# 2006-627: DEVELOPMENT OF A VIRTUAL REFRIGERATION APPARATUS TO PROMOTE UNDERSTANDING OF THE ACTUAL EXPERIMENT

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# Development of a Virtual Refrigeration Apparatus to Promote Understanding of the Actual Experiment

**Abstract**

A numerical simulation of an existing vapor compression refrigeration experiment has been created. This simulation can be used prior to lab to familiarize students with both the equipment and the phenomena. The fidelity of the interface toward duplicating the actual controls is intended to give students a basic understanding of how to operate the equipment when they arrive at lab. The modeled equations are intended to represent actual system variables allowing students to explore various behaviors of the system without having to worry about safety issues or harm to the system. This paper will describe how the program has been created within the LabVIEW environment. The assumptions which are employed and those which are allowed to be violated will be detailed as well as the resulting governing equations. Current performance of the "virtual refrigerator" will be discussed as well as the challenges in creating such a program.

## I. Introduction

Students in Mechanical Engineering often are required to take several experimentation courses covering the breadth of the curriculum. The experiments related to the thermal-fluid sciences generally include topics related to thermodynamic cycles and energy use. These experiments can encompass very non-linear and coupled phenomena. Subsequently, they can often be very time consuming to perform and difficult for the students to initially grasp. One such experiment is the study of a vapor compression refrigeration cycle. Adjusting one cycle parameter often induces changes in several others. It is common for students to operate the cycle in a way which violates standard cycle assumptions or which can create safety hazards.

For a laboratory instructor this creates three problems. First, students will take longer to perform the experiment as they struggle with the equipment. Second, students and equipment may be put at risk. Third, student comprehension and educational impact is reduced. To address these issues the LabVIEW software package has been used to create a virtual representation of a basic refrigeration experiment for use as a pre-lab exercise. This form of simulation has become more widely used as virtual experimentation has come of age[1,2].

This paper will describe the programming structure and such key components as thermodynamic property calculation. The assumptions that are employed and those that are not enforced will be detailed as well as the resulting governing equations. Methods of incorporating these into LabVIEW will be highlighted. The current version of the software does not meet all of the expectations. Therefore, plans for future modifications will be detailed and justified.

## II. Description of Refrigeration Experiment

The refrigeration apparatus under study (Figure 1) was designed and manufactured in 2003 as part of an ASHRAE funded Senior Design Project. The system uses a typical vapor compression cycle with R-134a as the refrigerant. For the compressor, a Seltec TM-08 unit was used. This compressor is commonly used in automotive applications.  It is powered by a 3 hp three-phase electric motor that is operated by a frequency controller.  Trunion bearings support the motor, which is connected to a load cell for measuring the torque applied to the compressor.  Heat rejection is accomplished through a coaxial condenser manufactured by Edwards Engineering. Cold water from the building supply serves to carry the heat away.  A Swagelok valve is used to throttle the process, thus controlling the refrigerant flowrate.  To simulate a refrigeration load, the evaporator is connected to an electric heater powered by a Variac power source.  For instrumentation, pressure transducers and thermocouples provide property data for all key state points.  Digital displays for pressure and temperature indicate a single value that is selected by user knobs.  The refrigerant and water flowrates are measured with in-line rotameters.  Digital

