A Parallel Thinking Problem Solving Pedagogy towards Development of T-Shaped Engineers

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Abstract

The purpose of this contribution is to present a work-in-progress that features an illustrative application of a parallel thinking problem solving pedagogy, as well as connections to enhancements in students' problem-solving skills, implemented in an undergraduate transport phenomena course focused on bio systems. The strategy is likewise being explored in multiple other courses in the Chemical Engineering (CHE) curriculum including heat transfer, fluid mechanics, mass transfer, and reaction engineering. Some of these courses comprise part of a larger Quality Enhancement Plan (QEP) curricular redesign in CHE focused on enhancing students' critical and creative thinking skills as related to challenge characterization (knowledge acquisition) and related problem solving (knowledge transfer). Leveraging the Renaissance Foundry Model, student teams are likewise envisioned to transfer and upscale their understanding of the parallel thinking approach to a challenge that they have identified.

Keywords

Lateral thinking, problem solving, Foundry, biotransport, T-shaped engineers

Introduction

Current trends in engineering pedagogy indicate that engineering students are expected to graduate with deep technical content knowledge and awareness of engineering systems as well as cross-disciplinary skills including such aspects as creative and critical thinking, entrepreneurial mindset, strong communication skills, and the ability to both identify and solve problems.[1-4] Achievement of this concept of a "T-shaped engineer" has been promoted as essential to successfully addressing complex societal problems.[2,3] Thus, advances in techniques to help students both acquire knowledge and develop skills in transferring such knowledge to solve both well-defined and open-ended, ill-structured problems is critical.[3-5]

With a principle focus on the problem-solving attributes of the T-shaped engineer, as described herein, a "Parallel Thinking Problem-Solving Pedagogy" (PTPSP) is being explored in a CHE transport phenomena course focused on bio systems in which students work in teams to solve problems using multiple approaches. The course is part of a larger QEP-supported curricular effort in the CHE undergraduate program of study which leverages the Renaissance Foundry Model (the Foundry) to engage students in knowledge acquisition and transfer processes for various applications within the CHE curriculum.[3,5] Given the complexity of the challenges facing society today, the development of advanced problem-solving capabilities that integrate skills both in problem analysis and problem identification is a highly important area of focus in higher education. As a recognized aspect of critical thinking, these integrated problem-solving skills represent a subset of attributes of a T-shaped engineer which is envisioned as a holistically-trained engineer possessing both deep technical content knowledge and skills that cut across disciplines.[4,6]

Background

Much of the discipline-based education research has generally been focused on approaches used in solving well-defined engineering problems, but less has been done for ill-defined problems.[7] Solutions to such complex problems require collaboration, creativity, and lateral thinking (as proposed by Edward de Bono as an important alternative (but complementary approach) to "vertical thinking"[8]) to stimulate idea generation and development of solutions. Arsad *et al.* described the use of an open-ended question methodology to force students to think laterally in solving a problem.[9] Syahrin *et al.* explored students' creative thinking patterns including their lateral thinking skills based on idea generation.[10] Further, the identification of the "real problem" including through such approaches as real-world immersion experiences[3,11] is also highly important to assist with assumption calibration and selection of real-world problem solving approaches. In *Strategies for Creative Problem Solving*, Fogler *et al.* detail problem solving heuristics and outline several methods such as brainstorming and the use of an open-ended algorithm for generating solutions.[12] These represent but a few of the efforts in this area. This contribution builds on these efforts while focusing on the development of a T-shaped professional.

About the Biotransport Course and Implementation of the PTPSP

The biotransport course (CHE 4661: Transport in Chemical and Biological Systems) is a three-credit hour course in our chemical engineering curriculum with an integrated lab that is taken during the second semester of the student's senior year. Within this integrated lecture/lab model, the PTPSP is being explored in which student teams (typically three to four students per team) seek to tackle identified problems (either instructor provided or identified by the teams) using each of *the four complementary techniques*: thought exercises, analytical solution methodologies, experimentation, and simulation that are ideally completed in modules over the duration of two to three weeks. For instructor-provided problem statements, students are ideally given materials to review prior to presentation of the problem statement which is subsequently presented, and students are asked to provide a written solution towards completion of the thought solution. Then, an analytical solution is developed. During lab, students work in teams to complete a carefully designed experiment with data collection and analysis. Finally, a simulation is completed (e.g., via COMSOL) and examined. While this represents a sequence of sorts, the "parallel" aspects are realized, as the solutions are generated in close proximity to each other (as ideally all solutions are produced in a two-week timespan), and students are routinely asked to continue thinking about their initial thought solution and how it might need to change. Further, efforts to help establish connections regarding types of information needed to develop solutions via a particular approach are pursued (such as recognition that a new experiment is necessary if values for properties or other parameters are unknown).

