FUNDAMENTALS OF CHEMICAL ENGINEERING

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The subject "Chemical Engineering" has structure. It is not an unrelated collection of about three thousand equations that we somehow put together to solve problems. The subject is built upon fundamental laws, concepts that allow us to use those laws, models, theories, semi-empirical correlations, and data. English and mathematics are the languages we use to work within the subject.

Unfortunately, some surveys of our graduating seniors reveal that many see the discipline as a "collection of isolated equations to be memorized and 'cooked' to solve problems." They see no relationship between such courses as thermodynamics and heat transfer—the topics are seen simply as different courses taught in different semesters by different instructors. Students fail to recognize links between the courses and the concepts in chemical engineering, and consequently they see little structure to the subject.

There are two vital types of structure: we use a structure of the knowledge to facilitate learning, and we use a structure of the knowledge to solve problems.

Structures to Facilitate Learning

To facilitate learning, Ausubel[1] emphasized the importance of providing students with "advanced organizers." Such advanced organizers help students see the structure of the subject and provide a "big picture" of the route ahead. The structure, selected to facilitate learning, provides a framework that we can hang new knowledge on as we learn it. One considers which concepts are easier to learn first and notes a certain sequence of topics. Most texts attempt to provide such structure, and most of us in the field of teaching attempt to provide such structure to facilitate learning.

The structures and relationships are created to facilitate learning. The structures may pertain only to the course and the subject we are teaching. Rarely does the structure interlink with other courses. Novak and Gowin[2] suggest "concept mapping" as a useful way of displaying the structure. Our work with seniors shows that they can create reasonable concept maps that reflect the structure used to help them learn. However, they provide separate and unconnected maps for each course. Furthermore, the maps are very detailed and tend to classify the information on the basis of the sequence in which it was taught. As they develop the maps they say, "First we had this, and then this, ..." Thus, what we and the textbooks are providing seems to help their recall. On the other hand, they rarely have thought previously about connecting the maps to see the bigger picture of *all* the undergraduate subject matter.

Structures to Facilitate Problem Solving

A crucial finding about problem solving is that the problem a person solves is their own internal, mental image, or representation of the problem. We do not simply solve "problem 6.3 at the end of Chapter 6." Although one reads the problem statement, the mental task is one of reformulating the words and images into some mental image of what "we think the problem is all about." The creation of that internal representation is dictated by the problem solver's

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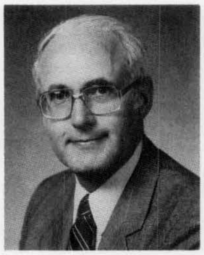

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internal structure of the subject knowledge.

For example, a student's internal representation of chemical engineering *for the purposes of problem solving* may be a "collection of unrelated equations." Unsuccessful problem solvers tend to use a trial-and-error tactic of using equations that will "use up" the information they are given. For example, a problem statement in Chapter 3 of a fluid mechanics textbook included extraneous viscosity data. One of the A+ students searched through the text until he found, in Chapter 5, an equation that included viscosity and all of the other information in the problem statement!

This behaviour might be interpreted as being related to people whose grasp of the subject discipline is only an unstructured collection of unrelated equations. Clement[3] and Larkin[4] provide evidence in the context of physics. Clement suggests that we use four interconnected and hierarchical modes of thinking with our internal knowledge: observations

