}$$

is linearized by taking the natural logarithm, transforming the equation to

$$\ln y = \ln a + bx \tag{3}$$

This form of exponential regression has a closed-form solution and is often taught to engineering students as a preferred method (for instance, in Reference [6]). However, the logarithm requires that y be strictly positive, so if the measured temperature difference θ in Equation (1) overshoots its asymptotic value (that is, $\theta \leq 0$), whether due to random error or other experimental effects, the logarithm cannot be calculated, and the regression cannot be performed. Students wishing to use the regression function must therefore reduce their data sets to avoid this issue, which once again costs them additional time for every analysis. Alternately, an iterative regression (not linearized) could be performed, which would require that an initial guess be generated, but which could accommodate experimental error around the asymptotic value. However, while such a solution could be implemented in Excel, it would be non-trivial in the author's opinion, and would require even more work of the students.

In addition to adding a theoretical curve to the data plot, the author wishes to improve the students' ability to perform statistical analysis of their results, better aligning with a stated course objective. Previously, students were asked to perform each measurement three times. To increase the number of data points without dramatically increasing time spent collecting and analyzing data, the diversity of data sets (number of sensors tested, or number of unique water bath temperatures tested per sensor) could be decreased in proportion to the increase in repetitions. Alternately, decreasing the time required to analyze each data set would also allow for an increase in test repetitions without increasing time requirements.

As stated above, the author recognizes that there is potential educational value in performing all of the current and suggested tasks in Excel, even if students struggle with the amount of time required. However, such value would come at the expense of other valuable outcomes, and might not be realized at all if students feel the course takes up too much of their times and therefore exert less effort. Additionally, the large number of steps required to complete the analysis, while tenable for a small number of data points, is excessive when considering the larger data sets that are desired for this experiment. Students are also given more responsibility for performing all the steps of analysis in their subsequent senior level laboratory course, so removing that experience in this experiment does not mean that it is removed entirely from the curriculum.

Tool Design:

To address observed student difficulties and create better alignment with new course objectives, the author set out to create the TC Tool. Based on the above factors, it was desired to produce a tool that could quickly and easily load the data file produced by the DAQ (including processing time stamps without user intervention), plot the data, allow users to select the portion of data to be analyzed, determine a time constant using one or more methods, and visually display the theoretical response(s) on the same plot as the experimental data. Furthermore, in order to accommodate all students using the tool on their computers simultaneously if desired, the tool should not rely on proprietary software to which the students do not have free access.

To meet these objectives, the author created the TC Tool as a graphical application on the GNU Octave platform. GNU Octave is free to download and use, is available on multiple operating systems, and has graphical interface capabilities; and the author was already comfortable writing programs in the language. While future improvements are planned, the author has designated the TC Tool presented here as version 1.0, which is fully functional for use in the laboratory. The tool runs on GNU Octave version 8.3.0 or higher.

The TC Tool has four main modes: Data, Plot, Analysis, and Results. Several functions are available in each mode. As seen in Figure 2, the mode selection buttons are on the right, mode-specific functions are available in the middle of the window, and (once a data set is loaded) the data are plotted on the left side of the window.