More specifically, the problem solution starts with students thinking about what a solution might look like. This "thought exercise" approach generally requires no math and could take the form of a representative pictorial-based solution or text. Students are challenged to apply what they already know to a problem and to reason as to what a solution might look like. The analytical solution leverages aspects that are likely somewhat familiar based on prior course work, but math is required. Analytical solutions in our curriculum often result in application of conservation and/or constitutive equations (e.g., conservation of energy, conservation of linear momentum, conservation of total mass, conservation of species mass, Fourier's Law of Conduction, Newtown's Law of Viscosity, Fick's Law of Diffusion, etc.) to solve the problem at hand which might be completed on paper, in Excel, or via Matlab (as examples). The solution obtained in this way can be very general (representing average values over time) or can take the form of a spatially-dependent solution. An experiment can be devised in any number of ways but generally would involve the selection of independent and dependent variables, execution of a procedure, collection of data, and resulting analysis. Simulations can be completed using software such as COMSOL. The visual aspects of the problem can be readily seen through this approach, and the physical selection ("left clicking") of domains and boundaries is conjectured to have a positive influence on student's understanding of the problem and solution.

It is conjectured that skills associated with the ability to think, to apply knowledge of course content and tools of mathematics, to design and conduct experiments, to formulate problems, and to work in teams are fostered. As many as three modules have been offered in a single semester of the course. While all of these are works-in-progress, in the most advanced version of the approach attempted, student teams are challenged to identify their own problem, develop a problem statement, and solve the problem using each of the four techniques.

Example Instructor-Provided Problem Statement and Solutions

An example instructor-provided problem statement along with representative "solutions" associated with the use of each of the four problem solving approaches is provided in Figure A. In choosing a problem statement, careful consideration must be made to ensure that the problem lends itself to solution via each of the four approaches. The specific problem statement shown here is from Roselli and Diller who, in their textbook *Biotransport: Principles and Applications* (Chapter 5), describe methodologies for solving fluid flow problems using macroscale-based approaches.[13] After sharing a journal article in which an electrical circuit is leveraged to demonstrate flow through blood vessels[14], students complete a thought exercise and prepare a written thought-based solution. The problem is then worked out in class through the use of the Hagen-Poiseuille equation and determination of individual resistances. Ideas for achieving a solution based on experimentation for this problem could be: 1) to purchase a commercial microchip with the desired geometry and connect to a fluid reservoir to achieve a given pressure drop with flow ultimately measured; 2) to prepare a macroscale version of the vessel network based on a variety of techniques (e.g., Shrinky Dinks[15]), and 3) the use of resistors, an LED, and a breadboard to create an electrical circuit. The latter approach leverages comfort that students may already have with DC circuits as this is a component of a physics class taken in the sophomore year. Finally, a simulation is completed through development of a COMSOL® model, a numerical approach, or another method for simulation such as using a mechanical device to demonstrate a solution. As illustrated in Figure A, a COMSOL simulation provides a graphical solution that can be examined in a variety of ways through appropriate use of the model-generated data set to produce, for example, the expected parabolic velocity profile. Ultimately, opportunities for weighing the pros and cons of each approach (e.g., experiments may be expensive) as well as comparing and contrasting results can be pursued to reinforce the importance of using complementary approaches, sometimes in tandem.

