Engineering an Educational Transformation Based on Analogies with Chemical Reaction and Flow Processes[1]

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Abstract

This white paper presents a new approach, based on parallels with chemical kinetics, that addresses in part the well-known, long-term challenges of attracting, supporting, retaining, and graduating traditionally underrepresented students in engineering colleges and programs. A model based on chemical reactions and flow processes is proposed as a possible means to achieve efficiencies premised on reaching a parity objective and which underscores the need for ownership of the processes by engineering institutions. Institutional ownership of the processes and their accountability for the outcomes will likely lead to diversifying engineering workforces at levels yet to be reached nationally. The model assists in the decomposition of challenges facing higher education (and particularly engineering education) into elemental steps and calls for adapting control strategies as best practices. It underscores the challenges associated with the points of transition from the upstream to the downstream parts of the flow process, where the ownership of the input may be widely distributed, and calls for participation of entities other than the individual engineering institutions who own the various contributions of the process. The model also brings to the fore issues that cannot be accurately captured with simple quantification, such as inclusion, and how those issues may be viewed in the present framework. It further suggests the possibility of alternative ways and platforms that will enrich and enhance traditional university-based educational approaches.

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The Pipeline Model: A Useful Analogy with Flow and Reaction Processes

The persistent lack of diversity in engineering and technology is well known. The reasons for such persistence are varied and numerous and have been amply described in the literature. But increasing the diversity in the engineering workforce is a profoundly identified need [1], [2]. As in many related such challenges, robust, impactful and lasting changes must recognize the pipeline character of the problem, and the characteristic times and time horizons involved.

The following schematic provides a model of a traditional engineering education in terms of a generic "flow diagram"

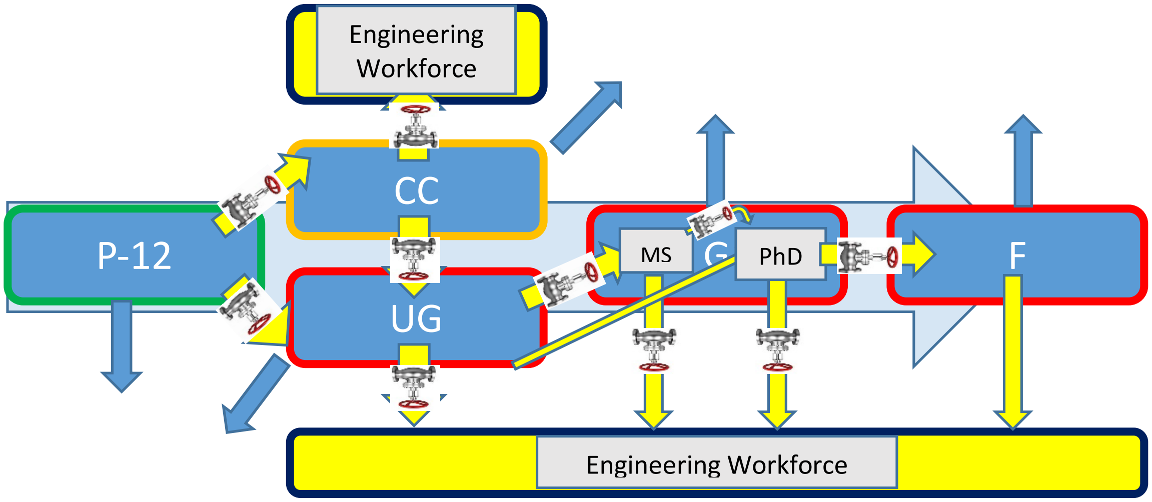

Figure 1: A schematic description of the engineering "pipeline" in terms of a flow process consisting of interconnected control volumes.

The overall process consists of individual "control volumes", denoted in Figure 1 as Pre-college ("P-12"), Community Colleges ("CC"), Undergraduate Programs ("UG"), Graduate Programs ("G"), the "Engineering Workforce", and Faculty ("F"). The directional arrows in the figure indicate the flow of graduates, with yellow arrows indicating successful transition to higher education and/or the engineering workforce, and with gray arrows indicating flows to non-engineering destinations, as a result of retention losses, change of major, and/or dropping out. Valves denote college admissions controls to the various programs. While the flow process shown does not explicitly capture additional "pathways" or "watersheds" and other ecosystems, these can be encompassed readily using the same logic.

