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Leveraging the Undergraduate Mathematics and Physics Curriculum to Strengthen the Advanced Manufacturing Workforce Pipeline

A Shared Language for Careers in Advanced Manufacturing

NIST Office of Advanced Manufacturing

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Manufacturing USA

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A Shared Language for Careers in Advanced Manufacturing

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About Manufacturing USA

Manufacturing USA® is a national network comprised of 18 institutes created to secure U.S. global leadership in advanced manufacturing through large-scale public-private collaboration on technology, supply chain, and education and workforce development. The network comprises the U.S. Departments of Commerce, Energy, and War; their sponsored manufacturing innovation institutes; and six additional federal agency partners, creating a whole-of-government, national effort to drive innovation in manufacturing. Each institute includes members from industry, academia, and state and federal governments with a shared interest in advancing manufacturing.

In 2024, these institutes collectively worked with over 3,100 member organizations to collaborate on more than 875 applied research and development technology projects of high priority to industry and engaged over 200,000 people in building workforce knowledge and skills in advanced manufacturing. The institutes attracted $392M from state, federal, and private funds in addition to $133M in base federal funding.

Abstract

This report provides faculty with advanced manufacturing terminology and data to articulate the occupational relevance of their teachings, without changing curriculum. The MFG USA Competency Framework can be used to make mathematics and physics certifications more accessible to employers and hiring managers. Undergraduate mathematics and physics courses develop abstraction, modeling under constraints, and reasoning with uncertainty, which are skills applicable to a wide range of advanced manufacturing career pathways. The academic language used to describe these skills can make it challenging for employers to interpret academic course relevance in the competency-based terms more familiar to industry. To address this systemic issue, the Manufacturing USA Advanced Manufacturing Occupation and Competency Framework (MFG USA Competency Framework) provides an industry-validated framework that outlines occupations, competencies, and knowledge, skills, and abilities (KSAs) in advanced manufacturing. By mapping the skills developed in familiar undergraduate coursework onto the framework's industry-wide and sector-specific competencies, this analysis highlights relevant connections between academic training and entry-level advanced manufacturing roles—connections that are often implicit to faculty but not immediately apparent to hiring managers, workers, and employers.

Keywords

Advanced manufacturing; Advanced manufacturing competencies; Advanced manufacturing credentials; Advanced manufacturing curriculum; Advanced manufacturing skills; Advanced Manufacturing workforce; Manufacturing Innovation; Manufacturing USA; Mathematics; Physics.

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Executive Summary

This paper provides a translation framework between undergraduate mathematics and physics course content and the advanced manufacturing workforce for educators. While mathematics and physics courses cultivate essential analytic and technical skills that directly connect to industry-validated core competencies, some skills remain implicit and invisible to either employers, hiring managers, or students. By mapping foundational existing curricula and courses to the MFG USA Competency Framework, institutions can make these capabilities clear to students without altering course content or intent. This course-to-industry framing can position academic credentials as clear signals of professional capability, strengthening the workforce pipeline and securing U.S. leadership in advanced manufacturing through the strategic alignment of academic and industrial language.

About Manufacturing USA

Manufacturing USA® is a national network comprised of 18 institutes created to secure U.S. global leadership in advanced manufacturing through large-scale public-private collaboration on technology, supply chain, and education and workforce development. The network comprises the U.S. Departments of Commerce, Energy, and War; their sponsored manufacturing innovation institutes; and six additional federal agency partners, creating a whole-of-government, national effort to drive innovation in manufacturing. Each institute includes members from industry, academia, and state and federal governments with a shared interest in advancing manufacturing.

In 2024, these institutes collectively worked with over 3,100 member organizations to collaborate on more than 875 applied research and development technology projects of high priority to industry and engaged over 200,000 people in building workforce knowledge and skills in advanced manufacturing. The institutes attracted $392M from state, federal, and private funds in addition to $133M in base federal funding.

About the Manufacturing USA Advanced Manufacturing Occupation and Competency Framework

The MFG USA Competency Framework was developed to provide a more organized set of competencies and skills for the industries served by Manufacturing USA institutes and their associated technology areas. Through a cooperative and iterative process with institute representatives, the KSAs needed by workers in advanced manufacturing were identified and catalogued. The result is a comprehensive set of competencies, sub-competencies, and KSAs interconnected across the Manufacturing USA network.

