AC 2009-2140: NONITERATIVE DESIGN OF MULTIPLE EFFECT EVAPORATORS USING EXCEL ADD-INS

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Non-iterative design of multiple effect evaporators using Excel add-ins

Abstract

All undergraduate engineering texts that cover multiple effect evaporation present the solution procedure as necessarily trial-and-error. We present a solution method for multiple effect evaporators that directly solves the nonlinear equations. We do this in Excel by using the solver function and a free add-in that automates steam table look-ups. The solution procedure draws heavily from the degree of freedom analysis taught in the introductory material and energy balances course.

Introduction

Multiple effect evaporation is an industrially important unit operation. It is the foundation of several industries, including, for example, the production of sugar, which had over $6.9 billion in revenues in the United States alone in 2008[1]. Teaching multiple effect evaporation in the junior year of the chemical engineering curriculum reinforces and integrates key topics from the sophomore year such as mass and energy balances, structured problem solving, and steam table calculations. As a side benefit, teaching multiple effect evaporation allows the opportunity to discuss the work of Norbert Rillieux[2], and his role as an inventor, entrepreneur, and engineer of color. However, in spite of multiple effect evaporation being industrially relevant and pedagogically useful, it remains relatively little taught.

Multiple effect evaporation is included in a few unit operations texts[3,4], but it is not covered in chemical engineering heat transfer, separations (with one exception[5]), design, or transport textbooks. However, every text that covers multiple effect evaporation presents the solution procedure as necessarily iterative (a.k.a. trial-and-error). Textbooks published as recently as 2006 continue to perpetuate this trend, despite the fact that with modern tools iterative solutions are no longer necessary.

In our program evaporation is covered in the sixth semester fluid flow and heat transfer class; concurrent with thermodynamics. In this paper, we present a non-iterative method students can use to solve multiple effect evaporator problems using a free add-in for Microsoft Excel.

In a typical multiple effect evaporator homework problem (Figure 1) the feed conditions and flow rate (F) are given. The overall heat transfer coefficients (U_i) are assumed to be known. The desired final concentration (x_1) is specified as well as the pressure (or equivalently, the temperature) of the saturated steam used as the heat source (P_s). Additionally, the pressure in one effect (usually the last) is specified (P_3). The task of the students is to find the amount of steam that must be fed to the first effect (S), the unknown liquid and vapor flow rates (V_1, V_2, V_3, L_1, L_2, L_3), the pressures in the other effects (P_1, P_2), and heat transfer area of each effect (A). Generally the heat transfer areas for all effects are assumed equal. H (h) is the enthalpy of the vapor (liquid) phase with corresponding temperature T_i and latent heat λ_i.

The governing equations are

- a total mass balance on each evaporator, ("effect") in the evaporation train,
- a solute balance on each effect,
- an energy balance on each effect, and
- the heat transfer rate equation for each effect.