Problem Based Parallel Thinking: Applications in Biotransport Phenomena

Problem Statement: The pressure drop across a network of microtubules with dichotomous branching is 35 mmHg. The hematocrit in large vessels is 40%, and the viscosity of plasma is 1.05 cp. Leveraging data in the provided table, estimate flow through the entire *in vitro* network.[13]

Generation	1	2	3	4	5	6	7	8	9
# of Vessels	1	2	4	8	16	8	4	2	1
Diameter (μm)	75	45	25	15	8	18	30	55	90
Length (μm)	2000	1600	1200	800	600	800	1200	1600	2000

Thought Exercise

We know that **fluid flow occurs in response to a pressure gradient** and that the fluid will **encounter resistance** to flow. This resistance will be related to the size of the tube through which it flows, the relative smoothness (or roughness) of the tube wall, and the fluid properties. Given that the fluid is blood, we would consider that it could behave in a Newtonian or non-Newtonian fashion depending on the flow regime. Assuming Newtonian behavior, then the Navier-Stokes equations along with the total mass continuity equation could be used to determine the velocity through each tube. To solve these, it might be appropriate to assume steady, laminar flow through straight circular tubes each of constant cross section. Considering an average velocity, such a solution could be represented in the form of the Hagen-Poiseuille equation. Per the Fahraeus-Lindquist effect, the relationship between tube size and the effects of tube size on blood viscosity would dictate resistance. Ultimately, **flow would be equal to the ratio of pressure drop and the overall resistance in the network**.

Analytical Solution

$$Q = \frac{\Delta P}{\mathcal{R}_{Total}}$$

The resistance to flow in each of the 46 microvessels is determined from the $\mathcal{R}_i$ expression provided below, and then the equivalent resistance for each of the 9 generations (G) is determined by treating the vessels in a given generation as a system of parallel resistors. The resulting resistances ($\mathcal{R}_1$ to $\mathcal{R}_9$) are added to give a total.

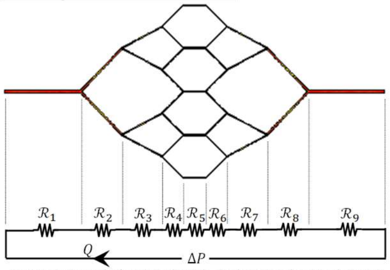

Figure 1: Visual of network with analogy to electrical circuit

$$\mathcal{R}_i = \frac{8\mu L}{\pi R^4}$$

$$\mathcal{R}_{Total} = \mathcal{R}_1 + \mathcal{R}_2 + \mathcal{R}_3 + \mathcal{R}_4 + \mathcal{R}_5 + \mathcal{R}_6 + \mathcal{R}_7 + \mathcal{R}_8 + \mathcal{R}_9$$

$$\boxed{Q = 0.0061\ \mu l/s} \qquad \boxed{\langle v \rangle = 0.0014\ m/s}$$

Experiment

Experiments could be completed (as examples) by either leveraging Shrinky Dinks to produce a plastic network (*Figure 2*) for molding in PDMS[15] or by building electrical circuits (*Figures 3 and 4*).

Figure 2: Plastic network

Figure 3: Example circuits

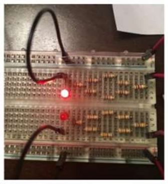

Figure 4: Working circuit

Simulation

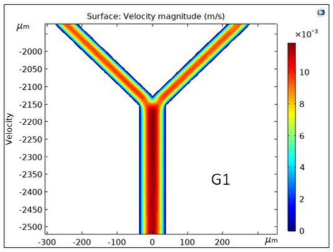

Figure 5: Representative simulated results

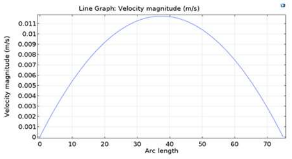

Figure 6: Example velocity profile for G1

$$\boxed{\langle v \rangle = 0.0065\ m/s}$$

Based on 2D model

Figure A: Problem statement and representative solutions as related to blood flow through microvessels. Another problem statement and solution set (related to drug release from porous beads) was previously described.[16]

Conclusions

Ultimately, in addition to solving a problem using each of the four techniques, students spend time thinking, connecting different approaches, and obtaining know-how regarding the use of computational modeling software. The answers should align, and when they do not, this creates an opportunity for further discussion and exploration. From this work, we envision several paths forward in seeking to better understand whether the PTPSP is an effective pedagogical approach.

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