1. Introduction: Manufacturing USA Advanced Manufacturing Occupation and Competency Framework

Advanced manufacturing is at the forefront of industrial innovation, implementing new technologies and the associated education needed to drive growth, improve productivity, and develop a skilled engineering and scientific workforce. In March 2026 when the data was finalized, the Manufacturing USA[1] network comprised 17 manufacturing innovation institutes, each formed as a public-private partnership uniting government agencies, universities and colleges, and private industry around a shared mission: to secure and expand U.S. leadership in advanced manufacturing. Each year, these institutes collaborate with thousands of member organizations on hundreds of applied R&D projects relevant to industry and engage thousands of people in advanced manufacturing education and training activities. The network identified 132 entry-level occupations spanning cross-cutting technology areas essential to their missions and in need of workers through 2030. [2,3] Many of the KSAs taught in mathematics and physics courses are needed for this advanced manufacturing workforce.

These institutes span a wide range of technology areas, from robotics and additive manufacturing to biopharmaceuticals and advanced composites. The institutes serve as hubs where members from industry, academia, government, and non-profits collaborate on research and co-invest in resources to solve challenges facing the ecosystem, which no single organization could tackle alone. By convening around specific advanced technologies, the Manufacturing USA network helps promising innovations move from lab demonstrations to commercial production, accelerating their adoption in domestic manufacturing processes and creating pathways for scaled commercialization. An integral part of this collaborative strategy is the training and workforce development activities needed to advance these new technologies.

Manufacturing has undergone a fundamental transformation over the past several decades, shifting from labor-intensive processes to data-centric, highly technical systems that incorporate modeling, sensing, optimization, and real-time decision-making. Technologies such as automation, robotics, cyber-physical systems, advanced materials, and data-intensive production workflows now shape manufacturing across sectors ranging from electronics and energy systems to materials, biomanufacturing, and advanced composites. These changes have intensified demand for workers who can model complex systems, analyze variability, optimize constrained processes, and reason quantitatively under uncertainty.

This dynamic landscape motivated the initial development of the Manufacturing USA Advanced Manufacturing Occupation and Competency Framework (MFG USA Competency Framework), which provides an industry-validated, competency-based description of the knowledge, skills, and abilities required across advanced manufacturing occupations. The framework establishes a shared language for industry and workforce development professionals by standardizing occupational expectations across sectors and technologies. This shared language is equally critical for academia. Many frameworks largely treat academic degrees as a prerequisite rather than as an active contributor to competencies for the job market, including industry-relevant

competencies, relegating industry tasks and job functions to higher-level tiers.[2] By mapping the skills developed within a course to this standardized language, the framework allows both employers and graduates to clearly understand the specific capabilities gained through academic study.

Undergraduate mathematics and physics programs equip students with valuable problem-solving skills, such as abstraction, modeling, analysis, and approximation. These skills are highly relevant to advanced manufacturing [4], yet employers struggle to recruit graduates for manufacturing roles. Moreover, many students at both the undergrad and graduate levels overlook manufacturing as a viable career path.[5–9] To address this mismatch, increased awareness is needed among hiring managers, guidance counselors, educators, and students about the career opportunities available in advanced manufacturing. Doing so can help solve the country's workforce challenges and provide students with rewarding, well-paying career options.

The primary issue is a misalignment that stems not from a lack of technical preparation but from a missing translation between academic training and occupational expectations. While mathematics and physics curricula already cultivate many of the competencies required for advanced manufacturing, those connections remain implicit to students and opaque to employers. This paper addresses that gap by explicitly mapping core undergraduate mathematics and physics coursework to industry-validated competencies defined by the Manufacturing USA network. By doing so, it provides faculty with a framework to make their curricula even more relevant to workforce pathways without requiring modifications to course work.