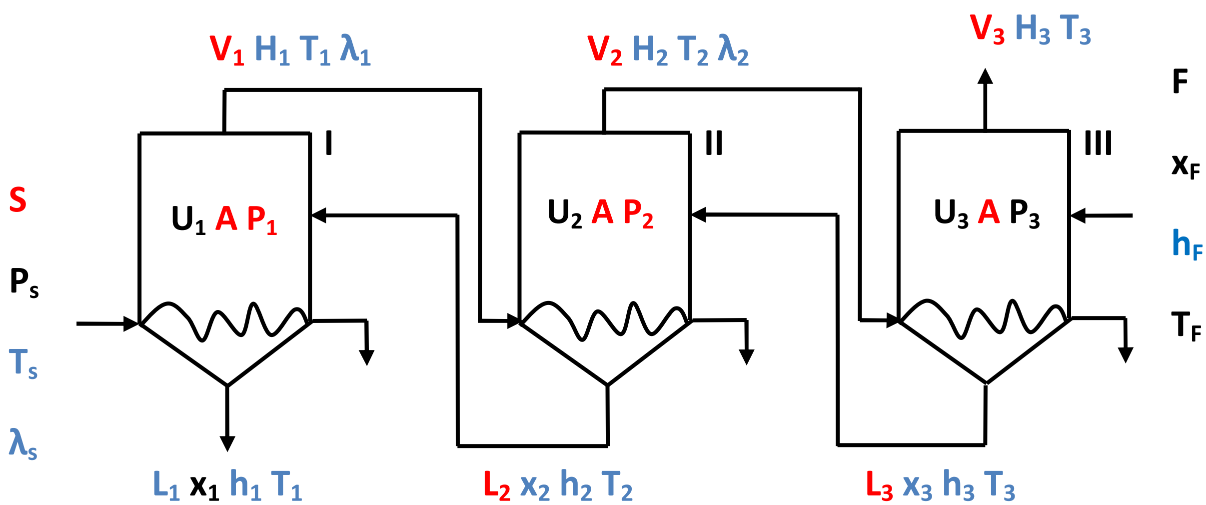

Figure 1. Typical triple effect reverse feed evaporator problem. Known variables are shown in black, guessed variables are red, and variables directly calculated from known or guessed variables are shown in blue.

Several approaches can be used to solve the typical multiple effect evaporator homework problem. All textbooks[3,4,5] that cover evaporation present a pencil-and-paper iterative approach. Although this method works and requires no expensive software, it has a number of limitations. The calculations are quite tedious, especially for larger problems. The method employs some heuristics that, while effective, tend to lead to "equation clutter" and cloud the students' understanding. While some may argue that an iterative approach allows the students to see "what is really going on," the textbook method does not distinguish which equations are physically fundamental and which appear merely because of the solution mechanism's heuristic. Additionally, the derivation of the textbook algorithm is not shown, so to the students it operates as a black box. ("Why do these steps in this particular order? Because the book says so.")

A second approach would be to use a commercial simulator. These include general purpose simulators such as ASPEN, Unisys, HYSYS, or ChemCAD, specialty simulators such as Simprosys or ProcesSimO that are specifically for modeling evaporation and drying, or ERI SYM, a desalinization simulator. In theory, these simulators merge two capabilities: the successive iterative calculations to close material and/or heat balance equations with a set of thermodynamic equilibrium correlations and data that successfully model the physical chemistry of the process. The bookkeeping capabilities of these programs are valuable but not unique. Other programs (e.g., a spreadsheet like Excel) can easily provide the same capabilities for bookkeeping of material and energy balance equations—especially through the trial and error calculations. In practice, most simulators require a substantial amount of data entry and/or entering/fitting of thermodynamic parameters to provide *any* results (let alone meaningful results!). For many of the general purpose simulators support for inorganics and/or biological/agricultural components (e.g., sugars) requires purchasing an additional "higher level" thermodynamics package. The presence in the marketplace of the specialty simulators is indicative of the level of performance of the general purpose simulators.

For students, using a simulator does avoid the tediousness of the iterative method. However, they will still probably invest considerable time entering and adjusting thermodynamic data. Thus, the simulators, when they are not robust for the problem at hand, often just displace the iterative solution method. Moreover, the simulator is an even blacker box for the students than the textbook iterative method. For educational institutions, purchasing licenses for (potentially) additional simulators or simulator packages is expensive, and as we will show below, unnecessary.

The third solution approach is to write the governing equations in matrix form and use a matrix algebra solver to obtain the solution. This approach is outlined in[6] and extended and improved by[7]. This approach has the advantage of presenting evaporation as a "stage-wise" operation and is numerically stable and computationally efficient. The first drawback of this approach is that the solution is slow because the student still has to look up enthalpies from the steam table for each iteration. Secondly, according to the authors, a significant investment of time is needed to train students to be able to rewrite the problem into the matrix format the solvers can handle.

We present a solution method for multiple effect evaporators that directly solves the nonlinear equations. The method builds on our sophomore materials and energy balances course where we teach students to perform a degree of freedom analysis and to use a spreadsheet to solve flow sheet problems**.** Since the students are already comfortable using a spreadsheet to solve a flow sheet problem, using a spreadsheet for a multiple effect evaporator problem is easy.

