STEM Education:
Navigating a Complex Network of Opportunity

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I Introduction

This paper explores the current tensions both within higher education and between education systems and society at large. These tensions lead to media portrayals and public beliefs about higher education that are not always accurate but which affect higher education policy which in turn affects education systems. Because the author's affiliation and background centers on the United States its educational systems are the focus of this article, but similar conclusions can be extrapolated to most Western democracies.

One only need look at the news to see pundits who identify myriad crises in education. What crisis one believes is most pressing depends both on one's position inside or outside the educational system as well as one beliefs about what the purpose of education should be. For example a colleague of the author sees falling standards and poor preparation of incoming students as the greatest threat to higher education. Other colleagues focus on how the university is undermining the value of a degree through grade inflation [1]. Such viewpoints are not just confined to today since the world's education systems have always seemed to exist in perpetual crisis yet still manage to educate students who contribute to society. Writings of any period of time discuss the pending crisis of preparing societies' youth, perhaps because education expresses humanity's most actionable hopes for its future and the future never seems to work out the way one planned.

The focus of this paper is not on the quality of students or standards of the academy but rather on issues of the access to and value of higher education. Here *access* means the ability to participate in a form and level of education that can make a positive difference in one's life circumstances. As the workforce increasingly shifts away from continual employment access to higher education becomes important not only in an individual's late teens and early twenties but also throughout one's life. Perhaps the most visible issue related to access is the rising cost of higher education. Cost has been much in the news as student debt has risen exceed credit card debt in the last few years in the US, over $1T[1], exceeded only by what people owe on mortgages. This level of debt has been blamed for slowing down the economy, driving down home ownership, and a flood of young people continuing to returning to their parent's homes following college [2]. The change in college costs is usually shown as a time series as shown in Figure 1. Note that the data looks different depending on whether one only looks at tuition or includes

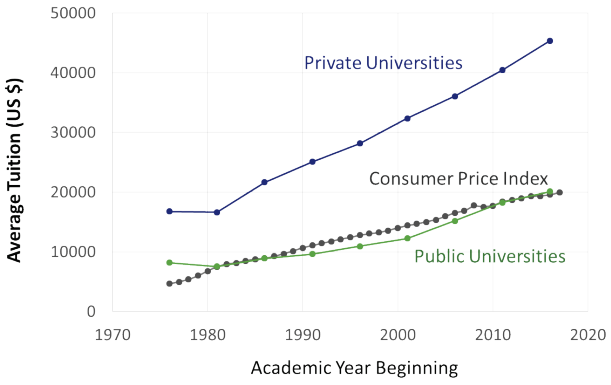

Figure 1: US college tuition costs over time [3].

[1] The notation of T for trillion, B for billion, and M for million will be used throughout this paper.

room, board, and fees. Fees in particular have risen greatly at public institutions to make up for lower state funding. Such cost increases have been particularly steep at elite private universities such as the author's. These costs are likely driven more by spending to maintain status and to administer the new programs than the cost to educate students [4].

If education were free to students and available to anyone issues of access could be eliminated, but that does not necessarily mean that such education has value to either the individual or society. Education is often taken as an unalloyed good, but education as any other process which is designed to change people does not necessarily increase *eudaemonia*, an ancient Greek word for human flourishing. If, for example, education narrowly trains individuals for nonexistent jobs it is not clear what value is created for the individual although corporate interests may benefit by having a large pool of workers to hire from thus depressing wages. Nor, as another example, does society benefit if education makes promises such as a college education ensuring a well-paying job or interesting work if these can't be delivered upon and leads to widespread dissatisfaction and perhaps civil unrest.

The two metrics of access and value are not easily quantified. Access is slightly easier since it is possible to compare costs of college, distribution of educational opportunities, and changing income distributions. To frame both access and value this paper adopts a Curt Carlson's framework for innovation – the NABC model [5]. The NABC model identifies four elements which are hypothesized as necessary to address in offering a good or service in order to create value:

- N = Need. What is the need driving demand for a good or service?
- A = Approach. How is the good or service to be created and made available?
- B = Benefit:Cost Ratio. Is the proposed good or service worth its cost?
- C = Competition. Who else can provide the good or service?

In education the need is widely accepted as a given, at least for some base level of education. The need for the current participation level in higher education is debated in the US, particularly if the purpose of education is viewed as preparing people for work. This is because while higher education is generally a prerequisite for well-paying future jobs the availability of such jobs is uncertain. In other words it is not clear that the return investment in college, which in the US still falls predominately on private citizens, will continue at its historically high levels thus affecting the benefit:cost ratio, B. In education the vast majority of effort has focused on the approach, A, and much work remains to be done on how to make education more effective. However much of the research on improving approaches has not made it into widespread practice [6]. Partially for this reason—the sense the academy is unable to change—some of the more exciting developments in higher education are in addressing the benefit:cost ratio, B, and developing new models which compete, C, with current educational systems. As will be discussed subsequently, these development have the potential to create major shifts in education. Academics generally focus on A and as will be discussed later are highly agile in devising new approaches to education but issues around B and C may shift the landscape in ways universities are less able to adjust to. While this is an exciting time in education, it is worth keeping in mind the words of the American novelist Ellen Glasgow who wrote, "All change is not growth, as all movement is not forward." Some of the competitors to universities are focused more on accessing the $1T the US spends annually on education—over 5% of GDP—than they are on student outcomes. In the US for-profit education has extremely poor outcomes [7].

The remainder of the paper looks more in depth at each the four elements of Carlson's definition of value, which is presented in the order N-B-C-A. The next section discusses the need for education from several different perspectives and is followed by a discussion of the benefit:cost ratio focusing particularly on issues of access. Competition is discussed next, particularly with regard to how technology is changing access to education. Alternative approaches that address the issues of competition and benefit:cost ratio as well new needs emerging in higher education are then discussed, and the paper concludes by summarizing the discussion, predictions for the mid-term future, and some recommendations for universities and policy makers.

II NEED

The need for education is rarely questioned in the US, particularly by those who are themselves well educated. Even those who are seeking to disrupt existing educational systems highlight the need for education. What is less often discussed is whose needs are addressed by an individual becoming educated. Various elements of society need different outcomes from education. Industry relies on education to provide basic skills for employees at all levels. Because skills with quantitative reasoning, algorithmic thinking and technology are in high demand in a technologically reliant society current crises are framed around producing sufficient number of qualified graduates in the STEM fields: Science, Technology, Engineering, and Math. The issues are framed as both the quantity and quality of graduates. Lack of jobs creates numerous problems, both economically and for elected officials, making the needs of employers and society intertwined [8]. Similarly a civically educated citizenry is necessary for western democracies to function, particularly for addressing complex policy issues such as climate change. Education is also of personal and financial benefit to individuals since the overall return on investment in college remains high [9]. In this space of multifaceted benefits it is important to be aware that while economic, societal, and individual needs are important and interrelated, education cannot be designed to equally serve all stakeholders. In other words, educating a student for the workforce may not provide a civic education or one that lets them make personal meaning of their life. For this reason the remainder of this paper makes the hypothesis that education needs to be chosen by and crafted for the individual. This hypothesis is predicated on the assumption that economic, workforce, and societal benefits will accrue from well-educated individuals but this process does not work well in reverse.