1.1. The Imperative for Transferable Skill Preparation

Labor market projections indicate robust growth in employment opportunities for mathematically trained professionals. The U.S. Bureau of Labor Statistics projects that employment of mathematicians and statisticians will grow faster than the average for all occupations over the next decade, driven primarily by demand in industry and government for analytical, computational, and data-driven expertise. [10] This demand follows a significant resurgence in the field after undergraduate mathematics degrees bottomed out in the early 2000s as students pivoted towards applied majors instead. [11–13] In contrast, first-year enrollment in graduate physics programs is estimated to have declined by 7–9% from 2024 to 2025, a substantial reversal after years of overall growth. [14] While industry and government sectors are expected to thrive, projected growth in postsecondary teaching positions within which tenure track roles constitute only a subset, is more modest and includes a substantial share of non-tenure track appointments which is increasing. [15,16]

For example, according to the 2023-2025 data from the U.S. Bureau of Labor Statistics, math and physics majors pursue highly diversified career pathways across a wide range of

industries.[17,18] Of the approximately 1.1 million people in the U.S. workforce with a mathematics degree, 50–60% work in private sector industry roles (often management, finance, tech, and manufacturing). Of the 350,000–400,000 people with a physics degree, 55–65% work in the private sector (often engineering services, data science, and aerospace/defense manufacturing). In addition to those preferred sectors, these degree-holders concentrate in several cross-cutting sectors:

- Computer and Mathematical Operations
  - About 24% of math majors work specifically in high-tech mathematical roles (software development, data science, actuarial science).
  - About 8–12% of physics majors work strictly in computer and mathematical operations. However, an additional 15–20% work in engineering and architecture roles that are functionally high-tech but classified separately from computer and mathematical operations.
- Education
  - Roughly 18% of people with a math degree work in education (primarily in secondary school teaching as tenure track academic research is a much smaller fraction).
  - Roughly 11–15% of people with a physics degree work in education. Like the field of math, the majority are in high school physics and physical science.
- Management and Business
  - Over 26% of mathematicians work in non-technical management or financial operations.
  - About 15% of physicists work in management roles.

The American Mathematical Society (AMS) [19] and the Mathematical Association of America (MAA) [20] note a significant split immediately following graduation as illustrated in Table 1 below.

Table 1. Workforce Distribution for Math Majors

Outcome Path	Percentage (Approx.)	Key Areas
Direct to Workforce	45%–55%	Insurance, defense, finance, tech
Graduate School (Math)	25%–30%	Research/academia
Graduate School (Other)	15%–20%	Law, medicine, engineering, data science

Similarly, the American Institute of Physics (AIP) Statistical Research Center [21] tracks outcomes for physics majors as presented in Table 2 below.

Table 2. Workforce Distribution for Physics Majors

Outcome Path	Percentage (Approx.)	Key Areas
Direct to Workforce	46%–50%	Aerospace, defense, tech, data science, engineering
Graduate School (Physics/Astronomy)	30%	Industry, research, academia and national labs
Graduate School (Other)	17%–20%	Engineering, law, medicine, data science, computer science

Consequently, mathematics and physics curricula should intentionally emphasize transferable competencies valued by industry, including system modeling, data analysis, uncertainty quantification, optimization, and computational reasoning. Aligning undergraduate instruction with these competencies not only reflects the realities of the contemporary labor market but also equips students to apply mathematical thinking effectively across a broad range of manufacturing, technology, and data-intensive domains.

2. Manufacturing USA's Competency Framework and the Role of Mathematics and Physics

The MFG USA Competency Framework was developed to address fragmentation in workforce credentialing and to provide a shared national language connecting occupations, competencies, sub-competencies, and KSAs across advanced manufacturing. [2]

The framework uses the following definitions, which will be utilized throughout this work:

- Occupation: a specific job or role that an individual performs in a particular industry or organization, often defined by a set of tasks, duties, and responsibilities that are required to perform the job; may encompass multiple roles
- Competency: a broader, larger set of related KSAs required to successfully perform a critical work function or role in a defined work setting
- Sub-competency: a specific subset, or bundle, of KSAs; several sub-competencies comprise a competency
- KSA: a specific knowledge, skill, or ability that a person needs to know or be able to do to perform well in a specific task within a job, occupation, or industry

The 2025 MFG USA Competency Framework contains 235 unique KSAs, categorized into 68 sub-competencies and 13 competencies. [2] The work aims to identify correlations and connections between advanced manufacturing roles. The report identifies over 1,200 connections and 137 unique occupations. In the context of this framework, a *connection* is defined as the specific link between one KSA and one occupation, understanding an "occupation" as a group of similar job titles or roles, as variations do exist across fields and with company size.

