An Ecosystem Analysis of Engineering Thriving with Emergent Properties at the Micro, Meso, and Macro Levels

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Bryan Watson, PE earned his Ph.D. at the Georgia Institute of Technology and his B.S. in Systems Engineering at the United States Naval Academy in 2009. After graduating, Bryan joined the nuclear Navy, serving as a submarine officer onboard the U.S.S Louisville and at the Naval Prototype Training Unit from 2009-2017. Significant milestones include earning the Master Training Specialist Certification (the military's highest instructor accreditation), Nuclear Professional Engineer Certification, two Naval Achievement Medals, the Military Outstanding Volunteer Service Medal, and a Naval Commendation Medal for his work troubleshooting and repairing the Moored Training Ship 635's reactor and electrical distribution faults. Following his transition from active duty, Bryan earned his PhD as a member of both the Computation and Advancement of Sustainable Systems Lab, where he developed a new method for distributed system demand estimation, and at the Sustainable Design and Manufacturing lab, where his work focused on increasing System of System resilience. Bryan's work has been published in the Journal of Industrial Ecology, Journal of Mechanical Design, and IEEE's Systems Journal.

At Embry-Riddle, Bryan's current work is focused on investigating the use of biologically inspired design to increase the resilience of modern system. The goal of their work is more reliable services to users, increased user safety, and increased sustainability for connected manufacturing, energy, and infrastructure systems.

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ABSTRACT

This paper combines prior work on engineering thriving and complex systems science to provide an ecosystem model perspective with implications at the Micro, Meso, and Macro levels. Prior work on engineering thriving has largely focused on the Micro level (individual focus) and Meso level (organizations focus) with little focus on the Macro level (social institutions focus). This systematic literature review includes 29 peer reviewed papers selected from 6 journals and 11 conference papers across three databases. The result of this work includes two contributions. First, we provide a definition and indicators of thriving at each of three levels in the engineering education ecosystem. Engineering educators can use these definitions and indicators as a reference point for understanding thriving from an ecosystem perspective, informed by complex system science. Second, we examine the influence of thriving between levels of the system by considering thriving an emergent property of the Meso and Macro levels. Findings indicate that the speed of the dynamics for each level slows as each level becomes larger, with Micro level dynamics generally changing fastest, while Macro level dynamics generally changing slowest. In addition, the Meso level holds a unique role in influencing Micro and Macro levels by being the most "fragile" level most susceptible to intervention. Overall, this work lays the foundation for future work that seeks to identify specific strategies and high-impact interventions to increase thriving across multiple levels of engineering education ecosystems.

INTRODUCTION

Shifting from pipeline and pathways models to an ecosystem model of engineering education is a testament that all factors related to engineering student thriving operate within complex systems [1], [2]. Benefits of the ecosystem model over prior models of engineering education include being less value-laden and more realistic than prior models, but the ecosystem model also captures a "quality of messiness" that is more difficult to study than the "cleaner" pipeline and pathway models [2, p. 50]. While ecosystem metrics and data representations are increasing, applications of complex systems science to ecosystem models of engineering education are currently underexplored. Complex systems science (sometimes referred to as the study of socio-technical systems) has been shown to provide novel insights into the dynamics of non-linear systems with embedded rational agents [3], and holds potential for novel application in our field to improve our understanding of engineering thriving. Complex systems science indicates that each level of a system (such as micro, meso, and macro) consists of nuanced and distinct emergent properties that intersect and influence one another in Micro-Meso, Micro-Macro, and Micro-Macro levels (see Figure 1).

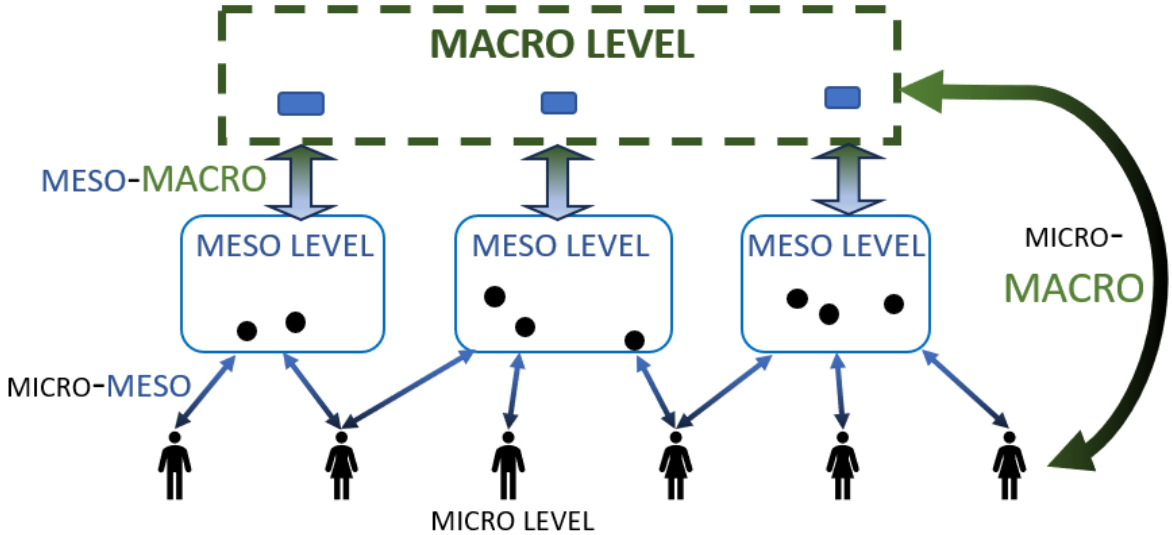

Figure 1. Generalized Micro-Meso-Macro Framework. Adapted from [4]. The framework consists of three levels (Micro, Meso, and Macro) and three influence paths (Micro-Meso, Meso-Macro, and Micro-Macro). By influence path (or thriving between levels) we refer to mechanisms which allow increased thriving at one level (e.g. improved belongingness in individuals at the Micro-level) to increase thriving at another level (e.g. improved team performance at the Meso-level). Influences flow bidirectionally. To maintain readability, only one Micro-Macro influence path is shown and only one Micro-level is labeled.

