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Curricular Complexity as a Metric to Forecast Issues with Transferring into a Redesigned Engineering Curriculum

Dr. David Reeping, Virginia Tech

Dr. David Reeping is a Postdoctoral Associate in the Bradley Department of Electrical and Computer Engineering at Virginia Tech. He earned his Ph.D. in Engineering Education from Virginia Tech and was a National Science Foundation Graduate Research Fellow. He received his B.S. in Engineering Education with a Mathematics minor from Ohio Northern University. His main research interests include transfer student information asymmetries, threshold concepts in electrical and computer engineering, agent-based modeling of educational systems, and advancing quantitative and fully integrated mixed methods.

Dustin Grote

Dustin currently serves as the Graduate Research Assistant for the Virginia Tech Network for Engineering Transfer Students (VT-NETS) Program with the Engineering Education Department at Virginia Polytechnic Institute and State University. His research focuses primarily on access issues for underrepresented/minority and low income students to bachelor degrees through community college pathways, curricular complexity for transfer pathways into engineering, higher education policy as barriers to access, and assessment and evaluation in a higher education context. Dustin is currently pursuing completion of a PhD in Higher Education with an emphasis in Research, Policy, and Finance. Prior to starting the PhD program, Dustin has worked in a variety of roles in admissions, recruitment and outreach for an array of public and private universities, community colleges, and for the department of higher education in Colorado. Beyond academia Dustin enjoys spending time outdoors hiking, mountain biking, skiing and playing sports with his wife, son, and dog.

Dr. Lisa D. McNair, Virginia Tech

Lisa D. McNair a Professor of Engineering Education at Virginia Tech and Director of the Center for Educational Networks and Impacts (CENI) at the Institute for Creativity, Arts and Technology (ICAT). She develops integrative education projects that transverse perspectives within and beyond the university. Her currently funded NSF projects include revolutionizing the VT ECE department, identifying practices in intentionally inclusive Maker spaces, and exploring professional identity development in Civil Engineering students with disabilities. Her work in CENI focuses on building networks between the University and multiple community sectors and supporting engagement in science, engineering, arts, and design. ORCID: https://orcid.org/0000-0001-6654-2337

Prof. Thomas Martin, Virginia Polytechnic Institute and State University

Tom Martin is a Professor in the Bradley Department of Electrical and Computer Engineering at Virginia Tech, with courtesy appointments in Computer Science and the School of Architecture + Design. He is the co-director of the Virginia Tech E-textiles Lab and the associate director of the Institute for Creativity, Arts, and Technology. He received his Ph.D. in Electrical and Computer Engineering from Carnegie Mellon University and his B.S. in Electrical Engineering from the University of Cincinnati. His research and teaching interests include wearable computing, electronic textiles, and interdisciplinary design teams for pervasive computing. In 2006 he was selected for the National Science Foundation's Presidential Early Career Award for Scientists and Engineers (PECASE) for his research in e-textile-based wearable computing.

Curricular Complexity as a Metric to Forecast Issues with Transferring into a Redesigned Engineering Curriculum

Abstract

This paper details quantifying the interconnectedness of a curriculum. We draw from Heileman's Curricular Analytics tool and the curricular complexity metric. We extend this metric to highlight how it can be used to forecast issues in transfer student experiences in redesigned curricula. We focus on structural complexity in this paper by consolidating transfer student pathways using plans of study from the Department of Electrical and Computer Engineering at a four-year institution, Virginia Tech, undergoing a large-scale programmatic change, with those from the department's feeder community colleges. We transformed the 24 pre and post-change prerequisite structures in the plans of study into networks, allowing for graph-theoretic metrics to be calculated and compared (pre-/post-change). These networks enabled us to identify bottlenecks in the curriculum and negotiate how transfer students could be supported in the new program. We discuss extensions to the curricular complexity approach, like using agent-based modeling to simulate student flow through a curriculum and predicting four, five, and six-year graduation rates.

Introduction

In designing curricula, it can be easy to focus on the experiences of first-time-in-college (FTIC) students. However, this focus is an idealization - as messaging about engineering from the first year is a critical junction for how students make decisions about persisting in an engineering program [see 1]. Not everyone has the opportunity or chooses to begin at a four-year institution. The National Student Clearinghouse [2] reports that, in the previous ten years, 49 percent of students who completed a bachelor's degree at a four-year university in the 2015-2016 academic year had also enrolled in a community college (two-year institution) for at least one semester. For those looking to revise their curriculum substantially, thinking about how to bridge transfer students into the new curriculum is a vital criterion to consider.

Despite the prevalence of transfer, enrolling in a four-year institution from a community college is still fraught with complications, which large-scale curricular changes exacerbate. Students are deluged with policies, resources, and advice during transfer – making it a complicated process for students to manage [3,4]. Relations between community colleges and four-year institutions can be tenuous, leading to inadequate information sharing between institutions and decreased quality of information given to the student through community college advising [5]. These complications could result in undesirable outcomes like losing credits – about 13 credits on average by one estimate [6] – or having the transferred credits not apply to degree requirements. Instead, credits could be designated as part of their electives, which Kadlec and Gupta [7, p. 7] describe as an "academic graveyard."

Students tend to rely on the information provided through the institutional website to navigate their transfer experience [8]. However, web-based transfer information tends to be scattered and written using hand-waving language at four-year institutions [9]. Moreover, the information on community college websites leaves much to be desired [10,11]. Lack of consistent, up-to-date information on articulation policies and contradicting information across webpages in one or more university websites are some common issues across both types of sites [see 9,10,11].