Figure 2: Bar chart of relative employment in science, technology, engineering, and mathematics.

It is important, however, to understand that the policy pressures to continue to educate more people and increase the quality of their education arises from other sources than a desire for individual development. This is particularly true in STEM because of the role STEM education has on the economy. Interestingly while much of the focus is on science and math education because it is deeply embedded in primary and secondary education (in the US K-12) the largest fraction of the STEM workforce according to the Bureau of Labor Statistics are engineers [10] as shown in Figure 2. This is not to say that there are a large number of individuals whom the BLS classified as engineers in the workforce, in fact as shown in Figure 3 engineers make up a relatively small percentage of people in college or in the workforce.

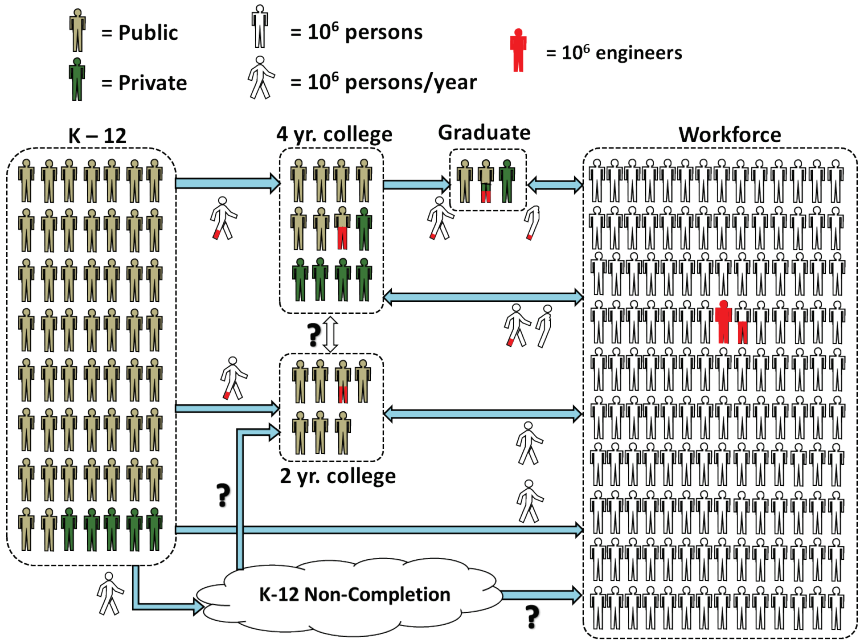

Figure 3: Relative populations (c. 2010) of individuals in K-12, university, and the workforce. Engineers are shown in red.

The reason that policy makers focus so much on STEM disciplines is despite the relatively small fractional representation these individuals have a disproportionate impact on the economy, particularly in growth of GDP. In fact it is estimated that 50% of growth in GDP comes from knowledge and technology intensive (KTI) jobs [11]. For policy makers who need to answer the question, "how does supporting this policy create jobs in my district?" this economic impact is a large factor.

The prospect of economic growth underlies many narratives in STEM education and these trickle down from the policy realm to affect the choices of individuals. For example Figure 4 shows a back-of-the-envelope estimate of the return on investment in STEM education based on figures from the former president of the US National Academy of Engineering [12] that was designed to illustrate the return on investment for funding engineering education.

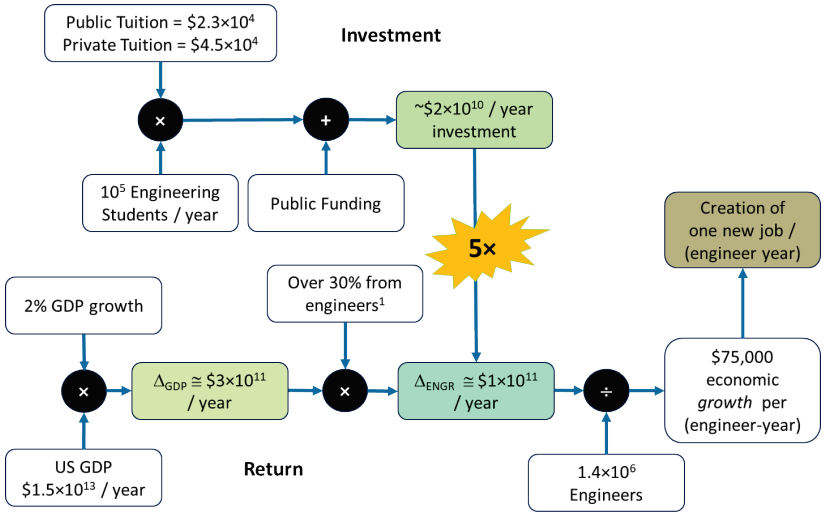

Figure 4: Rough estimates of investments in, and economic return on investment in engineering education.

Knowledge and technology are inextricably linked and have become exponentially more so as difficult-to-reproduce technologies have become both gateways to, and guardians of, knowledge [13]. The importance of technology in education is not just because it is increasingly important to learn about "capital T" technology [2], but because of the impact technology can potentially have on learning. Another more general way to phrase this is that Technology is becoming less of a byproduct of, and

[2] The phrase "Capital T Technology" denotes the fact that there is not one technology nor is it technology itself that is the sole factor for change, but rather how technology affects human patterns of behaviors and creates new affordances that may or may not support existing modes of acting and being.

more of a driver for, society. It is, however, a mistake to conflate technology with education. Technology is ultimately about convenience. What effort can I save? Technology is created through a process called engineering which has a culture in which efficiency is highly valued. Education is not about convenience, it is about personal growth which is difficult and uncertain, requires significant effort and resources, human community, and is an endeavor in which too much focus on efficiency may undermine effectiveness. It is thus important to distinguish the aims of education from the aims of technology. Such differentiation is often lost due to the fact that as society becomes more reliant upon technology education has become a critical societal infrastructure, like power, food, and transportation systems. As education becomes less a deliberate lifestyle choice and is increasingly needed to thrive as an individual or a society, the nature of need changes to become more insistent [14].

BENEFIT : COST RATIO

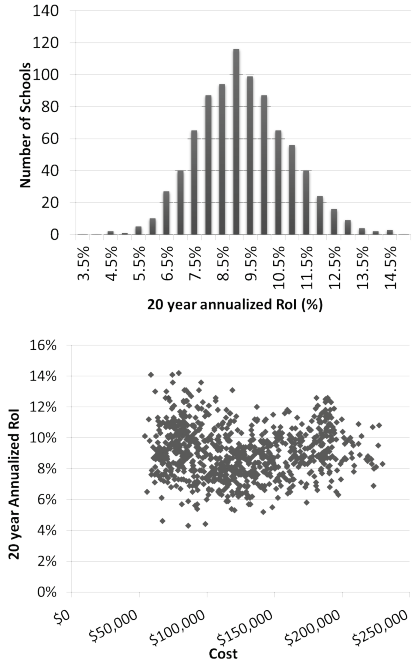

Figure 5: Economic return plotted as a distribution over schools and as a function of cost-of-degree.