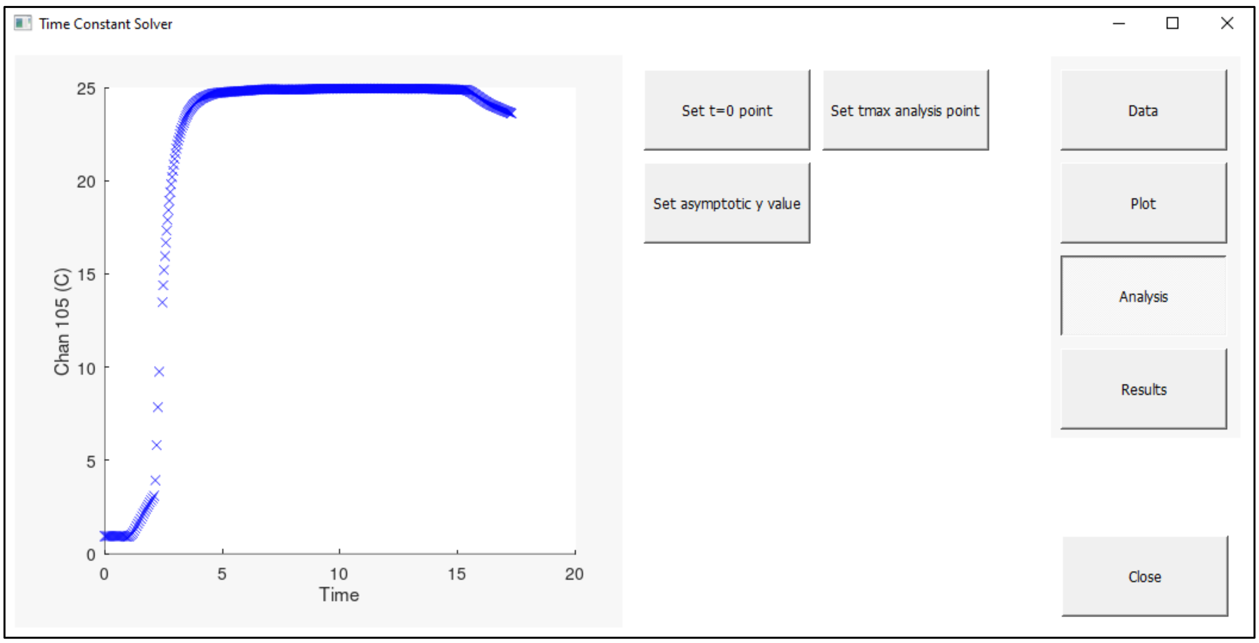

Figure 2: Time constant Tool window in Analysis mode.

In Data mode, the user can load a CSV data file, either in the format of the Keysight DAQ, or in a simple 2-column format with time represented in seconds. Data can also be saved to the 2-column format (easily readable in Excel or any standard spreadsheet program). Default save and load paths can be set, and data can be calibrated by applying an offset in the y direction. Data are automatically plotted once a file is loaded.

In Plot mode, the user can set the limits of the *t* (horizontal) and *y* (vertical) axes. Users can click a location on the plot, or type a value into a text box to set each limit. Data points are deleted from memory once they are excluded from view. The data deletion feature allows a user to load a data file, pare it down to desired data points in Plot mode, then go back to Data mode and save the reduced data file for later analysis, either with the TC Tool or in Excel.

In Analysis mode, the user can set the $t = 0$ point (that is, the first point to be considered in the analysis), the maximum time point (*tmax*) to be considered in the analysis, and the asymptotic *y* value. Setting the $t = 0$ point adjusts the time values of the data so the selected point is at time zero, as shown in Figure 3. Red triangles show the already selected t = 0 and *tmax* points (possibly difficult to see in this reduced size view), and the green dashed line previews the selected asymptotic *y* value. As in Plot mode, users can click on the graph or type a value into the text box to make any of these selections.

