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Developing an Integrated Environmental Engineering Curriculum

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Developing an Integrated Environmental Engineering Curriculum

Abstract

Many of the National Academy of Engineering's grand challenges are related to environmental engineering. There is broad recognition that these challenges will require environmental engineers to integrate concepts from the natural and physical sciences, social sciences, business, and communications to find solutions at the individual, company, community, national and global levels. Montana State University is in the process of revolutionizing the curriculum and culture of its environmental engineering program to prepare and inspire a new generation of engineers through a project sponsored by the Revolutionizing Engineering Departments program at the National Science Foundation. At the core of the approach is transformation of the hierarchical, topic-focused course structure into a model of team taught, integrated, and project-based learning courses grouped around the key knowledge threads of systems thinking, professionalism, and sustainability. Multi-disciplinary faculty developed specific and detailed program outcomes after review of ABET program outcomes; the Fundamentals of Engineering exam; Body of Knowledge documents from the American Academy of Environmental Engineers (AAEE), the American Society of Civil Engineers (ASCE) and the American Society for Engineering Management (ASEM); the Engineering for One Planet report sponsored by the Lemelson Foundation; and the KEEN Framework on the Entrepreneurial Mindset. The resulting outcomes were organized into competency strands and competency domains. Currently, outcomes spanning the spectrum of content are being crafted into integrated and project-based courses in each year of the undergraduate curriculum. This paper reviews the lessons learned from the process of developing knowledge threads, competency strands and domains, and specific program outcomes with a multidisciplinary group of faculty, as well as the challenges of developing integrated and project-based courses within an established undergraduate curriculum.

Introduction

Environmental engineers serve an important role in addressing the complex environmental challenges facing the planet. Almost half of the National Academy of Engineering's grand challenges [1] relate directly or indirectly to environmental engineering, including specific challenges for the field such as sustainable food, water, and energy; climate change mitigation and adaptation; elimination of pollution and waste; development of efficient, healthy and resilient cities; and improved decision making and actions [2]. According to a recent survey of almost 3,000 engineers in 80 countries, environmental issues will be their number one global challenge over the next 25 years [3].

There is broad recognition that solutions to these challenges require environmental engineers be educated in such a way that they can integrate concepts from the natural and physical sciences, social sciences, business, and communications [4]. Although the need for environmental engineers to expand their historic role is well understood, common approaches to education have not fundamentally changed since the origins of the profession. This work outlines the approaches being taken at Montana State University to address these shortcomings and develop a model approach to update content delivery and program outcomes in an environmental engineering undergraduate curriculum.

Current State of the Curriculum

In our current topic-focused undergraduate curriculum model, the math, science, and mechanics courses in the first two years cover the fundamental concepts used in engineering. Students often view these courses as something to "get through" rather than as foundational to future course content. In addition, several core humanities, art, or social science courses are required as part of the general education requirements, but these may not target development of relevant social and economics skillsets. On this foundation, professional courses are added in the junior and senior years where students first experience environmental engineering problems and engage in the topics that attracted them to the discipline. Finally, we add a capstone course, where prior knowledge integration is attempted. The system provides students with blocks of knowledge that have been stacked and sequenced but not well integrated or connected (Figure 1).

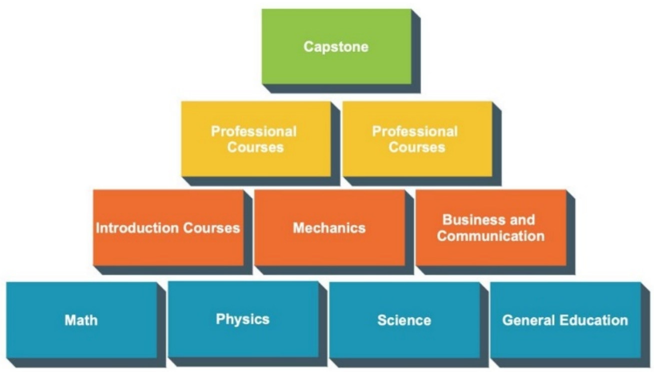

Figure 1. Current topic-focused undergraduate engineering model in which most engineering content is reserved for the junior and senior years, is siloed in individual courses, and not integrated until the senior year capstone course.