Transferring into engineering is particularly tricky for transfer students. There are different ways in which students can matriculate into their majors [12]. Also, the first-year experience can vary by institution and matriculation model [13] – adding further complications. Considering that information flows between four-year institutions and community colleges can be lackluster [5], students might be caught in a compromising position where their earned credits are incompatible with a revised curriculum. Forecasting these issues can provide an opportunity for collaborative discussions between community college partners and among faculty on how to best support incoming transfer students. We contend a quantitative approach to measuring curricular complexity could aid in understanding potential issues for transfer students.

Research Aims

The purpose of this paper is to demonstrate the value of the curricular complexity measure – specifically a component called the *structural complexity* – developed by Heileman et al. [14,15] in forecasting how programmatic changes could impact different populations of students, with a focus on transfer students. We overview the method, an application of using curricular complexity in practice, and a discussion on how the metric can be extended for further analysis.

Curricular Complexity

Here we will discuss the premise of curricular complexity as is it implemented in the Curricular Analytics [16] webtool (available at: curricula.academicdashboards.org). Curricular complexity is derived from two measures, the structural complexity and the instructional complexity.

Structural Complexity

Structural complexity can be calculated using existing data – plans of study for a degree program. Structural complexity quantifies the pre- and co-requisite structures in a curriculum to determine how interconnected the courses are. Adopting the Heileman et al. [14,15] curricular complexity framework, we represent the curriculum as a network composed of vertices and edges. The quantification of the curriculum is accomplished by treating each course as a vertex in the network. We then link any course with prerequisites or co-requisites using a directed edge leading from the subordinate course to the following course in the sequence. For example, Calculus I is a prerequisite for Calculus II. Therefore, an arrow would point from Calculus I to Calculus II in the network. While we can visually arrange the courses into the semester in which they are intended to be taken, the calculations in the base measure do not require chronological ordering. Advanced calculations *will* require chronological ordering, however.

Each course has a level of “cruciality” [14], which is calculated by considering two properties of the course relative to its position in the curriculum network. The first is the course’s “blocking factor.” The blocking factor refers to the number of courses inaccessible to students who fail the course in question [17]. The second is the course’s “delay factor.” The delay factor refers to the longest prerequisite chain to which the course belongs. The course's cruciality is then the sum of the blocking factor and the delay factor. This process is demonstrated in Figure 1 for the course shaded in gray. Summing all the course cruciality scores then yields the structural complexity for the curriculum.

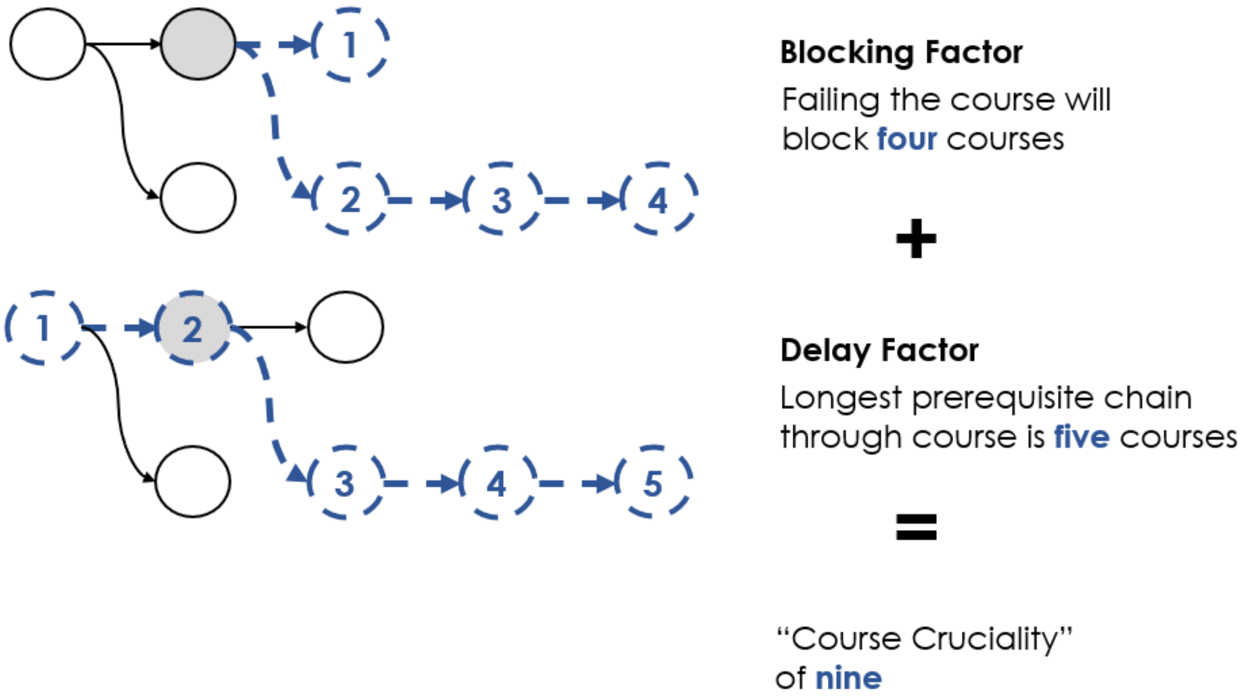


Figure 1: Calculation of course cruciality for an arbitrary course

We can also discuss the sub-complexity of a course. The sub-complexity is analogous to the structural complexity of the entire curriculum, but we only consider the prerequisite structure of one particular course. After picking a course to compute the sub-complexity, we remove any course that is not included in the chosen course's prerequisite structure. Next - recalculate the blocking and delay factors for all the remaining courses, then add these quantities to yield the sub-complexity.