The corresponding education is taking place within each of the control volumes: We can view this process as a sequence of "chemical reactors", following the analogy depicted in the two Figures below. First, we note that education at all levels (whether at P-12 or university levels and whether for engineering or other subjects) can be viewed as a process that augments an individual's state of knowledge, mindset and skillset [3-4]. We will borrow a chemical reaction formalism to schematically depict this transformation as a "chemical reaction"

$$A \xrightarrow{k} A^{*} \qquad (1)$$

Here, A denotes an education measure of the prior state (namely of the student prior to taking the class), and A^* the corresponding measure of the final state (namely of the student after successfully completing the class). We intentionally use this depiction for the following reasons: (i) educational processes involve transformation; (ii) the processes are not instantaneous but they follow dynamics (denoted above as "reaction kinetics", using the symbol k); (iii) the learning and teaching efficiency can be likened to a "reaction efficiency" (dictated by a number of parameters and factors).

The traditional educational providers require a minimum level (passing grade) before the student is allowed to enroll in another course in the particular sequence. Then, a collection of prescribed courses over a fixed time period (e.g., over four years in a standard undergraduate university curriculum), is the flow sequence of reactions and reactors indicated in Figure 2. Successfully done, such a flow process leads to graduation and the award of a degree (e.g., Bachelor's degree for a standard undergraduate curriculum). Extra-/co-curricular activities, the educational environment, culture and climate, and a number of other tangible and intangible factors also contribute significantly to the educational transformation process and, ultimately, to graduation.

We use k to denote the influence of a number of factors—from pedagogical to delivery methods—that affect the extent of this transformation, lumping into one symbol an equivalent "kinetic effect", from the quality of instructor to teaching methods, the environment and the culture. While we are acutely aware of the risks that this chemical reaction analogy entails (including the simplistic manner in which the process is treated, the lack of specificity regarding symbol *, etc.), our motivation is to take advantage of its benefit, which is that it can help address concepts, such as retention, graduation, and other measures of assessment and evaluation of the educational process in terms of an overall perspective. In the spirit of the chemical analogy taken, we will use the concept of "chemical reactor" to depict an individual course. The educational transformation occurring within each such reactor is (one or more) "chemical reactions" similar to (1). The extent of the educational transformation (the "reaction extent") for each individual student depends on a number of tangible and intangible factors, and is measured at the end of the process by the class instructor through a course grade (or other equivalent means). Figure 2 illustrates using the chemical reactor analogy. The notation $f_i(x)$ and $f_o(x)$ denote the input and output demographics, respectively.

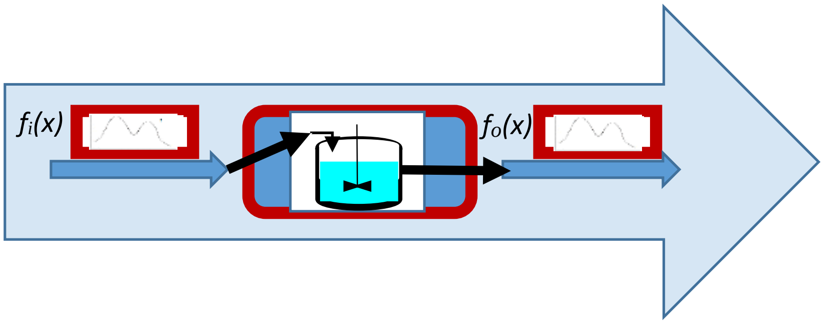

Figure 2. Chemical Reactor Schematic of the Educational Process in a *Single Course* of Study. The probability density functions at the input and output are meant to characterize demographic compositions prior to and after the class. Within the chemical reactor, reaction (1) is assumed to occur.