Known Issues with the Common Approach

The deficiencies of this stacked and sequenced topic-based approach are well documented in the literature and include:

- Students fail to identify as engineers early in their education. Failure to identify may prevent some students from choosing environmental engineering to begin with, cause them to drop out before they understand their professional role, or stay in the program largely because of the time already invested. In all cases, the current structure of the environmental engineering program hinders the recruitment and retention of the diverse students needed to solve the grand environmental challenges because their interest in environmental engineering is not sufficiently peaked or they feel they don't belong [5].
- Students struggle to understand how fundamental concepts learned during the lower division courses relate to the problems that interest them or the communities they care about [6]. The current approach silos information and for the most part requires students to make connections on their own. Disconnected knowledge is

unlikely to transfer to the new or emerging environmental problems they will encounter during their professional careers [7].

- Engineering students don't achieve a true understanding of interdisciplinary teamwork required for problem solving. Because students are taught courses in an isolated manner, they may develop the mindset that problems are solved by using skillsets from specific technical areas, instead of the merging of multiple areas of expertise [8].
- Students get minimal opportunities to practice combining skills and lessons from different disciplines, which limits students' ability to draw connections, integrate knowledge, and participate in the intentional practice of professional skills needed to develop expertise [7].

Recognition that an integrated approach to engineering education - where knowledge and skills are developed throughout the curriculum rather than presented in separate courses - is not new. In 2005, the development of ABET accreditation criteria clarified the need for a new education paradigm based on an integrated approach [9]. Research has demonstrated that an integrated curriculum can lead to better outcomes. In their review of engineering curricula, Froyd and Ohland [10] noted that integrated programs emphasize connections between topics and improve knowledge transfer to different problems. Integrated programs are also effective at developing learning communities which can improve retention rates, especially of under-represented and underserved students. In addition, there is evidence that students, especially those from underrepresented or under-served groups, show improved retention and preparation for their careers [6]. McGowan and Knapper [11] proposed that an integrated approach could address most of the professional skills and attitudes desired by employers and required by ABET. An integrated approach is better suited to developing the deep knowledge and skills necessary for professional engineering practice [7].

Although the research on integrated curricula are compelling, relatively few programs have implemented this approach. Changing curriculum requires the faculty and the university to make significant cultural and procedural changes. Individuals and institutions are often unwilling or unable to make these changes, so integrated programs are often not sustained [10]. The Civil Engineering Department at Montana State University is in the process of developing an integrated environmental engineering program to prepare and inspire a new generation of engineers. Our project, "Sustainable TRansformation of Environmental engineering Education for Modern society (STREEM)" proposes to develop an integrated program around major knowledge threads while developing a culture that rewards the use of evidence-based pedagogical best practices to promote continuous professional formation throughout the undergraduate program. The change to the environmental engineering program takes place in the context of a larger department. Lessons learned through this process can be used in future to integrate curricula within the other two undergraduate degree programs (civil engineering and construction engineering technology) offered by the department.

At the core of our approach is a transformation of the topic-focused course structure to a model of integrated and project-based learning courses throughout the curriculum that could be team-taught. This paper reviews the progress made to date in developing a curriculum that significantly replaces the classic course-based approach with a model that includes integrated and project-based learning opportunities in each year of study.

Outcomes Based Approach

We adopted a bottom-up outcomes-based approach to developing an integrated environmental engineering undergraduate curriculum. The Outcome-Based Education (OBE) model has been widely adopted in the decades since the Washington Accord was signed in 1989, establishing international accreditation equivalency standards for engineering education with emphasis on student outcomes rather than program content. There are relatively few reports in literature, however, which describe how specific and detailed learning outcomes are developed at a course level [12-14], and less at a curricular level [15, 16].