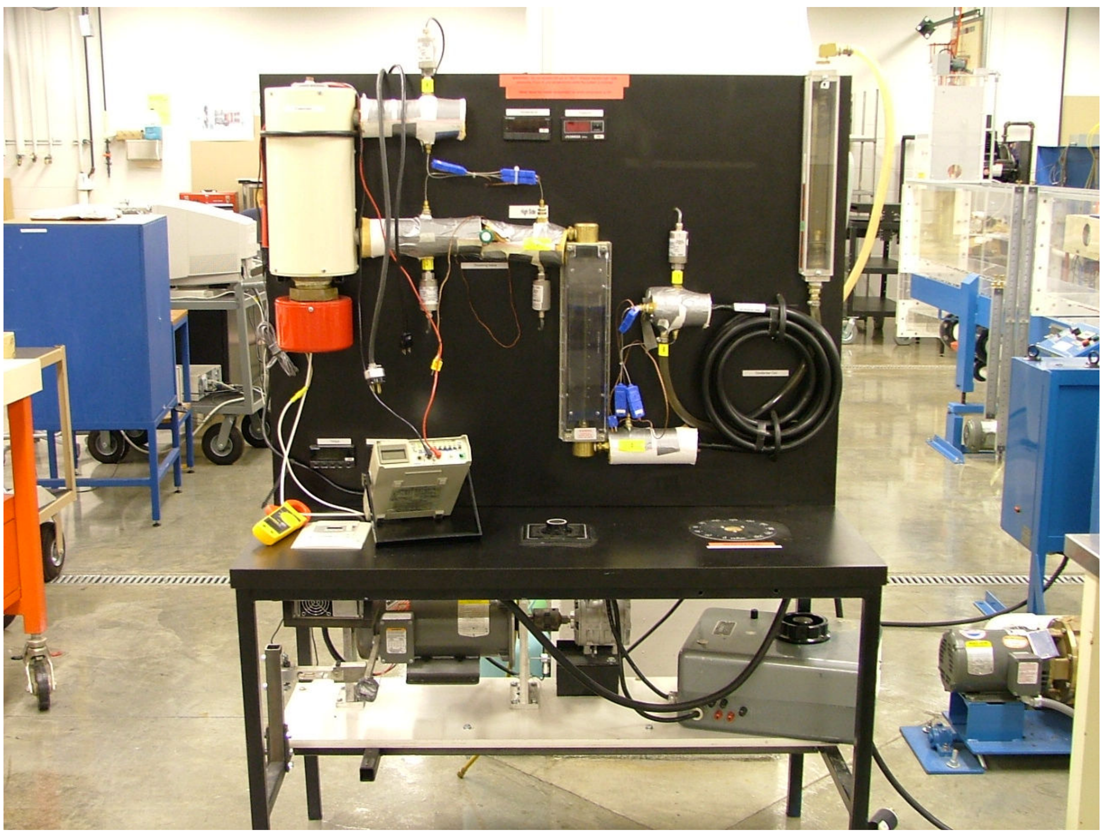

Figure 1:  Refrigeration experiment equipment.  The evaporator is located on the left and the compressor and Variac are located underneath.

displays indicate the motor RPM and the load cell measured force.  Finally, handheld multimeters are used to measure the voltage and current from the Variac.

This refrigeration apparatus gives students hands-on exposure to thermodynamic systems and an opportunity to experiment with theoretical topics from thermodynamics courses.  There are several drawbacks to this experience, however.  The system consists of several non-linear interactions.  Changing one variable often affects several others in a transient manner.  Students must, therefore, take time to learn to use the equipment properly before performing an experiment and taking data.  This limits the laboratory time available for assignments and student exploration. There are also safety issues. Improper use of the equipment can result in the potential for equipment and/or student harm. Primarily this comes through the possibility of over pressurizing the evaporator. If insufficient heat is being removed from the refrigerant the evaporator acts as a pressure vessel and poses an explosion hazard. An additional problem is the potential for violation of standard assumptions. If the rate of heat addition to the evaporator is too low then the refrigerant will not be completely vaporized. This causes a potential equipment problem as a two-phase refrigerant may be entering the compressor. Liquid may alternatively pool at the bottom of the evaporator thus adding an additional uncertainty to the refrigerant flowrate measurement. While this can serve as an excellent learning situation for the students it complicates the resulting data analysis and takes up additional laboratory time. Students can be given parameter ranges for measurement points, however; since the system must be taken through a transition phase between each data point there is still the possibility of encountering several of these problems. Based on a Minnesota State University Presidential Teaching Scholar Fellowship research was conducted by the course instructor to address these issues.

## III. The Virtual Experimentation Concept

Based on previous work for a Course, Curriculum, and Laboratory Improvement (CCLI) grant[3,4] the idea of creating a virtual experiment that simulated the in-lab experience was generated. It was determined that this simulation software could be used in a pre-lab format outside of the classroom to prepare students to conduct the laboratory. If the equipment controls and operation could be simulated realistically enough students could learn to operate the equipment prior to lab and thus perform the experiment quicker. This would also offer them greater freedom to perform independent exploration of the phenomena present, in preparation for the laboratory or afterwards to help explain data that was recorded. It should be noted that the simulation was not intended to replace the actual experiment but to improve its pedagogical efficiency.