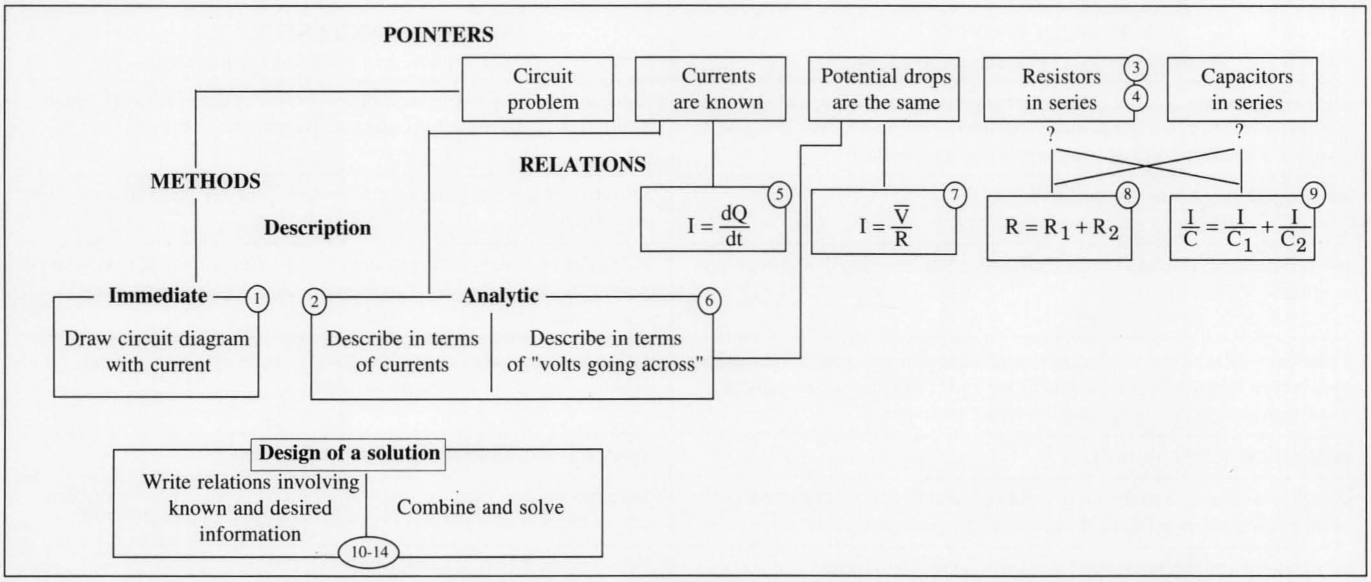

Figure 1. Unsuccessful problem-solver's script (From Larkin;[5] reproduced with permission)

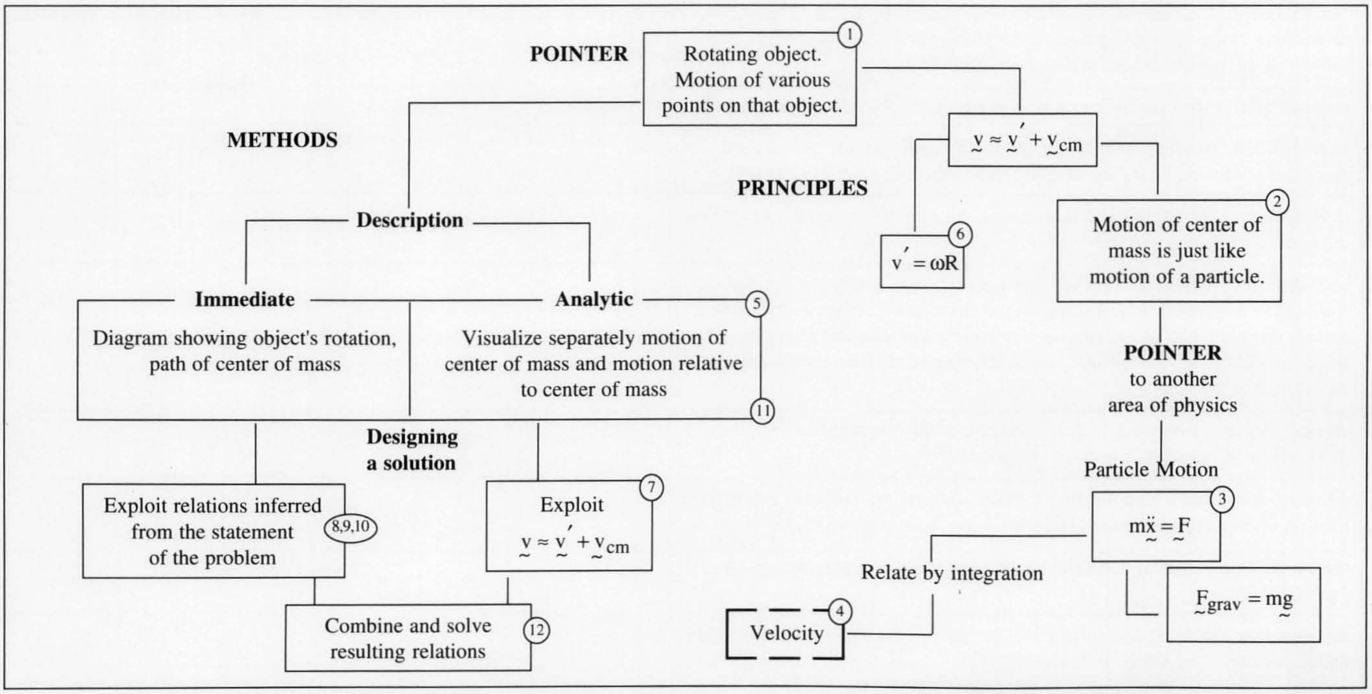

Figure 2. Successful problem-solver's script. (From Larkin;[5] reproduced with permission)