There are many benefits to college which include both personal development as well as an improved chance at a more lucrative job; these are outlined in a 2011 Pew report fittingly titled "Is College Worth It?" [9]. This report found that there are differing views of the benefit of college with the highest positive response coming from college graduates with over 85% saying it has benefited them. Graduates were most emphatic about the benefits of college for intellectual and personal growth. These responses vary across sectors, however, with for-profit college seen much more negatively than more traditional public or private institutions. From strictly economic terms, almost all measures indicate college is a worthwhile investment. Economic returns are often calculated either as an annual return on investment (RoI) over 20 years or as a monetary lifetime return. Annualized 20 year RoIs are high with a normal distribution and mean of about 10% as shown in Figure 5. Surprisingly the RoI is independent of the cost to attend a school. Similarly RoI is only weakly dependent overall on the exclusivity of the school as measured by admission rate. RoI does vary by discipline however, with most data showing a higher return for STEM disciplines. The numbers for overall, or lifetime return range greatly by the research study but typically give premium of about $700,000 over having just a high school diploma. The results are also highly dependent on college attended and major, again with generally higher returns to STEM majors [9], [15]. It is worth noting that these studies usually average incomes over the typical working life, from the mid-20's to mid-60's, and thus are aggregate graduates from many decades which means the results may not reflect opportunities for today's graduates. A recent study has indicated the gaps between disciplines are shrinking for more recent graduates. Such studies also report aggregate measures, typically median values, and it is worth noting that distributions within categories are as large as the differences in means between categories. In other words while education majors have the lowest lifetime RoI of all college majors the top 10% of education majors make more than the bottom 25% of chemical engineers, the most lucrative major [16].

The take-away from the above paragraph is that from both economic and personal development perspectives there is a clear benefit to going to college. However it can be argued that the overall benefit:cost ratio of college is currently more affected by the costs which are increasing (see Figure 1) rather than the benefits which have remained relatively static. A lucrative investment that is unaffordable remains a dream, and the increasing cost is driving down access to higher education. As prices go up, Figure 1, parents are increasingly looking at the costs of college and become more sensitive to the return on their investment which in turn may drive thinking about education towards more utilitarian directions.

There are two major factors that are driving the denominator of the benefit:cost ratio: rising tuitions and increasing income inequality. Tuition costs have been much in the news but the underlying story is somewhat more complicated than greedy colleges pandering to needy students and driving up costs, as this story is often portrayed in media reports. Tuition increases have been driven by decreases in state appropriations at public institutions (Figure 6) [17] which are driven not by costs of education per se, but by other economic and political factors. Both private and public institutions are seeing increasing operational and administrative costs, some driven by increasing governmental oversight. In addition at private institutions tuition is correlated with perceived status which drives institutions to keep up with tuition increases at peer and aspirant schools lest they fall in rankings [13], attract fewer applicants, and potentially enter a financial death spiral. Furthermore at private and many public schools the published sticker price over-estimates the actual cost of college since many students receive discounted tuition. The average amount tuition is reduced across all schools is known as the discount rate which has increased 10% over a decade at private universities and is now nearly 50% [18]. In brief while the costs of college are rising and being pushed on to private individuals the increases are partially due to factors outside the control of universities. While universities are trying to keep college affordable for those who need tuition assistance the reality is that college is increasingly difficult to afford.

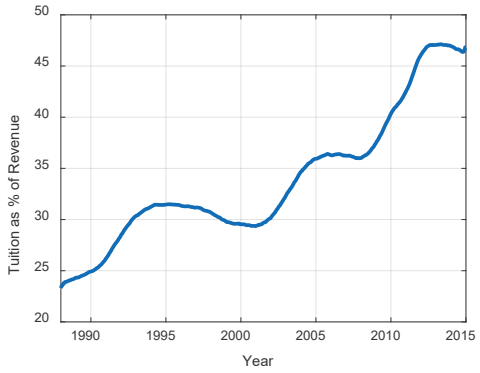

Figure 6: Tuition as a fraction of total institutional revenue. The fraction borne by students has almost doubled in a quarter century.

Perceptions about the affordability of college are also driven by one's own financial circumstances. These have changed unevenly over the last decades in the United States depending on what income group an individual belongs to. The topic of rising income inequality was highlighted in the US after the 2008 recession through the Occupy Wall Street protests which brought the terms "the 1%" and "0.1%" into common usage. Rising income inequality means that affording college is becoming more difficult for an increasing fraction of the population without assuming a significant level of debt. For example the lowest 5% of income earners saw a net decrease in their incomes of 2.5% over the decades from 1973 to 2015 while the highest 5% saw an increase of 36%. The rise of the top 1% and 0.1% were much more. The top part of Figure 7 shows this divergence by plotting normalized income by ventile for both 1973 and 2015 as well as the change income over this 30 year period [19]. The bottom of Figure 7 shows the cost of college as a percent of annual income for both public (orange) and private (blue) universities in both 1976 (circles) and 2016 (squares). Today to send one child to the average public

institution at sticker price the bottom 20% of households would cost more than their full annual income. The bottom 40% of American households would pay the same to send a child to the median cost private university.

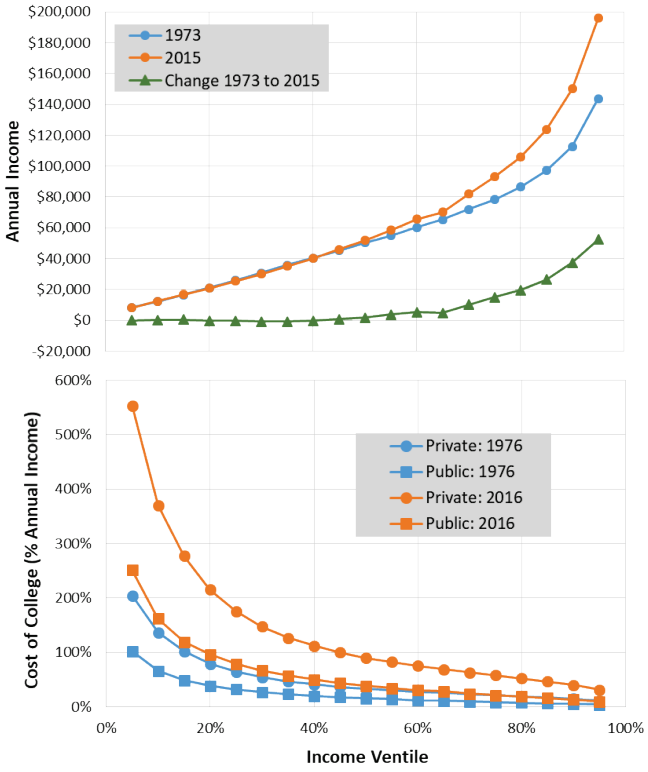

Figure 7: The top figure shows the divergence in income between 1973 and 2015 in constant dollars. The bottom figure is the cost of college as a fraction of annual income by income ventile (average tuition exclusive of discount) for the same years at public and private institutions.

In the United States low socio-economic status is not equally distributed among demographic groups or geographical regions. In 2000 four states—Louisiana, Mississippi, New Mexico, and West Virginia—had over half the primary school students in the bottom 40% of income earners nationwide. In 2013 the number rose to seventeen states including all the south with the exception of Virginia and four western states. These states have high percentages of Black or Hispanic Americans as well as including Appalachia which has low socio-economic status Whites. Since future income is strongly tied to education this distribution risks maintaining a positive feedback or reinforcing loop [20]. In such a loop rising costs result in fewer individuals having the opportunity to go to college which puts additional pressures on institutions that rely on tuition dollars to offer discounts. Lower college completion reduces incomes and thus the tax base and ability to attract employers that need college educated workers.