The sub-graph used to compute the sub-complexity allows the researcher to discuss a set of courses beyond individual course cruciality values. While the sub-complexity conveys similar information as the course cruciality, examining sub-sets of courses reveals large webs of prerequisite structures where students could get stuck. The sub-complexity of a course can be found automatically in the Curricular Analytics tool by hovering the mouse over the course you want to consider.

The value in calculating the structural complexity is that we can compare curricula across programs [e.g., 17]. We can also correlate the structural complexity with completion rates, which has been shown to be a negative relationship. That is, the higher the structural complexity, the lower the completion rates (e.g., four-year graduation rate) – which has held in simulations [14,18]. The negative relationship has also been corroborated empirically at a large mid-Atlantic institution, Virginia Tech. The authors compared four, five, and six-year graduation rates on all majors in the institution's College of Engineering with the respective structural complexity of each major's plan of study [19]. Structural complexity has also been associated with program quality – revealing that lower-quality programs tend to have higher structural complexities [20]. These initial applications begin to illustrate how the curricular analytics framework can be used to address practical educational research questions, especially in the effort of forecasting issues in a curricular redesign and structural complexity's effect on transfer students.

Other Metrics

More calculations can be made on the structural components of the curriculum graph. For example, the 'reachability' of a course is the dual of the 'blocking factor.' To calculate the reachability of a course, we count the number of courses that must be completed to enroll in the course we're considering [14]. The reachability measure provides similar information as the blocking factor, but from a different perspective. As part of the structural complexity, however, it is redundant.

Another metric that can be used is the 'degrees of freedom' of the curriculum, an allusion to the statistical and mechanical concepts relating to the number of components or variables allowed to vary in a system. In the complexity measure, the degrees of freedom quantity refers to the total number of unique ways a curriculum can be rearranged term-by-term while keeping logical prerequisite structures [14]. This measure provides insight into how much flexibility students have in designing their plans of study, such as delaying a certain course to a later semester that they deem to require more attention or allowing space to retake courses they failed. Curricula with few long prerequisite chains tend to have higher degrees of freedom than those with long, interconnected chains.

Finally, Heileman et al. [14] describe the 'centrality' of a course. A course has high centrality if it has several foundational courses as prerequisites and serves as a prerequisite itself for several courses in the junior and senior years. Social network analysis lends us several useful definitions of centrality, but 'betweenness centrality' works well to capture this type of 'center.' In betweenness centrality, vertices that often serve as bridges in the network are considered to have high 'centrality' [21]. An example of a vertex with high betweenness centrality is like a translator who connects the leaders of two groups who speak different languages. Once the translator explains what one leader said to another, the other leader relays the message to his/her group. The translator does not interact with the groups directly beyond the leaders, but allows communication to flow freely between them – this is the premise of high betweenness centrality. Heileman et al. [14] restrict the calculation somewhat by considering the centrality of a course to be the number of 'long' paths including the course. While these measures are useful in exploring individually, they were found to provide redundant information when considered with the delay and blocking factors [14].

Instructional Complexity

The second component of curricular complexity is instructional complexity. Unlike structural complexity, which can be entirely determined by examining the prerequisite structures present in a curriculum, the instructional complexity intends to capture the curriculum's qualitative components. Heileman et al. [14] admit this is a difficult task, especially in terms of quantifying latent qualities of such a system. Like structural complexity, we associate each course with a measure that reflects its position in the overall curriculum – however, it does not appear to have a specific name like 'cruciality.' The individual course instructional complexity is proxied by the pass/fail rate of the course. One could find the average pass/fail rate for the curriculum, mirroring the use of summing blocking and delay factors to calculate structural complexity, but this could be a weak measure. Order and concurrency or courses should matter in simulating student movement through the curriculum. That is, taking three courses with high pass/fail rates versus taking two courses with low pass/fail rates and one with a high/pass-fail rate are different circumstances. Future work can serve to elaborate on different aspects of instructional complexity and appropriately quantify them for analyses.

Applying Curricular Complexity in Practice

To show how curricular complexity can be used in practice as a forecasting tool, we provide an example of how the method was used to assess how transfer students would be affected by a large-scale curricular change in the department. We draw from an evaluation conducted as part of the Revolutionizing Engineering Departments grant in the Department of Electrical and Computer Engineering at a large mid-Atlantic institution, Virginia Tech [22]. The department had recently overhauled the entire second year of the degree program [see 23], creating a highly interconnected set of seven *base courses* students must pass in order to advance into upper-level courses. These seven courses include an Introduction to ECE Concepts course, the first block of three courses (Fundamentals of Digital Systems, Circuits and Devices, and Computational Engineering), followed by a second block of courses (Embedded Systems, Physical Electronics, Signals and Systems, and Integrated Design Project). This shift was designed to create a 'cohorting' effect so students would build a community between electrical engineering and computer engineering. Before the programmatic change, students in the two majors took few required courses together in the same semester. The department wanted to ensure the new courses exposed students to a broader spectrum of ECE before they matriculated into their major of choice.

We wanted to explore the extent to which we simplified the curriculum and how non-traditional populations, specifically transfer students, would be impacted by the programmatic shift. This question was well suited to the curricular analytics framework.

