The Interface Between Control Domains: A Powerful Principal Object of Knowledge (POK) to Learn Transport Phenomena

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Abstract

This contribution focuses on describing how implementing an inquiry-guided approach, embedded into the Renaissance Foundry Model, i.e. the Foundry, introduces students to the role of the interface, i.e., the region located between a control domain with its environment. The dual-level approach, i.e., pedagogically guided by the Foundry and physically centered on the boundary conditions, can help students to understand the physics that is controlling (in a global sense) the behavior of a given transport phenomena, such as heat transfer, without initially invoking the complexities associated with the full differential equation model. Furthermore, by using this pedagogical technique students can connect (the details of the) various learning pieces associated with, among others, fluxes, gradients, geometries, and the formulation of boundary conditions. The interface identifies a powerful Principal Object of Knowledge (POK) case useful to systematically introduce students to non-dimensional numbers and limiting cases chiefly needed to formulate mathematical models to describe, for example, temperature profiles. Ultimately, this dual-level approach offers a useful shift of focus as the interface contains as much physics as the rest of the control domain, yet it is (for most cases) considerably simpler from the mathematical point of view to describe it unless it is focused on curvilinear systems such as drops and bubbles. By using concepts mainly from energy and heat transport, this contribution will emphasize the helpful and beneficial role that an interface can play in helping students to efficiently understand transport phenomena. Impact from students will be also integrated and pointers for future work will be outlined.

Keywords

Interface in transport process; boundary conditions; non-dimensional numbers, limiting cases in boundary conditions; engineering modeling; Foundry-inquired driven protocol

1. Introduction:

Traditionally, transport phenomena[1] has followed a teaching approach centered on initially defining the system and its environment or (usually in thermodynamics) the "surroundings" followed by considerations of the boundaries/interfaces between them. This approach places heavy emphasis on the differential conservation equations that describe a given phenomenon, e. g., mass, momentum, or energy. However, as leading scholars[2,3] have indicated, there is as much physics on the boundaries as in the rest of the system under study. Thus, potentially, the boundary, i.e., the physical interface between the system and the environment could be the pedagogical focus to learn about the behavior of a given transport phenomenon. For example, students can *initially* learn how to identify fluxes, their direction and how these fluxes transfer information from one side to the other of the interface or whether such interface does not allow the transfer of mass, momentum or energy. In addition, by selecting two different phases, i.e. solid and fluid, students can learn about the critical idea of (heat or mass) transfer coefficients that, eventually, would lead to non-dimensional numbers such as the Nusselt number and the Sherwood number. In short, and while still maintaining some emphasis on the system, students learn a great deal about the physics associated with the transport phenomena under study without the complexities associated with conservation principles. In short, the interface is a powerful integrator or Principal Object of Knowledge[4] (POK), where critical elements from the physics of transport are integrated with geometrical aspects as well as with constitutive equations such as Fourier's and Fick's laws, among others. By using concepts mainly from energy and heat transport, this contribution will emphasize the helpful and beneficial role that an interface can play in helping students to efficiently understand concepts critically important for transport phenomena. Impact from students will be also integrated and pointers for future work will be outlined.

2. Role of the Interface in Describing a Control Domain: The Heat Transfer Case

In traditional chemical engineering curricula, when students are taking courses focused on transport processes of energy, mass, or momentum conservation in engineering majors, they are already familiar with domains and boundaries (or at least end points) from calculus courses in engineering mathematics. In these courses, the introduction of a mathematical function[5] requires the identification of a domain with proper boundaries. In calculus courses when focusing on one-dimensional systems, "end points" in such a domain are enough to properly describe the extent of a domain. In courses dealing with the learning of transport process, a useful way to introduce students to study a given system is to integrate this previous knowledge and expand it to, for example, 3D (i.e., volumes) where *surfaces* are effectively *the boundaries* associated with these *control domains*. The description is complete by indicating the notation for control domains as "S (t)" for the case of surfaces or "$V_c(t)$", in case it is a volume, and the use of "E" for denoting the environment. Students are also introduced to the "union" of the system and the environment, i.e., the "universe" that is indicated by $U \equiv S \oplus E$. Armed with this introduction, students are then moved into learning the application of conservation principles and the formulation of differential models[1]. In this scenario, one critically important concept is the physical interface located at the mathematical boundary of the system or control domain and its environment.