Such reinforcing loops—along with rising costs, income inequality, and decreasing access to higher education—help to undermine public confidence in the value of, or ability to access, college [21]. As higher education becomes less accessible but increasingly necessary it is not surprising that alternative forms of education would arise that seek to disrupt existing models [22]. Such disruption has always occurred in education but in the current political climate there are increasing pressures to privatize and monetize all sorts of services, education included. Such pressure contributes in some part to the rising chorus of complaints against education at all levels with articles and books decrying the failure of education systems despite evidence to the contrary. Given that the US spends about $1 Trillion on education annually between primary, secondary, and higher education, shifting education from a public to private model would open new markets for private enterprise. There have been several barriers to such privatization. One barrier, which exists with all forms of education disruption, is that most voters and taxpayers have strongly supported educational institutions with which they have some affiliation. A second barrier is that for-profit higher education has abysmal outcomes compared with private and public non-profit universities [7]. The narrative of educational failure is not, however, confined to those who seek to disrupt existing educational structures. Those within higher education, STEM education in

particular, have taken advantage of this larger narrative to frame ongoing crises in STEM education [23], [24]. Adopting a mentality of crisis knocks loose resources for STEM education that might not otherwise be available from policy makers, particularly given that degrees in engineering and the physical sciences are among the more expensive to offer.

In summary, while the benefit of a college education is historically clear, rising costs and flat incomes have decreased access for many in the United States and led to increased questioning of its overall value. Such questions of value are based on personal circumstances and an individual's view of, hopes for, and confidence in the future. These in turn are influenced by underlying beliefs about the future economy and labor force. It is thus not surprising that most people do not behave as fully rational economic actors when it comes to higher education. In this environment there is an increasing belief that alternatives to traditional college are becoming viable.

COMPETITION

In Carlson's framework competition provides alternatives to an existing good or service [5]. This section discusses two forms of competition: alternative pathways to an education credential which compete *against* universities for enrollment and resources, and competition *between* universities for status, students, and other resources. To understand the effects of competition—which are historical rather than purely recent phenomena—it is necessary to appreciate the resilience of universities. The university as a societal institution traces its lineage back nearly one millennium to the places medieval scholars became educated. The word "university" comes from the Latin phrase "*universitas magistrorum et scholarium*" or "community of masters and scholars". The form of today's university first emerged at the University of Bologna which was founded in 1086. A millennium ago formal knowledge was not readily available and difficult to reproduce given books were copied by hand. The value of written works led to university organizational structures dedicated to preserving, transmitting, and creating knowledge. Around these structures grew a diffuse and pervasive culture which defined education as much as the espoused goals of the universities themselves. This culture is referred to as the "hidden curriculum" [25] and has a significant effect on learning. These structures, and the cultures they maintain, for the most part still define modern universities and also engender institutional loyalty which has economic and political consequences. Since university structures are designed to guard knowledge and enculturate students into existing ways of knowing, it is not surprising that universities resist change [26].

Forwarding to the present time, new educational pathways [27] that are credential- rather than institution-focused are emerging as alternatives to existing colleges and the credentials they provide [28]. These alternatives are driven by the access issues described in the previous section. While there are claims such programs and the technologies that underlie them pose an existential threat to higher education [29] few other societal institutions have the staying power of universities which has, justifiably, led to a belief that they will continue indefinitely into the future in close to their current form. This belief is supported by the fact that over the years alternatives to universities—correspondence courses in the mid-19th century, distance education via television, for-profit institutions, and more recently massively open online courses—have filled niches in the larger education ecosystem but have not significantly displaced traditional colleges. For example at the start of the 20th Century as many engineers were educated in courses taught at local YMCA's as graduated from universities [30].

Large companies, which have their own training needs, have always run their own internal versions of universities. Boeing, the airplane manufacturer, offers over 4000 courses internally to its employees. More recently for profit institutions of various forms have enrolled large numbers of students. To date none of these has unseated universities, yet… While universities have proven highly resilient and relatively immune to external pressures environmental change does impact university structures and processes [26]. Should these pressures become too great it is not inconceivable that new forms of competition may force rapid adaptation in higher education.

Over the long time scales of universities many of the environmental pressures have proven to be transient. Natural cycles in factors such as politics, demographic changes, changes to areas of study, and even beliefs about the aims of education [31] tend to cancel out over decades leading to a "wait it out" attitude at universities. However over the last century there have been three areas that have exerted constant rather than cyclical pressure on university operations: the cost of education on a per-student basis has been increasing [32], the demand for higher education has been increasing, and individuals' access to technology (although this is complicated by the fact that technology changes form over time) increases [30 *see table 702.10*]. It would also be appropriate to include the growth of knowledge into the environmental pressures on higher education although this is more difficult to quantify. It can be argued that each of these pressures stems to a greater or lesser degree from Capital "T" technology[3]. The need for education increases as more people are required to maintain technological infrastructure and cost increases as institutions expand to address new areas of knowledge created by technology and also adopt the technologies. The growth of knowledge is sustained by the ability of technology to store and transmit information at increasing rates [34] and, in the future, increasingly generate knowledge independent of direct human intervention.

It is uncertain whether current universities can continue to adapt to the pressures created by Technology as they have in the past or whether the pressure will become large enough that alternatives to universities become viable [29]. Rising competition does not presage the demise or complete disruption of higher education. Rather if alternatives become widely accepted enough they may cause a sufficient rapid change in business models that shifts in education cannot be assessed, controlled, or thought through from the many perspectives needed to ensure a nations education infrastructure is maintained. Thus the questions most relevant to competition are:

- In which ways do alternative forms of education create sufficient value for students, parents, and employers that they have the potential displace existing systems?
- To what extent and how rapidly can such alternatives shift enrollment from more traditional universities?
- How are different demographic groups affected by these shifts?
- Which universities will be most affected by such displacement?
- How well can competing educational alternatives recreate the unique and as yet poorly understood conditions critical to adolescent and young adult development that are hallmarks of today's education [35]?

[3] The distinction of "Technology" as distinct from "technology" refers to how it is increasingly interwoven into society and our lives as well as our increasing dependence on technology. As such Technology, except when it advances, becomes increasingly invisible.

Ultimately if competition succeeds in displacing a significant fraction of students it will need to address the community and social needs a university education provides rather than just seek to offer alternatives to knowledge acquisition. For example Massively Open Online Courses (MOOCs) were at one point seen as a possible successor to traditional universities. However data soon emerged that showed rather than shifting enrollment from traditional programs early MOOCs were predominately taken by individuals who already had a college degree, were widely distributed geographically and in age [36], and who sought additional education. They thus addressed an unfilled niche in the larger ecosystem rather than displacing large swathes of that ecosystem.