Informed by complex systems science, we investigate a new approach toward understanding engineering thriving as an emergent system property. Engineering thriving is broadly defined as "the process by which engineering programs facilitate the environments for students to develop optimal functioning in undergraduate engineering programs" [5], [6]. Figure 2 shows a model of engineering thriving that emphasizes the cyclical process by which students' internal thriving competencies and external thriving outcomes affect each other based on influences from engineering culture, systemic factors, resources, context, and situation. The current model of thriving focuses on the individual student (Micro-level) and the engineering culture from the programs, departments, and institutions they are embedded in (Meso-level) but larger societal influences remain underexplored (Macro-level).

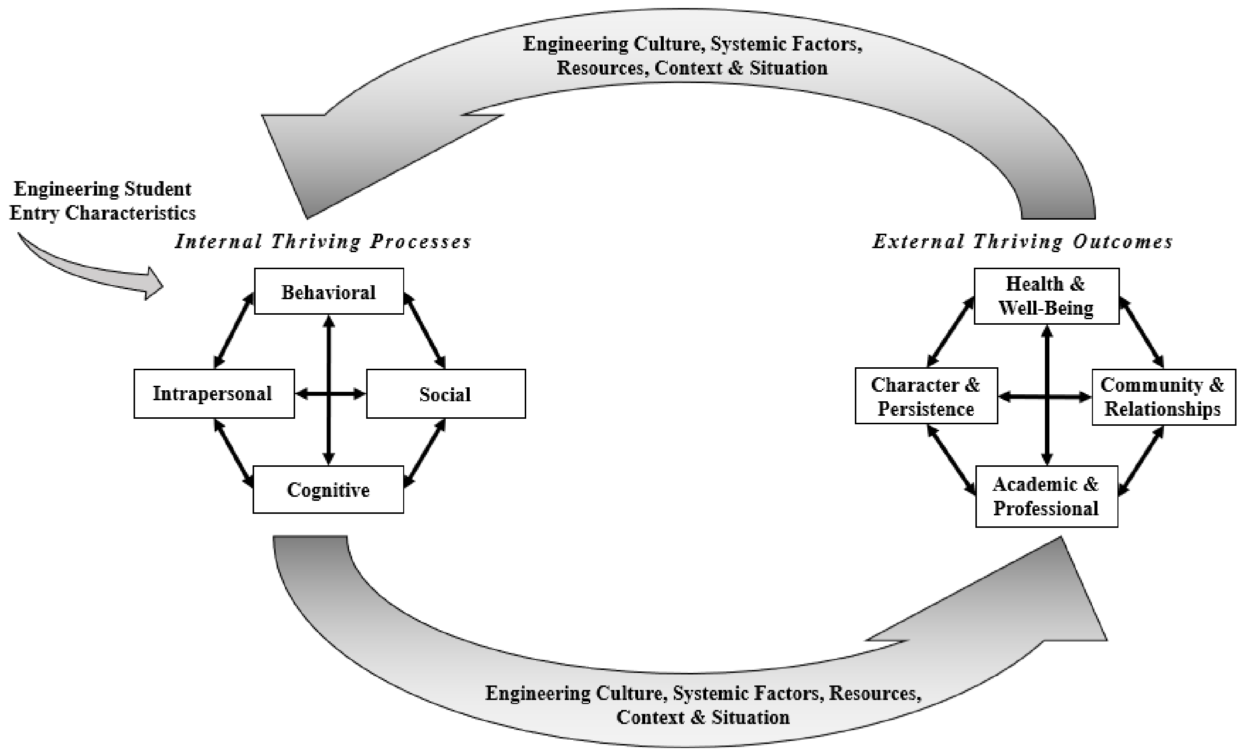

Figure 2. Model of engineering thriving, from [6], which focuses on the Micro-level (individual) and Meso-level (organizations)

In this research paper, we perform a systematized literature review to explore the distinct functioning of engineering thriving at the Micro, Meso, and Macro levels, as well as intersections of these levels, such as Micro-Meso, Micro-Macro, and Micro-Macro influences. We contribute to the current research shift from individual focus to systems-level focus in engineering education by viewing engineering thriving as an emergent property at the Meso and Macro levels. Emergent properties are higher-level properties that exist due to the interaction of constituents [7], [8], [9]. A significance of this broadened focus is that it challenges the assumption in prior work that thriving is a resultant (sum of Micro-level properties) property of the Meso or Macro level, rather than an emergent property (resulting from the properties of the lower levels as well as the interactions between them). As an emergent property, different intervention strategies are needed at each level. Large effects at the Meso or Macro-level may have negligible impact at lower levels [10]. For example, facilitating a large increase in industry diversity could only result in a minimal increase in faculty availability. A single Meso-level entity (e.g. College of Engineering shifting to hybrid courses) can cause a large Macro-level change (e.g. educational affordability). This non-linear coupling provides us with pause when considering that many historical examples focus on large Macro-thriving interventions (e.g. "No Child Left Behind Act"). These large interventions may not predictably result in improved Micro or Meso thriving [11].

Overall, the two contributions of this paper include:

1) <u>Engineering Thriving at each Micro, Meso, and Macro Levels (MMML) (nodes):</u> This review surveys the existing literature to define thriving at each level of the engineering

education ecosystem as well as provide a shared language around indicators of thriving at each level. Developing shared definitions and language around engineering thriving at each of these levels is an essential first step to understand the unique properties of thriving at each level.

2) Engineering Thriving between the MMML (paths): Through the perspective of emergence theory, thriving not only functions differently at each level but can also influence between (e.g. Micro to Meso thriving) and among (Meso to Meso thriving) levels. This review maps the relationships as pathways of influence between and among levels.

BACKGROUND

The background section summarizes interdisciplinary Micro-Meso-Macro definitions and the flows between levels (e.g., Micro-Meso), with insight from systems science and emergence theory. The goal of this section is to guide and ground our systematized literature review within the broader context.