Data Collection and Analysis

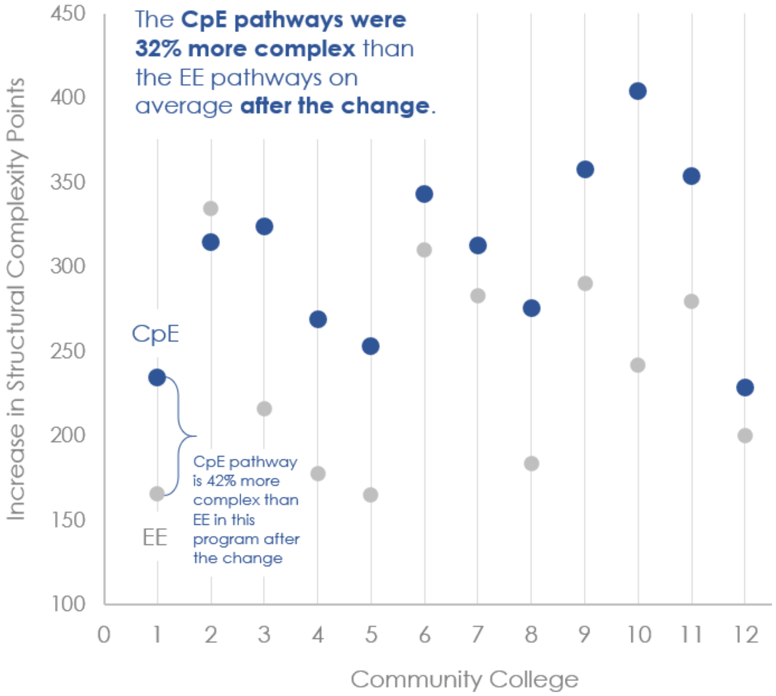
We consolidated plans of study outlining the required courses in Electrical and Computer Engineering at the four-year institution, Virginia Tech, before and after the curricular change. We also collected community college plans of study from which the department had received students – based on the current enrollment. Of the 144 transfer students enrolled in the department, twelve of their sending institutions were applicable to this evaluation.

We then found the Associate of Science degree in engineering plans of study at those twelve community colleges, substituting an electrical or computer engineering pathway for the general plan of study where one existed. The prerequisites from the community college were then mapped to the appropriate courses in the four-year institution to consolidate the two plans of study into one aggregated pathway. We assumed the worst case in constructing the pathways. Under this assumption, students would only receive general education or elective credit for the electrical and computer engineering courses they took at the community college, with none of those major-specific courses being applied to their degree. Our approach was congruent with the idea behind ‘revolutionizing’ the curriculum, in that a one-to-one mapping to previously transferrable and applicable courses should *not* exist. This process yielded 48 community college to four-year institution pathways, one set of 24 before the change and 24 after the change.

We then entered these plans of study into the Curricular Analytics site and calculated the structural complexity for each pathway. We then took the difference between the structural complexity of the new curriculum pathways and the old curriculum pathways. Crucialities and sub-complexities of the new courses were tabulated to determine if any courses were more crucial than others – despite being deemed ‘equally important’ by design.

Results of the Application

We found that the structural complexity of the entire program increased substantially from 324 to 543 (+219) in Electrical Engineering and 612 to 726 (+114) in Computer Engineering for FTIC students. Similarly, the pathways for transfer students into Electrical Engineering increased in structural complexity by an average of +240 and for Computer Engineering by an average of +300, potentially impacting completion rates and time to degree. Computer Engineering exceeded Electrical Engineering in complexity for each pathway except for one case and became 32% more complex on average. These results are summarized in Figure 2.


The **CpE pathways were 32% more complex** than the EE pathways on average **after the change**.

CpE pathway is 42% more complex than EE in this program after the change

Figure 2: Increases in structural complexity by transfer student pathway in Electrical Engineering and Computer Engineering at the four-year institution

The initial results allowed us to build an argument that transfer students would likely need different types of curricular support, as convincing the state community colleges to prepare students for such a specialized program was infeasible.

We did not stop our analysis with the overall complexities; we continued by examining the pathways themselves for how the new courses influenced the increase in structural complexity. Compared to other ECE programs, the base courses are more constrained prerequisite-wise than others. These structures have a positive intent – forming cohorts of students such that they take the same courses together and build relationships throughout their first two years. However, they create bottlenecks. Fundamentals of Digital Systems was identified to be the most crucial course in the sophomore year as the prerequisite structure prevents students from making any progress if they do not earn a satisfactory grade.

We made our inference about cruciality more explicit by examining the course crucialities and sub-complexity networks of the individual courses. The sub-complexity was found by picking one of the base courses, deleting all courses not connected to it to via a prerequisite structure, and recalculating the structural complexity. Figure 3 shows the sub-complexity for each of the new courses. The Introduction to ECE Concepts course was the most essential course, but this finding is a trivial result because the prerequisite structure bars students from enrolling in any of the following courses in the department if they do not pass the introductory course. However, the Fundamentals of Digital Systems course had a considerably more complicated prerequisite structure than the other new courses.