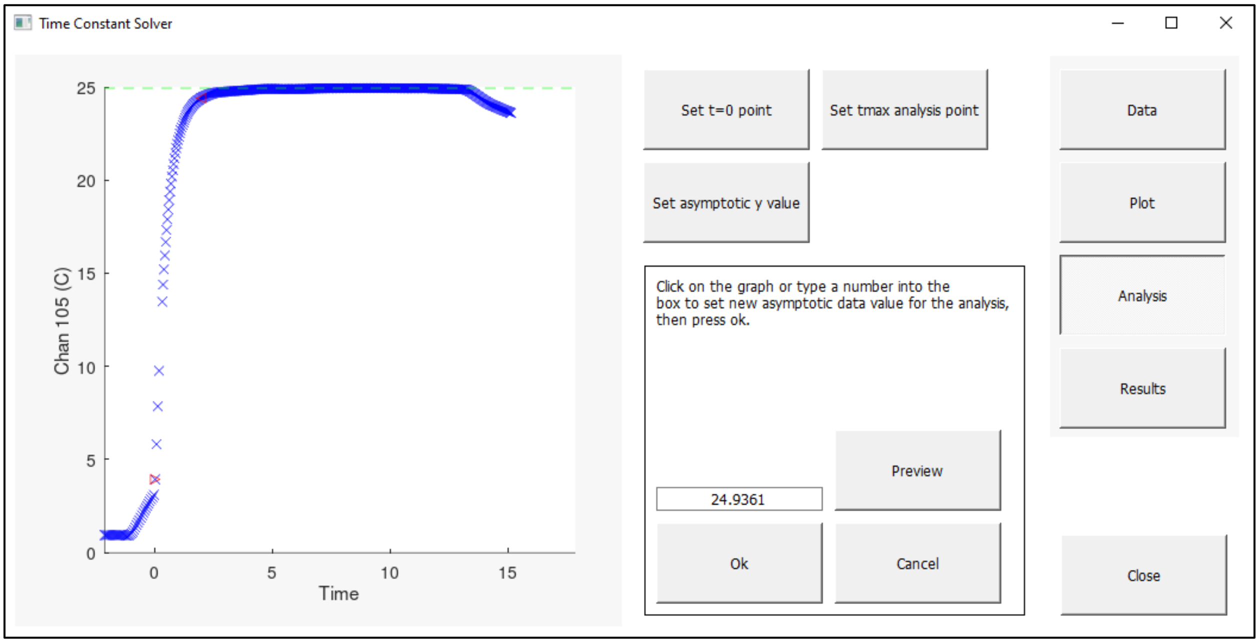

Figure 3: Analysis mode with t = 0 and *tmax* already set, and user choosing the asymptotic *y* value.

Finally, Results mode provides two options for finding the time constant. Using the values selected in Analysis mode, the Tool will find the time constant using either the percent change method (the method students previously used without automation to find each time constant) or one or more regression methods. In addition to displaying the numerical value of the time constant, each results function also plots the theoretical response on the data graph for comparison purposes. With the percent change solution, shown in Figure 4, the theoretical response is plotted as a dotted line, and a circle is plotted to represent the point at $t = \tau$. A horizontal dashed line shows the *y* value of the 63.2% change, and a solid line (too small to see well in this case) connects the two data points where the linear interpolation was performed to find the point marked as the circle.