For a three effect evaporator train (Figure 1) there are 9 unknowns (S, A, P_1, P_2, V_1, V_2, V_3, L_2, L_3). In general for N effects there will be 3N unknowns and 3N equations – namely a mass balance, energy balance, and heat transfer rate equation for each effect; the solute balance having been used already to calculate the x_i's. In principle, these equations should be relatively easy to solve. However, the coefficients in the equations depend on the unknowns through thermodynamic relationships. We address this by using a free add-in for Excel that automates steam table lookups[8]. This allows vapor and liquid enthalpies and the temperature of each effect to be calculated automatically from the other data in the spreadsheet. Now we can use Excel's solver function to find the values of the 9 unknowns. The method is:

1. Create a spreadsheet with a diagram of the process. Fill in as much information as possible.
2. Determine the total amount of vapor produced using an overall mass balance. For an initial guess, make the vapor produced in each effect equal. Using mass and solute balances, determine the liquid product and composition in each effect. These are initial guesses.
3. Set up your spreadsheet to calculate solids mass fraction from the guessed flow rates. Use the guessed pressures and/or solids fractions to calculate boiling point rise, saturation temperatures, and liquid enthalpies.
4. Using the steam table functions, fill in all vapor enthalpies.
5. Create cells for a mass balance, energy balance, and the heat transferred in each effect (3N equations). The equations should be in the form where all the variables are on the left hand side and the right hand side of the equation is equal to zero.
6. Set up Excel's Solver to solve for the unknowns. Add Solver "constraints" that each unknown must be ≥ 0. Add constraints that all mass balance, energy balance, and heat transfer equations must be equal to zero. Your objective function should be to minimize the sum of the squares of the mass balance, energy balance, and heat transferred equations. The solution should converge rapidly.

Students understand the approach easily and tend to have little to no difficulty with implementation since it directly builds on the practices of their sophomore courses (mass and energy balances, spread sheet programming). Multiple effect evaporation is usually taught in one day, with about half of that covering overall ΔT and boiling point rise, and the other half working an example with the spread sheet on the projection screen. This allows us to use a more active, problem-based teaching strategy that focuses more on the characteristic features of multiple effect evaporators that make them interesting and challenging to study, e.g, boiling point rise failure and sensible heat demand failure[6], and less on the mechanics of solving the problem.

Example

The method is illustrated with the following example problem adapted from[3].

A feed containing 2 wt% dissolved organic solids in water is fed to a double effect evaporator with reverse feed at a rate of 1000 lbs/hour. The feed enters at 100 °F and is concentrated to 25 wt% solids. Boiling point rise and heat of solution are both negligible. The effect of the solute on the heat capacity of the liquid solutions may also be considered to be negligible. The second *effect has a pressure in the vapor space of 0.98 psia. The first effect is heated by the condensation of saturated steam at 100 psia. The overall heat transfer coefficients are 500 and 700 btu / hr ft² °F for the first and second effects respectively. What is the heat transfer area needed to accomplish the desired exit concentration?*

As is common in many material and energy balance courses, a spreadsheet is used to solve this multi-unit problem. We use a spreadsheet and its drawing tools to create a diagram and fill in known information (Figure 2).