Our project team comprises faculty members from Environmental and Civil Engineering, Chemical and Biological Engineering, Mechanical and Industrial Engineering, History and Philosophy, Political Science, and English. Together, these multidisciplinary faculty brainstormed and discussed the specific knowledge, skills, values, and attitudes desired in a successful undergraduate engineering student, without regard to existing course content. We utilized key references to guide development of the integrated environmental engineering educational outcomes. These included:

- The seven ABET program outcomes (2019) [17] define requirements for accredited engineering programs and emphasize project-based learning for problem solving and self-directed lifelong learning. ABET outcomes were used as a guide in defining specific outcomes used to evaluate existing course offerings and to develop new courses.
- Fundamentals of Engineering (FE) Exam specifications for Environmental Engineering [18] helped identify the areas of technical knowledge expected of an undergraduate environmental engineer. Performance on the FE exam is an important program assessment measure.
- The ASEE Environmental Engineering Body of Knowledge (EnvEBoK) [19] identifies 18 high-level outcomes grouped as Fundamentals, Enabling Knowledge and Skills, and Professional Outcomes. Each outcome is briefly described and references relevant knowledge domains. The EnvEBoK provides rubrics for each outcome based on Bloom's taxonomic levels in the cognitive domain to define the level of achievement expected at the end of an undergraduate program, after a master's degree (30+ credits), and after 4 years of professional experience. Each sub-outcome is also mapped using the Daggett Rigor/Relevance Framework [20] to highlight the practical relevance at each achievement level.
- The ASCE Civil Engineering Body of Knowledge (CEBoK) [21] captures the foundational, technical, and professional outcomes required of a practicing engineer. The CEBoK outcome rubrics are organized by Bloom's taxonomy across the cognitive and affective domains to identify the level of achievement for each outcome necessary for entry into professional practice, at the postgraduate level, following mentored professional experience, and self-developed through life experience.
- The Engineering Management Body of Knowledge (EMBoK) [22], published by the American Society for Engineering Management (ASEM), describes eleven domains that

combine for the successful engineering manager, many of which apply to all engineering fields.
- The Engineering for One Planet (EOP) draft report [23], sponsored by the Lemelson Foundation and Venture Well ™ and developed by a broad group of stakeholders, aims to facilitate transformation of engineering education so that all engineers are equipped to apply principles of environmental sustainability. The EOP framework comprises a set of learning outcomes related to environmental sustainability and mapped to five ABET program outcomes as well as to the United Nations Sustainable Development Goals.
- The Kern Entrepreneurship Education Network (KEEN) Framework [24] describes engineering education outcomes intended to promote an entrepreneurial mindset, defined as a mindset which cultivates curiosity, promotes making connections, and creates value. (www.engineeringunleashed.com)

The use of on-line collaborative note-taking software and concept mapping software provided convenient, shared on-line tools that facilitated brainstorming. Regular group discussions between the core Environmental and Civil Engineering faculty members allowed for the technical outcomes to be revised and refined over time. We met with our collaborating faculty members from other disciplines, first in small groups then later as a whole team, to develop learning outcomes related to professionalism and sustainability. Over time and with much discussion, granular outcomes were winnowed, grouped, and generalized to a level where they could guide the development of our integrated courses and project-based learning activities. Like the EnvEBoK and CEBoK, we applied Bloom's taxonomy to our outcome rubrics and developed outcomes for both the cognitive and affective domains. Through this brainstorming and discussion process, we developed a program hierarchy made up of Knowledge Threads, Competency Strands, and specific Competency Domains to organize the outcomes.

- **Knowledge threads** are the top-level categories which connect the desired knowledge and competencies across the curriculum. The original proposal specified a *technical thread* to integrate math and science concepts with critical environmental engineering concepts, an *economic thread* to integrate life cycle costs and risk assessment with fundamental business, economics, probability, and statistics concepts, and a *social thread* to integrate the environmental engineers' role in educating the public and policy makers with understanding of how leadership, law and regulations, and public process influence decisions and projects. Ultimately, these proposed threads failed to adequately capture the breadth of outcomes we desired for our program and the relationships we discovered between them. Faculty determined that the EOP framework provided a more appropriate model and adopted *systems thinking*, *professionalism*, and *sustainability* as the three knowledge threads that link all the outcomes in the program (Figure 2).

  The *professionalism* thread encompasses the skills and behaviors desired of a graduate that will allow them to progress in their careers and advance as technical experts and leaders. In addition to serving to connect content across knowledge areas, the professionalism thread contains outcomes related to communication, ethics, social justice, leadership, and teamwork. Professionalism encompasses fundamental skills necessary to communicate effectively with a wide range of audiences and make ethical and just decisions in the practice of their profession. Professionalism thus also includes development of virtues and leadership characteristics. The professionalism thread acknowledges that students develop as professionals over time and with repeated exposure to professional concepts and multiple opportunities to practice and reflect.