The space of online learning continues to evolve rapidly, however, as evidence by offering such as SPOCs (small private online courses) offered by companies such as Microsoft that offer alternative pathways into the workforce and offer alternative approaches to education. Microsoft is offering many courses now in partnership with EdX that can be credentialed in a way that lead directly to employment at a cost of about $100 per course but which are also free to audit. Similarly Boeing has partnered with MIT and EdX on an introductory system engineering course that mimics some of the social aspects of traditional university courses.

Since the educational ecosystem is not infinite in extent such competing systems may cause individuals to choose alternative pathways to an education. Such enrollment decisions have the potential to displace enrollment from existing structures and institutions [22]. At the current time there is more speculation about change than there is true disruption in the higher education ecosystem since there has not yet been significant shifts in enrollment from established institutions. However it is generally accepted that while the extent or distribution of the effects competition will have on universities can't be predicted smaller, less well-resourced universities are at more risk since they rely most heavily on tuition revenues.

The vulnerability of some universities to disruption is exacerbated by competition between existing institutions. The effects of current policies and the competition for numerical ranking drives many decisions on university campuses to the extent it has been characterized as a "status arms race" [13], [37]. The quest for status has, in part, led to large disparities between universities. The diverse and complex US education system is well described by various long tailed distributions. For example about a quarter of US engineering students come from the 20 largest schools while another quarter come from over 200 of the smallest schools [38]. Long tailed distributions often arise from positive feedback loops, or "rich get richer" phenomena, which lead to increasing inequality between institutions [39]. In the United States such positive feedback loops arise from multiple factors including charitable giving and top rankings to high status institutions which in turn allows investments to faculty salaries, research facilities, large application pools, and programs which serve to further enhance status and thus donations. Similarly wealthy institutions can afford better endowment management and thereby enjoy higher rates of return. Such features are not intentionally part of the mission of higher education but rather arise from the underlying structure of how higher education is funded, maintained, and managed [40].

Two factors that are correlated with the vulnerability of a university to shifts in student educational pathways are a university's assets and enrollment. Figure 8(a) shows the distribution of schools plotted

by total assets per student drawn from 2015 IPEDs data [41]; several universities with over $1M per student are not shown on the graph since they distort the scale. The inset shows the same data on a logarithmic scale illustrating that the distribution extends over six orders of magnitude. Enrollment and financial resources are two factors that are hypothesized to provide some resilience to competition. The same data set is plotted as a scatter plot in Figure 8(b) as a function of reported enrollment and total assets with each point representing a different university. It can be seen from the graph that both these factors are widely distributed. It is generally accepted that schools with low enrollment and/or low assets are more liable to be negatively affected by competition. If a horizontal line were drawn on Figure 8(b) representing an enrollment threshold for vulnerability to disruption each dot below the line represents a university that could be impacted by competition. Those dots above the line would be those schools not affected. Similarly a vertical line represents an asset threshold with dots to the left representing vulnerable schools and dots to the right one that are more resilient to forms of competition.

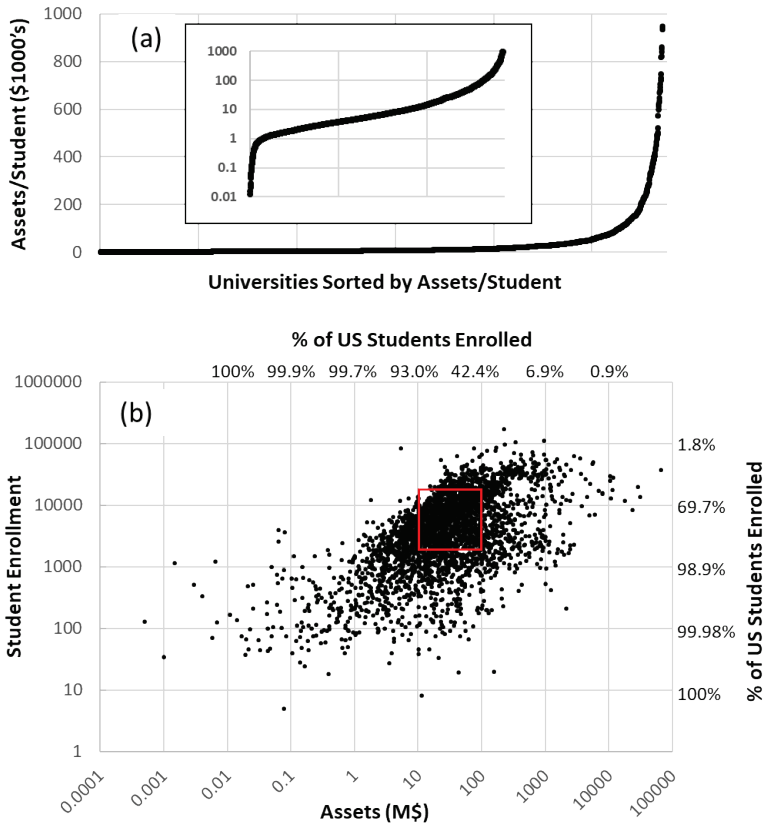

Figure 8: (a) shows the long-tailed distribution of universities sorted by assets per student while (b) is the scatter plot of all reporting universities in the IPEDS database showing assets vs. enrollment.

While clearly the effects of competition would not be distributed based on such simple numerical cutoffs, the distribution does illustrate that a fair number of universities fall into a region with low assets and low enrollment and thus are more likely to be affected by competition. This graph is easy to misinterpret for three reasons, however. First, since larger schools tend to be wealthier, assets and enrollments are positively correlated. Second, about half of the 2800+ schools in the IPEDs data set fall into the small region shown by the red box with assets between $10M and $100M *and* enrollments between 2000 and 20,000 students. Finally because enrollment and assets follow a long tailed distribution, a fair number of universities could close before a significant fraction of the students in the United States were impacted because the percentage of students who attend the smaller or poorer universities that would be most affected by competition represent a relatively small fraction of the total US student population. The percentage of students is shown by the alternate cumulative distribution scales on the top and right axes of Figure 8(b) which adjust the scales for the percentage of students who attend a university with assets or enrollment greater than the corresponding vertical or horizontal

grid line respectively. For example 93% of US students attend a university with greater than $10M in assets and 98.9% attend a university with an enrollment greater than 1000 students.

Figure 9 shows a more detailed cumulative distribution drawn from IPEDs data used in Figure 8. Unlike typical distribution functions the graph shows the percentage of students who attend a university with *greater than* the assets per student shown on the horizontal axes of Figure 9. The shape of the graph shows that the impact of competition—considered as a fraction of the total number of enrolled US students—has little effect until it begins to affect the large tier of universities with assets of $1000 or more per student at which point the slope of the line becomes about 70% per decade. Thus if competition for higher education begins to affect enrollments at schools in this range the effects on university operations could be rapid and far reaching. The steep slope for this range of assets per student arises from the tight clustering of universities shown by the red box in Figure 8(b).

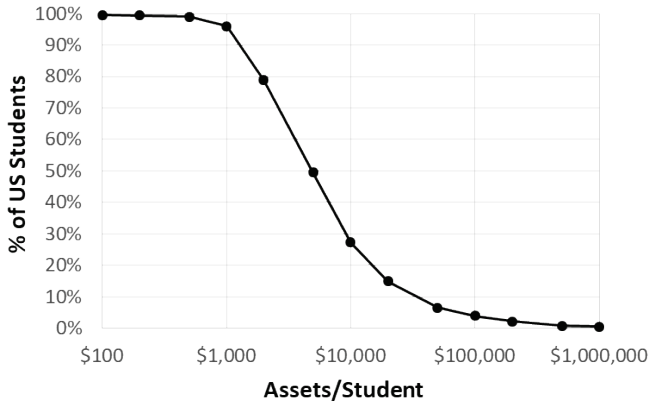

Figure 9: Distribution of student enrollment as a function of university assets per student.