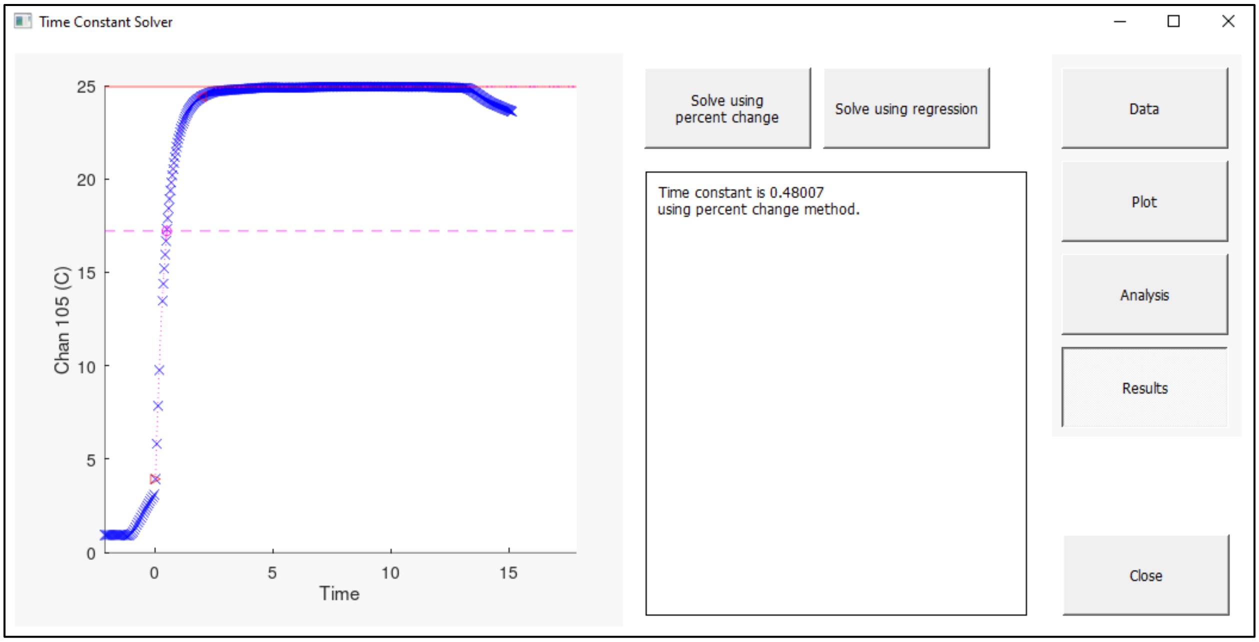

Figure 4: Results Mode with percent change solution shown.

The regression solutions are shown in Figure 5. This version of the TC Tool uses three regressions, labeled regression curve methods 1 through 3 in the figure. The motivation for three different regression methods was to give students options on how many regression values were constrained. In method 1, the *y* intercept and the *y* asymptote are constrained. In method 2, only the *y* intercept is constrained, and in method 3, neither value is constrained in the regression.

