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 challenge 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.

Motivation and Background

There is a critical need for more students with engineering majors to enter into, matriculate, and graduate from postsecondary institutions. Increasing the diversity in the engineering workforce is also a profoundly identified need [1], [2]. Recent research has indicated that students who are strong problem solvers, and who understand how to seek assistance and navigate college campuses, are most likely to persist to degree completion. However, on average, there is a persistent difference in degree attainment among different demographic groups. Figure 1 shows data compiled by ASEE over the 10-year period of 2005 – 2014 for differences in engineering degree attainment-to-enrollment ratios for various demographic groups (see Profiles of Engineering and Engineering Technology Colleges [3]; similar data are also distributed by the

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NSF in its Women, Minorities, and Persons with Disabilities in Science and Engineering Digest [4]).[3] The differences in the percentages give an indication of the increased retention or attrition, respectively, of various demographic groups relative to other groups in earning the degree once enrolled. The data do not correspond to a specific cohort, but rather show the aggregate averages between 2005 – 2014 of all students in the particular demographic group enrolled and the aggregate of those graduating (e.g., Hispanics comprise 9.27% of all undergraduate students enrolled in ASEE engineering colleges and programs but only 7.5% of those who successfully attained a Bachelor's degree in engineering during the same period, resulting in a negative difference of 1.77). Larger or smaller ratios are indicative of higher or lower success rates, respectively. There is a consistent lag in disparity for all degrees for Hispanic Americans (-1.77 difference from a hypothetical parity baseline for the Bachelor's degree, -1.24 for the Master's degree and -1.11 for the PhD degree). Other differences show a consistent tendency among other sociodemographic groups, including a significant disparity for women earining Ph.D. degrees. Negative differences in the enrollment and attainment percentages indicate higher attrition (or lower retention) for the demographic group relative to the parity baseline. These ratios will also be reduced if the enrollment of the demographic group has increased significantly over the time period being aggregated, i.e., graduation lags behind admissions even with good retention. Cohort-specific data can be obtained by individual schools and would be worth analyzing for the same.

An alternative way to show this effect using the same data is by considering the attainment-to-enrollment ratio (Figure 2), with the ideal achievable ratio being 0.25 for Bachelor's degree (4 years in residence), 0.75 for a Master's degree (1.5 years in residence) and 0.2 for a PhD degree (5 years in residence). Hispanic groups show a persistent lag in all categories. Likewise, the Bachelor's and Master's degree ratios for African Americans are comparable to Hispanic Americans and are significantly lower than other demographic groups.

These figures show the challenges facing engineering institutions' abilities to (a) attract diverse and often non-traditional students to a broad array of college campuses, and (b) once admitted, to assist such students to matriculate and graduate with engineering majors [5-7]. In research on diversifying the engineering workforce, Chubin, May, and Babco [8] identify various key priorities. Two such priorities focus specifically on the climate of engineering education environments and retention. Being underrepresented in a particular field can influence the ways