We use the example in Table 3 below to explain the hierarchy of the terms *occupation*, *competency*, *sub-competency,* and *KSA,* as well as illustrate how incorporating this framework in coursework can help bridge the communication gap between employers and job seekers.

Table 3. Illustrating Levels of the Advanced Manufacturing Occupation and Competency Framework

Framework Level	Example	Student's Perspective
Occupation	Process Engineer	"This could be my future job title."
Competency	4.5 Quality Assurance	"This is one of the roles I would perform on a team at work."
Sub-competency	4.5.12 Data Analysis and Presentation	"As part of my job, I do this to accomplish specific tasks." "This is one of the learning outcomes listed in the syllabus for the math course *Probability and Statistics* that I took."
KSAs	(i) Data Quality (ii) Data Visualization and Reporting (iii) Understanding and Execution of Data Quality Fundamentals and Control	"These will be tasks I do to accomplish my work goals." "These concepts relate directly to the homework I did."

Framework Level	Example	Student's Perspective
	(iv) Data Collection and Reporting	

The MFG USA Competency Framework utilizes the Department of Labor's (DOL's) Advanced Manufacturing Competency Model (DOL-AMCM), which organizes competencies into five tiers:

- Tier 1: Personal Effectiveness Competencies
- Tier 2: Academic Competencies
- Tier 3: Workplace Competencies
- Tier 4: Industry-wide Technical Competencies (e.g., operations management, quality assurance, process design)
- Tier 5: Sector-specific Competencies (e.g., smart manufacturing, materials design, digital automation)

The DOL-AMCM categorizes Tier 2 academic skills, such as math and science, as foundational prerequisites rather than direct occupational signals, aligning with the needs of entry-level occupations. For example, the sub-competency 2.3.2 Computation comprises topics such as taking averages, addition/subtraction, and simple pattern recognition—all of which are foundational for more advanced training in high school, college, and training programs. While some students and workers may require additional training in Tier 2 and Tier 3 competencies, this analysis treats them as prerequisites that enable training in Tier 4 and Tier 5 KSAs.[22] This paper therefore treats Tier 2 competencies as prerequisites that enable Tier 4 and Tier 5 work KSAs. From this perspective, undergraduate mathematics and physics courses serve as the student's introduction to Tier 4 and Tier 5 KSAs.

This paper focuses on Tier 4 and Tier 5 competencies, which are associated with tasks that workers perform regularly and have been validated by industry. These competencies are particularly valuable for hiring managers and education faculty seeking curricular alignment. By focusing on Tier 4 and Tier 5, we can better understand the skills and knowledge required for advanced manufacturing roles.

The Tier 4 Industry-Wide Technical Competencies are outlined in Table 4, providing the descriptions for the six broad competency groupings, labeled as 4.X. The higher-level Tier 5 Industry-Sector Technical Competencies are outlined in Table 5, providing the descriptions for the six broad competency groupings, labeled as 5.X.

Table 4. Department of Labor Advanced Manufacturing Competency Model Tier 4 Competencies and Corresponding Descriptions

Competency	Description

4.1 Manufacturing Process Design/Development	Research design, implement, and continuously improve the manufacturing process to ensure product meets customer needs.
4.2 Operations Management	Set up, operate, monitor, control, and improve manufacturing processes and schedules to meet customer requirements.
4.3 Maintenance, Installation, and Repair	Maintain and optimize manufacturing equipment and systems.
4.4 Production in the Supply Chain/Supply Chain Logistics	Plan and monitor the movement and storage of materials and products in coordination with suppliers, internal systems, and customers.
4.5 Quality Assurance and Continuous Improvement	Ensure product and process meet quality system requirements as defined by customer specifications.
4.6 Process and Equipment Health, Safety, and Environment	Equipment, practices, and procedures which promote a healthy, safe, and secure work environment.

Table 5. MFG USA Competency Framework Tier 5 Competencies and Corresponding Descriptions

Competency	Description
5.1 Additive Manufacturing	Design and manufacture products using layer-by-layer fabrication by understanding and applying additive manufacturing principles.
5.2 Smart Manufacturing Technology	Implement fully integrated, collaborative manufacturing systems that respond to changing factory operations in real time.
5.3 Information Technology	Advanced knowledge and application of information technologies to manufacture systems.
5.4 NICE Framework/Cybersecurity	Advanced knowledge and application of cybersecurity fundamentals in manufacturing operations.
5.5 Experiments, Tests, and Analyses	Implement specific scientific techniques to synthesize, assess, and maintain manufactured products derived from biological system processes.
5.6 Biomanufacturing Production	Implement advanced processes for the manufacture of bioscience products.
5.7 Material Design and Production	Implement advanced materials design and production methods to manufacturing systems.