In summary, the systemic educational inequalities in the US, technology that is inexorably creating viable alternatives to brick and mortar institutions, as well as decreasing affordability signals new vulnerabilities for many smaller and regional institutions. Competing alternatives will have little effect on the overall US education system if they only affect smaller and poorly resourced institutions that are less able to respond to competition, Figures 8 and 9. While it is easy to dismiss closures of smaller universities as systemically unimportant, the more vulnerable institutions may fill niches in the larger higher education ecosystem that meet regional needs or provide education to a specific demographic group that are not well served by larger institutions. Should, however, competing educational alternatives become increasingly attractive to potential student and thus require large investments from universities to maintain enrollments, shifts in where students go to earn a credential could reach a critical point where large number of universities become affected, Figure 9. Once the larger cluster of mid-range universities begins to be affected a significant amount of expensive restructuring becomes necessary resulting in the possible fragmentation of the education system. While higher education has shrugged off competitors and even thrived for centuries there is no guarantee this situation will continue indefinitely. If the US educational system is at a point where alternative structures are becoming viable the shift from established higher education institutions to competing models may be rapid with the outcomes less certain than proponents of alternative models envision. The next section explores approaches to higher education, highlighting areas in which universities have both strengths and vulnerabilities.

APPROACH

Approaches to higher education exhibit both wide variation and surprising similarities. In general there is considerable variation and adaptability at the "fine-grained" level or how material is presented and how courses are taught. The similarities are structural and organizational since higher education

maintains structures established hundreds of years ago which vary relatively little across institutions. Higher education's mission of knowledge preservation, transmission, and creation as well as the need to ensure transportability of educational credentials supports these structural similarities. The term "structure" can best be defined as how the core functions of higher education—which are to aggregate many independent learning experiences into an integrated, coherent whole which can then be awarded a societally recognized credential—are organized and supported within the institutional culture. While there can be a high degree of variation between the assignments completed and classes taken by students, the ways assignments determine a class grade and how classes determine a credential are quite similar across institutions. Another way to think of structure is as the constraining or enabling rules that determine how this process of aggregation is instantiated within an institution and the culture and norms that arise to support this core activity.

The reason that higher education can change rapidly at the level of students' learning experiences is due in part to the academic freedom faculty have to make such changes which enables such innovation to be driven by individuals or small groups rather than institutions. Federal funding from the US National Science Foundation and other groups has similarly supported innovation in educational techniques or pedagogies such as active learning which affect the fine-grained level by making classroom activities more effective [42]. These investments have been made based on an assumption innovation will scale across universities, but the independence of faculty inhibits the diffusion of innovations while simultaneously enabling such innovation to occur. An instructor's beliefs about the aims of education [31] and personal epistemology [43] strongly influence their willingness to adopt or adapt new methods. The diversity of beliefs makes organizational or structural change difficult, however, since faculty beliefs are generally not aligned or even openly discussed. Thus it is difficult to achieve the consensus of views needed to support organizational change. Changing the approach of higher education at the organizational level is further complicated by the wide range of stakeholders within the higher education ecosystem and the fact that these stakeholders have developed strong opinions based on their own experiences within their institution, many of which were integral to forming their identity. In summary the aggregation-based definition of structure illustrates how approaches to higher education, which have evolved over centuries, are highly flexible on a fine-grained level yet are rigid and lack agility at the institutional scale due, in part, to the many constraints derived from universities' mission and credentialing functions.

A specific example from engineering education is the challenge of integrating development of professional skills into engineering degree programs which has been a recent focus at the US National Science Foundation [44]. Such preparation is represented simplistically and idealistically in Figure 10 as a Cartesian graph[4] on which an individual's ability in both technical and professional skills can be plotted. If one could somehow measure candidates' abilities on both axes through some simple means and plot them they would fall into four quadrants shown. Those who have both technical and professional skills are good candidates while those that lack both should not be hired. According to the engineering firm those who have technical but not professional skills can contribute to projects but do not develop the skills they need to advance within the organization and often leave. Those with professional but not technical skills do not garner sufficient respect in the strongly engineering-oriented

[4] This figure was shared with the author by a human resources manager from a large aerospace engineering firm.

culture which impedes their usefulness. While this representation is both simple, actionable, and backed up by many studies [45] and think-pieces from employers who are the stated constituents of most US engineering programs it has proven surprisingly difficult to get engineering programs to focus on professional skill development in the curriculum. There are several reasons. The first is that doing so in a significant way usually requires commitment from multiple faculty and changes to multiple courses if not the curriculum. A second is the university's focus on knowledge rather than skill development, which is seen as a lesser status activity. As a result only a handful of engineering schools have made significant efforts to develop engineering students in the upper right quadrant, and many of these were founded or restructured specifically for this purpose such as the Iron Range program and Olin College in the US, NMiTE and Dyson Institute of Engineering and Technology in the UK, and Charles Sturt University in Australia.

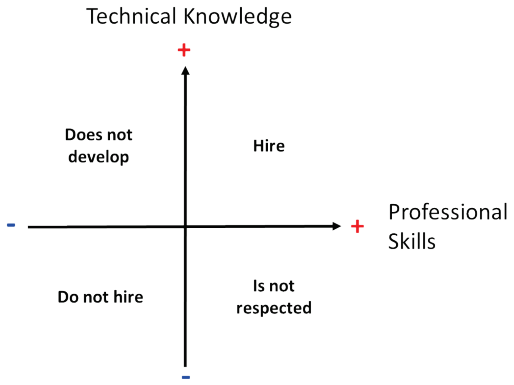

Figure 10: Cartesian view of technical and professional preparation of engineers.

While the two-level view of institutional structure—highly flexible at the level of the individual instructor where learning occurs but rigid and difficult to change at the credentialing level—is simplistic, it highlights the intertwined strengths and weaknesses of current approaches to higher education. While universities are seen (and critiqued) by many as static and unchanging, this view is incorrect since efforts at change commonly focus on what is structurally possible, i.e. fine grained activities which may be externally invisible rather than more visible structural changes. The ability to rapidly adapt at the broad, diffuse base of the larger structure explains how universities are able to adapt to then envelop competition. To date these competitors have predominately focused on creating alternatives to providing knowledge, that is replicating what is done in the classroom. Adapting to such competition is a strength of current universities (provided they are well enough funded). However the strengths at the fine grained level—academic freedom, tensions within institutions and the productive dialectics they cause [26], and diversity of the US higher education ecosystem—may be weaknesses at larger scales. Diverse viewpoints and educational philosophies make it difficult to develop shared vision. Change at fine-grained scales can rapidly become incoherent, reaching a point of diminishing return and drawing energy from more structural change efforts. Because of the strong interdependencies and shared power structures that arise from the process that aggregates learning to a credential it may be more difficult for universities to adapt to competition which focuses on the credentialing functions of universities than competitors which focus on learning.