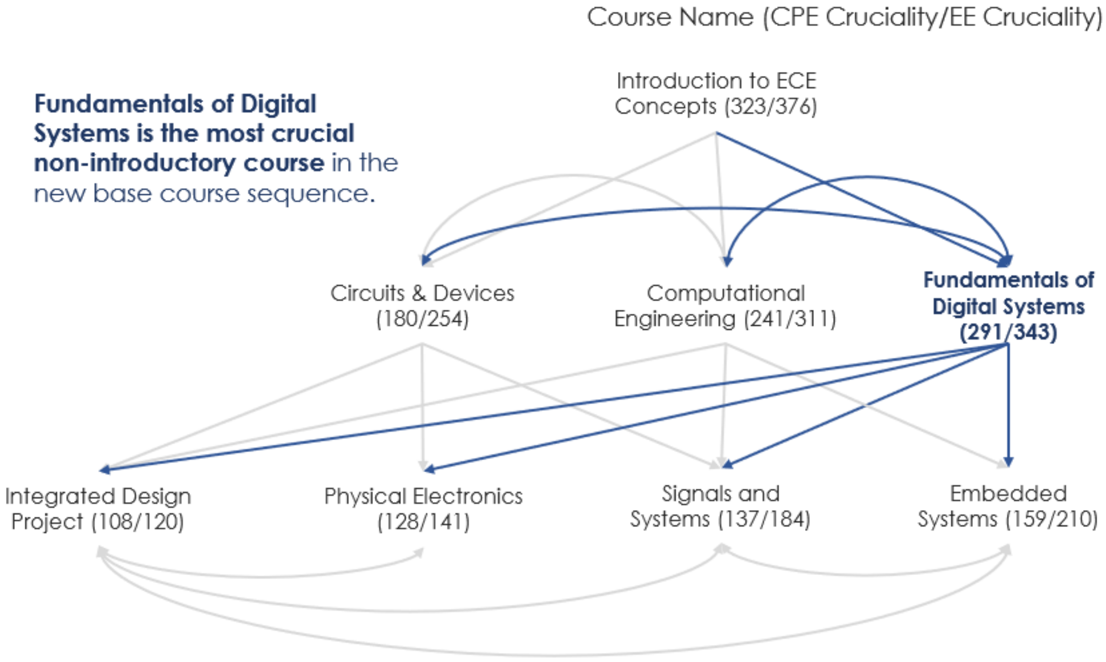


Figure 3: Sub-complexity for the new courses in the Computer Engineering and Electrical Engineering degree program with the prerequisite structure represented by arrows, Digital Systems is mathematically the most crucial course.

The sub-complexities in Figure 3 and the corresponding crucialities used to calculate the structural complexity in Table 1 tell us that failing Fundamentals of Digital Systems can be far more detrimental than failing, say, Circuits and Devices. Compared to the course cruciality scores (Table 1), the sub-complexities do not add much depth to the course's influence on the overall network – as we discussed previously. The crucialities and sub-complexity scores are almost perfectly linearly correlated ($r = 0.9975$ and 0.9840 for CPE and EE, respectively). However, we deliberately introduced the sub-complexity scores because the sub-complexity networks from which they are calculated can provide a discussion tool for practitioners.

Table 1: Comparing course cruciality to sub-complexity

Course	*CPE Cruciality*	*CPE Sub-Complexity*	*EE Cruciality*	*EE Sub-Complexity*
Introduction to ECE Concepts	32	323	33	376
Circuits and Devices	23	180	29	254
Computational Engineering	27	241	31	311
Fundamentals of Digital Systems	31	291	32	343
Physical Electronics	20	128	21	141
Signals and Systems	21	137	25	184
Embedded Systems	22	159	26	210
Integrated Design Project	19	108	20	120

For example, we can visualize the web of courses blocked by Fundamentals of Digital Systems by using the sub-complexity operation in the Curricular Analytics platform. The sub-complexity network for Fundamentals of Digital Systems is shown in Figures 4 and 5 for Computer Engineering and Electrical Engineering, respectively. The overall interconnectedness of the courses, particularly the Fundamentals of Digital Systems course is a troublesome configuration for those who do not enter the four-year institution directly – or if it is failed. The boxed course, Fundamentals of Digital Systems, blocks all of the subsequent courses in the second-year ECE program. For Electrical Engineering, the course blocks the vast majority of technical electives in the junior and senior year – exceeding the sub-complexity of any course in the Computer Engineering pathways.