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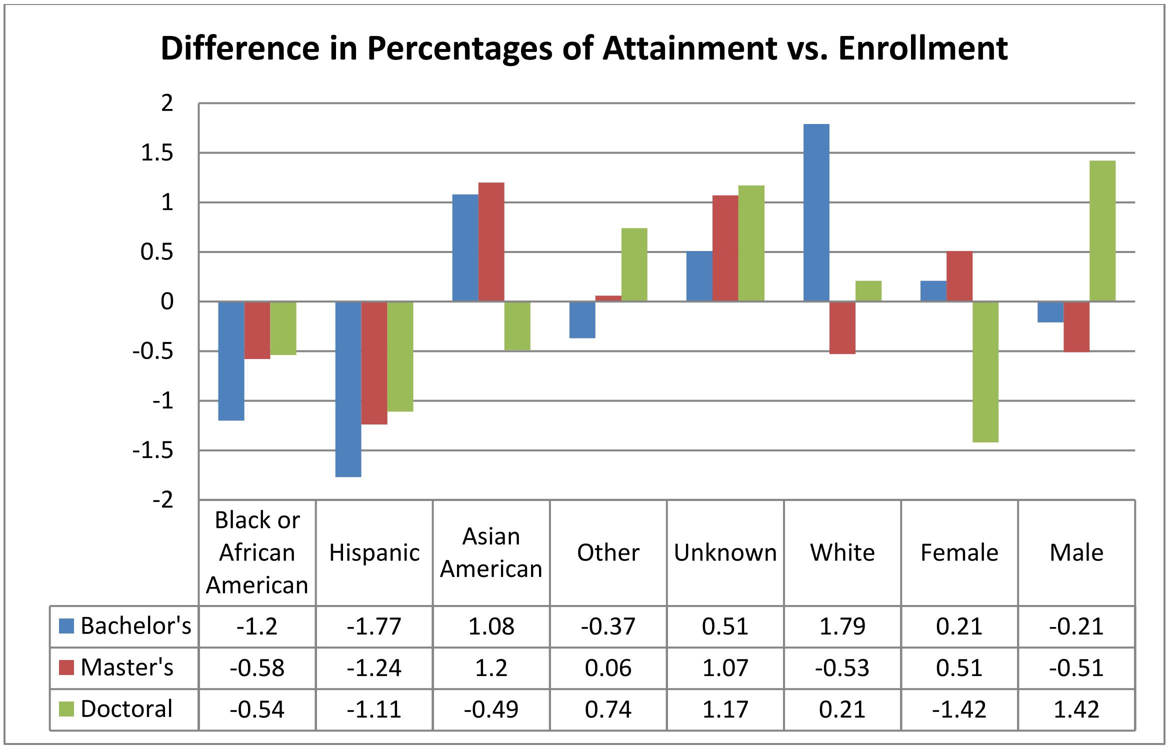
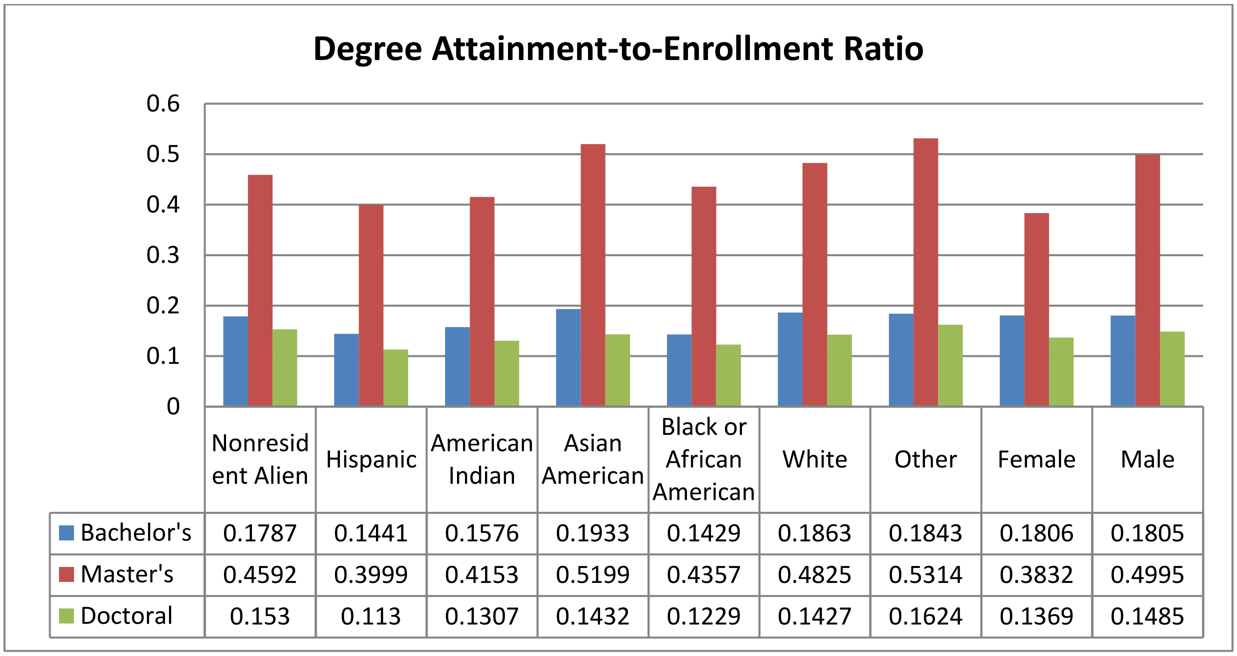
[3] For the ASEE data, ethnicity is based on the following categorization: *Hispanic* (or Latino)—a person of Cuban, Mexican, Puerto Rican, South or Central American, or other Spanish culture or origin, regardless of race. Data on ethnicity do not include foreign nationals. Race is based on the following five categorizations: *American Indian*—a person having origins in any of the original peoples of North and South America, and who maintains tribal affiliation; *Asian*—a person having origins in any of the original peoples of the Far East, Southeast Asia, or the Indian subcontinent; *Black or African American*—a person having origins in any of the black racial groups of Africa; *Native Hawaiian or Other Pacific Islander*—a person having origins in any of the original peoples of Hawaii, Guam, Samoa, or other Pacific Islands; *White*—a person having origins in any of Europe, the Middle Ease, or North Africa. The *Two or More Races* category includes any combination of two or more races and not Hispanic ethnicity; the *Nonresident Alien* category includes persons not reporting race and ethnicity (unknown). In Figure 1: *Other* includes American Indian, Native Hawaiian or Other Pacific Islander, and Two or More Races; *Unknown* includes persons not identified with a particular demographic group (but does not include foreign nationals). In Figure 2: *Other* includes Native Hawaiian or Other Pacific Islander and Two or More Races.