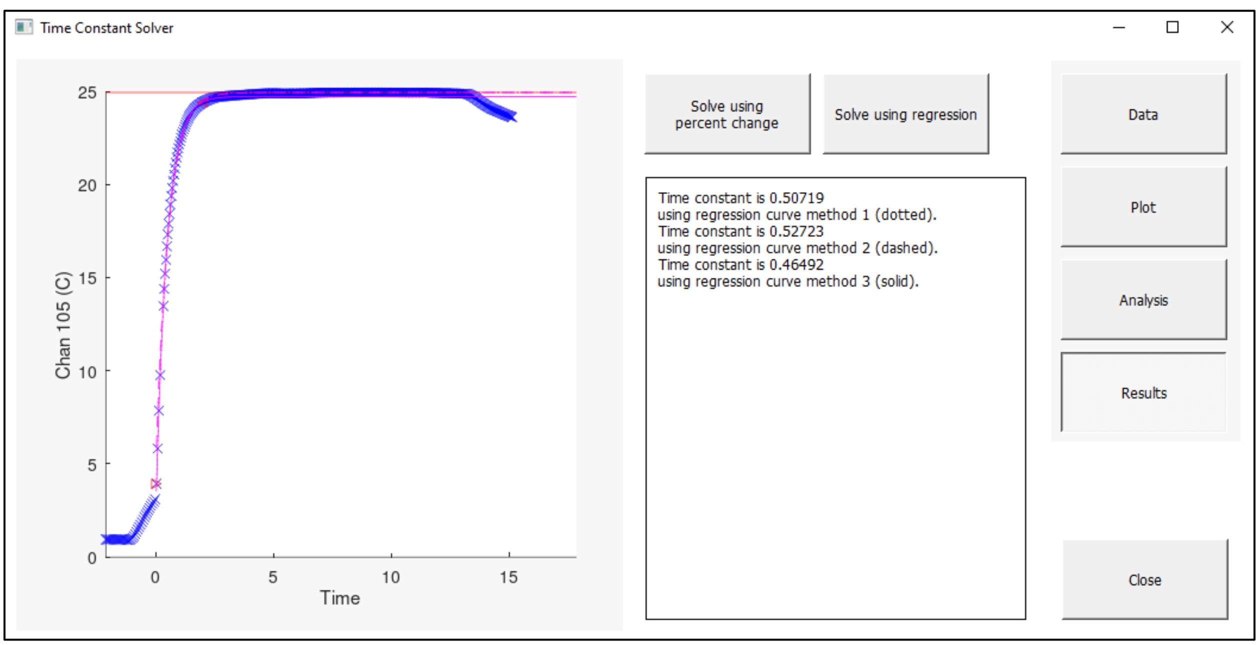

Figure 5: Results Mode with regression solutions shown

Mathematically, methods 1 and 2 are linearized regressions. The linearization process requires a known *y* asymptote, so that value must be constrained for both methods. In method 1, the *y* value of the user-selected $t = 0$ data point is fixed as the *y* intercept, whereas in method 2 the *y* intercept is not constrained, and is found instead as an output of the regression. Method 3 is an iterative regression method without linearization, and is not constrained by either the user-selected *y* intercept or *y* asymptote. However, as an iterative method it requires seeding with an initial guess. It uses the solution of the percent change method for this purpose, meaning that the user selected limits can still influence the method 3 results even if they do not constitute explicit constraints.

For the example data analyzed in Figure 4 and Figure 5, the percent change and the three regression methods give similar values for the time constant, with about a 13% difference between the smallest and largest calculated time constants. Visually, the theoretical curves all seem to match reasonably well with the experimental data, indicating further confidence both in the calculated time constants, and in the lumped capacitance model. In less ideal cases (such as noisy data, poor user choices, or data that does not correspond well to the lumped capacitance model), the time constant results can differ much more significantly.

Comparison of Analysis Methods:

Since the mathematics do not change, the accuracy of time constant calculations is theoretically unchanged whether using Excel or the TC Tool. Excluding user errors, then, the main differentiator of the two options is time. The author timed himself performing the analyses using three different methods, with results shown in Table 1. Excel LTSC refers to Microsoft Office LTSC Professional Plus 2021 installed on a desktop computer, and Excel 365 means Microsoft Office 365 accessed online through a web browser. For the Excel cases, the author created notes and performed each task several times, recording the shortest value as being most representative of a proficient user. Having already used the TC Tool extensively due to its recent development, the author needed to use it only once to get representative time values.

Table 1: Estimated time required for a proficient user to perform analysis operations.

Step Description	*Time (s)*		
	Excel LTSC	*Excel 365*	*TC Tool*
Convert time data to seconds	38	42	0
Create plot	29	49	0
Set zero/max times, remove other data	59	116	15
Find time constant using percent change method	104	91	8
Manipulate data for regression calculation	87	68	0
Find time constant using linearized regression (with constrained intercept)	39	45	6
Find time constant using iterative regression	N/A	N/A	0
Total Time (s)	*356*	*411*	*29*

In this analysis, it was assumed that the data file had already been opened in the relevant application before timing commenced. Note also that the 6 seconds required to perform linearized regression using the TC Tool include re-selecting the data points to be analyzed, which would often be unnecessary in practice, depending on what was selected for the percent change method. Finally, the iterative regression was performed only with the TC Tool, which required negligible additional time once the linearized regression was set up.

Based on the author's tests, the TC Tool is shown to significantly reduce the amount of time needed to calculate time constants. Considering analysis alone, using Excel takes 12 or more times as long to analyze a data set than using the TC Tool. If one assumes 60s of additional time is needed to collect a set of experimental data, a proficient user can collect and analyze about 4 to 5 data sets with the Tool in the time it takes to analyze one data set using Excel. (In practice, one student might be analyzing data while another collects additional data sets, thus increasing the advantage of the TC Tool.) Based on the author's estimation and experiences, the relative benefit of the TC Tool to the non-proficient user (*i.e.*, students performing the experiment for the first time) will be even greater.

Implementation:

The TC Tool was introduced into the time constant experiment in 2024. In addition to instructions for the experiment, student materials included a software operation manual and information about how the various regressions were performed. Based on the expectation of significantly less time being spent calculating time constants, students were directed to collect and analyze many more data sets than was previous required, and to newly perform various statistical analyses with these larger data sets. First, they were directed to find the uncertainty of each time constant based on a statistical confidence interval. They were also instructed to perform statistical hypothesis tests to answer such questions as whether two different sensors had (statistically significant) different time constants, or whether one sensor had a different time constants when tested at different temperatures. In addition to these prescribed analyses, students were also asked to develop and test a hypothesis stating that changing some aspect of their procedure or data analysis would produce a (statistically significant) change in either the measured time constant, or in the measured variance of the time constant. (This extra hypothesis was also required to be unique for each group in a given lab section.) This directly and meaningfully addresses the course catalog's "identification of experimental objectives" outcome, as the students must generate an additional objective for their experiment. This also addresses the Models objective (among others) from the Fundamental Objectives, since many of the possible hypotheses students could make would stem from an understanding of the physical phenomena involved in the experiment which are not fully considered in the initial lumped capacitance model. Relatedly, other possible hypotheses could explore how well a given regression model (and the subset of data that is analyzed) represents the experimental data.

When considering Bloom's Taxonomy, the introduction of TC Tool (and associated changes in the experiment) facilitated lines of inquiry on various cognitive levels. These might be asked informally during the laboratory period, or as a question which must be answered in their reports. For instance, the following questions might correspond to the Remember/Understand levels:

- Explain the different regions of the data plot and what is happening in each.
- Show where the zero time point should be on the plot, and explain why it is there.

The consideration of these questions was previously possible, but it is significantly facilitated by the automatic timestamp conversion and graphing of the data sets with the TC Tool. At the Apply/Analyze levels, prompts might include:

- Use statistics to find the time constant for one sensor under certain conditions, including a range of uncertainty.
- Is there a statistically significant difference between the time constants of {two different types of sensors; two sensors of the same type; a welded and a soldered thermocouple; a single sensor under two different conditions; *etc*.}? What might cause them to be different?

In these cases, the ability to quickly calculate many time constants using the TC Tool is imperative. The second point includes a few examples of hypotheses that students might test as part of identifying an experimental objective, discussed above. Finally, at the Analyze/Evaluate levels, prompts might be:

- Determine which regression method (or the percent change method) is best for calculating time constants, and explain why.
- Considering only the portion of your data that looks approximately exponential, what is the best subset of that data to analyze when determining the time constant? Explain why.
- Does any of your data deviate from the theoretical lumped capacitance response? Explain what might cause this, including supporting reasoning/evidence related to your own data sets.

In these cases, the inclusion of regression analyses and the automatic plotting of one or more theoretical curves with the students' data gives the students visual clues to help them to determine how well their data matches theory. If the tool is modified in the future to also report the coefficient of determination for regressions, that may help students answer these questions more quantitatively.

Results:

Based on the author's observations, the TC Tool was successful in significantly reducing both regression analysis time and errors. While students initially made many of the same analysis mistakes as before, most such mistakes were observed and explained by the instructor or teaching assistant during the laboratory period (due to the analysis time reduction). As a result, students also corrected their mistakes during the laboratory period, and thus presented time constants in their reports that were mostly in the expected range of values.

Results for the new statistical analyses were more mixed. Many students either performed statistical analyses incorrectly, or performed a different analysis than was intended by the instructor. It is expected that instructional improvements can largely address both issues. Students also had varying amounts of difficulty in identifying a new hypothesis to test, but helpful discussions with the instructor eventually resulted in every group finding a suitable hypothesis.

Future Work:

Thus far, the TC Tool and other experiment changes described herein have been implemented for one cohort of students. The author has identified some potential software improvements to make, including user interface improvements (*e.g.*, customizable font sizes to accommodate different screen resolutions) and various changes to the solution methods (possibly including giving students more options with the regressions, providing a coefficient of determination, and automatically correcting certain invalid analysis choices the user can make).

Some improvement in instruction and instructional materials is warranted. Lab handouts and software documentation will be modified to avoid some misunderstandings that students had the first time. More in-depth statistical instruction and analysis will also be included throughout the lab course (a change that was already planned, along with corresponding modifications to other experiments), which will give students a better background for implementing the necessary statistical tests in this experiment.

Finally, as this and other changes are completed in the lab course, a regular student feedback mechanism is planned. While many details must still be decided, it is hoped that a survey can be developed to help measure the effectiveness and relevance of the lab course and of each experiment over the long term.

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