A Primer on Interdisciplinary Perspectives to Micro-Meso-Macro Perspectives (Levels)

To understand Micro-thriving, Meso-thriving, and Macro-thriving, it is important to first acknowledge the distinctions between the terms "Micro," "Meso," and "Macro", and the relationships among these terms. The distinctions between Micro, Meso, and Macro have been widely acknowledged in engineering ethics and related fields such as economics, sociology, and psychology, as they provide a framework for analyzing ethical considerations at varying levels of scale and influence within complex systems [12], [13], [14]. ***The Micro-Level*** pertains to individuals, the ways they act, and the rules and motives behind it [15]. In engineering ethics, Micro-ethics concerns problems internal to the professional world of engineers, such as conflicts of interest, intellectual property, and whistleblowing [12]. This level is closely associated with individualism-based frameworks [16]. The field of engineering ethics tends to focus on Micro-ethics, since engineering education tends to focus on problems that directly impact professionals in the field. Micro-ethics is often explored through in-depth case studies, providing a nuanced understanding of the intricate dilemmas faced by engineers in their day-to-day activities [12]. Micro-ethics concerns itself with issues and responsibilities bearing on individuals within the professional sphere, making understanding Micro-ethical issues crucial for fostering a deeper understanding of the ethical dimensions of individual actions within the engineering community.

Micro-ethics is often taught through case studies focusing on individual Micro-ethical issues, where an individual engineer is faced with an ethically difficult situation. These cases are very accessible to students, who have limited professional experience [17]. However, focusing on Micro-ethical issues alone can decontextualize these issues, and so students often have trouble connecting their individual decisions with unintended social consequences at the Macro-level [12].

Similarly, in Microeconomics, the term "Micro" pertains to individual actions, such as contracting, pricing, and evaluation [13]. The term originated from the economic theories of self-interest and the "invisible hand" of the market created by 18th-century philosopher Adam Smith, which highlighted the tendency of individuals to act in ways that benefit themselves without considering the greater effect of their actions [18]. These individual actions can have a cascading effect on the larger system it is contained in, emphasizing how the Micro-level can affect the higher-order levels of Meso and Macro.

Within complex systems, the Micro-level focuses on the processes that guide the individual agents within each complex system [4], [19]. Agents are entities that exist in an environment, can sense, are able to communicate with other agents, and conduct autonomously, rational, goal-directed behavior [19], [20], [21], [22]. Although complex systems also often includes non-human entities as agents (e.g. robots or animals), for the purposes of this review, the Micro-level is limited to human agents.

The *Meso-Level i*ncludes departments and institutions. The Meso-Level also generally describes the structures and/or processes occurring between the Micro and Macro levels of the system. In the Micro-Meso-Macro framework, Meso plays an important role as an intermediary layer between the Micro and Macro layers [23]. In engineering ethics, Meso refers to the level of organizations, particularly concerning issues involving their structure and culture. For example, Meso-level analysis includes an organization’s decision-making process, policies, or overall conduct [23]. The Meso layer is a bimodal component, it is both a structural component existing between the Micro and Macro, but also a process component because it translates the ideas and actions happening at the Micro-level to its outcomes and consequences at the Macro layer [24].

In economics, mesoeconomics refers to a middle and connecting layer between microeconomics and macroeconomics. In this theory, innovation at the Micro-level is followed by imitation and adoption, creating the Meso-level, before causing transformative economic development at the Macro-level [25]. Recently, this Meso-level perspective has garnered renewed attention in modern economics as scholars develop a more comprehensive Micro-Meso-Macro approach. In the Micro-Meso-Macro framework, the Meso layer is recognized as a connector between individual actions and broader system consequences [24].

Within complex systems, the Meso-level applies to complex systems-level analysis, where complex systems consist of the interaction between cooperating agents (Micro-level), their environment, and technical artifacts within that environment [22], [26]. The inclusion of agents is critical, creating a distinction between large engineering systems (e.g. a nuclear submarine’s power plant) and a complex system (university level ASME chapter). At this scale, intervention often focuses on altering the environment or technical artifacts (since agent-level interventions are Micro-level interventions) [26]. Meso also performs the key function of sharing or shaping expectations for individual behavior within a group of agents [22]. The Meso-level performs a function that still has value, even if no longer interacting with other Meso groups within a Macro framework [27]. Of course, isolating Meso-levels will minimize their effectiveness. Finally, due to consisting of rational agents the Meso-level will exhibit complex dynamics including non-linear responses, non-ergodicity, bifurcation points, and sensitivity to initial conditions [3], [28], [29], [30].

Macro-Level refers to the most comprehensive level of analysis in the Micro-Meso-Macro framework, concentrating on societal or systemic structures. In engineering ethics, Macro-ethics addresses external issues that impact the world of professional engineers. This level is often associated with holism [16]. The Macro level includes issues that impact engineering as an entire profession, such as privacy rights, environmental protection, and the relationship between infrastructure and social justice [12]. Despite its significance, Macro-ethics is a current focus area in the field of engineering ethics, as Macro-level ethical issues can be more difficult to research than individual, Micro-level issues.

In engineering ethics education, Macro-ethics is often taught through case studies that emphasize the social and political consequences of engineering design principles [17]. These Macro-level case studies are helpful because they highlight the consequences of decisions made in the engineering process. However, they often use disasters or tragedies as examples of the impact of engineering principles and decisions, which can be overwhelming for engineering students.

In economics, Macroeconomics provides a holistic understanding of economic systems, addressing topics such as allocative efficiency, intervention rationales, and environmental considerations [13]. Macroeconomics gained prominence during the Great Depression, with John Keynes popularizing the term in the 1930's [31]. Keynesian economics emphasized the distinction between Micro and Macroeconomics, advocating that an economic recovery from a crisis as large as the Great Depression did not depend on individual demand, but rather actions from the entire United States government and large economic sectors.