The *systems thinking* thread encompasses the skills and behaviors desired of a graduate that will lead them to make design decisions that incorporate an understanding of the broad context in which engineering occurs. Systems thinking is a holistic approach to design that requires understanding the connectedness of engineering projects and decisions to broader social, economic, and environmental systems. In systems thinking it is understood that the components of a design act differently when isolated from the environment or other parts of the system. Thus, there is an inherent need for interdisciplinary collaboration to best understand the impacts and tradeoffs of engineering design decisions.

The *sustainability* thread encompasses the skills and behaviors desired of a graduate that will allow them to navigate the environmental, social, technical, and economic contexts of sustainability [25-27]. Building on the *systems thinking* thread, outcomes related to sustainability are grouped as fundamentals, infrastructure and society, and sustainable development. The sustainability thread includes understanding of technical concepts like life cycle analysis, material selection, and global ecosystem services as well as awareness of governance structures, stakeholder analysis, and how climate change impacts engineering designs.

- **Competency strands** represent primary topic areas where students will develop knowledge and skills, reflecting the multi-disciplinary program outcomes (Figure 2). The strands identified for the program include:

    - Engineering fundamentals
    - Science fundamentals
    - Sustainability fundamentals
    - Groundwater
    - Solid and hazardous waste
    - Hydraulics
    - Surface water resources and hydrology
    - Air quality and control
    - Water and wastewater treatment
    - Engineering management
    - Project management
    - Regulations
    - Public Policy

- **Competency domains** provide additional detail on the content of each competency strand. Each competency strand was divided into several competency domains that represent the areas covered under each strand. For example, the Engineering Fundamentals competency strand includes the following competency domains: Fluid

Mechanics; Mass Balances; Kinetics; Ideal Reactors; Unit Operations; and Engineering and Computational Tools. Within each competency domain, we developed program outcomes to define specific knowledge and skills students will achieve during their undergraduate education.

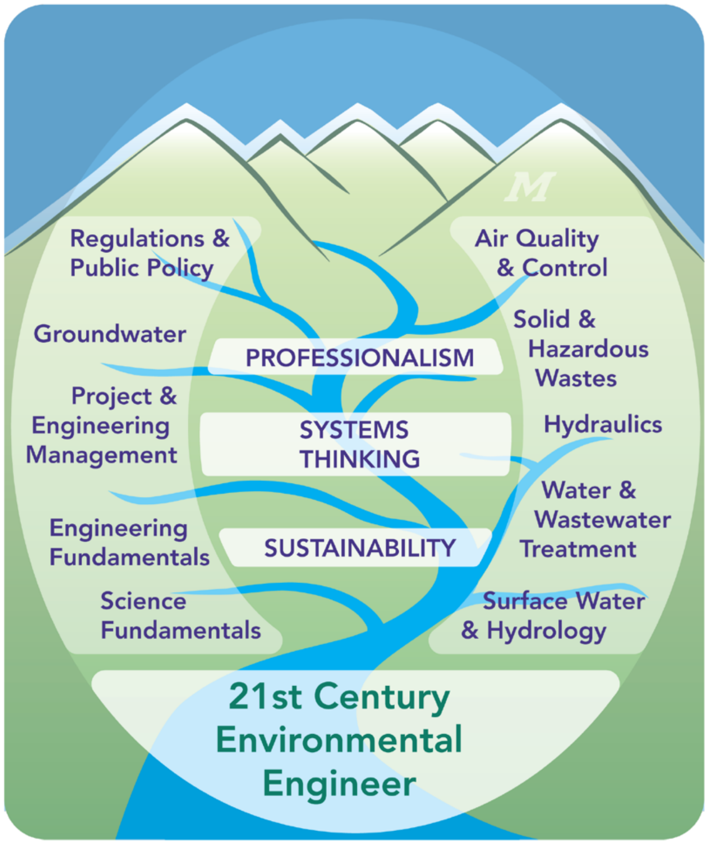

Figure 2 – Integrated undergraduate engineering model showing connecting knowledge threads and connecting competencies.

