
AC 2011-1662: THE FIRST COURSE CHE STUDENT: LOST IN TRANSLATION

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The First CHE Course Student: Lost in Translation ?

Introduction

My first year graduate training at Northwestern University included a linear algebra course, lovingly taught at 8 am, winter quarter, by a professor of mathematics. The early morning walk from the Engineering north parking lot to the southern Mathematics building led me to sit in the back row of the small class auditorium, with my nearly frozen head laid back against the steam radiator under the window. Looking down on the master of ceremonies performing his routine for the sleepy audience, I was surprised one day when he turned from the board to the audience and announced: “You should think about linear algebra as a three ring circus. Whenever you are given a problem, you should visualize not one or two, but three approaches to seeing, and solving, the problem.”

We take this academic pulpit preaching as a metaphor for the typical process statement in a chemical engineering first course. Each fully worked problem typically contains a **verbal** statement, requires construction of a **visual** process flow diagram, and ultimately leads to an **analytic** (mathematical) formulation which allows for solution. The engineering student solving a problem is eventually required to understand and express this problem in all three “circus rings” or universes: verbal, visual, and analytic. ***The thesis of this paper is that challenges to solving such flow sheet problems derive in part from difficulties in translation between these worlds.***

Introductory engineering courses typically occur in the first semester of the sophomore year. Historically, the attrition rate in such offerings is substantial. In chemical engineering, it is not uncommon for students who have done well in freshman year to struggle with their first chemical engineering course: mass and energy balances (MEBs). This difficulty is curious, as the course is based largely on concepts first encountered in high school chemistry (conservation of elemental mass, stoichiometry) and first year physics (conservation of energy).

The central intellectual activity for our MEB course, using the now classic text¹ by Richard Felder and Ron Rousseau (F & R), is reading problem statements, creating process flowsheets and solving the associated algebraic equations which result. The general solution approach is efficiently described as a series of steps, each carefully delineated to ensure creation of future needed information in a logical sequence. An example sequence for an isothermal process appears in Table 1 (next page), from FR, pp 101-102 (3rd ed).

The process of executing Table 1 steps 1-11 in proper sequence represents a level of solution complexity not previously encountered in high school or first year science and

mathematics courses. It is at first a bit intimidating, and the interconnectedness of steps requires a strict sequence approach, without which hazards abound.

Table 1
Sequence of operations to solve process balances (F & R)¹

Step:	0.	Read the problem statement
	1.	Chose a mass basis: flow rate (continuous) or amount (batch)
	2.	Draw a flowchart
	3.	Fill in values of known variables (mass rate, composition)
	4.	Label unknown stream variables (e.g., m_i , x_i)
	5.	Express what problem asks for in terms of labeled variables
	6.	(Convert all values to consistent units)
	7.	Do Degree of Freedom (DOF) analysis to determine number of equations (mass and energy balances, other constraints), n_R , and number of unknowns, n_U . Calculate $DOF = n_U - n_R$
	8.	If $n_U - n_R = 0$, write out all equations, in order which allows easiest solutions path (single variables first, simultaneous equations later). (If $n_U - n_R > 0$, further specification is needed before an unique solution is possible; if $n_U - n_R < 0$, problem is overspecified and must be reformulated)
	9.	Solve all equations
	10.	Calculate any other required variables not present in mass and energy balances (e.g., selectivity , volumetric flow rate, etc.)
	11.	Rescale process to new basis, if requested.

We propose an alternate view of the problem-solution universe vs. that explicitly identified above. Its structure suggests potential difficult areas for the student by reconsidering the specific mental processes involved in several steps. In the broadest sense, the vocabularies in which the problem –solution universe is represented are three: verbal, visual, and analytic. The problem may be fully represented in each individual realm, yet steps 1-11 above involve the student in all three. In particular, steps 0 and 1 are verbal, steps 2-3-4 are visual (flow sheet) , and steps 5-11 are mathematical (analytic).