The simulations were created in the programming environment of LabVIEW, produced by National Instruments. LabVIEW is an industry standard software package for data acquisition and instrument control. It is well known for its easy modular programming structure and the ability to create realistic user interfaces that look and operate just as an actual instrument would. In other words, input and output comes through images of knobs, dials, switches, and other common instruments found in industry (Figure 2). These objects can be manipulated with the mouse and function as they would in the real world (knobs turn, switches flip, etc.). By using the modular programming to simulate individual thermodynamic processes (such as turbines, heat exchangers, compressors, pumps, etc.) more complex systems (such as gas turbines, coal power plants, refrigeration systems, etc.) could easily be pieced together simply by point and click techniques. The instructor would then create an appropriate interface, made to look and operate like the actual control panel found in industry and students would use the software to get data similar to the physical equipment.

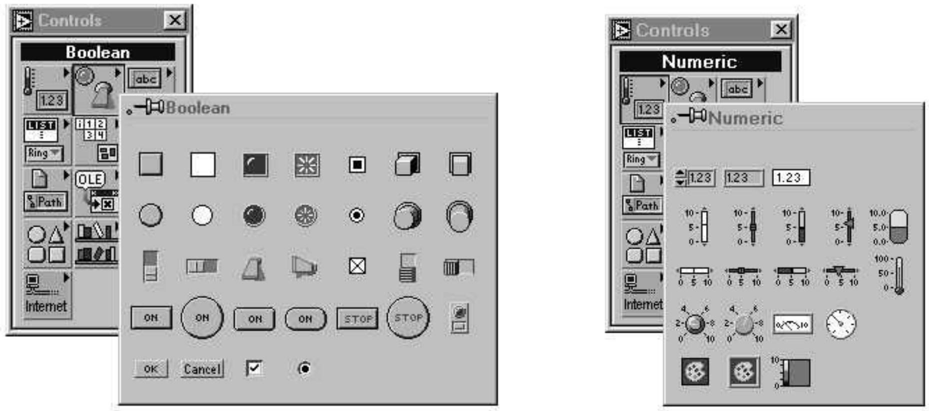


Figure 2: Boolean and numeric controls and indicators used with LabVIEW.

The objectives for the refrigeration software were defined as:

1. Mimic the appearance and physical operation of all user controls and indicators.
2. Provide realistic data in comparison to the physical experiment.
3. Allow the cycle to violate normal assumptions and correct operation of the equipment.
4. Be able to be used through a web page without the full LabVIEW package.

In order to create software which students can access remotely though a web page there are two options; using the LabVIEW Player and creating an executable file with the National Instruments Application Builder. While executable files are generally the preferred method of distribution they lack the dynamic quality of the Player. The Player option from National Instruments allows programs to be executed without the end user needing to purchase a LabVIEW license but rather through downloading a free player program. The Player allows more options for the software to be distributed while still in the development phase and provides the capability for students to view the programming structure behind the software.

## IV. Property Calculation

In order to model any thermodynamic system a method of determining thermodynamic properties, such as enthalpy, must be available. Previous research with LabVIEW programs[5] used property data input in data tables with interpolation routines to calculate specific values. This posed several difficulties, particularly with determinations near the vapor dome on the superheated side. More accurate calculation methods were then researched, however; one drawback of the LabVIEW Player files is that they cannot call external code such as dynamic linked libraries (DLLs) or Active X components. This prohibited the majority of property calculation options since they would involve external code. A remaining option was to use the Refprop code developed by the National Institute of Standards and Technology (NIST) for thermodynamic property calculation[6]. When inquiries were made to NIST, however; it was determined that the required licensing fee prohibited this option.

A decision was made to create new equations for property calculation that could be programmed directly in a LabVIEW VI. A polynomial interpolation procedure was used as shown below (Eqns. 1 and 2). First, property data was input from an appropriate source[7] using a desktop scanner and optical character recognition (OCR) software. Initially the data was input to an Excel spreadsheet for formatting. From here the data was copied into Matlab data structures. In the superheated region for each property (represented by Y) linear regression interpolation routines in Matlab were used to generate the polynomial coefficients ($a_i$) in Eqn. 1 for each value of pressure (P). The coefficients were then taken as functions of pressure and fit to Eqn. 2 using the same linear regression techniques. The resulting 16 coefficients (4 for each of 4 $a_i$ coefficients) allow all properties, except pressure, to be computed as polynomial functions of pressure and any other variable. These calculations are easily made in LabVIEW using the built in "Polynomial Evaluation" VIs. For the saturated property data single polynomials as functions of temperature or pressure were generated (similar to Eqn. 1).