Within complex systems science, the Macro-level refers to Systems of Systems (SoS). SoS have three defining characteristics: operational autonomy (each systems acts according to its own best interest), an evolving structure (can change the systems involved), and demonstrates emergent properties [7]. System or SoS level properties can either be emergents or resultants. Emergent properties are higher-level properties that exist due to the interaction of constituents [7], [8], [9]. For example, the spatial distribution within a flock of birds depends upon both the "rules" birds follow but also the interaction between the members of the flock. Resultants are properties that can be found by summing the lower-level properties. For the human brain, the total mass of all the neurons is a resultant, while consciousness is an emergent [32]. Although a requirement for the Macro-level, emergence exists across all hierarchical boundaries (Micro-Meso and Meso-Macro).

Interdisciplinary Perspectives on Flows Between the Micro, Meso, and Macro levels

Dynamics within each of the Micro, Meso, and Macro levels are influenced by the conditions of the other levels. A high Micro-level of thriving might prevent a decrease in Meso thriving following a disruption at the Macro-level. For example, a community of resilient individuals might have minimal disruption to their ASEE student chapter meeting schedule during the COVID pandemic due to shifting their meetings online. This section discusses how the boundaries from Micro to Meso, Meso to Macro, and Micro to Macro have been viewed in other fields.

Micro-Meso refers to the relationships between Micro (individual agents rational agent) and Meso (system) levels, where the system contains multiple interacting agents as well as their environment and any technical artifacts (i.e. built objects). In this framework, Meso is the rule and its population, while Micro denotes the individual carriers of rules . Consider the human brain as an example, where Micro-elements like neurons collectively make up a Meso-level component, the brain itself [33]. In this example, individual agents (neurons) interact with their environment (Cerevrospinbal fluid) and technical artifacts (any medicine absorbed in the body). In a system, actions taken deliberately at the Micro-level have the ability to induce significant changes at the Meso-level, exemplifying the connection between these two levels [15]. These changes can be divided into resultants and emergents. This Micro-Meso process is most often demonstrated in contexts involving the establishment of new expectations, organizations, interactions, laws, and institutions. Here, the actions of individuals at the Micro-level create a novel Meso landscape.

In economics, the concept of path-dependency (ergodicity) serves as an illustration of a Micro-Meso process by highlighting how individual choices at the Micro-level can set the course for larger economic trajectories [15]. Although Micro-level choices alone do not determine Meso-level properties, these choices (through the process of emergence) impact the final state-distributions possible at the Meso-level. Continuing with our brain analogy, consider the injury to Phineous Gage that damaged many of his neurons (Micro-level). This injury did not solely determine his personality after the injury (Meso-level emergent property), but the possible dispositions we should expect after this injury were different than those before the injury. This relationship underscores the interconnectedness between Micro and Meso levels, shaping the dynamics of diverse systems across various domains.

Meso-Macro is a relationship between the Meso and Macro levels, where Macro is composed of Meso units, and each Meso is contained in a higher-order Macro structure. Additionally, actions, behaviors, and structures of Meso entities have a direct influence on the Macro environment. As an example, institutions and companies at the Meso-level have direct effects on the greater capitalist marketplace [15]. The Meso-level interactions between different institutions and companies contribute to the form and evolution of their Macroeconomic landscape. Thus, the Meso-Macro relationship highlights the significance of understanding how entities at the Meso-level collectively influence the broader Macro system. These relationships can be both emergents or resultants, but at least one emergent property must exist for the entity being examined to be considered Macro-level (see definition of Systems of Systems above). This provides one of the distinctions between a “large” Meso-level and the Macro-level. For example, although the University of Alabama College of Arts and Sciences population is larger than Williamstown, MA (home of Williams college) the college is considered Meso-level while Williamstown is Macro-level. Williamstown consists of systems with operational autonomy (public works, college, business sector), can add or subtract systems (businesses can start or close), and demonstrates emergence (traffic patterns).

Micro-Macro refers to the dual consideration of individual-level ethical decision making (Micro) and the broader societal impact of engineering practices (Macro). While considered by some economists, philosophers, and engineers to be “obsolete” in light of the developments of Micro-Meso-Macro theories, the Micro-Macro theory has support among ethicists who argue for its continued relevance [23]. It has been proposed that ethical considerations are best understood through a Micro-Macro framework, as the levels of Micro and Macro are complementary to each other [12]. It can be dangerous to isolate Micro-level issues from the Macro layer, as inquiries of Micro-ethical concerns may be rendered useless if they cannot be considered or applied in a broader societal context at the Macro layer. Therefore, the Micro-Macro framework is a more comprehensive approach that allows Micro-ethical issues to be contextualized within a larger social framework, offering a more nuanced understanding of their implications. Similarly, Macro-ethical issues can be placed in an engaged practical framework at the Micro-level, ensuring that ethical considerations are addressed at both the individual and systemic levels.

In engineering ethics education, Micro-Macro analysis can consist of case studies that highlight how engineering decisions and practices at the Micro-level can have large impacts at a societal level. For example, when Microsoft and IBM developed facial-recognition technology, it was able to correctly identify white male faces 99% of the time, but it correctly identified black female faces only 65% of the time [17]. If this technology were to be adopted into the criminal justice system to make decisions on incarceration, it would exacerbate racial and gender inequalities in society. Likewise in complex systems science, the Meso-level is often treated as a black box so impacts on the Macro-level from Micro interventions can be studied.

METHODS

This study uses a systematized literature review process to identify, screen, and analyze relevant articles. A systematized literature review was chosen to provide a broad overview of perspectives [34]. This review resulted in 458 papers collected from three databases, with 29 papers selected for full-text review. In consultation with two librarians, three databases were selected for this review: IEEE Xplore, Education Resources Information Center (ERIC), and Scopus. After selecting the relevant databases, one search string for each database was created based on common keywords and terms from the papers included in the background section (see Table 1). With guidance from the thesaurus of each database, synonyms and related words or phrases were created for each of the main terms. For example, search phrases for “thriving” include “success,” “wellbeing,” and “flourish.” As a quality check, we only included relatively recent articles between January 1, 2000-Dec. 26 2023 (the date papers were collected) that were peer-reviewed. Due to limited resources for translation, only articles in English are included.