We represent these three universes below:

Verbal (steps 0-1)=====> Visual (steps 2-4) =====> Analytic (steps 5-11).
(translation) (translation)

and connect them by arrows to indicate information flow. Since these worlds utilize different vocabularies, the passage of information between them represents acts of translation

Each domain contains, explicitly or implicitly, the same information. The principles involved, conservation of mass and/or energy, do not care whether they find expression in verbal, visual, or mathematical forms, as the earlier die example illustrated. The solution sequence is stated empirically, but achieves its useful form because it uses the respective advantages of each universe at the appropriate times:

1. The problem statement is a verbal representation which allows for problem delineation accessible to the broadest audience, and global or specific quantities may be conveniently stated.
2. The flow sheet is a simple, visual representation of the actual process which will achieve some desired task.
3. The analysis uses a mathematical representation to ascertain if the verbal problem was well poised (solvable) and if so, to determine values of the desired, but unknown, variables.

Example illustration

Consider the orange juice concentrate flowsheet below. The solution procedure outlined by F & R indicates communication between the three universes in the sequence:

Verbal → Visual → Analytic

Finding all flow rates for this multiple unit operation chemical process requires steps expressed in three different vocabularies, as the following Table 2 summary indicates.

Example 1: Orange juice concentrate(after F&R¹, pp166-167)

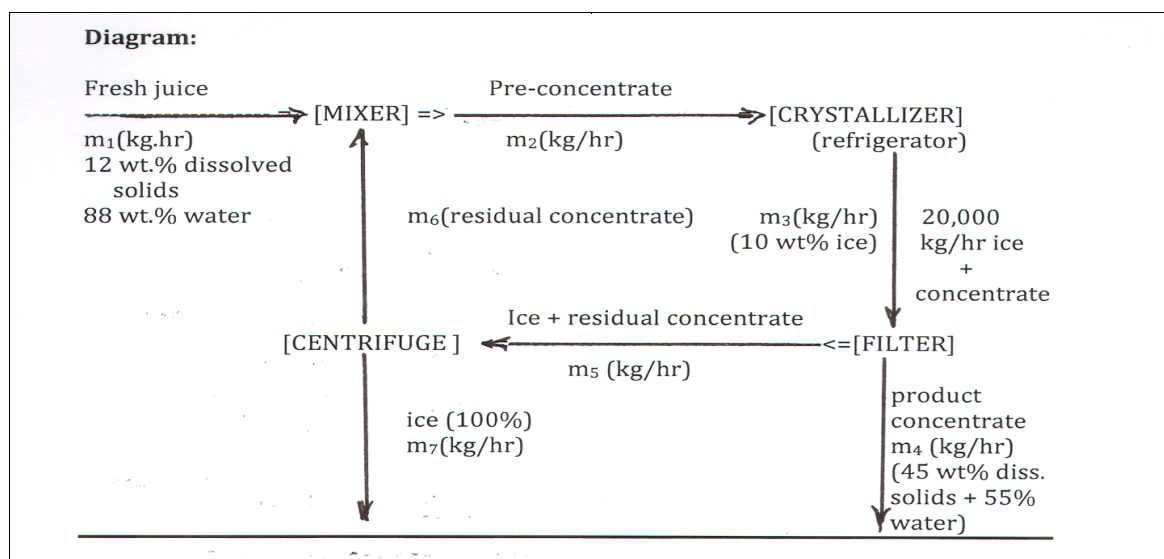


Table 2
Vocabularies for Orange Juice Concentrate Process

Universe	Variables	Vocabularies
Verbal Statement	Stream & rates	Words (stream labels): fresh juice, product concentrate, ice crystals, pre-concentrate, concentrate recycle, filtrate
	Unit Operations:	Words (device labels): mixer, refrigerator, filter, centrifuge
Visual Statement (flowsheet)	Stream directions & connections	Arrows (→)
	Unit Operations	Geometric figures: (boxes, figures, pictures)
Mathematical Statement	Stream rates, compositions	Symbols: m_1, \dots, m_i x_1, \dots, x_i
	Unit Operations	Balance equations for mass and energy conservation
	Other constraints	Equations for phase equilibria, maximum temperature, selectivity, etc.