$$Y = a_o + a_1 X + a_2 X^2 + a_3 X^3 \quad (1)$$

$$a_i = b_{oi} + b_{1i} P + b_{2i} P^2 + b_{3i} P^3 \quad (2)$$

Currently these fitted equations generate reasonable values in most regions. However, some property combinations result in property errors of 20%. Also, due to the nature of the original data source and the method of coding the interpolations it was not possible to calculate a pressure from other variables in the superheated region. The largest difficulty, however; comes with calculating specific volumes. The interpolation method described above gives very poor results for this property. Therefore, a temporary method of calculation is being used which assumes ideal gas behavior. Using pressure and either specific entropy or enthalpy the temperature is computed. The specific volume is then found from the ideal gas law using pressure and temperature. This appears to offer only minimal additional error beyond the temperature polynomial.

**V. Governing Equations**

The derivation of an appropriate numerical model was complicated by two factors. First, the governing equations need to be written in terms of the variables the students could physically control rather than the variables traditionally used in texts. Second, since the model is intended to reproduce instances of improper equipment use standard assumptions could not be used in the equations. As a first stage the governing equations were developed in a steady state form in order to verify the appropriate physical modeling. The inputs are those values that the student can control in the physical experiment; motor RPM (N), water flowrate ($\dot{m}_W$), throttle valve position ($\%_{throttle}$), and position of the Variac control knob ($\%_{Variac}$). Note that the equations that follow do not include conversions between specific unit formats, r and w subscripts refer to the refrigerant and water respectively, and all enthalpy values (h) refer to the refrigerant.

The compressor was modeled as a reciprocating unit. The mass flowrate must be determined using the rotational speed as a user input (Eqn. 3) where V is the total displacement volume and $\eta_v$ is the volumetric efficiency. To date, complete manufacturer data for the compressor has not been located. Therefore, the displacement volume and volumetric efficiency were combined into one value and a curve fit was performed using existing experimental data. The exiting pressure is then determined as a function of the mass flowrate (Eqn. 4) as determined from experimental data. The justification for using this functional relation does not come from thermodynamics theory but from the fact this gave better numerical performance and results for the cycle solution. Entropy of the inlet state is calculated and used with an isentropic efficiency ($\eta_s$) specified in the program to find the exiting enthalpy (Eqn. 5). The inlet and exit enthalpies are then used to solve for the torque (Eqn. 6) and the exit temperature is computed from the exit pressure and enthalpy.

$$\dot{m} = \left(\frac{V}{\eta_v}\right)\left(\frac{N}{\upsilon_{inlet}}\right)\left(\frac{1}{60}\right) \tag{3}$$

$$P_{outlet} = 422.39\,\dot{m}_r^{-0.2875} \tag{4}$$

$$h_{exit} = h_{inlet} - \eta_s\left(h_{inlet} - h_{exit,s}\right) \tag{5}$$

$$Torque = \dot{m}_r\left(h_{inlet} - h_{exit}\right)\left(\frac{1}{N}\right)\left(\frac{60}{2\pi}\right) \tag{6}$$

The pressure loss through the condenser was specified at a constant value and the exit pressure was found by subtracting the loss from the inlet pressure. In the actual condenser there is a possibility for the refrigerant exiting to still be superheated, saturated, or liquid. At this stage it was assumed that the exit enthalpy of the refrigerant could be calculated as the saturated liquid enthalpy at the exit pressure. Based on visual inspection of the refrigerant in the flowmeter vapor exits the condenser during a brief startup period only. Exit temperature was then found as the saturation temperature at the exit pressure. The exiting water temperature can then be found from an energy balance between the water and the refrigerant (Eqn. 7) where c is the constant specific heat of the liquid water and the water inlet temperature is considered a given constant.

$$T_{w,exit} = \left(\frac{\dot{m}_r}{c\,\dot{m}_w}\right)\left(h_{inlet} - h_{exit}\right) + T_{w,inlet} \tag{7}$$

Pressure loss due to the throttle valve is found by multiplying the valve closure ($\%_{throttle}$) by an input change in pressure per %-closed value. A conditional check was included to ensure the pressure does not go below zero. Currently it is assumed that the valve is isenthalpic (constant enthalpy) and that the exit temperature is the saturation temperature at the exit pressure.