As a pivotal point, we contend that this represents a wonderful, yet often missed, opportunity in practically all undergraduate and most of the graduate level textbooks available in the current literature to make connections between these concepts. This contribution thus departs considerably from the approach described above for the learning of the transport process central to the course by focusing on the interface and its role in describing essential features of the potential behavior of such a system associated with the transport process of interest. In the sections below, we will be centered on the case of heat (energy) transfer as an example of transport phenomena for the discussion of the application of the approach. We formulate the key learning objectives and related question/s, illustrate the work implemented to answer these questions, share preliminary observations, and outline potential aspects for future work. As this project under progress is guided by the framework of the Renaissance Foundry Model[6,7], a brief introduction to key aspects of the Foundry are included as well.

3. The Foundry Model: A Brief Overview

The Renaissance Foundry Model, i.e., the Foundry[6,7], is a pedagogical platform that assists students in engaging with student-centered learning strategies geared towards innovation-driven learning. Therefore, the Foundry helps guide students to identify and manage their activities when learning a new subject (i.e., the Challenge) and identify a plan to develop an outcome (i.e., the Prototype of Innovative Technology [PIT]) to resolve such a challenge. Students have at their disposal six key elements to transition between these two ends, from the selection of a given challenge while they collaboratively work towards the building of a PIT. In addition to the challenge and PIT, the Foundry list of six elements includes: the Organizational Tools, Learning Cycles, Linear Engineering Sequence (LES) and the Resources element that provides both sources of information and skills helpful to assist the students to guide the implementation of their activities towards collaboratively identifying a given learning challenge and then proceed with the building of the PIT. These six elements are encompassed within two major learning paradigms: the Knowledge Acquisition (KA) and the Knowledge Transfer (KT) paradigms. Arce et al[6]., provide a detailed discussion of the different terminology associated with the Foundry elements and their use. The Foundry is intended to be used as a sequential but iterative process between the two paradigms to help students in acquiring *knowledge* and *transferring this knowledge* by focusing on understanding the challenge and making progress towards the building of the PIT, respectively.

A useful analogy is to view the Foundry as an engine with two pistons, i.e., the paradigms, working together to move students on their journey on building the PIT after the challenge has been identified. This engine is a useful tool for implementing the different activities that students may want to design and apply during their work moving (constantly) the challenge towards the PIT; however, this engine does not impose to students where to stop or to go back and retake their work towards the PIT. Based on the challenge and the level of knowledge that the students may already have, they may decide when to switch from acquiring to transferring knowledge and vice versa. For example, two different teams of students could take very different strategies to identify a challenge and arrive to their PIT, always moving forward. The Foundry has been applied successfully to different activities including regular and service-learning programs, and recently to the remodeling of a chemical engineering curriculum to develop a new type of professional, one that is innovative, holistic, socially responsible and with an entrepreneur mindset[8].

Connections to Physical Interfaces as POKs

A key goal of this work in progress is to overview the Foundry-guided strategy, coupled with an inquiry-guided learning approach[9,10], that is used to introduce students to the powerful integration of both physical concepts and their mathematical formulation centered on the use of an interface between a control domain and its environment (see more later). For the students' purpose of learning, the transport process that is central to the course can be addressed by focusing on the interface, which becomes the learning challenge, as described above, with the interface likewise serving as a POK thus becoming a foundational component of this process. A

POK is considered to be a central building block to student learning wherein other auxiliary or complementary concepts build upon the central tenets of the POK within the course[4]. In accordance, without this central knowledge, students' extrapolation of the knowledge constructed upon this concept and its connection to other related topics is limited within the course.

As part of this work in progress, then, we offer a pedagogical strategy which leverages the Foundry-inquiring coupled approach to place the POK of transport process using physical interfaces as a central challenge which students must learn more about by iterating between knowledge acquisition and transfer on the concept. To clarify, the identification of the role of the interface to help students understand the transport process is an excellent proposition of a learning challenge where the Foundry becomes a helpful facilitator or scaffolding tool (at the macro scale or "global" level) while the details (the micro level scale) are implanted via the inquiry-centered approach for the students. Thus, the overall description of the interface's role on learning transport phenomena and its helpful integration with flux concepts, gradients, and geometry of the interface are then guided by the application of the Foundry while how these concepts work will be guided by an inquiry-driven approach. In the sections below, we describe key aspects of the mechanics we used to guide and implement the Foundry-inquiring approach as a guiding tool in collaborative activities to learn the physics as well as their details of a given transport phenomena starting with the interface between the system (or control domain) and its environment.