These three worlds utilize differing vocabularies. The process of moving from one world vocabulary to another is a process of translation. That such translation might provide difficulties for some students is evident from considering student learning types as well as human physiology and neuroscience. The verbal and analytic domains of activity favor the verbal type: written and spoken words and formulas, while the process flow diagram favors the visual type (pictures, diagrams, graphs, demonstrations). The proposed FR problem solution technique marches the student from verbal through visual to analytic representation. If the student has a substantial weakness in translation between domains, this first process engineering course will be more challenging than prior courses. Said differently, the student's 11 step chain for problem solution is complete, but may suffer the classic fault: "A chain is only as strong as its weakest link."

Generalizations of the issue

Verbal problem statements, creation of flowsheets, and corresponding analytical models are common exercises used in many engineering disciplines, as the examples below indicate:

Chemical process flow: mass, energy flows (chemical, mechanical engineering)
Electron flow (electrical engineering)
Traffic flow (civil engineering)
Work flow (industrial engineering)

Thus if student translation problems exist in one engineering discipline, they are likely to be identifiable in others as well.

Art of representation

Perhaps we can learn from study of another language, music, discussed by David Levitan in his recent book *The World in Six Songs*². He argues that music was invented in man's dawn as a logical result of brain developments which gave humans "three cognitive abilities that characterize the musical brain. The first is perspective-taking: the ability to think about our own thoughts and to realize that other people may have thoughts or beliefs that differ from our own. The second is representation: the ability to think about things that aren't right-there-in-front-of-us. The third is rearrangement: the ability to combine, recombine, and impose hierarchical order on elements in the world. The combination of these three faculties gave early humans the ability to create their own depictions of the world-painting, drawing, and sculpture-that preserved the essential features of things though not necessarily the distracting details. "

These talents are also found in engineering, where we also create and solve problems which "preserve the essential features of things" through problem statements, process flow sheets, and mathematical representations, all of which represent a thing (actual chemical process) which is not "right there in front of us". Further, the design and optimization of a process often involves "the ability to combine, recombine, and impose hierarchical order on elements of the (chemical process) world".

While representation was evidently an ability developed early, the talent of translating between representations must have come later. How translation works requires an understanding of where these individual worlds-verbal, visual, and analytic-reside and function in the brain.

Whole Brain Model of Learning

From a neurological viewpoint, the conceptualization of the human brain as being compartmentalized became popular, according to Ferguson³, with Maya Pines and others. Her summary report was that "the right side of the brain is the seat of "artistic [and] musical ability [and] spatial perception", while the left side of the brain is the

locus of “language and analytical ability.” This view became popular, though perhaps too simplistic according to psychobiologist Roger Sperry (Ferguson). Nonetheless, this description of the various, non-identical loci of different brain functions suggests that the solution procedure of Table 1 requires information movement in space ,i.e., “translation” from the left side (verbal) to the right side (visual) and back to the left side (analytic).

Herrmann’s opus, *The Creative Brain*⁴, reports results of surveying more than half a million subjects which led him to propose a four quadrant version of brain activities, divided as left vs. right brain, and cerebral vs limbic locations. He presented these results both in verbal form, Table 3⁵ below and graphical(analytic) form, Figure 2. An alternate visual representation⁶, Figure 3, shows a closer analogy to the actual geometry of the human brain. All three represent the brain, an object which “is not there in front of us.” Each representation indicates clearly that the example 11 step problem solution procedure involves lingual and spatial translations within the brain.

Table 3

A General Description of Herrman’s Four-Quadrant Model of Thinking Modes⁵

Examples of Descriptors			
Left-Oriented Descriptors		Right-Oriented Descriptors	
Quadrant A	Quadrant B	Quadrant C	Quadrant D
Factual	Ordered	Musical	Artistic
Logical	Detailed	Spiritual	Holistic
Rational	Sequential	Talkative	Flexible
Theoretical	Controlled	Emotional	Imaginative
Mathematical	Conservative	Empathetic	Synthesizing

Source: Herrmann, Ned, *The Creative Brain*, Brain Books, Lake Lure, NC, 1990.