Table 1. Search Strings and Limits Applied to Three Databases for the Systematized Literature Search

Database	Search String	Limits Applied	Number of Papers
ERIC	(Thriv* OR success* OR Wellness OR wellbeing* OR character OR Strength* OR Well-being OR Flourish* OR education) AND (engineer*) AND (Micro* OR "college student*" OR stud* OR faculty OR staff OR instructor OR individual* OR independen* OR self* OR agent OR Meso* OR college* OR universit* OR department* OR institution* OR organization* OR cultur* OR “higher education” OR entity OR workplace OR Macro* OR societ* OR profession* OR global* OR national OR international OR government* OR country OR career OR worldwide OR state) AND	Include only: Academic journals Peer-reviewed Higher education	64

	(interconnect* OR equity OR integrat* OR intersect* OR cross-level OR multilevel OR link OR union OR converge OR bridg* OR connect)		
Scopus	TITLE-ABS-KEY((Micro* OR individual* OR self* OR agent OR Meso* OR department* OR institution* OR organization* OR workplace OR Macro* OR societ* OR world OR global* OR national OR international OR government* OR country OR worldwide OR interconnect* OR equity OR integrat* OR intersect* OR cross-level OR multilevel OR link OR bridg* OR connect) AND (thriv* OR wellness OR wellbeing* OR flourish*) AND (engineer*) AND ("college student*" OR college* or universit*) AND (education OR ethics)) AND PUBYEAR > 1999 AND PUBYEAR < 2025 AND PUBYEAR > 1999 AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA,"ENGI") OR LIMIT-TO (SUBJAREA,"COMP")) AND (LIMIT-TO (DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English"))	Limited to engineering and computer science Limited to English Limited to journal articles and conference papers Limited to 2000-2024	234
IEEE Xplore	(Micro* OR "college student*" OR student OR students OR faculty OR staff OR instructor OR self OR agent OR Meso* OR department OR institution OR organization OR workplace OR Macro* OR society OR global OR national OR international OR government OR country OR worldwide OR interconnected OR equity OR integrate OR intersect OR cross-level OR multilevel OR link OR bridge OR connect) AND (engineer*) AND (education OR ethics) AND (Thriv* OR success* OR Wellness OR wellbeing OR Well-being OR Flourish) AND (college OR colleges OR university OR universities OR “higher education”)	Only include journal papers Only include papers published 2000-present Limited Journals: IEEE Transactions on Education	160

The screening process followed several steps. First, all papers were reviewed after duplicates were removed. Next, we reviewed the title and abstract of each paper, marking papers we deemed to be relevant to our selection criteria (Table 2). From the papers selected after the initial title and abstract screening, a full text review was done, and any papers that did not meet the selection criteria were removed. Some papers were unclear if they met the selection criteria or not, prompting team discussions of whether to include these papers and revisions to our selection criteria. Through this iterative process, we developed the final selection criteria in Table 2.

Table 2. Selection Criteria and Justification for the Systematized Literature Search

Selection Criteria	**Justification**
Focus on thriving, ethical, or asset-based perspectives	This criterion is directly relevant to the research goals. This criterion excludes perspectives that solely focus on deficits, barriers, problems, and disabling conditions.
The study context is the ecosystem of engineering in higher education.	This criterion includes individuals in engineering colleges or universities (such as students, faculty, instructors, or staff). Multiple perspectives within the engineering education ecosystem are included, such as engineering thriving, engineering ethics, and engineering ethics education. K-12 students are excluded since they are not considered part of the engineering education ecosystem in higher education. Thus, the scope is from matriculation to graduation in engineering program. This criterion includes engineering departments, universities, and the engineering profession. This criterion includes papers that focus on more than engineering (such as STEM, Computer Science, Engineering Technology, and STEAM) as long as results specific to engineering students are presented. This criterion includes perspectives from participants outside the United States to be inclusive of perspectives beyond Western, Educated, Industrial, Rich, Democracies that seem to dominate current psychological research [35].
The paper is published in English	We only included articles published in English given limited resources for translation.
The paper includes research (qualitative, quantitative, or mixed methods)	This criterion focuses on research papers (qualitative, quantitative, or mixed methods) or interventions that create positive change at the Micro, Meso, or Macro levels. These

	papers must provide methodological details for reproducibility (e.g. search strings or databases for literature reviews). This criterion excludes instrument development, personal opinions (e.g. book reviews), program evaluations, descriptions of activities, and incomplete studies.
The study includes intervention on at least one of the levels (Micro, Meso, or Macro) or on the relationships between levels (Micro-Meso, Meso-Macro, Micro-Macro).	This criterion is directly relevant to our broader research goal. The purpose of the larger study is to investigate interventions within and between levels. This criterion excludes papers that are practically focused, excluding papers that focus only on theory or opinion, guest editorials.
Peer reviewed	This criterion provides an indicator of quality.

The screening process is shown in the PRISMA diagram in Figure 3. After searching the databases, a total of 458 papers were collected from the three databases. After removing 5 duplicates, there were a total of 453 unique papers. Following review for exclusion criteria (Table 2), 29 papers were selected for analysis.