There was not an easy way to determine the power out of the Variac as a function of control knob position ($\%_{Variac}$). Therefore, the power delivered ($\dot{Q}_{input}$) is computed from the knob position and a power per % knob position value. The displayed current and voltage are calculated from experimental curve fits as functions of power (Eqns. 8 and 9). The heat loss in the evaporator was defined as a constant value. The evaporator was assumed to be at constant pressure and currently the exit condition was assumed to be saturated or superheated vapor. The exit enthalpy is found from an energy balance on the evaporator (Eqn. 10) and the exiting temperature is then found from a property relation using pressure and enthalpy.

$$i = \left( \frac{Power}{21.201} \right)^{0.5050} \tag{8}$$

$$V = \left( \frac{Power}{0.0440} \right)^{0.4951} \tag{9}$$

$$h_{exit} = \frac{\left( \dot{Q}_{input} - \dot{Q}_{loss} \right)}{\dot{m}_r} + h_{inlet} \tag{10}$$

The thermodynamic cycle is solved for in a successive substitution format. Initial values for inlet pressure and enthalpy to the compressor are specified. Each component is solved for explicitly starting with the compressor. The resulting information is then passed to the next component. When the evaporator calculations are completed the results are passed back to the compressor as an input for the next loop.

## VI. Program Version 0.5

The program was developed as a series of sub-VIs (similar to subroutines). VIs were created for each of the four main components. Component properties and constants, such as inlet water temperature or isentropic efficiency, were set on the front panel of their associated sub-VIs. The successive substitution solution for the system was created by using a While Loop and passing values from one sub-VI to the next within it. Data input or displayed on the main interface was grouped into sets of four clusters. The clusters were then used to connect with the main interface and pass values between loops.

The existing version does serve an important role in evaluating the operation and appearance of the user interface (Figure 3). It was determined that an exact replica of the experimental apparatus was not possible or desirable. Emphasis on operation and appearance of all indicators and controls was the primary concern. As seen in Figure 1 there are a number of minor equipment details that could be included. However, the majority of these were considered extraneous. In addition, including everything on one computer screen at a reasonable size was not possible. A more abstract representation was selected which included enough detail to give the impression of the physical apparatus but not so much as to distract the user. All items on the interface were created using basic LabVIEW icons with simple size or color modifications. While the visual representation could be further refined the level of reproduction possible without refinement is substantial.

The current version of the software is not considered complete. As will be discussed in the following section there are several modifications that will be made. Objectives 2 and 3 are only partially addressed and the finished product has not yet been tested in an online version. The majority of data output from the program compares very well with experimental data. However, there are currently two numerical difficulties. Certain combinations of input variables cause the program outputs to oscillate. Usually one side of the oscillation involves floating point errors (i.e. divide by zero or overflow). Problems of this type are not uncommon when using the successive substitution method. Similarly to the physical experiment some input combinations will result in assumptions being violated. Without the algorithmic structure to handle this, the results tend to become unstable. Generally this occurs near the vapor dome and is promoted by inaccuracies in the property calculations. An additional, and unforeseen, problem was discovered just before the experiment was to be performed. The campus Facilities department conducted routine maintenance on the refrigeration equipment and recharged the R-134a to an apparently different amount. Several of the system curve fits no longer matched and