	Black or African American	Hispanic	Asian American	Other	Unknown	White	Female	Male
🟦 Bachelor's	-1.2	-1.77	1.08	-0.37	0.51	1.79	0.21	-0.21
🟥 Master's	-0.58	-1.24	1.2	0.06	1.07	-0.53	0.51	-0.51
🟩 Doctoral	-0.54	-1.11	-0.49	0.74	1.17	0.21	-1.42	1.42

Figure 1: Difference in percentages of degree attainment and enrollment for various demographic groups from 2005 – 2014 for Bachelor's, Master's, and Ph.D. degrees, respectively.



	Nonresident Alien	Hispanic	American Indian	Asian American	Black or African American	White	Other	Female	Male
🟦 Bachelor's	0.1787	0.1441	0.1576	0.1933	0.1429	0.1863	0.1843	0.1806	0.1805
🟥 Master's	0.4592	0.3999	0.4153	0.5199	0.4357	0.4825	0.5314	0.3832	0.4995
🟩 Doctoral	0.153	0.113	0.1307	0.1432	0.1229	0.1427	0.1624	0.1369	0.1485

Figure 2: Degree attainment-to-enrollment ratio for various demographic groups averaged over the 10-year period from 2005-2014 for engineering Bachelor's, Master's, and Ph.D. degrees, respectively. The ideal achievable ratio is 0.25 for Bachelor's degree (4 years in residence), 0.75 for a Master's degree (1.5 years in residence) and 0.2 for a PhD degree (5 years in residence).

in which students navigate engineering programs. Accordingly, higher education institutional structures, policies, and practices should be designed to assuage barriers that impede degree attainment for underrepresented students [9]. In addition to a comprehensive curriculum, factors such as socialization, sense of belonging, professional identity development, diverse and inclusive environments, are equally vital to the success of students. Although the responsibility of the educational transformation of students sits with a number of institutional units, this white paper emphasizes the role of engineering schools and programs in achieving such a transformation.