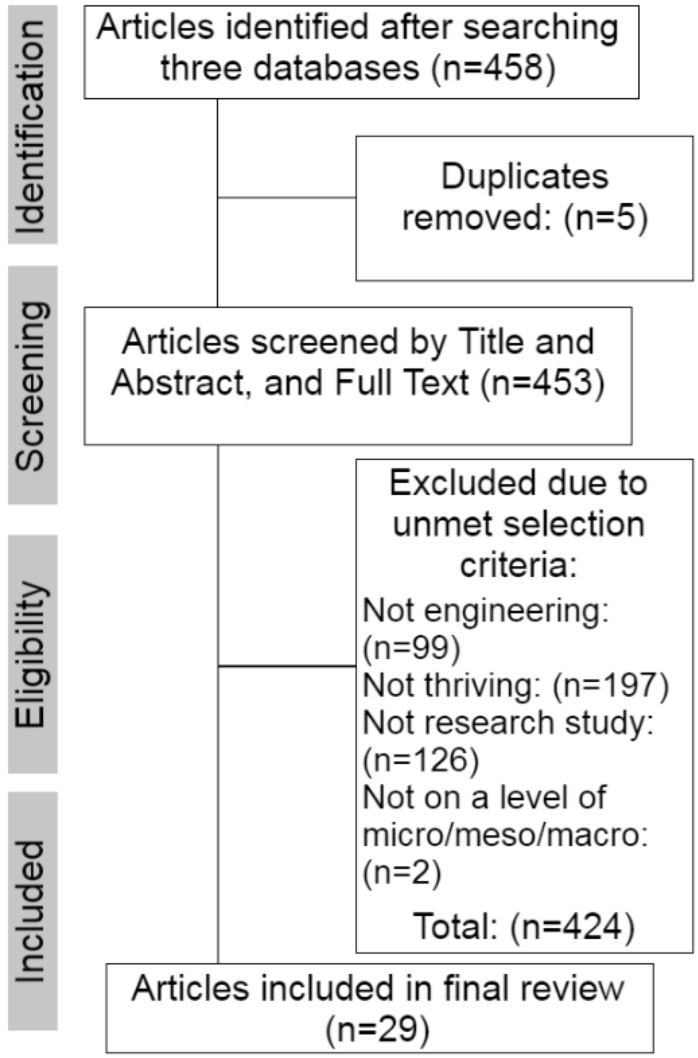

Figure 3. PRISMA Diagram Outline Review Process for Papers

Characteristics of the papers are reported in Table 3. The papers were a mix of quantitative, qualitative, and mixed methods. A total of 6905 students were surveyed across the 29 papers.

Table 3. Characteristics of 29 Papers included in the Analysis

Number of Journal Papers	11
Number of Conference Proceedings	18
Publication Date Range	2002-2023
Number of Journals Represented	6
Number of Conferences Represented	11

Charting the results

After finalizing the papers, the results were charted in a spreadsheet. The information extracted from the paper was: the paper title, author(s), paper source, key takeaway, method, type of study, sample size, characteristics of study population, industry or organization name, minority perspectives, how thriving is defined, how thriving is measured, what level the key focus of thriving is on (Micro, Meso, Macro, or a combination of the three), definition or examples of the thriving on applicable level(s), and interventions.

RESULTS

Contribution 1: Engineering Thriving at each MMML (nodes). Engineering thriving requires unique definitions at each of the MMML due to the unique functioning at each level.

Table 4. Results of Literature Search for Micro, Meso, and Macro thriving in engineering

Level	Example(s) of the Level	What Thriving Means at this Level (Summary)	Example Indicators of Thriving
Micro	Individual	Individual Empowerment	• Motivation [36], [37], [38], [39], [40], [41] • Academic performance [42], [43] • Confidence [39], [44], [45] • Mindfulness [46] • Self-awareness [47] • Creativity and innovation [48] • Ability to work in team [39], [41], [45], [49] • Problem-solving skills [46], [50] • Communication skills [41], [46], [50] • Achievement-oriented [41], [51] • Sense of purpose and intention [38] • Agency [45] • Self-efficacy [38], [39], [42], [45], [52], [53], [54] • Growth mindset [55], [56] • High metacognitive awareness [47] • Relationships with peers, professors, instructors [57] • Faculty [58]: organizational socialization, relationship identity and community building among faculty, sense of well being and belonging, faculty retention

			• Faculty [58]: Organizational identification, organizational integration, familiarity with supervisors, acculturation, recognition, involvement, meaningfulness, and happiness
Meso	Departments and Institutions	Resources & Supportive Communities	• Collaborative and supportive learning environment [37], [59] • Student & faculty morale [58] • Increased number of university resources [41], [44], [52], [57], [59] • Level of student involvement in clubs and professional development organizations [51] • Level of faculty accessibility [49] • Student-teacher ratio [49]
Macro	Societal and Larger Systems	Ethics & Diversity	• Diversity in engineering profession as a whole [40], [51], [52], [57], [60] • Diversity in leadership positions [51], [57] • Affordability of education [39], [44], [57], [60], [61] • Awareness of macro-ethical consequences of micro-ethical actions [17]

Micro-thriving in engineering is defined by empowered individual members of the engineering education ecosystem (such as students, faculty, instructors, and staff). A distinguishing feature of Micro-thriving is constant change, as an individual's experiences are constantly changing and thriving at this level depends largely on an individual's ability to navigate change [24].

Meso-thriving in engineering is defined by connected, supportive, and resilient communities, often built around shared goals, and that take on characteristics separate from the sum of individual members. In our review, Meso-level thriving can refer to an engineering department, institution, committee, campus organization, and additional communities for which members of the engineering education ecosystem belong. A unique property of Meso-thriving is the development of a "group identity" that is separate from that of any single individual in the group and the set of accompanying shared values, experiences, and/or goals that define the group. Compared with Micro-thriving, Meso-thriving (e.g., positive morale) appears to be more stable than Micro-level thriving and also require more effort to change.

Macro-thriving in engineering is defined by sustainability, social justice, equity, as well as the broader systemic and societal impact of the profession of educating engineers. Thriving at the Macro-level in engineering involves shared cultural values around general conceptions of broader impact (such as improving diversity and access to engineering education). Based on our review, these broader shared values are typically determined by national and international organizations and rarely receive unanimous support at the Micro-level due to differences in political opinions, Meso-level culture, etc. Change at the Macro-level tends to be slowest and require disruptive cultural changes in shared values.

Contribution 2: Engineering Thriving between the MMML (paths). The relationships between and among levels provides several insights into factors that can create broader systemic change in the engineering education ecosystem.