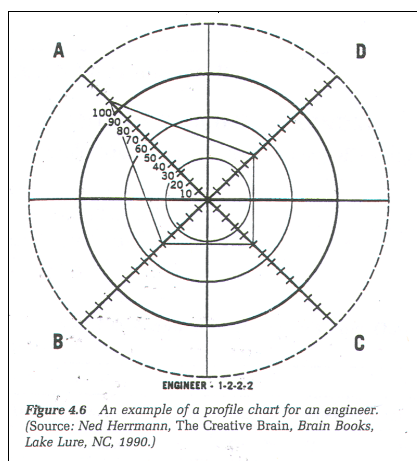
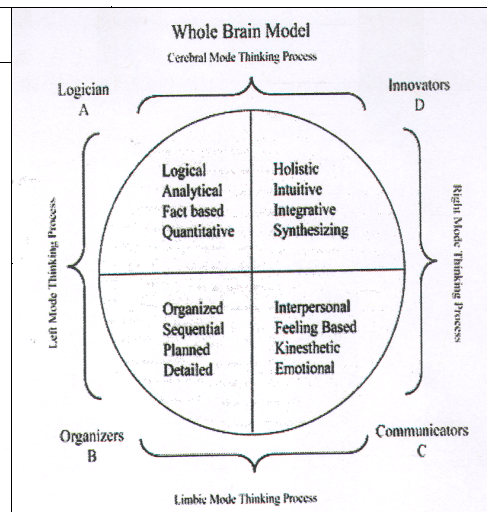


Figure 2 (Wright p. 85)
HBTI Profile chart for an engineer⁵



The Invisible Role of Translation⁷

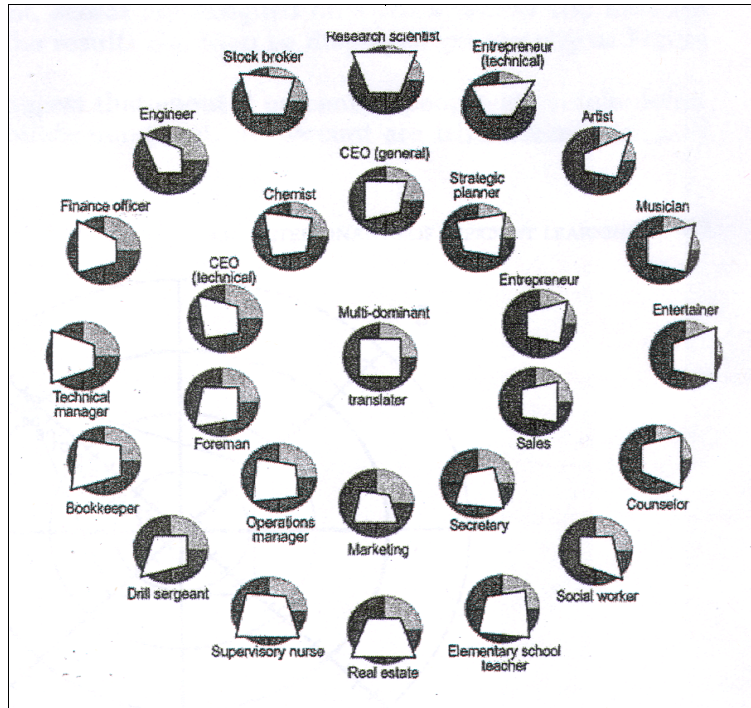


Figure 4 Occupations and their placements in preferential learning quadrants. (Herrman⁷)

A “representative array of occupational profiles” is given later by Herrmann⁷ (1999) on his website, indicating preferential learning quadrants of various professionals. In the middle of this figure appears that of the invisible professional, the “Multi-dominant translator.” The centrality of this translator’s placement strongly suggests an important role, yet this professional is discussed nowhere in Herrmann’s accompanying text, i.e., s/he has been “lost in translation” from diagram into words !

Translation is difficult

Within engineering, translation difficulties abound, as illustrated beautifully by Ferguson in his text, *Engineering and the Mind’s Eye*³. In an historical example of design description, he quotes medieval engineer Guido da Vigevano: “...and when needful (the hinged railings) are stood upright as is made clear and obvious in the illustration because I cannot so well set it forth in words as I see it in my mind’s eye. But the picture will show it.” Guido da Vigevano, 1335. Ferguson, p. 41.)