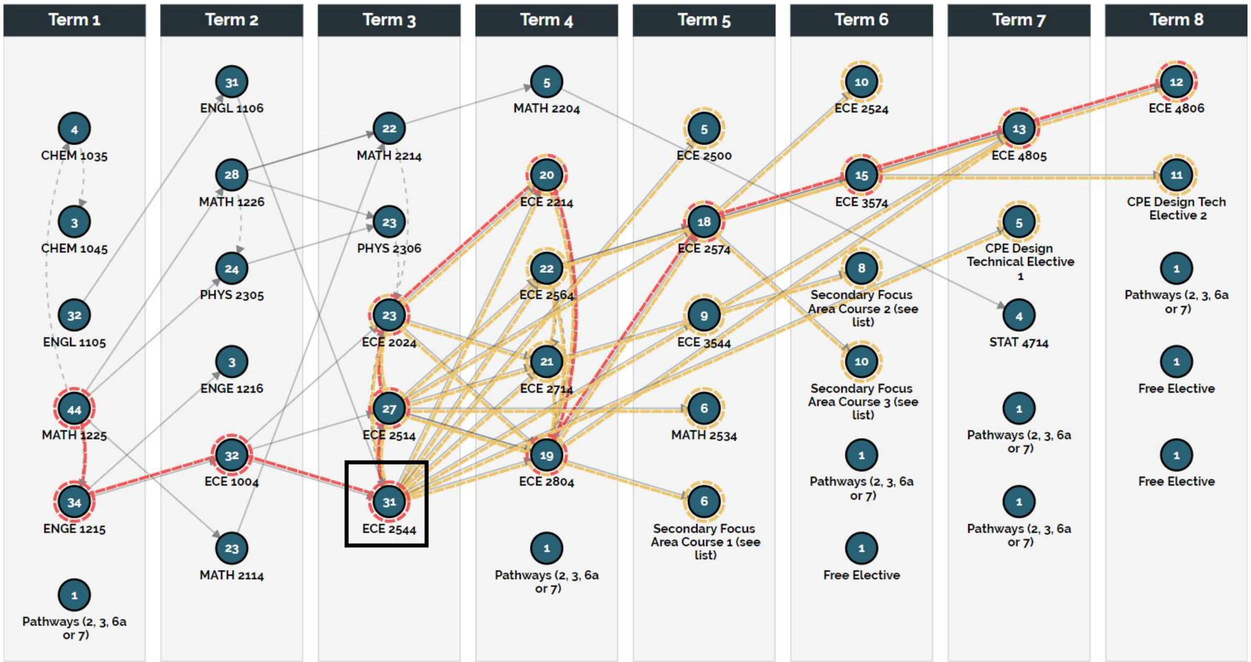


Figure 4: Screenshot of sub-complexity graph of Fundamentals of Digital Systems (boxed), the longest prerequisite chain is shown in red. New Computer Engineering curriculum shown

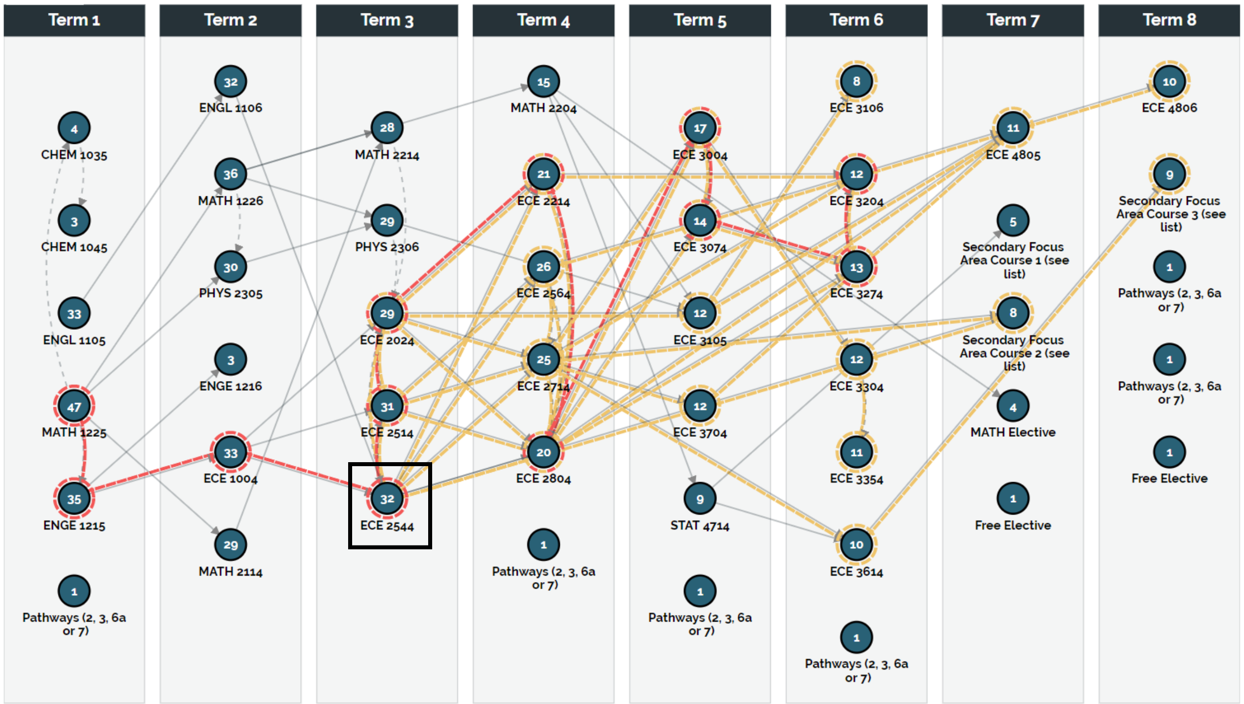


Figure 5: Screenshot of sub-complexity graph of Fundamentals of Digital Systems (boxed) from Curricular Analytics platform, the longest prerequisite chain is shown in red. New Electrical Engineering curriculum shown

Transfer students can be disproportionately affected by such structures, especially for students missing prerequisites like Differential Equations or the Introduction to Engineering course required of all engineering students, leaving them even further behind than before. This possibility can be seen in the following pathway in Figure 6, where the general Introduction to Engineering course is taken in Term 5 and the disciplinary Introduction to Engineering class for the ECE department needs to be taken by itself before getting into any of the departmental classes. These types of networks illustrate such bottlenecks in transfer student pathways and quantify the impact of the bottlenecks.