Traditional education providers, such as bricks-and-mortars universities, have as ultimate objective to impart at the highest rate and efficiency possible the educational transformation of their enrolled students through a comprehensive curriculum. The curriculum describes a sequence of elementary processes, such as individual courses (and/or co-curricular activities), within which education is delivered by instructors/mentors, in a specified time interval (typically quarters or semesters), and in a prescribed sequence. Viewed in its totality, therefore, the overall process is a "flow and reaction" process, where a new cohort of students enters the sequence of "reactors" each year, with a residence time in each reactor of one semester (or quarter) and an expected overall residence time across the system for attaining a degree (four years for a typical undergraduate curriculum). The analogy also allows for students to repeat a class or to change the curriculum process, as needed. This is shown schematically in Figure 3.

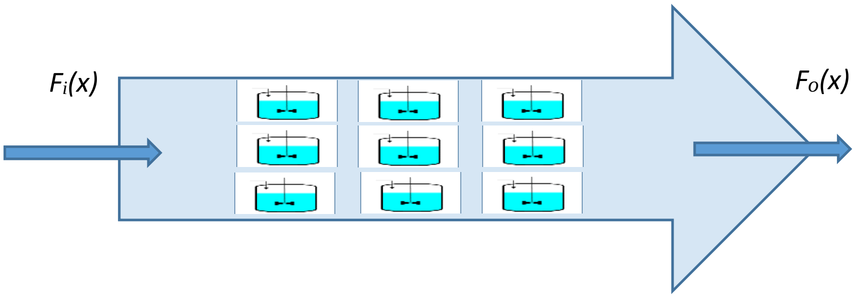

Figure 3. Flow and Reaction Schematic of the Educational Process in a *Curriculum* (namely within each of the "Control Volumes" of Figure 1). The probability density functions $F_i(x)$ and $F_o(x)$ at the input and output are meant to characterize demographic compositions at admission and at graduation. Within each chemical reactor, the process described in Equation (1) and in Figure 2 is assumed to occur. Each reactor denotes a course.

Before proceeding further, we must stress that systems involving a human element, such as education, are much more complex. In any attempt at their description and design one must account for behavioral, cognitive, organizational, social, economic and possibly policy/political phenomena [5]. By contrast, systems relying on physicochemical processes only, for example a chemical plant, can be described, designed and controlled primarily by physical and chemical phenomena, and while such systems may be complicated, they are nonetheless amenable to prediction, measurement, optimization and control. Despite the clear differences between these two types of systems, and with full knowledge of the risks entailed, we believe that the flow and reaction process analogy described above can be fruitful for deriving many objective benefits. Importantly, parallels of design, measurement, assessment and control can be fruitfully developed using such an analogy. Specifically, we postulate that such an approach applies to any educational endeavor, such as P-12, undergraduate education (whether through an Associate's degree from a community college or through a Bachelor's degree from a college or university), coursework delivered by different means (e.g., MOOCs, f-2-f, or other means), as well as for graduate work.

Delivery, instruction, assessment and duration (i.e., the type of the "reaction", "reactor" and "kinetic constants") will vary among the various cases. Nonetheless, one could apply the analogy of chemical reaction and chemical reactors to each of these educational processes and their collective impact. With this understanding in mind, we are interested in extracting strategies for how to impact the educational output, retention and graduation rates, and, ultimately, the question of how to enhance diversity and inclusion. The underlying objective will be to identify specific points for intervention and implementation along a multidimensional educational continuum, and the achievement of measurable goals, in view of the large multiplicity of issues and challenges, which often imparts an inertia that makes it challenging to formulate concrete action plans to address key issues. It is also important to clarify that the reactor analogy also includes all of the complex processes that happen for each student in the various courses, including pedagogy, climate, belongingness, co-curricular experiences, peer influences, etc. This may be especially important for first generation and underrepresented minority students.

The Parity Objective

Using the above analogies allows us to come now to the most important part of this paper, namely to the **specific objective of enhancing diversity and inclusiveness (D+I)**. While we focus on colleges and universities (with the red outline in the figures denoting the corresponding "control volumes" these entities own), whether for only-undergraduate or for research universities, the principles also apply to any other learning activity within a suitably defined control volume (e.g. P-12). For simplicity, we will use the term "socio-demographics" as a shortcut for D+I. In all contexts, but particularly in the context of engineering colleges and programs, enhancing D+I relates to two distinct but interrelated outcomes: (1) admission rates (valves in the schematic of Figure 1), and (2) the reaction process (reactors in the schematic of Figure 3).