Motivated by the above challenges, this paper provides an approach that formulates the problem using a "chemical reaction and flow" process model. The approach decomposes the overall engineering education pipeline in terms of individual "control volumes", and articulates the establishment of a *parity* principle that relates the input and output demographics. At the least, this principle can be viewed as one of maximizing "process efficiency", which should be a logical objective for any educational provider, and particularly of engineering schools, in addition to enhancing access. Adoption of such a principle automatically implies the need to introduce and implement "control practices" to help achieve the desired outcomes. Indeed, if parity were to be achieved while maintaining the highest ratios of any demographic group for each degree, a significant increase in degrees attained by African Americans, Hispanics, and other populations would also be achieved, making a non-trivial impact on increasing the diversity of the engineering pipeline at all levels.

Educational Transformation Modeled by Chemical Reactions and Flow Processes

The essence of education both at P-12 and university levels is the process facilitating learning [10-11]. Education can also be viewed as a process that augments an individual's state of knowledge, mindset and skillset. We borrow chemical reaction formalism to schematically depict this transformation as the following "chemical reaction"

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

Here, A denotes an education measure of the prior state (that of the "reactant"), and A^* the corresponding measure of the final state (that of the "product"). 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 process efficiency can be likened to a "reaction efficiency", dictated by the kinetics and other parameters.

In Equation (1) above, we have used k to denote the influence of a number of factors—from pedagogical to delivery methods—that affect the extent of this transformation. This notation lumps into one symbol, k, an equivalent "kinetic effect", from the quality of instructor to teaching approaches, environment and culture. While we are acutely aware of the risks that this chemical reaction analogy entails (including the simplistic manner in which stoichiometry is treated, the lack of specificity regarding symbol *, etc.), our goal 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. This is particularly useful in the context of the present paper.

Traditional education providers, such as bricks-and-mortars universities, have as an ultimate objective to impart at the highest rate and efficiency possible an educational transformation in 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. 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 that described by Equation (1) above. 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 3a illustrates using the chemical reactor analogy. The notation $f_i(x)$ and $f_o(x)$ denote the input and output demographics, respectively.

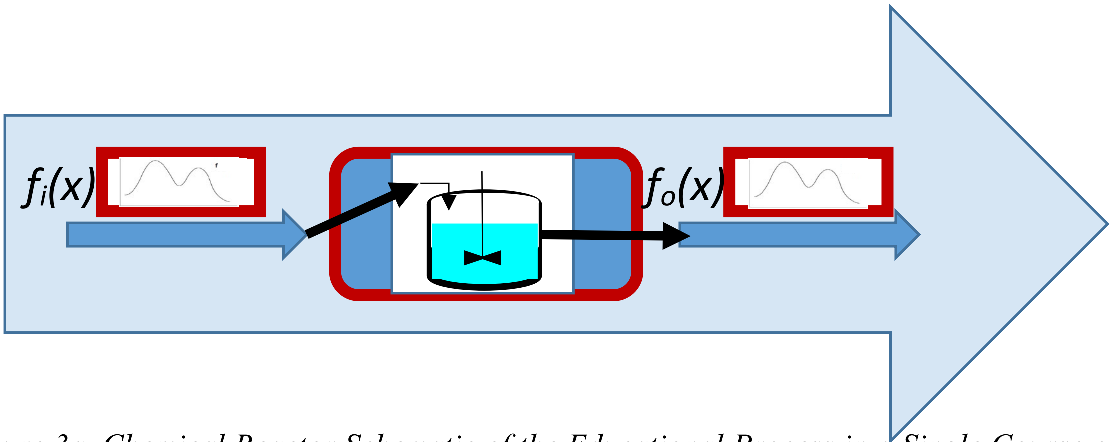


Figure 3a. Chemical Reactor Schematic of the Educational Process in a Single Course of Study. The probability density functions at the input and output are meant to characterize demographic compositions prior to and after the class. Within the chemical reactor, a reaction described by Equation (1) is assumed to occur.