Program Structure and Delivery

Our approach ultimately resulted in over 400 desired program outcomes. Developing a new curriculum structure to deliver these outcomes required an iterative approach that reviewed existing courses and identified needs for new courses. An Access database of the new program outcomes in all knowledge threads, competency strands, and domains was created to sort, prioritize, and link learning outcomes across the program. By comparing our desired program outcomes with the outcomes from our existing courses, we were able to critically evaluate how existing courses contribute to the desired program objectives and identify competency domains and outcomes missing in the current curriculum.

We identified three types of courses in our program during the outcomes analysis process:

- Existing courses that contribute significantly to the desired program outcomes with few modifications. Typically, these courses provide instruction on fundamentals principles, serve not only our environmental engineering students but also other students in the department or college, are part of the university core requirements, or are delivered by other departments on campus.
- Existing courses requiring revision to contribute meaningfully to desired program objectives. These courses typically lack sufficient focus on or are missing desired competencies developed during the outcomes-based evaluation process. With some modification, these courses could be refocused to meet the desired program outcomes and objectives. Typically, these courses are delivered by the department making modification easier as only department faculty are involved in the change process.
- New courses to integrate the knowledge threads, competency strands, competency domains, and associated outcomes that do not currently exist in the program. These courses represent opportunities to integrate concepts across the curriculum through projects and team-teaching.

The proposed program structure is shown in Table 1. After the outcomes analysis, some existing courses were determined to satisfactorily contribute to the desired program outcomes without significant change (e.g., fluid mechanics, mechanics of materials). Frequently, these courses serve all students within the department, not just environmental engineering students. Some of these courses were judged as being critical to meeting the University core requirements (e.g., first year seminar) or determined to be too difficult to change because the primary responsibility for the course resided in another department (e.g., calculus).

Four existing courses within the program were identified for significant modification. During the outcomes review, we determined that these existing courses deliver some critical outcomes, but lacked focus, often repeating concepts covered in other classes. These courses also provide an opportunity to integrate concepts covered in other courses.

Three integrated project-based courses have been added to the 1st, 2^{nd,} and 3rd years of our curriculum. The existing 4th year capstone course will be modified to account for the new sequence of project-based courses. The project-based courses will be designed to provide students with repeated opportunities to practice designing and communicating complex environmental engineering systems that require integration of multiple knowledge domains and effective teamwork [28].

Table 1 – Proposed program structure resulting from an outcomes-based curriculum analysis

	No Changes	Significant Changes	New Project-based Integrated Courses
1st Year	Chemistry I and II Calculus I and II Writing I First Year Seminar Physics I Computer-based Computations Univeristy Core Electives	Intro To Civil/Environmental Engineering: introduces professionalim, sustainability and systems thinking outcomes	emphasis on developing engineering identity
2nd Year	Biology Drafting and Design Calculus III Differential Equations Statics Intro to Chemical and Biological Engineering Mechanics of Materials	Environmental Science Fundamentals: revised from chemistry for environmental engineers to include sustainability and systems thinking concepts	emphasis on engineering context and societal contribution
3rd Year	Fluid Mechanics Statistics Physical and Chemical Treatment Processes Biological Treatment Processes Business Fundamentals	Environmental Policy and Sustainability: revised from Environmental Laws and Regulations to include sustainabilty and and public policy outcomes	emphasis on teamwork, leadership, and communication
4th Year	Water Resources Engineering Soils or Geotechnical Engineering Construction Practice Univeristy Core Electives Water Resources Electives Environmental Engineering Electives Fundamentals of Engineering Exam	Project Based Integration Course: capstone course revised to build upon skills gained in year 1-3; emphasis on holistic, sustainable design, collaboration and effective communication	

Environmental engineering faculty will select one to three projects per year in cooperation with industry partners for use in the project-based courses. Students in each year will work on an aspect of the project appropriate for their knowledge and skills development. First year students will engage in project-based learning (PBL) activities designed to link fundamental concepts to professional practice to establish a robust professional identity. Second year projects will focus on service learning or community-focused components of the project. Service-learning activities will emphasize the societal value and contributions of the environmental engineer. This focus aims to improve retention and inclusivity during the "sophomore slump" [29] by helping students understand how fundamental concepts relate to the problems that interest them or the communities they care about [6]. In the third year, students will engage in project components directly related to professional practice and intended to further develop interdisciplinary teamwork and communication skills in the context of a project-based course. Finally, in the fourth year, learners will be challenged with a complex aspect of the project and teams of students will be responsible for completing and documenting a design. The PBL activity will expose students to the proposal, design, specification, and bidding processes commonly used in practice. This PBL course sequence provides students with repeated practice in building and integrating skills and lessons from different disciplines, which improve the student's ability to draw connections, integrate knowledge, and participate in the intentional practice of professional skills is needed to develop expertise [7].