We note the following: (1) The flow rate input to each valve is not explicitly controlled by the specific entity receiving the flow stream (in this case, the college or university). (2) To the extent that admission rates and selectivity are under its control (which may vary widely, particularly for some state institutions), the institution *owns* its corresponding control volumes (U, G and F) and, hence, must *assume the responsibility* of delivering an *efficient and complete* education for *each of the control* volumes it owns. Universities do not directly control outcomes from P-12 or CC, hence do not control the input flows to the UG valve, although many engineering schools now increasingly reach out to P-12 and CCs to help strengthen the pre-engineering input flows. For example, in the ASEE Diversity Pledge to increase D+I, now signed by more than 210 engineering schools, such outreach is specifically designated in the pledge as two of the four action items [6]. Likewise, industry, which is the main destination of engineering graduates, does not control the outcome from engineering schools, although many corporations have strong relationships with all parts of the education pipeline, from P-12 to colleges and universities, in order to increase flow rates and conversion efficiencies.

Consider, now, the *process efficiency* through *each of the control volumes* a college or university owns. Viewed strictly from a mechanistic perspective, it is only logical to articulate the following fundamental **parity objective**, which is the key point of this paper:

In each "control volume" the aggregate demographic characteristics of the output flow rates (e.g., undergraduate retention and graduation rates), denoted in Figure 3 by $F_i(x)$ and $F_o(x)$ respectively, should be statistically the same as those of the input flow rates, namely $F_i(x) \approx F_o(x)$.

Such a principle, if adopted and implemented by all entities, will help address the fundamental issues in D+I. We hasten to state that the articulation of such a principle assumes the following: sufficiently large numbers, for statistics to be meaningful (e.g., for a law of large numbers equivalent to apply); that admitted students are on-average expected to succeed, regardless of demographics; and that the entities owning the control volumes, as well as the flow rates to them through admission (valves), own and strive for the process and reaction efficiencies to be as high as possible through each of the control volumes owned.

An obvious measure of increased efficiencies in colleges and universities then is that output measures (e.g., graduation rates) are demographically invariant. Viewed from this perspective of "control", this implicitly calls for the implementation of existing, and/or for the discovery of new, best practices (the "control strategies") needed to meet this objective. The principle is schematically illustrated in Figure 4.

Figure 4: A schematic of the overall control volume that relates input and output rates and compositions (demographic groups) and calls for control measures to reach highest efficiencies (by **demographically invariant** outputs compared to inputs).

Taking the above view, enhancing D+I in each control volume owned by the educational institution means establishing parity on input and output, which, at the least, reflects a measure of **process efficiency, to which an institution ought to aspire**. Assuming that such ownership is declared, then best practices should be developed that will help affect the "kinetic parameter" *k* in each reactor, in order to meet the parity objective. Of course, developing such best practices is a non-trivial task. It will depend on a number of factors, and it will require coordinated action, cultural change, knowledge and information exchange between different institutions, and institutional commitment. But at the very least, the reaction/reactor/kinetic effect in each reactor or combined in aggregate across all reactors of the degree program must account for and proactively address the non-uniform distribution of skills, background, preparedness, and other possible attributes that might be present or prevalent in various demographic populations—perhaps due to preexisting factors arising from members of the population having been underserved, historically oppressed, economically depressed, provided lack of opportunity or exposure, the target of implicit and/or explicit biases, or having experienced other such disadvantage(s), or more generally the misrepresentation of engineering in terms of old, fixed mindsets. This brings about the need for, and is the object purpose of, best practices, including changing the conversation about engineering, on who we are, what we do, and what we look like.

In this regard, equity does not necessarily mean being equal as different interventions might be more appropriate to members of some demographic populations than to others. Taking ownership of and becoming accountable for their output, as a function of input rates, implies developing and implementing needed best practices, which should inevitably address specific demographic populations as needed, designed to counter-balance and offset any inherent disparities preexisting in the input flow distributions (given by the probability density function, *f(x)*, described in the previous section). Such well-designed best practices likely are imperative to achieving the desired process efficiencies and stated parity objective for the various output flows.