4. Goals and Key Steps in Guiding the Learning Mechanics of Using the Interface as a POK for Transport Phenomena

The course of focus wherein this Foundry-inquired driven strategy was implemented was the ChE 3050 Transfer Science I, a 3-credit course central to the chemical engineering curriculum of a medium size and regional university focused on technologically infusion-style curriculum. The questions at the focus of the design and implementation of this Foundry-guided strategy are as follows:

- *From the point of view of the facilitator of learning (i.e., the course instructor), what would be a useful series of student-centered activities to introduce the key physical characteristics of the interface associated with a given transport phenomenon?*

- *Furthermore, what would be the relation of these characteristics to the mathematical formulation of related concepts including fluxes, gradients, and limiting cases determined by the physical conditions of the environment?*

The pedagogical approach used to answer the questions above is centered on an inquiry-guided model immersed within the Foundry. While the first question is centrally focused on the knowledge acquisition paradigm of the Foundry, the second question is guided by the knowledge transfer paradigm. Moreover, following this model, students are guided with key activities (that may include questions, list of pointers, discussion, observations from the instructor, etc.) and shared resources (through the Foundry) to identify important physical characteristics of the interface and the learning of how these are related to the type of transport process under study. This knowledge acquisition is then transferred to the mathematical formulation of concepts related to fluxes, gradients, and limiting cases. These "global-level" activities include, for example, classroom learning exercises, course projects, assessments, and documentation protocols within the entire semester.

In order to answer these guiding questions, *a list of key activities* used to guide the students within the inquiry-guided approach coordinated with the framework of the Foundry is presented in Table 1. These activities are helpful for engaging students in *acquiring the knowledge*, needed to describe the physical characteristic of the interface and then, *in transferring such knowledge* to the mathematical formulation of several of these concepts into transport equations. Figure 1 sketches one of the typical examples used in the ChE 3050, Transfer Science I course mentioned previously. This particular example shows a solid-fluid interface developed as a thin film of water is flowing, from a reservoir, over a solid surface that is maintained at a constant temperature, $T(x=0)= T_w$. The thin film is also in contact with air that is maintained at a constant temperature, T_∞.

After students are reintroduced to the elements and paradigms of the Foundry (See Activity 1, Table 1), they are exposed to the notions of the system, its environment, and the interface (See Activity 2, Table 1) where they are also introduced to the role of control domains and their relation to the mathematical function used in, for example, calculus courses. Since students are guided by an inquiry-centered approach coupled with the Foundry, students are focused on bringing concepts, tools, and skills learned previously either in other courses or during the weeks before the topic under discussion to the Resources element of the Foundry for immediate use (See Activity 3, Table 1). It has been customary in the courses taught based on the approach used in this project, to guide students using practice exercises; therefore, Activity 4 (Table 1) is centered on reviewing key aspects useful for describing physical aspects in engineering systems. For example, sequences similar to the "Systematic and Integrative Sequence Approach", SISA[11] are discussed and applied to sample exercises.

After students have gained practice on the description of physical aspects of a system, Activity 5 (Table 1) engages students about critical physical characteristics associated with the interface via a series of prompt questions. Referring to Figure 1, students are questioned, for example, about the number of phases present in the solid-fluid interface, the type of energy transfer (i.e. conduction vs convection) potentially occurring at the interface, and geometry and anchoring the coordinate system at the interface, among other aspects. After students have the chance to acquire knowledge about the physical characteristics of the interface, Activity 6 (Table 1) is focused on reviewing and exchanging ideas among students and with the instructor. This is very helpful to alert students to potential areas that need retuning and deeper understanding. Once this activity is completed, students are guided to transfer the acquired knowledge (Activity 7, Table 1) to the formulation of the physical concepts in terms of mathematical equations and the review and application of the laws such as Fourier's law of conduction and Newton's law of cooling are brought into the picture[12]. The review of the different types of boundary conditions associated with heat transfer applications is useful here, and the potential connections with the interface of Figure 1 are discussed and implemented. Students are able to obtain a possible PIT for this part of the learning as they write the following boundary condition for the solid-fluid interface of Figure 1:

$$-k\frac{dT}{dx}(x=0) = h\,[T(x=0) - T_\infty\,] \tag{1}$$

Where k is the thermal conductivity; h, the heat transfer coefficient; T, the temperature and x, the distance perpendicular to the interface. This equation becomes very useful to explore potential impact of the phases on both sides of the interface and how their transport properties may control the behavior of the system. In other words, students may have selected a pathway that led to a boundary condition different than equation (1) and, effectively, a different PIT. In order to make sense of the potential validity and connections between these PIT's, a systematic analysis of the physical conditions at the interface is needed. This systematic non-dimensional analysis is introduced to the students, and using a *guided series of questions*, they are asked to perform such analysis on Equation (1), (see Activity 8, Table 1). The result leads to the following non-dimensional version of Equation (1):