and practical knowledge—leading to qualitative physical models—leading to concrete mathematical models—leading to written symbol manipulation. Successful problem solvers tend to start solving problems by checking the observations, qualitatively understanding what is going on, invoking mathematical models, and then manipulating symbols to obtain a quantitative result. Thus, they start with observations and a qualitative understanding of what is going on. Unsuccessful problem solvers depend solely on symbol manipulation. Larkin's research uncovered key differences between unsuccessful and successful problem solvers: the unsuccessful problem solver, as illustrated in Figure 1, selects "pointers" in a problem in DC circuits that lead to a broad set of relationships that then had to be played around

TABLE 1

Comparison Between Unsuccessful and Successful Problem Solvers' Use of Knowledge

UNSUCCESSFUL Problem Solvers' Use of Subject Knowledge	**SUCCESSFUL** Problem Solvers' Use of Subject Knowledge
cannot quickly and accurately identify the pertinent subject knowledge; tend to play around with many equations;[4,5] tend to manipulate symbols and combine what they select as being a relevant relationship[3,4]	rapid and correct identification of the pertinent subject (usually within seconds of completing the reading of the problem statement)[5]
misinterpret and misuse "pointers"[5]	identify and use "pointers" to zero in rapidly on key principles and fundamentals[5]
redescription and creation of mental image is limited, formal, and often not helpful[5]	redescription is rich, accurate, and uses assumptions and approximations rapidly to identify key features;[5] use qualitative analysis to point to crucial concepts[6]
a particular relationship is recalled independently of any general relationship upon which it is based;[5] no restructuring and "chunking" of knowledge; work with independently applied individual principles[6]	strong structure connecting concepts, principles and laws[5] apply related "chunks" of subject knowledge[6]
do very little qualitative analysis[6]	do extensive qualitative analysis of the situation[6]
unwilling to guess, to make approximations, and have no memorized, order-of-magnitude values to assist them in doing a qualitative analysis[10,11,12]	have memorized "tacit" or order-of-magnitude experience factors that allows them to do rapid and extensive qualitative analysis[10,11,12]
have incomplete and imprecise knowledge about knowledge[8]	have a complete set of knowledge[8]
lack an organized, hierarchical and abstract knowledge structure that is based on fundamentals and tied to the real world by pointers[9,10]	possess an organized, hierarchical, and abstract knowledge structure that is based on fundamentals and tied to the real world by pointers[9,10]
do not know when to apply general theory and when to apply specific subsets of the general theory that seem to apply[6,8]	
confuse specific and special cases with generally applicable relationships[8]	
have difficulty recalling/identifying conditions under which special case equations apply and hence try to apply these when they are inapplicable[7,8]	
have difficulty identifying and formulating the specific information to which the general principles apply[8]	
have difficulty reasoning from basic principles; instead rely on "beginning" and "end" events without reflecting on the chain of events between the two; depend on redescriptive activities which merely rephrase the problem situation without advancing one's understanding of it; depend on inappropriate arguments by analogy[8]	
cannot distinguish between additive and non-additive quantities;[8] have difficulty working with "intensive" properties[8]	
place more emphasis on collecting sample solutions and working examples than on understanding the fundamentals when "learning" a subject[10]	
replace precise technical definitions with imprecise, everyday usage, *e.g.*, "velocity"[8]	
fail to realize that once certain physical parameters are set, other measurable quantities cannot be varied independently[8]	
have conceptual difficulty applying calculus in physics[8]	

with and "cooked" to see which one might apply. The successful problem solver, illustrated in Figure 2, selects "pointers" in a problem on a falling disk that show a direct and rapid connection with fundamental principles and methods. A summary of the research on unsuccessful and successful problem solver's use of subject knowledge is summarized in Table 1. (3 - 13)

More specifically, research has shown that successful problem solvers have a structure to their subject knowledge that—instead of being a collection of unrelated concepts and equations—is characterized as follows:

1. *The knowledge is structured hierarchically (with fundamental laws and principles at the higher levels and surface structure and pointers at the lower levels.* [6,9,14,15,16]
2. *The highest levels in the hierarchy—or the underpinnings—are the fundamental laws, the abstractions.*[5,6,9,14]
3. *Related to the fundamentals are concepts and "chunks" of information that allow us to apply the fundamentals effectively. The knowledge is encoded to include conditions and constraints when the knowledge is applicable.*[4,7,16]
4. *The lower levels are the surface structure (key words in a problem statement that trigger one to use certain approximations or concepts or descriptions of the everyday events that work because of the fundamentals) and "pointers" that link the surface structure to the fundamentals.*[5,6,7,16,17]
5. *Encoded with the subject knowledge is "tacit" or memorized, order-of-magnitude numerical values that allow qualitative application of the knowledge.*[10-12]
6. *Subject knowledge is organized in block or "chunks" convenient for mental processing.*[6,7,12]

Concerning the types of knowledge, there are

- *the fundamentals*
- *concepts or defined terms to allow us to use the fundamentals*
- *the procedural knowledge about how to work with the information*
- *the pointers or links*
- *a rich set of episodic knowledge that gives us a qualitative understanding of what is going on, as opposed to a series of symbolic equations that one manipulates. This includes memorized, numerical, and order-of-magnitude knowledge.*

Glaser[14] suggests that the knowledge structure is not static; rather, as new knowledge comes in it should be embedded in the hierarchy, attached to the fundamentals, and related to the episodic knowledge so that it relates to our past experience. This embedding modifies the original structure.

IDEAS ABOUT THE FUNDAMENTALS

Identifying the fundamentals is not easy. Sometimes the things we call "laws" are "wishes," not laws; sometimes "principles" are really laws, etc. Some terminology might be:

Law • A universally applicable explanation of how things behave; *e.g.,* the conservation of mass.

Constrained Law • An explanation that is applicable over a defined set of circumstances; *e.g.,* the ideal gas law.

Balance • An equation applied to a conserved entity—thus one would have a "mass balance," but not a "mole balance" or a "volume balance."

Model • A representation of a situation for the purpose of explaining how it behaves.

Theory • A mathematical relationship between the dependent and independent variables that is almost completely based on fundamental laws and constrained laws. There may be a few constants that have to be used to tune the theory to the specific situation. There may be many different theories for one particular behaviour.

Empirical Correlation • A mathematical relationship between the dependent and independent variables. No theory or fundamentals were used in creating the relationship. It considers the system to be a "black box."

Semi-Empirical Correlation • A mathematical relationship between the dependent and independent variables that is based on some fundamental laws and constrained laws.

Concept • A general term for an entity or idea that is useful in applying a law; *e.g.,* the concept of "force."

Convention • An agreed-upon set of rules; *e.g.,* Gibbs convention for the dividing surface in surface phenomena.

Postulate • A simplifying set of agreed-upon conditions.

Examples of "laws" and "postulates" pertinent to chemical engineers include[18,19]

LAWS

1. Law: Mass is neither created nor destroyed; it is conserved; the total mass is conserved; the mass of an element is conserved (unless nuclear reactions occur or $E=mc^2$ occurs, in which case, mass and energy will exchange).

2. Law: Electrical charge is neither created nor destroyed; it is conserved.

3. Law: Energy is neither created nor destroyed; it is conserved (unless nuclear reactions occur or $E=mc^2$ occurs, in which case mass and energy will exchange).

4. Law: Momentum is conserved.

5. Law: The law of definite proportions is related to compounds and their formation.

6. Law: The second law of thermodynamics—systems of processes occur so as to minimize the total free energy in the system. Concept: free energy.

7. Law: If a process proceeds spontaneously, the reverse process can never proceed spontaneously.

8. Law: If a system is left alone, it will go to a state of dynamic equilibrium that has equal forward and reverse rates and no available free energy.

Extensive details are needed for each law or correlation.[4,12] The details include

- a statement of the fundamental principle law of equation
- an identification of the meanings of all the concepts used in the law
- identification of the dependent and independent variables
- numerical units of measurement
- listing of the region of application, identification of the limitations and assumptions
- hints to prevent errors in the application
- utility hints (tacit information) about when a particular principle is most useful

In addition, we must have a qualitative understanding of what is going on as predicted by the law.