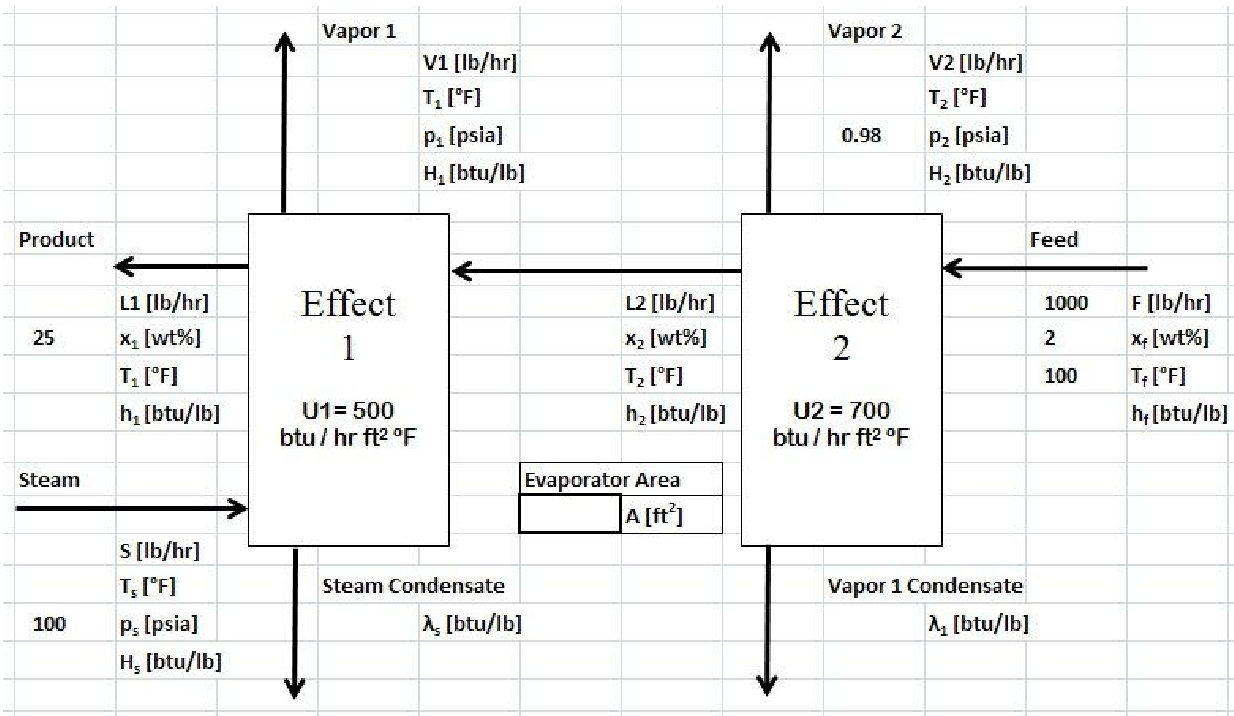

Figure 2. Initial spreadsheet showing process flow diagram with known information from the problem statement filled in.

As is mentioned in[7], mass and energy calculations may be decoupled. We begin the solution of the problem by guessing one vapor flow rate, as shown in Figure 3. Mass and solute balances allow us to calculate the remaining liquid a vapor flows. Here we use the common heuristic that vapor flows are approximately equal from each effect as a first guess (other heuristics would work equally well). The remaining thermodynamic quantities that can be directly calculated are filled in next (the yellow cells in Figure 3). The next step is to guess values for the remaining unknowns (pink cells in Figure 4). These are the heat transfer area (A), the pressure in the first effect (P_1), and the steam feed rate (S). Given a pressure in the first effect we can calculate the heat released by vapor from the first effect condensing in the second effect. Energy balances and heat transfer rates can now be calculated from information in the spreadsheet. By putting the equations in homogeneous form we check for closure of the balance equations (Figure 4). Note that because we have only two effects a mass balance equation is not needed in the sum of squares. The Solver add-in is used to balance equations balance and to give the final solutions as shown in Figure 5.