$$\frac{d\theta}{d\zeta}(\zeta=0) = Nu\,[\theta(\zeta=0) - 1] \tag{2}$$

Where the variables $\theta = \frac{T}{T_\infty}$ and $\zeta = \frac{x}{L^*}$ are non-dimensional variables selected by students in collaboration among themselves or in discussion with the instructor. Also, the Nu is the non-dimensional number known as Nusselt number and that contains information about the thermal conductivity, heat transfer coefficient and typical dimensions associated with the system under analysis. Students are also introduced to the name Biot and the different schools of thought as part of the history of science associated with the heat transfer science related to the course. Equation (2) is central to guide students to potential limiting cases originated from the impact of physical conditions at the interface (see Activity 9, Table 1). For example, students are quizzed about what would be the impact of Nu→∞ and what physical situation would lead to this particular or asymptotic case. Students also learn that the result of this situation leads to:

$$\theta(\zeta=0) = 1 \tag{3}$$

Equation (3) could have been identified, by other teams of the students and, in fact, another PIT. Finally, during the implementation of Activity 10 (see Table 1) students are invited to connect the different physical situation with mathematical formulation and learn the parallelism among them. During this activity, students also learn an *important corollary of the analysis*, and this refers to the integration of the different physical characteristics and the mathematical aspects along the way of the POK concept[4] and make conclusions as to why the interface is an excellent example of POK for heat transfer applications.

5. Preliminary Observations:

In general, and from an instructor perspective, the different activities guiding the students in the learning of the physical characteristics of the interface and how these can be transferred to understanding the mathematical formulation of important concepts such as gradients, fluxes, and mixing conditions of the fluid phase of, for example, the case of Figure 1, are very effective. The inquiry-guided approach coupled with the Foundry framework facilitates the placing of previous knowledge from other courses or previous topics within the Resources element of the Foundry and permits an effective retrieving by the students when they are needed. With relatively simple mathematical tools such as the Fourier law in one dimensional fashion and the Newton's law of cooling, students are able to conduct the transition between the KA and the KT paradigms of the Foundry. Furthermore, the results from their analysis allow them to inspect the potential impact of physical conditions (at the interface) on the resulting form of the boundary conditions and clearly connect with the physical meanings of non-dimensional numbers such as the Nusselt. One immediate pedagogical outcome is that students are introduced to non-dimensional variables and numbers with the idea of these being tools to be used for further characterization of the behavior of the system when applied to asymptotic cases. Also, the Nusselt number is intimately associated with the interface of an engineering system.

Finally, students also learn that the interface can work, effectively, as a POK[4] in acquiring a firm conceptual structure of the course material and making connections among seemingly unconnected subjects such as geometry, coordinate systems, and location within the control domain. This also affords students a better understanding of what sort of learning exercises would be beneficial to achieve a successful mastering of the learning objectives of the course. In addition, the role of the Foundry facilitates students' activities and their focus on meaningful exercises from the understanding of the challenge (i.e., identify physical characteristics of the interface, for example) and what is needed to be learned for an effective transfer towards a mathematical formulation of boundary conditions. It also helps to implement an inquiry-guided learning strategy with a relatively minimum input from the instructor as the students have available a clear pathway to achieve the development of the PIT. Additional work is needed to determine the extent of the student improvement related to critical thinking skills and understanding of transport phenomena topics and how these are critically- important to learn the course content at a level useful for their major.

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Table 1: Key Activities for the Inquiry-Guided Strategy to Guide Students in Understanding the Physical Characteristics of the Interface and their Relation to Mathematical Modeling of Transport Concepts.