POSTULATES

To simplify our ways of thinking about nature and how it behaves, we often define simplifying postulates. Rase[19] provides the following examples of postulates:

1. Postulate: Isothermal (constant temperature)

2. Postulate: Isobaric (constant pressure)

3. Postulate: Isochoric (constant volume)

4. Postulate: Isentropic (constant entropy); simplification for a compressor or turbine

5. Postulate: Isenthalpic (constant enthalpy); simplification for flow through a valve

6. Postulate: Adiabatic (no exchange of energy between the inside and the outside of the system); simplification for perfect insulation

7. Postulate: Equilibrium exists (assume an infinitely fast rate)

8. Postulate: Reversibility (neglect friction)

9. Postulate: Ideality (this has many subcomponents); ideal gas when the ideal gas law applies; ideal liquid (could be zero viscosity or Newtonian depending on how ideal is defined); ideal Hookean solid, ideal isotropic solid, ideal solution, ideal mixture, ideal crystal, ideal catalyst

10. Postulate: Models for mixing; plug flow or complete mixing

11. Postulate: Incompressible flow $(\nabla \cdot v) = 0$

12. Postulate: Unidirectional flow

13. Postulate: Black body radiation and grey body radiation

14. Postulate for shape and configurations: infinite shape, semi-infinite shape, perfectly smooth surface, zero thickness surface region, point source, constant total cross-sectional area, and perfect geometrical shapes (flat, cylindrical, spherical)

15. Postulate for time: steady state, pseudo steady state, zero time, infinite time

16. Postulates about limiting cases

As we move from laws to models, through concepts and through to postulates and conventions, we move down the structure. Indeed, the pointers that connect the real world to the structure are usually connected to "postulates."

SUMMARY

Knowledge has structure. Having the appropriate structure facilitates learning and problem solving. Key characteristics of the knowledge structure to aid in problem solving are that knowledge is hierarchically organized with the fundamentals at the higher levels and pointers at the lower levels. Knowledge is "chunked" to include the bases, assumptions, conditions of application, and tacit or experience knowledge. Some example "laws" and "postulates" have been given in this paper.

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ChE ***book review***

FLUIDIZATION ENGINEERING

(Second Edition)

by D. Kunii, O. Levenspiel
Butterworth / Heinemann, Stoneham, MA 02180; 491 pages, $145 (1991)

Reviewed by
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Princeton University

The first edition of this book, which appeared over twenty years ago, enjoyed considerable success in drawing together the research results available at that time and synthesizing from them a connected account of direct value to engineers involved in the design of fluidized beds. It is, therefore, a hard act to follow—but this second edition succeeds in preserving (and even enhancing) the virtues of its predecessor, while at the same time weaving many newer ideas into the fabric of the text.

Though some passages from the earlier work are retained, the present book is essentially a completely rewritten text. Even where the material is similar to the earlier presentation, it has been reorganized, expanded, and supplemented with more worked examples. There is much more attention paid to matters such as the influence of the properties of the particulate material on fluidization behavior, resting on concepts (such as the Geldart classification) which have appeared since publication of the first edition. Variants on the classical dense fluidized bed are also treated; for example, a whole chapter (entitled "High Velocity Fluidization") is devoted to turbulent beds and fast fluidized beds, configurations that have become increasingly important. On the other hand, the many students and practitioners who have benefited from the information in Chapter 3 of the first edition (which provided explicit instruction on how to estimate such elementary, but vital, properties as the terminal velocity of fall and the minimum fluidization velocity) will be happy to know that the same chapter of the second edition provides the same help, but in an updated and improved form.

My only criticism of the first edition was that the very success of the authors in presenting the material in such simple, clear exposition tended to give a false impression that the material was well established, reliable, and beyond controversy. In fact, this was far from the truth. Many of the correlations presented were extrapolations from limited data, while the models, though reasonable and the best available at the time, were gross simplifications which had been subjected to only the most superficial testing. In short, the story was told so well that it made the state-of-the-art seem much more firmly based than it really was.

I have some of the same feeling about the second edition. The unwary designer might easily be seduced into following the path so clearly marked out, only to receive a rude awakening further down the road. The subject remains today a very messy one, in a state of continuing flux, with both the physical principles and the tools available to apply them changing very quickly.

But this is only a minor reservation about a book which is likely to be as well received as was its predecessor. We might even hope that the rapid changes in the field will encourage the authors to venture a third edition at some time in the future. ❒