Table 5. Results of Literature Search for influences that impact flows between Micro, Meso, and Macro levels of thriving in engineering

Flow	**Examples of how thriving influences and crosses levels**
Micro-Meso	Faculty integration, participation, and identification with their engineering program affects the thriving of engineering students. The integration and socialization of individual faculty have consequences on the students' engineering education and programs, which affects the thriving of students on an institutional level [58] Systems of support at the meso-level, including relationships with peers, professors, minority networks, and professional development organizations affect an individual's thriving [57] Institutions implementing professional development workshops & programs increases the confidence, communication skills, and strengthens students' engineering identities [39] Institutions can provide greater access to university resources and academic enrichment programs to increase students' confidence and willingness to learn [44] Thriving is not only influenced by personal perceptions, but also by interpersonal relations, as well as contextual and institutional conditions [41] Institutions can include an ethics-based course in their engineering curriculum to foster the ethical and moral development of students [56] Institutions can provide disability inclusion programs and resources such as access to professional development resources, accommodations, and disability awareness [52].

Meso-Macro	A country's government can change the requirements of its engineering programs to better foster creativity, problem-solving skills, and collaboration skills [50]
Micro-Macro	Engineering Ethics Education connects Macro-ethical results to Micro-ethical decisions [17] Individual response to global events (e.g. COVID-19) [62] Women's early exposure to STEM and engineering and sociocultural norms contributes to women's feelings of belonging, self-efficacy, and agency [45] Students are more motivated to pursue a career in engineering if the career is perceived as being altruistic; students want to pursue a career where they feel they can give back to their communities [37]

Micro-Meso Thriving in Engineering is characterized by the flow of interactions between individuals and our environment. In alignment with prior work, a unique distinguishing feature of Micro-thriving is that individuals ultimately have the most direct and immediate control over our own actions and behaviors [6], while we also influence one another and the environment [63]. Thus, the ways in which faculty members integrate, participate, and identify with their engineering department affects the thriving of engineering students [58]. The integration and socialization of individual faculty affects their morale, happiness, sense of meaningfulness, and teaching, all of which have consequences on the students' experience of thriving. Greater access to resources, such as libraries, tutoring, mentoring, and access to counseling services (Meso-level) increases thriving at the Micro-level when individuals are empowered to take advantage of these resources [41], [44]. Universities can offer additional programs, such as professional development workshops, to increase students' confidence, communication skills, and prepare them for job interviews [39]. Institutions can create additional resources to contribute to the thriving of women, minority, and disabled engineering students [52], [57] by increasing opportunities for people to find belonging. Finally, universities can alter the curricula itself to promote thriving, such as by implementing an ethics-based course for students [56]. Although it is not yet shown in the literature to have a significant effect on students' ethical principles, including an ethics-based course in engineering programs has the potential to bring awareness to students' ethical choices on a Micro-level.

Meso-Macro Thriving in Engineering is characterized by influences from the Macro-level on the Meso-level in our review. National organizations can create policies and accreditation criteria to shape engineering education degree requirements. For example, ABET accreditation criteria influences institutions to adapt curricula and teaching methodologies based on established standards. Furthermore, federal government can determine the course of future research and interventions through allocations of grant funding [50]. The scarcity of Meso to Macro influences in our review suggest opportunity areas for future work and interventions to support thriving from the Meso-level to Macro-level in engineering.

Macro-Micro Thriving in Engineering is characterized by ways in which individual-level actions shape broader societal-level thriving, and vice versa. In engineering thriving, individual choices, innovations, and ethical considerations cumulatively influence the direction, ethics, and progress of the entire engineering discipline. Thus, engineering ethics education serves as a bridge connecting Macro-ethical outcomes to Micro-ethical decisions [17]. By instilling a sense of responsibility and ethical awareness at the individual level, engineering education empowers students to make ethical decisions in their communities. When this Micro-level motivation is held by many engineering students, it collectively contributes to the engineering profession at a Macro-level by creating an engineering workforce that is not only technically proficient but also motivated by a shared commitment to societal betterment.

DISCUSSION & IMPLICATIONS

The purpose of this section is two-fold: First, this section uses complex systems science to contextualize the results regarding levels and flows of engineering thriving between the Micro, Meso, and Macro levels. Specifically, we discuss the role of emergence in building and maintaining thriving at each level and provide guidance for decision makers (see Table 6).

Table 6. Recommendations for Engineering Educators, Basis in Complex Systems Science, and Implication of these Recommendations.

<table>
<tr><th>Recommendation</th><th>Basis</th><th>Implication</th></tr>
<tr><td>When measuring or making efforts to improve thriving, the level of intervention (Micro, Meso, Macro) should be informed by the time available, resources, and urgency of change.</td><td rowspan="2">The speed of the dynamics for each level slows as each level becomes larger.

Micro generally changes fastest, while Macro is the slowest.</td><td>The slower dynamics at the Meso and Macro levels will result in a longer time delay between intervention and improvement at the Micro level.

Individuals can make the quickest impact by focusing on individual thriving at the Micro level.</td></tr>
<tr><td>If you desire for thriving interventions to have “staying power” consider focusing on the Meso or Macro levels.</td><td>Interventions at the Meso or Macro level will improve the outcome for longer (future generations). This is necessary to consider when allocating finite resources.</td></tr>
<tr><td>When planning interventions to increase thriving, be aware that influences between levels are difficult to predict. For example, do not simply</td><td>Flows between levels are difficult to predict.</td><td>Failure to consider interactions between levels of the system can result in wasted effort and resources.</td></tr>
</table>

attempt to increase Micro thriving in order to improve Meso or Macro thriving. Likewise, a large Macro intervention may not result in increased Micro thriving.	Influences and dynamics between levels of the system must be considered.	
If, however, a department or institution has limited resources to support thriving and must pick one level to focus on, focus on the Meso level as this is the most likely to impact the Micro and Macro levels as well.	The Meso level holds a unique role in that it influences Micro and Macro levels. It is also the most "fragile" and thus susceptible to intervention.	This provides a basis for departments and institutions to focus interventions on the Meso level (if only one level can be focused on). Additionally, changes established at the Meso level (if declared formally) tend to be adopted at the Micro level.