Traditional educational providers require a minimum level (passing grade) before the student is allowed to enroll in another course in a particular sequence. A collection of prescribed courses over a fixed time period (e.g., over four years in a standard undergraduate university curriculum), can also be viewed as a sequence of reactions and reactors, as indicated in Figure 3b. Such a flow process taken successfully by students 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 contribute significantly to the educational transformation process and ultimately to graduation. 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.

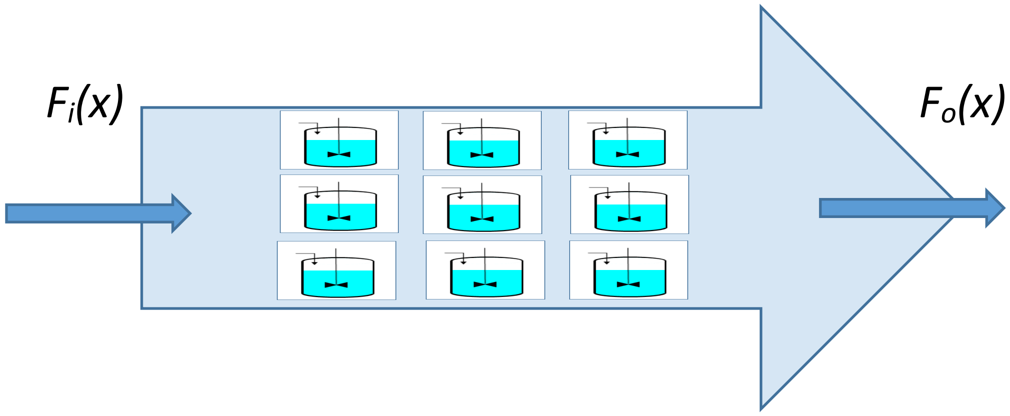


Figure 3b. Flow and Reaction Schematic of the Educational Process in a Curriculum (namely within each of the "Control Volumes" of Figure 4 below). The probability density functions $F_i(x)$ and $F_o(x)$ at the input and output are meant to characterize demographic compositions at admission and at graduation. Within each chemical reactor, the process described in Equation (1) and in Figure 3a 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 complex. In any attempt at their description and design one must account for behavioral and or cognitive, organizational, social, economic and possibly policy/political phenomena [12]. 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 will borrow the flow and reaction process analogy described above in order to derive as many objective benefits as we can from such a description. Importantly, parallels of design, measurement, assessment and control can be fruitfully developed using such an analogy in the presence of such complications. 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.

The latter can principally involve coursework (e.g., for a Master's degree) or the pursuit of scientific research (e.g., for a Ph.D. degree), which conditions graduation and the award of the degree on novel scholarly outcomes based on the assessment of academic experts. 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 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.

By following the chemical flow and reaction analogy, we can then model a traditional engineering education in terms of a generic "flow diagram", as shown in Figure 4. The overall process consists of individual "control volumes", denoted in Figure 4 as Pre-college ("P-12"), Community Colleges ("CC"), Undergraduate Programs ("UG"), Graduate Programs ("G"), the "Engineering Workforce", and Faculty ("F"). Within each of the control volumes is a sequence of "chemical reactors", where the educational transformation takes place following the analogy depicted in Figure 3b. The directional arrows in Figure 4 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.