The collective impact of the adoption of the parity objective can be significant and promises to make real impact on increasing the diversity of the engineering pipeline, whether at the undergraduate, the graduate, or the faculty levels. Indeed, if every engineering institution commits to reaching parity in each of the control volumes it owns, the output flows will automatically strengthen in terms of D+I to help increase incoming streams into the next downstream (admission) valves for each control volume. Because of the pipelined, sequential nature of education, downstream flows and successes crucially depend on upstream flows. Ultimately, the most important determinant is that the parity objective is also implemented and adopted at the P-12 level, not only at successive higher education levels illustrated in Figure 1. This is a national issue of key importance for the economic competitiveness of the nation in a world where technology innovation is and will continue to be the dominant driver for economic growth and wellbeing.

Indeed, according to the U.S. Census Bureau for 2010-2014 and statistics gathered by the NSF, 39% of Americans in the P-12 age range and 37% in the college age range are Hispanics, Native Americans, and African Americans; yet these ethnic and racial groups—combined with Native Hawaiian, Pacific Islander, and other U.S. domestics identified as being of two or more races—comprise only 21%, 17%, and 12% of all students enrolled in Bachelor's, Master's, and Ph.D. engineering degree programs in the U.S., respectively [7]. Likewise, while the gender balance is approximately equal for society at-large, the representation of women in engineering programs remains unbalanced. According to the 2010 U.S. Census Bureau, 50.8% of the U.S. population is women. However, only 19.9%, 24%, and 23.6% of enrollees in Bachelor's, Master's, and Ph.D. engineering programs (U.S.), respectively, are women, according to ASEE 2014 data.

That said, and while engineering institutions adopting the parity objective in their own control volumes will not be a sufficient condition to addressing the enhancement of D+I in the engineering workforce, it will be a necessary condition for addressing the continuing imbalance of the output flow of engineering graduates. The current ASEE engineering pledge [6], initiated by USC Viterbi, does contain such an acknowledgement of the importance of the P-12 outputs, which is consistent with this paper.

Concluding Remarks

The present paper provides a "flow and reaction" process model in order to help the decomposition of overall challenges facing higher education—and engineering education specifically—into elemental steps and calls for adapting control strategies, as best practices. It underscores the challenges associated with "gates," where the ownership of the educational input may be widely distributed, sometimes by including entities other than the individual engineering institutions who own the various contributions of the process. It also brings to the fore issues that cannot be accurately captured with simple quantification, such as diversity and inclusion, and how they could be viewed in the present framework. It suggests the possibility of alternative ways and platforms that may help improve on traditional university-based educational approaches.

The framework of chemical reactions, reaction efficiencies and flow processes is intended to help abstract the process and to provide a mechanistic view that can be adopted by engineering educators in support of the more traditional diversity and inclusion arguments. It is argued that a non-trivial step in the overall enhancement of diversity and inclusion would be taken if all engineering institutional owners of the individual control volumes were to endeavor to reach a **parity objective**, which is ensuring that output and input flow rates are **demographically invariant**. This principle originates from seeking optimal efficiencies. At the very least, it can help complement and improve local intervention approaches. But more importantly, its universal adoption will help bring in an important change in the engineering graduate demographics and help maximize the nation's economic competitiveness.

It should be added that the present argument assumes that every student input, regardless of demographic identity, is ready or prepared for the curriculum and that there is no difference in expectation of success on the basis of demographic group. While this can perhaps be safely assumed in relatively selective institutions, in open access or less selective institutions, control volumes may vary quite a bit, and the interventions necessary to achieve parity may include additional components. In either case, best control practices will likely also involve support programs, extra/co-curricular activities, or other non-course elements, which must also use best practices to ensure demographic invariance. approaches.

The views shared in this white paper are intended to be part of, and help to stimulate, a broader national conversation and proactive agenda for further enhancing diversity and inclusion in engineering education and the engineering workforce. The authors encourage the sharing of other view points and calls to action within the engineering community to advance this issue. The recently developed best practices site may be used to facilitate this ongoing national dialog and the sharing of ideas and proposed actions.

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