First, the Micro, Meso, and Macro levels of engineering thriving each have unique properties which impact thriving at and between each level. First, the temporal scale of the dynamics at each level can vary widely. Transients at the Micro-level (e.g. increasing student confidence) generally occur much more quickly than the Meso or Macro levels (e.g. societal sustainability initiatives) [10].

Second, the dependence (flows) between the levels is difficult to predict, consistent with Meso- and Macro-thriving being emergent properties [8]. Thus, large effects at the Meso or Macro-level may have negligible impact at lower levels [10]. For example, facilitating a large increase in faculty diversity (an indicator of Meso-thriving) may only result in a minimal increase in faculty availability (an indicator of Micro-thriving). These interactions are further complicated by the fact that there are both top down and bottom-up interaction pathways, such that the Meso-level has four influence paths (Micro to Meso, Meso to Micro, Meso to Macro, and Macro to Meso) [10], [64] . Additionally, it is erroneous to think that many Micro level entities are always needed for a higher-level change, because emergence will occur once a threshold is passed [9], [10]. A single Meso-level entity (e.g. College of Engineering shifting to hybrid courses) can cause a large Macro-level change (e.g. Educational Affordability). Likewise, large scale Macro-level interventions may not predictably result in the intended Micro or Meso thriving [11]. Research does indicate, however, that beliefs tend to flow downward from the Meso to the Micro-level especially as the Meso-level is more formally defined in terms of space and procedure [64]. For example, formally stating Meso-level ethical standards (e.g. university honor code) is expected to permeate to Micro ethical standards for each individual. Although decision makers can combat emergence through tight coupling of the Micro, Meso, and Macro levels (e.g. inserting Meso policies that limit Micro autonomy), authors note that emergence is what enables the Meso and Macro levels to achieve their desired functions (in our case, thriving) [65], [66]. Lastly, even if Micro-level behavior is known and controlled perfectly, it still may be impossible to predict the emergent Meso- and Macro- outcomes [67].

Finally, Meso-level entities have a unique role in that individual consensus coalesces into an organized entity [4]. The Meso-level is not merely a larger scale, slower evolving Micro-level [11]. Instead, this level organizes agents and codifies norms of behavior which influence individuals [16], [64]. While generally having slower dynamics than the Micro-level, the Meso-level is the most fragile of the three levels. These entities can merge, split, and cease to exist as Micro-level agents join or abandon them [4]. This "fragility" provides a unique opportunity for intervention, as the creation or modification of existing entities provides an avenue for Meso, Micro, and Macro change (e.g. starting an engineering affinity group) [64]. However, opportunities to influence Meso levels can be constrained by the existing Micro and Macro levels [64]. For example, it is important to establish clear shared group goals and values to determine the identity and function of the group and to guide the investment of limited resources. Future work can examine the role of conflicting goals between Micro members and Meso entities and the influence of these conflicts on Meso thriving [11], [16].

In summary, our findings result in several recommendations for engineering education decision makers. First, we advocate for an abundance mindset for Micro-level thriving in engineering. Contrary to a scarcity mindset at the Meso or Macro levels (dividing limited resources toward multiple initiatives), the magnitude of one individual's thriving does not take away, but often contributes, to the thriving of their network. In alignment with principles of emotional contagion [68], when one individual experiences more confidence, gratitude, or care, these positive states of mind tend to affect their social circles. Second, the ultimate goal for interventions that empower thriving is to create a culture of thriving where individuals are thriving even when or once external intervention is no longer available. To achieve this goal, educators and faculty must carefully consider the integration between cultural and institutional (Meso) thriving and personal (Micro) thriving. The needs of the person and institution must align and reach a balance among multiple temporal and spatial scales as Micro, Meso, and Macro ethical decisions interact, reinforce, and enable each other [16]. Micro thriving is not expected in a society without Meso or Macro thriving [64].

CONCLUSION

This work applied an ecosystem perspective of engineering education by exploring the distinct functioning of engineering thriving at the Micro, Meso, and Macro levels. This article combines complex systems science, engineering ethics, and thriving research to interpret the results of a systematized literature review. The review includes 29 papers selected from 6 journals and 11 conference papers. The result of this work was two contributions.

First, we provide a definition of thriving at each of three levels in the engineering education ecosystem. This contribution provides a shared language as well as a list of indicators of thriving at each level. Engineering educators can use these definitions and indicators as one reference point for understanding thriving from a complex system science perspective. Future work will focus on expanding upon these indicators to understand interventions and evaluation methods. The initial model (Fig 1), however, is a simple representation and more sophisticated modeling will be applied in future efforts (e.g. Causal Loop Diagrams and Agent Based Modeling) to further explore the dynamics of thriving at each level.

Next, we examine the influence of thriving between levels of the system by considering thriving an emergent property of the Meso and Macro levels. By mapping influence paths between the levels, this work lays the foundation for future work that seeks to identify specific strategies and high-impact interventions to increase thriving. Informed by complex systems science, this work also provides specific considerations for engineering educators to support thriving as well as the ethical implications of these considerations.

Overall, this paper serves as a first step in understanding the interplay between complex systems science and engineering thriving through an exploration of Micro, Meso, and Macro levels of thriving in engineering. Thriving at any of the levels discussed in this paper is unlikely to emerge from unidimensional approaches, as such perspectives often lead to fragmented solutions. The work of engineers impacts the thriving of society at large. The qualities of individually empowered members of the system (Micro), under favorable environments and supportive communities (Meso), directly enables more thriving societies (Macro). In this sense, all members of the engineering education ecosystem must work together to ensure that the end goals, which affect every facet of our lives, promote thriving and improve lives for students, employees, and the communities we serve. This goal is an end to which engineering education must aim.

AWKNOWLDGEMENTS

The authors would like to thank librarians Suzanne Eichler and Patricia Martinez for helpful guidance on the literature search process to produce this paper. The authors gratefully acknowledge the support of Embry-Riddle Aeronautical University.

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