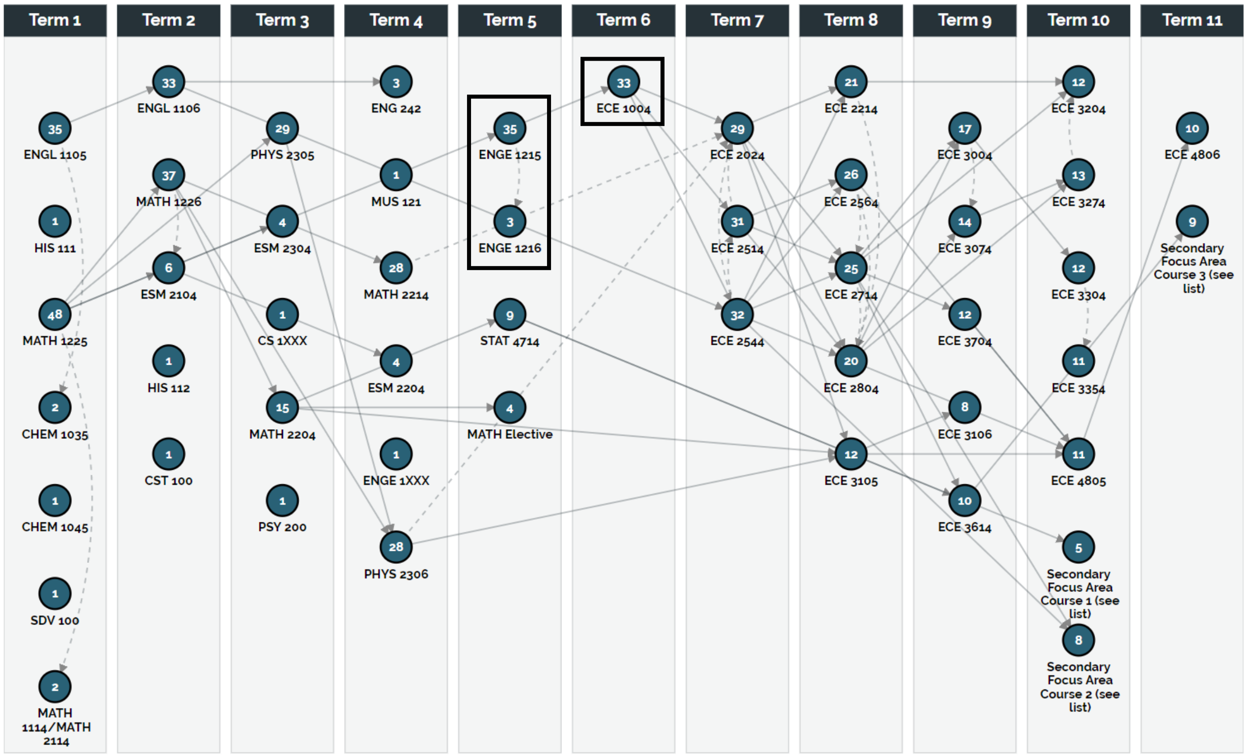


Figure 6: Example of a pathway without the Introduction to Engineering sequence (boxed) in the community college curriculum, which could lead to an increased time-to-degree

Rather than attempting to trace all the affected courses, the curricular analytics method of analysis allowed us to both identify and communicate trouble points, like Fundamentals of Digital Systems in the curriculum – including how failing such a course can cascade throughout the network. Practitioners can use these types of networks to predict issues in transfer credit, such as which courses would be blocked by rejecting the application of credit to a particular course. This type of visualization would be especially useful for advisors for both FTIC and transfer students in understanding how the students could flow through the curriculum.

Using the analyses presented in this paper, we were able to argue for broader considerations of transfer credit by working with a subset of the more typical community college pathways to map the older courses onto the new curriculum. A more typical pathway, one of the least affected pathways by the curricular change is shown in Figure 7. Note that it is ‘more typical’ because students have access to a common course load each semester they are enrolled – in contrast to

Figure 6 where 3 semesters are spent taking a small load of courses involved in a prohibitive prerequisite chain. A more extensive transfer student experience in the department is also being discussed.