One other advantage enjoyed by universities that has been difficult for competitors to address is that fact that success in college may depend more on the overall learning ecosystem and less on exactly how the formal curriculum is structured. A recent study at Hamilton College, a small liberal arts school, looked in-depth at what factors contributed to success in college at their institution [35]. What they found overlaps with larger, earlier studies [46], [47]. Critical factors in student development were good relationships with a few committed teachers/mentors; having a tight and supportive social network, the willingness to take advantage of the opportunities available in a rich campus ecosystem consisting of academic, co-curricular and extra-curricular activities; and exposure to a wide diversity of people and

opinions. In other words those students who succeed in college do so by navigating a rich environment which is tightly connected by human supports. Factors that had little influence on success in college included trying to tightly control student behavior, over investing in facilities, and too much reliance on pedagogy to achieve desired outcomes.

Comprehensive studies such as the one done at Hamilton are important because they provide insights on the approaches that make college both a personally transformative experience as well as providing a significant return on investment (see Figure 5). It is likely that most of the competitors to universities, by focusing on replacing the learning function, have not effectively replicated the "secret sauce" of higher education which is close human interaction within a community that centers across both academics and non-academic identity development. The difficulty with competing in this domain is that providing a rich ecosystem and substantial mentoring is part of what makes college expensive and thus less accessible (see Figure 7). As these factors become better understood competition in these domain is starting to emerge. For example some large institutions in the US are adopting "honor college models" that create a small college experience in a large university. However at the current time most of the institutions that best create the factors described above are smaller, liberal arts universities that tend to fall on the right side of the distribution shown in Figure 9. Because these are the institutions that are more at risk from rising costs and forms of competition there may be a risk that some critical aspects of civic and humanistic development are lost as competition forces a more utilitarian approach to education.

SUMMARY & CONCLUSIONS

The above sections outlined the current status of and tensions in higher education's NABC value proposition [5]—defined by Need, Approach, Benefit:Cost ratio, and Competition—as it impacts individuals, institutions, and society. In summary there is a well-documented and increasing need for higher education along with a decreasing benefit:cost ratio driven mainly by college affordability. As access to university education falls and the need increases driven by rapid changes in the workplace there are increasing calls for change in higher education. The calls for change are both initiated by, and in response to, new technological affordances which enable new forms of competition. While to date these competitors have focused on replicating the learning function of universities, there is increasing interest in devising alternative credentials, which may challenge the underlying structures of universities, and area in which they are less able to respond. While higher education has weathered challenges from competing approaches throughout its history today's pressures stem from rapid changes in technology. In order to compete with new credentials universities may need to make significant investments in restructuring their operations and shifting cultural values. Given that the US education system is described by a long-tailed distribution of affluence, however, many universities may not be able to afford such investments making it likely some institutions will not be able to adapt to competitors should alternative credentialing system gain societal imprimatur. Given the great uncertainties at this point in time it is impossible to predict the extent of any future paradigm shifts.

What is not well captured in the value proposition framework discussed above are dynamic changes in the workforce and society which influence the content, process, and value of education. As mentioned previously technology has been the engine which drives other change processes in higher education. Technology is similarly transforming workplaces—which do not have higher education's mission of

knowledge preservation, transmission, and creation—at a more rapid pace as it also changes aspects of society and individuals' expectations for education. These changes have been called a fourth industrial revolution [48] characterized by greater interconnection between what were separate domains of knowledge or expertise and the capability of artificial intelligence to increasingly take on tasks that were once only managed by humans [49]–[51]. While driven by technology, such shifts have an epistemological component as well since artificial intelligence will likely change how some forms of knowledge and skill are valued and thus are represented in education. The fourth industrial revolution will create challenges for higher education since from the perspective of policy makers and the business community universities have proven surprisingly immune to changes in the external environment [26]. This resilience likely stems from the many functions universities undertake to support [22], functions which are often in tension with one another. For example, one of these dialectics is whether education should focus on timeless knowledge that reflects universal human values or the changing knowledges and skills needed to succeed economically in the world [52], [53]. While such dialectics help universities engage in the ongoing discussions needed to balance their multiple missions, they make it difficult for higher education institutions to adapt to environmental change, particularly when those changes are rapid. The fourth industrial revolution is also causing the amount of knowledge and the rate of its production to increase [54], [55]. In response college campuses have created new majors and programs of studies that align with existing structures of credentialing. The effect of knowledge growth on the workforce, however, has been a flattening of organizational hierarchies and individuals shifting jobs more frequently which does not align with the increasing specialization promoted by universities. The structure of education, which limits and defines educational processes, has been seen as either sacrosanct or difficult to change. However if changing epistemologies place more importance on interconnections between knowledge rather than knowledge within a discipline the investments colleges have made in expanding the numbers of programs may have been wasted. Shifting structures is challenging since many faculty see preservation of their discipline as the main goal of education [31].

Due to the rapid changes, strong and established belief systems, and tensions discussed previously it is likely impossible to predict what the future holds for current higher education institutions and the system as a whole. Some insights may be gained, however, from taking a more systemic perspective and adopting tools from systems thinking [20], [56]. From a systems thinking perspective some interventions are more effective than others. Less effective approaches include focusing on changing numbers such as degrees, enrollment, etc.; changing the timing of a system; and changing structures as has been advocated here since while this approach has high impact it is very difficult to achieve in practice. More effective approaches focus on shifting mindsets by changing the goals of a system; supporting new ways of self-organization and reorganization; and both understanding and transcending existing paradigms. As a particular example of such a paradigm STEM education has been viewed for years using the analogy of a leaky pipeline, Figure 11. The signaling model [57] provides explanatory power for why the return on investment is greater for STEM majors which may, along with STEM beliefs

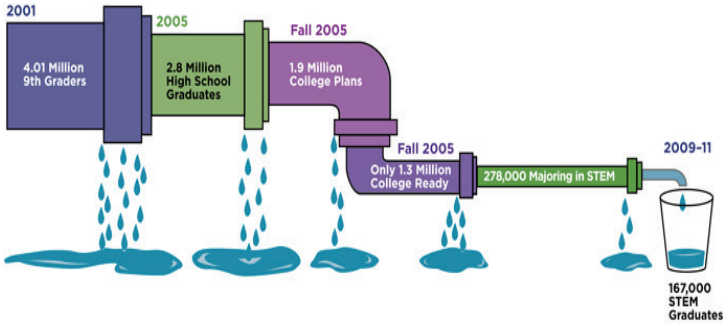

Figure 11: The leaky pipeline analogy for STEM education (image from http://shinstitute.org/about/stem-pipeline/)

about rigor, may explain the popularity of this analogy. The implications mentally derived from this analogy give rise to concerns about the *efficiency* of education by policy makers who see knowledge of technology as crucial to an educated democracy and competitive economy. This paradigm has informed many well-intentioned but ultimately ineffective investments in STEM education in the US. For example this pipeline model has led to a mistaken view that retention in STEM is a problem that can be fixed through appropriate investments. In engineering the problem is seen to arise during the first two years of college so many efforts have focused here even though a closer look at the data engineering shows no more retention problem than any other major [58]. The reality is that what is seen as loss and issues in retention are just naturally shifting interests among young people who are still discovering their path in life.