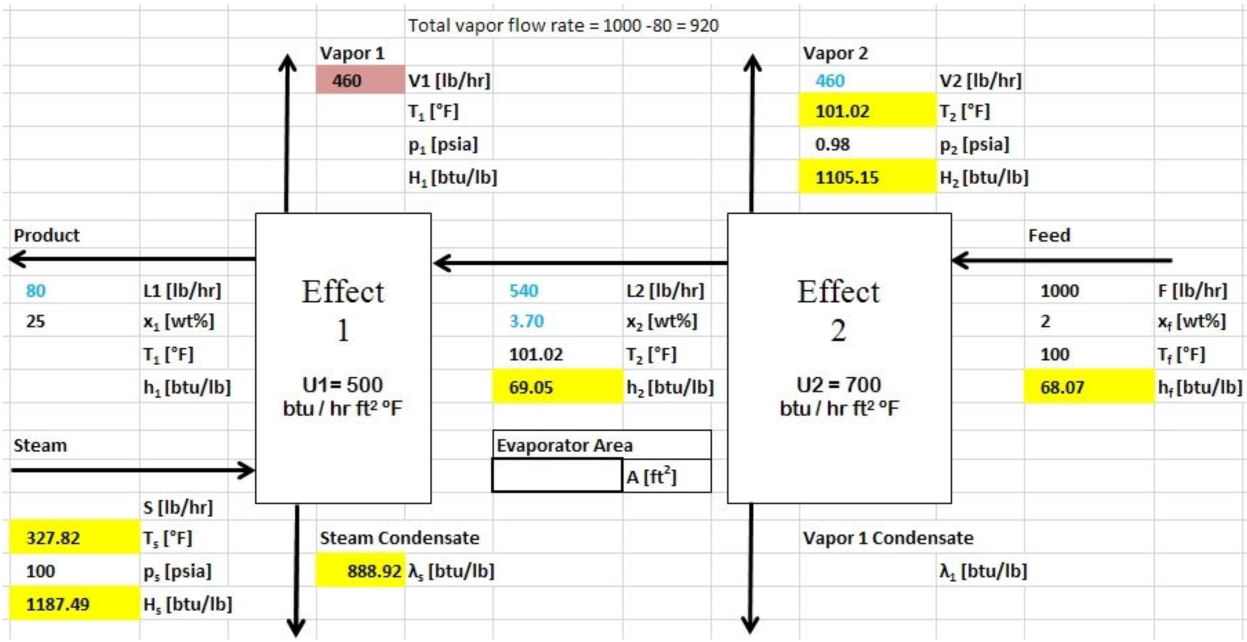

Figure 3. By guessing one vapor flow rate (pink cell) all other mass flow rates and solute concentrations may be calculated directly (blue text). From known temperatures and/or pressures all known thermodynamic data is filled in (yellow cells).

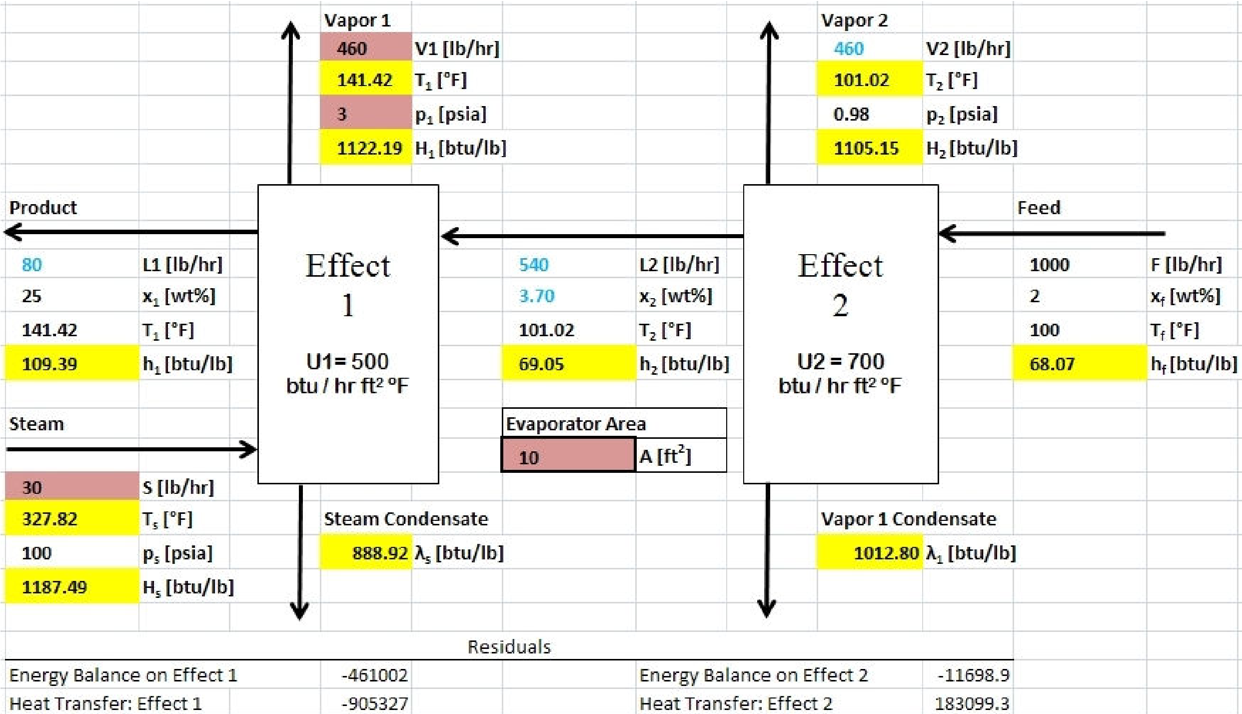

Figure 4. Guesses are filled in for the remaining missing variables (pink cells). Energy balances and heat transfer rates are check for closure.