Schedule and Milestones

The outcomes-based process to redesign the environmental engineering required a year of consistent effort. Work began in January 2021 and culminated with the draft curriculum shown in Table 1 approximately 1 year later. Core faculty met almost every week for 1-2 hours and several extended workshops and retreats were conducted to brainstorm ideas and develop program structure throughout the year. The timeline for this process included:

- Month 1: Faculty discussed overall change goals and objectives and explored the use of collaboration tools (e.g., CMap, Padlet, etc.).
- Months 2-5: Developed and defined project terminology (primarily for the technical components of the curriculum) and began developing desired outcomes for identified knowledge threads, competency strands and domains.
- Months 5-7: Expanded the outcomes discussion to the non-technical elements of the program and began to solicit student feedback on the existing program and proposed outcomes.
- Month 7: Conducted an all-faculty retreat to review project goals, objectives and outcomes. Developed a framework for integrating knowledge threads throughout the curriculum.
- Months 8-12: Analyzed existing courses for consistency with desired outcomes. Modified existing courses and developed new integrated and project-based courses to achieve desired program outcomes. Developed a framework for integrating knowledge threads throughout the curriculum. Balanced new course requirements with faculty workload limits.

Lessons Learned

Over the last year, we have taken an outcomes-based approach to develop an integrated environmental engineering curriculum that addresses many of the known deficiencies in the classic, siloed approach and that can be delivered by a relatively small faculty. Through this process, we have learned that:

- The exercise of intentionally reviewing course and program outcomes provided us insight into the program that did not previously exist. We learned, perhaps for the first time, what topics our colleagues are covering in their courses, what approaches and techniques they use in the classroom, and how they develop course- and lecture-level outcomes. It may be beneficial for faculty in the other programs in our department to undertake a similar exercise, if only to increase understanding of how content is distributed, delivered, and assessed.
- Reviewing course and program outcomes also revealed multiple redundancies and gaps in the program. We found several instances where faculty were unintentionally covering the same material and examples of important material not being covered. Gaps and redundancies were discovered because we began our process by developing outcomes without reference to existing courses (i.e., bottom-up approach) and then identifying if they were being covered. If we reversed the process, by collecting the existing outcomes from every course to serve as our set of program outcomes, we may have found the redundancies but not the gaps. The painful and messy collective brain-dump at the beginning of this process was important.
- Even with the stated intent of breaking the siloed approach, we found it difficult to change our mode of thinking. In developing outcomes, we often reverted to thinking about what is covered in "that class" instead of thinking broadly about what outcomes we wanted to achieve in the program overall. We also found ourselves resistant to significantly changing the content in our existing technical courses. This was partly due to the staffing and logistical constraints of a small program. Moreover, each faculty member has developed technical expertise in their area of interest and we each love to share that knowledge with our students.
- Developing outcomes at the appropriate level to guide course revision and integrated course development was difficult. Often, we either developed outcomes that were too vague and general or far too specific. Initially, in fact, we created a list of 700 program outcomes! Developing the final set of approximately 400 outcomes was a messy, non-linear process that required multiple iterations and revisions and much discussion to achieve clarity. This task took longer than anticipated, and was frustrating, but our resulting outcomes database is central to this project.
- We expect the outcomes-based approach will make our transition to team teaching easier. Deconstructing and reassembling the program was an excellent team building exercise that developed a new and deeper shared understanding between the faculty.

As of this writing, faculty are revising and developing the 1st year integrated and project-based courses so that they can be delivered to the new class of environmental engineering students starting in Fall 2022. New courses will be rolled out one year at a time to slowly shift the program to its new curriculum. Next steps include meeting with our student and external advisory board to review the proposed curricular changes, soliciting and designing projects for PBL activities, and revising and designing the 2nd year integrated and project-based courses.

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