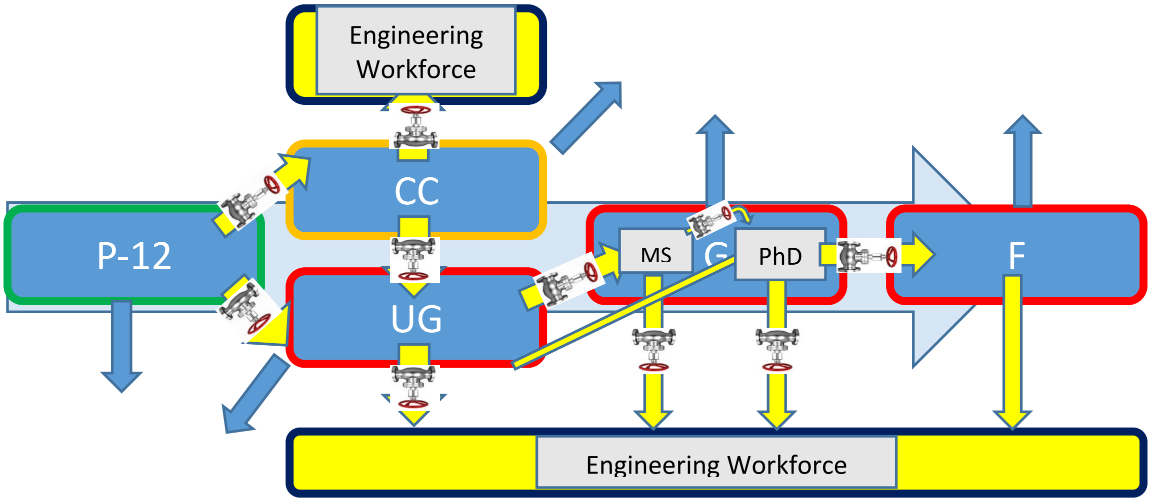


Figure 4: A schematic description of the engineering "pipeline" in terms of a flow and reaction process consisting of interconnected control volumes.

Ownership/Accountability and Achieving the Parity Objective

The remaining discussion is devoted to the process as it applies to 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, and will focus on 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 the latter.

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 4), and (2) the reaction process (reactors in the schematic of Figure 4). We note the following: (a) 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). (b) 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 one should note that 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 over 210 engineering schools, such outreach is specifically designated in the pledge as two of the four action items [13]. 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 volume*s a college or university owns. Viewed strictly from a mechanistic perspective, it is only logical to articulate a fundamental principle—the ***parity objective,*** which is a 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 3b 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 discussed in the motivation section of this paper. It must be stressed 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), should also own and strive for the process and reaction efficiencies to be as high as possible through each of the control volumes owned.