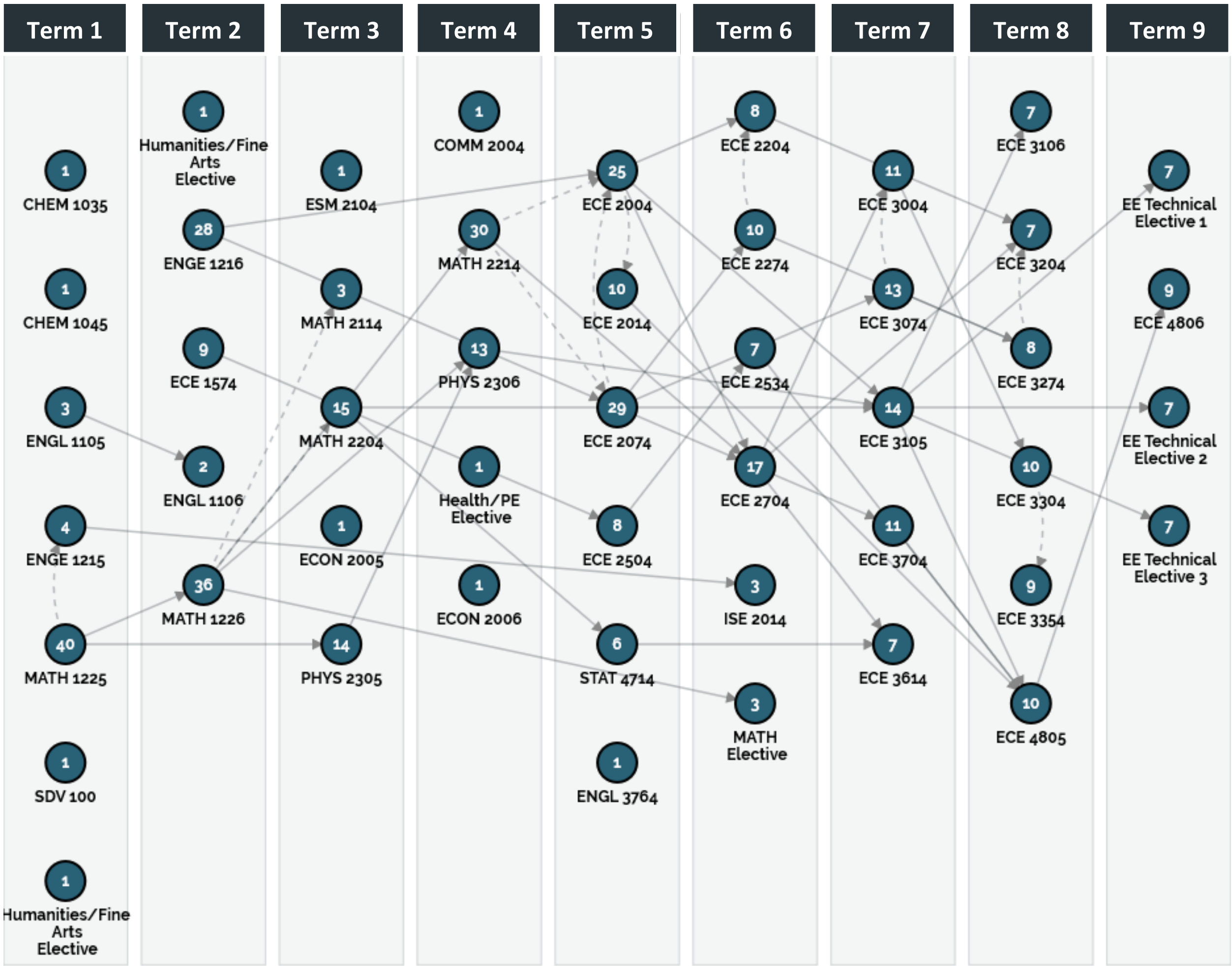


Figure 7: A screenshot of the curriculum map for a more typical transfer student pathway into the department after the change where students have access to a range of courses

Extensions to the Descriptive Approach

Currently, users are not able to simulate student flow through the curricular networks, although it has been advertised as a feature in development. This simulation would complete our analyses by complementing our descriptive results of the transfer curricular pathways using structural complexity with a predictive model for four, five, and six-year graduation rates. However, we would need to estimate what the pass/fail rates would be for the seven new courses – most of which have not been offered more than once. We would also need the pass/fail rates for the community college courses. Nevertheless, we can discuss some extensions to the curricular analytics approach.

It is unclear when the simulation feature will become available or how the simulation will be done, but we can find some quick approximations. A simple way of estimating the pass rate of the overall curriculum would be to use probability laws to calculate the joint pass rate across the different prerequisite structures. Specifically, we could treat each node as an event, passing the course, and find the probability of passing all the courses by multiplying down the prerequisite chains to the final course. This process would be an idealized way to compute the completion rate.

However, the statistic we use, the pass/fail rate, is hiding dependencies. The students did not take the course independent of others, so the pass/fail rate could be dependent upon the other courses the student took while enrolled in the class we are considering. While the plan of study outlines which courses should be taken at a given time, this is not true for all students. It might be possible to treat these variations as an admissible error in our estimates, as curricular complexity seems to correlate negatively with empirical completion rates [14,17].

Given the promising proprietary simulations [14,17], we are developing an agent-based approach in NetLogo [24] to simulate student flow through the curriculum, as it is a methodology particularly congruent with the intentions of the simulation. Agent-based modeling involves specifying a set of agents, interaction rules, and parameters to adjust [25]. We could treat students as agents moving through the curriculum with interaction rules dictating how the course-taking process is modeled. The adjustable parameters can be a vector of pass/fail rates for each course. Given the curricular analytics metrics, we can simulate students completing a curriculum and find bottlenecks to student progress. Experimental designs can also be constructed to eliminate or add certain prerequisite structures to examine how adjusting requirements affect the overall completion rate.

Conclusion

The goal of our RED project is to welcome a broader range of students into the department, expand student curricular choices, and widen the number of possible careers for graduates. The changes brought about a set of seven interconnected courses unique to the institution that all students enrolled in the department must pass to advance into their specializations. Although the change was made with positive intentions to unify a fragmented department across disciplinary lines and expose students to essential knowledge cutting across Electrical and Computer Engineering, a paradox in the goal of broadening participation emerged. How do these shifts affect the transfer population? The new courses have no direct one-to-one mapping to the previous curriculum, so transferring the old versions from a community college partner in the state would, at best, require transferring sets of courses to apply to a single class.

Accordingly, our objective was to assess the extent to which engineering transfer students could be affected by the lack of applicable credit to the new courses by using Heileman et al.'s curricular analytics framework. We calculated structural complexities from graphs of the prerequisite structures from community college pathways into the department. These prerequisite structures were found to be more complicated than their previous iterations, supporting our assertion that the new structure could crowd out transfer students.

The method of analysis was useful in quantitatively articulating concerns regarding curricular structure for transfer students and prompted the department to consider ways of integrating transfer students into the new curriculum. We offered suggestions for implementing such analyses to forecast potential issues brought about by curricular change and other extensions to the technique to simulate student movement through the curriculum.

Acknowledgments

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