Activity	Foundry Elements-Learning Focus	Comment
1. Review of the Foundry Model, its elements, and paradigms	Acquisition of knowledge of key background aspects; review of the Foundry elements and paradigms	The Foundry Model is used as the guiding learning protocol for students to collect information, identifying the challenge and develop the PIT (the understanding of the physical characteristics of the interface).
2. Introduction of system, environment, control domains, universe, and interface	Focalizing students on the understanding of basic role of the interface as the "connector" between system and environment	Students are exposed to the physical location of the interface as a boundary that bridges the control domain and its environment. Different types of interfaces (e.g., constant temperature, flux condition, etc.) are discussed.
3. Discussion with students of key resources available to them to identify physical characteristics of the interface	Meetings with students to facilitate understanding of the resources (coordinate systems, definition, type of energy transfer, etc.) at their disposal	Students need to understand potential laws, coordinate systems, characterization of control domains so that they can connect them to the interface and identify the different physical aspects.
4. Practice exercises in describing general physical systems	This part of the learning question is about describing physical characteristics of a given system	Students are trained in key steps to describe information applicable to physical systems related to transport.
5. Guided questions for identifying key transport features at the interface	The interface has plenty of physical characteristic to identify by the students	After students have been trained in describing general aspects of physical system, they are guided to apply these to the interface.
6. Discussion with students and exchange input from the instructor	Feedback from the instructor for potential corrections and adjustment of the student work	The first description of the interface by the students usually contains several aspects that need adjustment and the instructor offers feedback to achieve these potential corrections.
7. Guided questions for identifying laws and their forms in describing concepts	Students have discussions and exchange of ideas to identify relevant transport laws	It is a very effective way for the students to have discussions among themselves and with the instructor guided by key questions.
8. Non-dimensional approach to the interface equations used to describe transport	Characteristic lengths and non-dimensional variable need to be identified to obtain non-dimensional numbers	This activity is useful to obtain a better understanding of the connection among the different cases described by the equations.
9. Asymptotic cases by taking limiting values on non-dimensional numbers	The use of mathematical limits is useful to obtain cases that describe physical cases	Students guided by proper questions and through discussions among themselves can gain a deeper understanding of the impact of physical situations on the mathematical expressions of boundary conditions.
10. Reflectional activities related to the integration of the different concepts via the use of the interface	The understanding of the integration of different physical aspects with mathematical concepts is useful to gain a framework	Realizing the role of the interface in connecting different concepts with mathematical formulation leads to a better building of knowledge related to transport process.

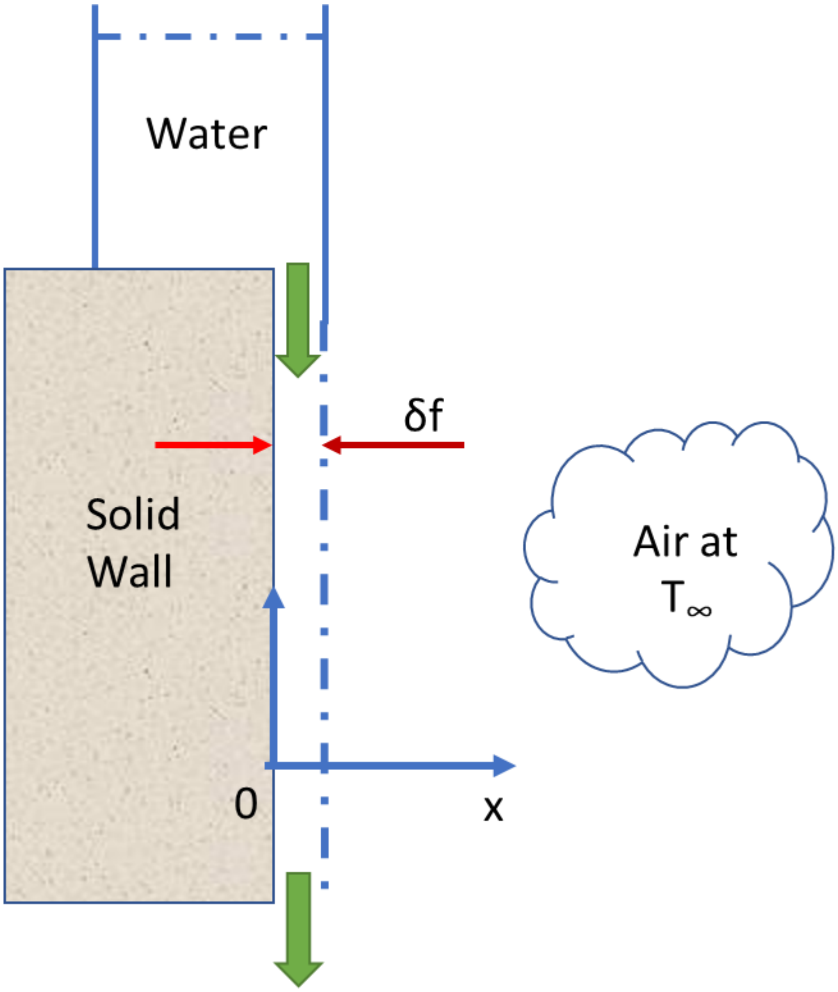

Figure 1: Typical system displaying a solid-fluid interface