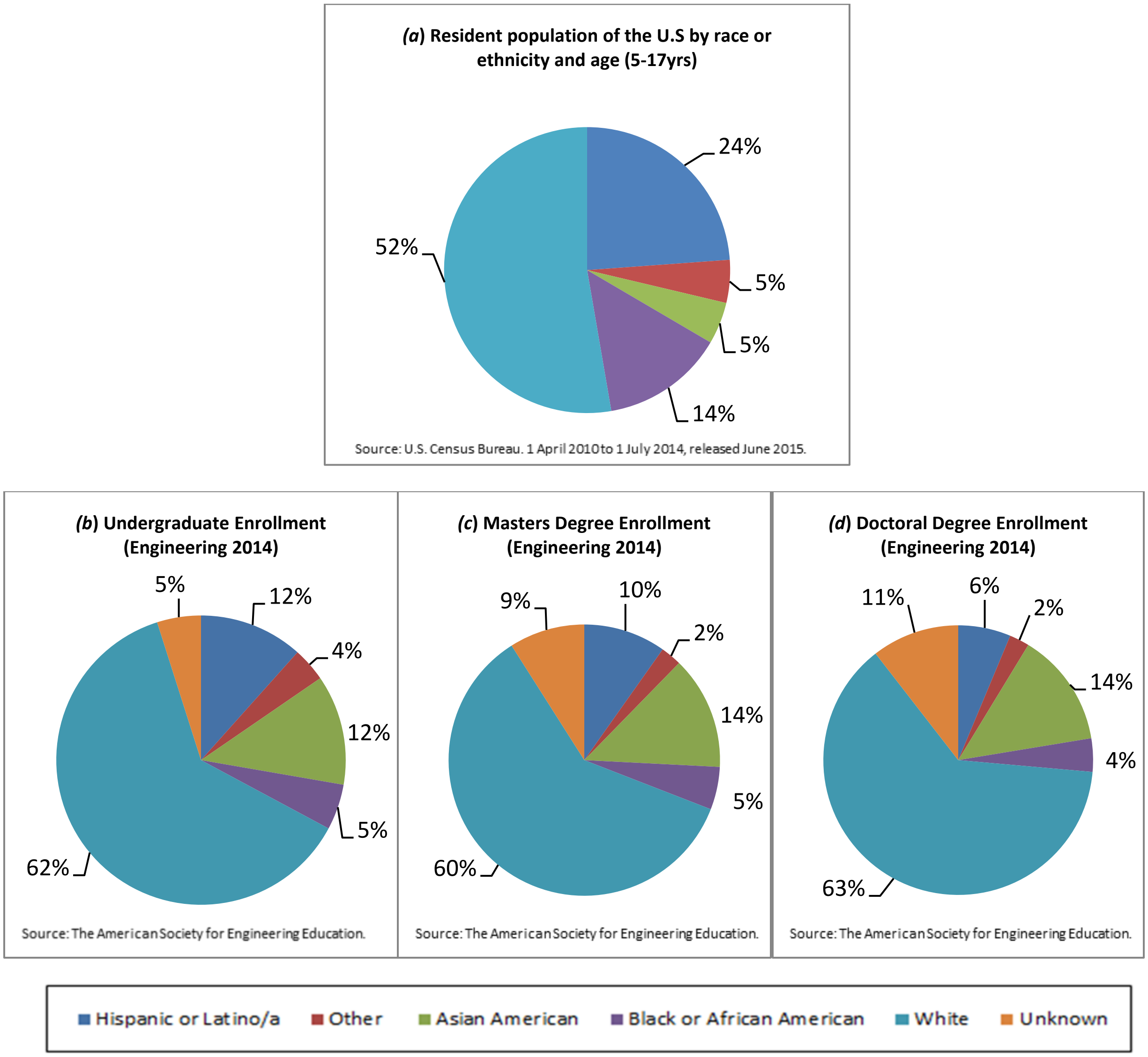
An obvious measure of increased efficiencies in colleges and universities then is that output measures (e.g., graduation rates) should be *demographically invariant*. Viewed from this perspective of "control", this implicitly calls for the implementation of existing, and/or for the discovery of new, best practices (the "control strategies") needed to meet this objective, as illustrated in Figure 5.

Figure 5: 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 earlier). 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 4. 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.


(*a*) Resident population of the U.S by race or ethnicity and age (5-17yrs)

Source: U.S. Census Bureau. 1 April 2010 to 1 July 2014, released June 2015.

(*b*) Undergraduate Enrollment (Engineering 2014)

Source: The American Society for Engineering Education.

(*c*) Masters Degree Enrollment (Engineering 2014)

Source: The American Society for Engineering Education.

(*d*) Doctoral Degree Enrollment (Engineering 2014)

Source: The American Society for Engineering Education.

**American Indian, Hawaiian/Pacific Islanders and Two or More are combined in Other.*

Figure 6: Breakdown by ethnicity, gender and race for (a) resident U.S. population of ages 5-17, (b) Bachelor's enrollment in engineering, (c) Master's enrollment in engineering, and (d) Ph.D. enrollment in engineering in 2014.

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 [4] (Figure 6). 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 [13] does contain such an acknowledgement of the importance of the P-12 outputs, which is consistent with this white 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 equity 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-curriculars, 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. A recently developed best practices site may be used to facilitate this onging national dialog and the sharing of ideas and proposed actions.

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