Working engineers have long understood this translation difficulty. Ferguson notes that “for more than 500 years, engineers have made increasing use of drawings to convey to workers what is in their heads.”

Ferguson cites numerous situations in which the problem statement first appeared in diagrams, then words and equations. For example, “Albert Einstein said that he rarely

thought in words at all; his visual and ‘muscular’ images had to be translated “laboriously” into conventional verbal and mathematical terms” (Ferguson, p. 45). Perhaps, like Einstein, our students find translation of images into verbal and mathematical terms to be laborious as well.

Ferguson also claims a mid-20th century cause for weakness in student visualization abilities. The 1952 Grinter report on engineering education reform argued that “those courses having high vocational and skill content” should be eliminated, as should “those primarily attempting to convey engineering art and practice.” If design originates in the mind’s eye as Ferguson argues and is only subsequently expressed verbally, then more practice in translation from images to words is needed.

The evolution of student competence, from “novice” to “expert” indicates the need for development of translation skills. Wankat and Oreowicz⁸ offer distinctions between novice and expert problem solvers which include the activities under discussion here.(Table 3). These excerpts indicate that the “novice” student has to be taught to translate the verbal problem statement into a visualization (define and draw, sketch, and show motion) as well to increase use of the verbal world (explore, write questions, subvocalize), before attempting quantification in the analytic world. Through this dual path, the student moves towards thinking like an “expert“.

Table 3
Differences between Novice and Expert Problem Solvers
(Excerpted from Wankat and Oreowicz⁸, p. 69.)

Characteristic	Novice	Expert
First step done	Try to calculate	Define and draw Sketch Explore
Sketching	Often not done	Considerable time Abstract principles Show motion
Actions	No clear criteria Inactive Sit and think Quiet	Use paper and pencil Very active Sketch, write question Subvocalize (talk to self)

The involvement of both brain hemispheres is also implicit in discussions of problem solving blocks as well: “Trying to solve a problem without an appropriately drawn figure can be an expressive block.” (Wankat and Oreowicz⁸, p. 75.) The irony of this approach is that we faculty usually first express a problem in words, then demand that the student construct a diagram or figure or sketch. Since visualization appears to be

more primal than verbal discourse, we are presenting the problem in our “second” language, then rephrasing it in our first, apparently in order to gain a more solid ground.

Need for translation practice

We claim that some appreciable portion of problem solving difficulties is attributable to the challenge of translation between verbal, visual, and analytic worlds using their respective vocabularies. If true, then practice in translation could prove useful.

Translation as an activity in problem solving is noted by Diana Laurillard in her book, *Rethinking University Teaching: A Conversational Framework for the Effective use of Learning Technologies*, 2nd ed⁹. She discusses a crystallography lecture, in which a real world object (crystal) is represented three ways: the actual object, a three dimensional sketch, and a diagram derived from a mathematical representation. The response from one student indicates translational difficulties:

“There are so many ways of describing one crystal, it seems illogical. We draw it naturally, the way our eyes see it, then we’re told to draw it in three-dimensional projection to see it that way, Now we’re told to draw it in a circle. Totally illogical. Then we have to see not only how the crystal fits in the circle-and that looks nothing like a crystal to me- we have to see how it works in that diagram by drawing another diagram and another circle....It would be nice if we had one thing now that brought all these planes, this stereographic projection and this [diagram] and tried to relate them all and show exactly how they fitted, in a sort of sequence of events, whereas we’ve been given them totally separately.”⁹

Laurillard observes students who “recognize the need to practice the mapping process between the formalism and the reality it represents. It is not sufficient to follow someone else’s practice. ***For the representation to be intelligible, they need to practice the translation in both directions.(italics added) In doing so, they will begin to see how the abstraction works, which aspects of the reality this perspective attends to, and how it can be generalized beyond specific instances.***”

While Laurillard refers to translations between the real world object and its representation in one form or another, our engineering challenge of the present paper is the translation between three virtual representations, a higher level of abstraction, since the actual process is never “is right there in front of us.”