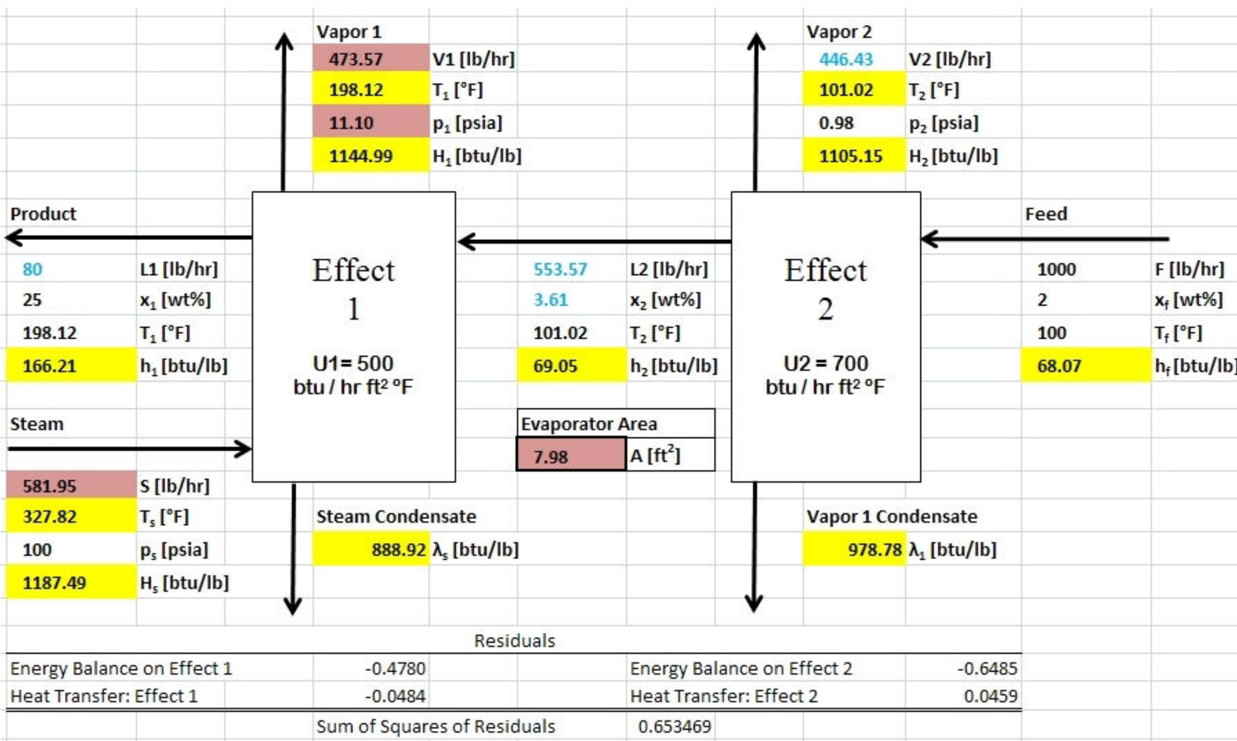

Figure 5. Solver is used to find the unknowns/guessed variables (pink cells).

Concluding Remarks

Hopefully, this paper has inspired you to try a new way of teaching at least one topic in one of your courses.

The solution method outlined in this paper works for multiple effects (even beyond the usual three) and in cases where pressure is unknown, temperature is unknown, or composition or flow rate are unknown. It works for both forward and reverse feed. It handles solutions with boiling point rise and liquid heat capacities that are dependent on solids concentration. Data for sugar solutions is given in[3] and data for sodium hydroxide solutions is given in[7]. The method itself is generally applicable but the free add-in only works for systems where water is the solvent (as the only automated look-ups for Excel are the steam table functions). However, the same method could be implemented with other software (such as Aspen Properties) that has thermodynamics for other solvents in a straightforward manner.

With different instructors teaching the course different years and class sizes of only five to eight students we unfortunately do not have any reliable measures of whether teaching the non-iterative spreadsheet way improved student learning. Anecdotally, students seem to prefer the non-iterative way as it is more intuitive and they are very comfortable working with Excel. Students have an automatic negative reaction to anything perceived as "old fashioned" such as the pencil-and-paper iteration. When teaching the textbook method, one instructor spent several class periods showing the iteration method for one multiple effect evaporator example problem. The students then spent an average of 4+ hours working out one homework problem with three effects. Afterwards, several students came to office hours and asked not to be given any problems with more than three effects.

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