By mapping undergraduate mathematics and physics as Tier 4 and Tier 5 enablers, the curriculum becomes legible to employers and actionable for students.

3. Translation Gap

The concept of a skills gap is often cited as a major concern in workforce readiness discussions, implying that graduates and some of the existing workforce lack the technical skills required by industry. However, evidence from Manufacturing USA and related workforce analyses suggests a different diagnosis. Across the Manufacturing USA network, some of the most highly selected essential KSAs are not necessarily role-specific, such as:

- Data collection and analysis (4.1.7)
- Understand and execute test and measurement assays (4.2.11)

Rather, they rely on analytical skills, many of which are cultivated or supported in undergraduate mathematics and physics courses and applicable to a wide variety of career pathways. The MFG USA Competency Framework analysis reinforces this conclusion. [2]

A significant number of KSAs are shared across institutes and technology areas. For example, in the dataset, 50% of essential KSAs are shared by three or more institutes, 33% of essential KSAs cross technology area lines, and 29% of essential KSAs align with eight or more occupations. In this context, the persistent difficulty employers report in recruiting people into manufacturing roles may stem in part from a narrow interpretation of who is qualified to fill a given role and reflects an inability to translate academic preparation and previous work experience into terms that are occupationally meaningful for educators, students, and hiring managers.

3.1. How Translation Breaks Down

The translation gap manifests at multiple levels:

- **Students** typically encounter mathematics and physics as a sequence of abstract courses, with high school and introductory college courses serving as prerequisites for intermediate and advanced courses. While this scaffolding effectively develops technical competence, it rarely provides students with a framework for articulating what they can do in ways that resonate with their future career pathways beyond the classroom. As a result, students often struggle to describe their preparation in resumes, interviews, and professional conversations, often defaulting to listing course titles on a resume rather than competencies.
- **Employers**, for their part, rely on job postings that emphasize functional capabilities and work activities. Often these task- or role-based descriptions do not clearly align with traditional academic course work. When academic transcripts and course descriptions do not clearly map to occupational expectations, employers may underestimate the relevance of mathematical and physics training. Consequently, employers may view candidates from more visibly applied disciplines as better prepared, even when the underlying competencies closely align.
- **Faculty** play a crucial role in bridging this gap, yet they often face challenges in framing their courses in occupational terms. While instructors recognize the power and generality of mathematical reasoning, they may not routinely frame course content in

occupational terms, particularly when such framing educational content in terms of occupations and roles within industry feels extrinsic to the goals of their discipline. Faculty play a unique role in assisting students understand and organize their education in terms of the job skills they are teaching.

This lack of a shared language creates a barrier among students, faculty, and employers, leaving each group operating with incomplete information about the others.

3.2. Careers as Trajectories, Not Endpoints

The traditional view of careers as a series of discrete job titles can be misleading in advanced manufacturing. Entry-level job titles such as Analyst I or Process Engineer are often treated as destinations instead of starting points within longer professional trajectories. In reality, advanced manufacturing careers involve continuous movement across roles, responsibilities, and technical domains.

Competency frameworks, such as the one developed by Manufacturing USA, are explicitly designed to support this mobility. Tier 4 competencies, which capture behaviors that enable workers to grow, adapt, and take on increasing responsibilities over time, provide a foundation for career progression. Undergraduate education is not expected to produce fully formed specialists but rather to provide the analytic foundation upon which career progression depends. Furthermore, most training programs are not designed to provide full mastery of a topic, as on-the-job training and situational adaptation are necessary in nearly all work environments.

When students understand their coursework in terms of transferable competencies rather than static credentials, they are better equipped to navigate these complex career trajectories. By framing their academic preparation in this way, students can see how their education supports long-term professional growth and development.