It should be emphasized again that the tensions between need and access are leading to new forms competition to established universities. While many of these new competitors will fail over time what will likely emerge are partnerships with established institutions that spin off "educational hybrids", much the way in which cross-breeding can drive natural evolution. While such hybridization has always occurred in higher education what seems interesting about this period is that hybridization may affect university structures more than in the past, leading to potentially new models. The current system of education is structured for certain outcomes, and structure determines outcomes in a way that is often invisible to those who exist within the structures [40]. The structures of today's higher education have evolved over ages in which hand-copied books were worth as much as a small farm to more recent transitions from an agricultural to an industrial and then to an information and service society. These structures typically view education as a stage in one's life which prepares one for a later stage of work and life in a civic society. Each of these stages are well defined and each stage occupies a distinct phase of an individual's life. Pipeline metaphors make sense in such paradigms. However changes in the work force and decreasing access to traditional four year degree programs are making such discrete-stage mental models less relevant to tomorrow's students. As costs have risen more students are following a meandering pathway to a degree that includes two and four year degrees, certificates, and multiple institutions. Increasingly those in STEM education refer to pathway rather than pipeline models [27] in which students build a credential from multiple institutions in a more haphazard fashion as dictated by pragmatic issues of access and affordability setting the stage for new models of credentialing [28].

This paper has sought, by discussing current issues and trends in higher education, to assemble a picture of an education system in transition where the future structure is much different than that which exists today. Many of these issues have been described previously as mass disruption [22], [29], but the reality is more likely a forced evolution. What might the future of higher education look like? While systems of primary and secondary education will likely continue in close to their current form, the options for higher education will likely expand as resource pressures eventually force universities away from "follow the leader" models driven by status. Universities who thrive will strategically plan to move sideways rather than up and seek new niches in the educational ecosystem. Many of the more rote activities for acquiring knowledge will become supported by intelligent tutors and other AI-based systems that incorporate rapid assessment and can more successfully support personalized learning [54], forcing changes in the role of faculty. These systems will incorporate social networking features which extend students' contacts outside the physical bounds of their universities. As the students interact on such platforms the "data exhaust" is mined by potential employers who are seeking talent in particular areas. The access to data which has previously been difficult to collect or not accessible results in both new synergies between employers and educators, but also rapid positive feedback loops in which students

"game" the system to achieve desired outcomes. The increasing rate at which new technologies and opportunities arise in business combined with a desire for "higher quality" workers as well as new ways to identify such workers creates a more porous boundary between school and work in which students may leave before they earn a four year degree then seek to return later. This trend exerts increasing pressure to create smaller, more transportable, credentials like certificates which are increasingly popular [41]. These credentials may eventually have depreciation schedules attached to them. The desire for new forms of credentials [28] in turn puts increasing pressure on existing higher education finance models which can be considered as large, up-front investments with long pay-off times similar to a mortgage. Alternative models will need to be developed. These models will likely be structured similar to insurance plans which allow smaller payouts over time and funded by individuals, employers, and governments with the costs, or premiums, calculated by past educational performance.

The most accurate term to summarize the rapidly changing landscape of higher education and the workforce is "fragmentation". To introduce another visual analogy, or paradigm, imagine education as the task of navigating across a landscape. If the landscape is smooth and orderly with clearly delineated features and landmarks then navigation is a relatively simple task and the pathway to one's goal is generally easy to find and pipelines flow where they are supposed to. However as the landscape becomes more fractal or fractured—from a prairie to canyon lands—navigation becomes more difficult, landmarks harder to see, and paths may end abruptly or lead to unexpected destinations. This fragmentation is made possible by "capital T" technology and driven by economic and utilitarian concerns and the issues of need and access described previously [5]. It seems clear that the issues of need and access which are driven by technology will change education regardless of any rearguard actions by threatened institutions. While such fragmentation will undoubtedly change higher education, not all change is progress [6] and change usually benefits some while disadvantaging others. Below are six suggestions—from high level to the most actionable—for possible actions that can help ensure that environmentally forced change does not unintentionally damage the aspects of higher education that lead to personal transformation:

- First, it is important to develop a philosophy that complements rather than rejects emerging technologies in order to have meaningful dialogs about systemic issues in education. Such a philosophy would delineate claims, analyze arguments, clarify underlying assumptions, and ask really damn hard and penetrating questions about how to keep what is good in higher education and discard what has been made obsolete. Changes in education always have ethical, epistemological, and ontological implications which need to be articulated.
- Second, there is a need to better understand what intangible civic and humanistic benefits current models of education offer, how to enhance these under different structural models, and what the risks of losing them could be. Some work points to the value of close relationships, rich educational ecosystems, and bound autonomy as critical factors [35] but how to scale and better support these aspects of traditional education need to be further understood.

[5] It should be noted that current higher education system and institutions have contributed to the issues of access.

[6] The full quote attributed to John Wooden is: "*Although there is no progress without change, not all change is progress*."

- Third, new paradigms and metaphors are needed to understand and describe the fragmenting educational landscape. Because there are many interconnected factors at play an emerging paradigm is to consider higher education as an ecosystem [43]. The term ecosystem implies that individuals; families; local, state, and federal government; educational institutions; foundations; and commercial enterprises all contribute to, and are interconnected through, the ways education is provided and financed. Developing new understanding of the changing ecosystem will be needed to preserve the good.
- Fourth, technologically driven change offers a unique opportunity to reorient the institutional hierarchies which have been ossified by status, rankings, and algorithms [13]. In the ecosystem analogy a fragmented educational landscape creates new niches in the ecosystem which could allow new experiments to succeed in ways they have not been able to in the past. While in the past success has been predicated on rising in institutional rankings a new landscape may enable struggling colleges to move sideways into an underserved niche rather than up.
- Fifth, populating a fractured landscape will require bold experimentation. Given the high stakes and inherent conservatism of institutions which have historically calibrated themselves against peers will require support from other major players in the ecosystem including government, industry, and private foundations. In practice this will require founding new colleges or offshoot programs which can explore alternative structures. To be successful these experiments will need to articulate their underlying philosophies as well as how they create value. Key to value creation in this new landscape will be restraining costs, awarding transportable and societally relevant credentials, and increasing convenience for students who increasingly will transition in and out of the workforce.
- Finally, as the educational landscape fractures students will need to develop skills in finding and selecting educational opportunities then integrating them into a meaningful credential. Such abilities can be best characterized as navigational skills. How education programs can develop these competencies and when to develop them in students are still open questions.

In summary technology is supporting new, and potentially more effective, ways of learning about and making sense of the world. These challenge, and threaten to fragment, not just the processes of higher education, but its underlying structures. Higher education seems poised at a branching point. Issues of cost and access are becoming critical while demand—the need for education in a world that relies increasing on technology—rises. These needs and rising costs help drive increasingly utilitarian views of education which threaten to overwhelm the humanistic and civic value education provides. While the path forward is obscured by opaque finance models [4], political posturing, and an ongoing status arms race the new affordances that technology provides offer hope for fundamentally new structures to arise. Whether or not these new structures will be just, inclusive, and support *eudaemonia* is still to be seen.

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