A Modest Proposal for Translation Practice

Following Laurillard’s suggestion, we propose inclusion of explicit “translation” exercises for the student and professor as well. The following paragraphs offer some illustrations.

1. Verbal => visual (familiar): Physiological processing of food requires the intake of both food and water, the grinding and attrition of food into wetted particles, the acid hydrolysis in the stomach to convert high molecular weight components into low molecular weight compounds, the anaerobic processing of the acid hydrolysate to allow further reaction and simultaneous absorption of nutrients (small intestine), and the slurry dewatering of the organic residue in the large intestine, ultimately to produce urine (liquid soluble waste) in the bladder and partially dewatered solids. Draw a flow sheet for this digestion process, identifying each "unit operation." Label all flow streams with mass flow variables required for eventual mass balances.

2. Visual => verbal: Combustion Process Flowsheet

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Air=====→ ***** Exhaust
               *      Combustion chamber      * =====→
Fuel==>( filter)→ *****

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Create a verbal problem statement for this visual flowsheet. Add conditions, composition, heat of combustion, heat capacities, etc., and indicate what variables are to be calculated. Include a Degree of Freedom check to verify that you have created a properly posed problem.

3. Analytic => Visual: Consider the following mass conservation equations

$$\begin{aligned}
 m_1 + m_2 &= m_3 \\
 m_4 + m_3 &= m_5 + m_6 \\
 m_6 &= m_7 + m_8 \\
 m_8 &= m_2
 \end{aligned}$$

Create a process flow diagram for these equations when

- (a) The process involves only liquid streams
- (b) The process involves six liquid streams (m_1 - m_4 , m_6 , m_7) and two vapor streams (m_5 , m_8).

In each case, identify your chosen unit operations explicitly.

Does the conversion of these equations into a flow diagram generate an unique set of unit operations, or are multiple solutions possible ?

4. Visual A => Visual B => Verbal: For the orange juice problem, reverse the flow arrows of the given streams and replace the original unit operations and mixing point labels to create a new process. Given the same initial basis for mass flow rate except for the reversal of flow direction, is it possible that the mass flow rate magnitudes are the same as those in the original problem ? Create a word statement for your reversed flow configuration.

5. Visualization. Eugene Ferguson argues in his book *Engineering and the Mind's Eye*³ that non-verbal thinking, in particular visualization within the brain, has played a dominant, yet under appreciated, role in the history of engineering. Comment on the following historical quotes from various engineers, as summarized by Ferguson. Drawing on your life experiences, do you agree or disagree with these opinions? Be specific in your responses. Under what circumstances have you made use of your “mind’s eye?”
- a. “Drawing techniques are the “true alphabet” of the engineer” Isambard Kingdom Brunel, civil engineer.
 - b. “Most eminent scientists agree that non-verbal forms of thought are much more important to their thought than verbal ones.” Root Bernstein.
 - c. For an 18th century water-powered flour mill design: “The arrangement I have so far completed [in my mind] before I began [to build] my mill that I have in my bed viewed the whole operation with much anxiety” Oliver Evans.
 - d. On motorcycle repair: “When we’re stumped, when we have diagnosed ‘the’ trouble and then found that we were wrong ... just stare at the machine. There is nothing wrong with that. Just live with it for a while. Watch it the way you watch a line when fishing and before long, as sure as you live, you’ll get a little nibble, a little fact asking in a timid, humble way if you’re interested in it. That’s the way the world keeps on happening. Be interested in it.” Robert Persig: *Zen and the Art of Motorcycle Maintenance*.
 - e. “The tool-maker wants not a verbal description of the thing he is asked to make, but a careful picture of it...without pictures, most of our modern highly developed technology could not exist. Without them we would have neither the tools we require nor the data about which we think.” William M. Ivins, Jr., 1953
 - f. “Reading an engineering drawing is a decoding process. Experienced readers know what to look for, and pursue the wanted information until they find it or until they are satisfied that it is not on the drawing. Readers of an unfamiliar drawing first build in their mind’s eye a three dimensional picture of the object depicted, then they proceed to whatever details they need to determine the intention of the drafter.” Ferguson, p 87.
 - g. On 16th century mining technologies: “...with regard to [mine] veins, tools, vessels, sluices, machines and furnaces, I have not only described them, but have also hired illustrators to delineate their forms, lest descriptions which are conveyed by words should either not be

understood (by men of our times} or should cause difficulty to posterity.”
Agricola , De Re Metallica, 1556.