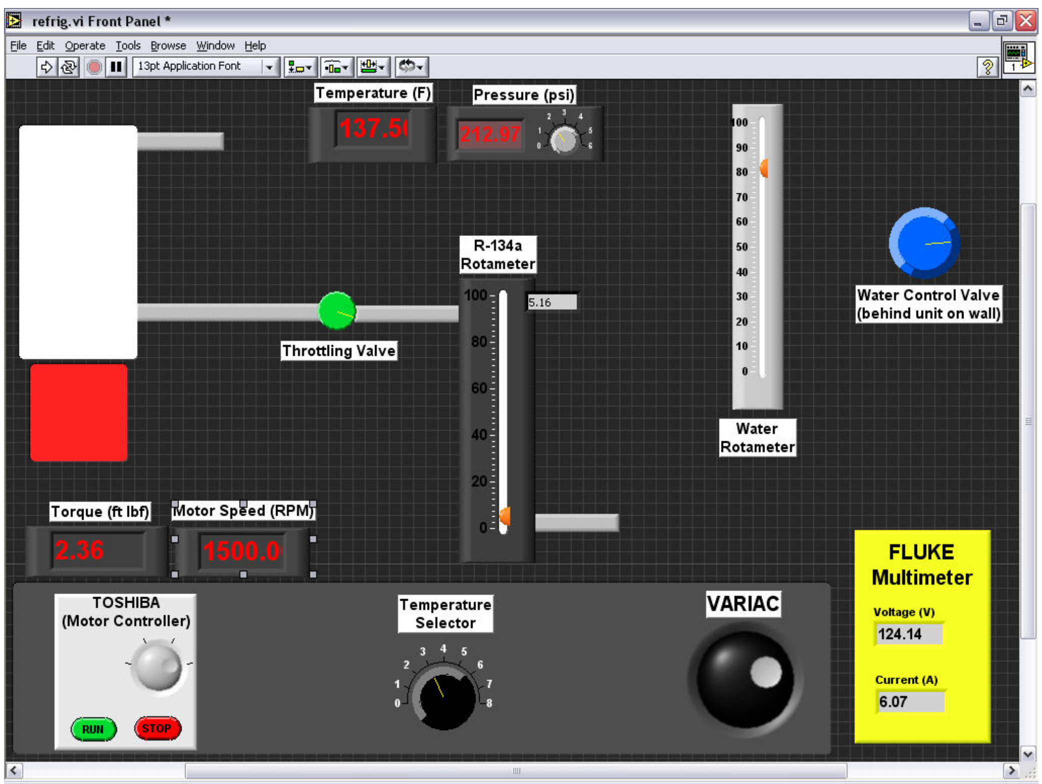


Figure 3: Graphical user interface for the LabVIEW refrigeration simulation Version 0.5.

experimental output values were altered. It was originally intended to test this software with the Fall 2005 course, however; a decision was made not to employ it without further modifications. While the program could be used to reinforce lecture or as a homework assignment in a thermodynamics course it does not have the fidelity required to serve as an effective pre-lab exercise at this time.

## VII. Conclusions and Future Work

This work seeks to address student issues with a refrigeration experiment in the Mechanical Engineering curriculum. The LabVIEW software package has been used to create a virtual representation of the basic refrigeration experiment. This simulation can be used prior to lab to familiarize students with both the equipment and the phenomena. The application is different than simulations used previously in the thermodynamics courses. The fidelity of the interface toward duplicating the actual controls is intended to be high enough that students have a basic understanding of how to operate the equipment when they arrive at lab. The modeled equations are intended to better represent non-standard behavior allowing students to explore various behaviors of the system without having to worry about safety issues or harm to the system. While some numerical issues remain before the software can be fully used by students, the results to date, especially with regards to the interface, have been very positive.

The majority of challenges with this research have arisen due to two factors; realistic modeling and the user inputs necessary. A number of assumptions are inherent in traditional analysis of refrigeration systems. Since these can be violated in this program the algorithms need to allow for numerous alternative solutions procedures. For instance, the ability to handle incomplete phase changes in the evaporator and condenser must be added. The governing equations must also be written in a form that allows for some nonstandard inputs, such as valve position. In order to match the operation of the physical equipment as much as possible a purely theoretical modeling of these issues will not produce the correct results. Future work will concentrate on correcting the above-mentioned problems. Currently two undergraduate students are undertaking research directed toward this goal. One student is performing additional experimental analysis to better characterize compressor performance and system parameters. The second student is refining the property calculation equations and characterizing their uncertainty. The instructor's emphasis is currently on improving the logic structure of the software to allow more options within the governing equations. The next development stage will be to modify all the governing equations to transient formats. This should allow students to use the simulation exactly as they would the real equipment.

Several lessons with regard to virtual experimentation have been obtained. Creating a user interface that gives the same kinesthetic feel as the physical equipment is possible. However, simulating the physical behavior of a system is more difficult than simulating a generic system. Different data and governing equation formats are required. Often theoretical knowledge must be combined with experimental data and some numerical slight of hand. The downside to this is a tendency for the program to be inflexible to changes in the physical equipment that may occur during a semester or from year to year.

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