Quotes from Morris Kline’s Mathematics and the Search for Knowledge¹⁰ are also instructive and potentially useful for student conversations.

6. Analytic vs. Verbal: “We have yet to cite another important feature of mathematics-the use of symbols. Although a page of mathematical symbols can hardly be described as appealing, there is no question that without symbolism mathematicians would be lost in a wilderness of words.” Is this claim also true for engineers ? (Kline, p. 49.)
7. Flowsheet idealization: “To get to the heart of the phenomena, Galileo urged and practiced one more principle, namely, idealization. By this he meant that one should ignore trivial and minor factors.” (Kline, p. 101.) Consider the orange juice concentrate problem statement, flowsheet, and solution. What “idealizations” can you identify in the flowsheet and proposed solution ? What “trivial and minor factors” may have been ignored ?
8. Stereotypes. Kline recounts “It has been said of computer programmers and engineers that ‘Yours is not to reason why, yours is but to quantify. ‘ “ Do most of your engineering courses follow this approach, or is process purpose explained so that you know “Why”.
9. Analytic to Verbal The translation of equations into verbal statements is probably the least practiced activity. Except for the standard “degree of freedom” test for solvability of a set of equations, the procedure of solving equations does not communicate with the problem statement. Reconsider the set of equations in exercise 3 above. Create a word statement which includes sufficient information that your “degree of freedom” calculation shows solvability. Solve your problem for all flow rates.
10. Verbal to Analytic The quotes from Ferguson, the multi-step procedure of Felder and Rousseau, and the differences between novice and expert cited in Table 3 all suggest that a direct translation from verbal to analytic worlds is a difficult, and often unproductive, path to problem solution. Consider the following problem statement:

A three component (A,B,C) mixture is to be separated into three product streams. The process proposed allows the liquid feed stream to combine with a recycle liquid stream, then pass into a distillation tower where the volatile component A is flashed to give a vapor stream of 0.9 A and a liquid bottoms stream. The latter is fed to a vacuum distillation tower which produces a top vapor product of 0.8 B and 0.15 C. The liquid stream from the second column is divided in half, to produce equal third product and recycle streams. Define your stream and mol fraction

variables. Write down the component balances, do a degree of freedom analysis and add any additional information necessary to produce a unique solution. Solve for all flow rates and compositions. DO NOT DRAW OR USE A FLOWSHEET OR DIAGRAM.

Does this abbreviated approach save you time in solving the problem ? Why is it difficult to draw out the balance equations from a verbal statement ? When you draw a flowsheet, does it stick in your mind so that you “see” it in your “mind’s eye?”

11. Verbal vs. Visual You are asked to invent a new process problem which will include both a verbal statement and a flowsheet. The process must include three unit operations, connected in any fashion of your choice. Will you first compose the verbal statement or the flow sheet ? Why ?

Conclusion

Various authors indicate that the “engineering method” in their texts includes the passage through verbal, visual, and analytic (mathematical) representations when solving engineering problems. Given that these worlds have individual vocabularies and are processed in different parts of the brain, we argue that students having “trouble” with course materials, problem sets, and quizzes may be challenged in part by the translation activities needed for problem solution using the conventional verbal => visual => analytic sequence of representations . This activity of translation between sequential representations appears to have been little studied per se in order to establish whether and which students have difficulties originating from such translation tasks. This paper suggests that further study in this direction could be useful.

Acknowledgement

My unfortunately anonymous linear algebra professor of some forty plus years ago didn’t have engineering courses in mind when he argued for viewing his problem world as a “three ring circus, “ but his exhortation is gratefully acknowledged as a major stimulant for this article. Eugene Ferguson’s summary of non-verbal thinking in engineering indicates that problem solving is universally involved in translating verbal statements into visualizations, and vice versa. Finally, the author acknowledges Richard Felder’s eternal, annoying and persistent question: “How do engineering students learn, anyway? ”

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