3.3. Why Translation is a Faculty Opportunity

The translation gap between academic preparation and workforce needs is often treated as a problem for career services offices or employers to solve after graduation. This can severely limit the application process for students, hindering effective and timely placement within industry. It also limits students' ability to contextualize material, as specific skills are often utilized within specific situations. Learning material outside of its primary context could impede confidence in the skill and ability to apply it initially. Many of the most effective interventions must occur earlier, within the curriculum itself. Faculty are uniquely positioned to address these gaps by making the implicit explicit: naming the competencies embedded in coursework, modeling how analytic reasoning applies across contexts, and helping students develop language that connects theory to practice.

Addressing the translation gap does not require faculty to redefine course content or learning objectives. Instead, it involves reframing existing material through a lens that highlights transferability and application. This approach preserves disciplinary rigor while enhancing

relevance and clarity. Faculty can build on existing practices, such as discussing common career pathways with students, to expand the range of career options available to mathematics and physics majors.

Discussions of engineering, actuarial science, finance, data science, software development, and analytics are already familiar in many departments. These examples serve an important role in helping students see the relevance of their education, but they can be vague in terms of workforce titles and examples of companies that employ them. Advanced manufacturing is a significant and growing field where the same competencies are in demand, [23] yet it is often absent from conversations with mathematics and physics majors. By explicitly mapping undergraduate coursework to industry-validated competencies, this paper provides faculty with the supporting structure needed to include advanced manufacturing as a credible, well-articulated career pathway. In doing so, the paper helps shoulder the burden of translation, allowing faculty to focus on what they already do best: teaching within their discipline.

3.4. Implications for Curriculum Mapping

The curriculum mappings presented in Section 4 are not intended to convert mathematics or physics into vocational training nor to suggest that every course must explicitly target a specific job role. Rather, they demonstrate how core coursework already supports industry-validated competencies when viewed through a competency framework. By making these connections visible, departments can help students articulate their preparation, help employers recognize the value of mathematical and physics coursework, and strengthen the alignment between undergraduate education and advanced manufacturing workforce needs.

4. Mapping Undergraduate Mathematics and Physics to Tier 4 and Tier 5 Manufacturing Competencies: A Faculty Guide

To better serve students and educators as they prepare the future workforce, it is important to make explicit what is already implicit in undergraduate mathematics and physics education. Rather than proposing new courses or curricular restructuring, this mapping demonstrates how existing coursework aligns with industry-validated Tier 4 and Tier 5 competencies identified in the MFG USA Competency Framework. As a bridge between industry's future needs and common academic courses, these mappings are intended to provide faculty with a vocabulary for translating disciplinary learning into occupationally meaningful competencies.

The central premise is straightforward: careers, which include many occupations, are composed of competencies, not just course titles. Undergraduate courses develop clusters of KSAs that support professional performance across multiple roles. The challenge is not whether mathematics and physics prepare students for advanced manufacturing roles but whether those preparations are legible to students and employers and can be implemented effectively in job searches and career pathway selection.

4.1. From Coursework to Competencies to Careers

The MFG USA Competency Framework provides a critical link between education and occupations through its competency-based approach. Competencies (X.X) serve as the bridge between coursework and careers, enabling students to develop the skills and knowledge needed to succeed in a rapidly changing workforce. A single occupation may draw on multiple competencies, and each competency is supported by multiple sub-competencies (X.X.X) and KSAs. For example, a Process Engineer role may require competencies in operations management, quality assurance, and process design, all of which depend on mathematical reasoning developed through standard coursework. By understanding how coursework feeds into KSAs, as well as how these skills collectively form competencies, students can better navigate the career landscape.

However, students may not always be aware of these connections or be explicitly guided to recognize them. The mappings that follow are designed to make this hierarchy clear and actionable for both educators and students, enabling them to understand how the knowledge and skills gained through courses apply pragmatically to job searches and roles across different technology areas and career pathways.

To make the course mapping actionable, each course can be deconstructed into three levels that align with components of the framework:

- Competency Level (Faculty Framing): *"This course develops capabilities used in Operations Management (4.2) and Quality Assurance (4.5)."*
- Sub-Competency Level (Unit Framing): *"This unit supports Statistical Process Control (4.5.11) and Production Monitoring (4.2.11)."*
- KSA Level (Student Articulation): *"I can collect, analyze, and interpret production data to diagnose process variability."*

Each level of the framework can be referenced by both faculty and students to connect coursework to KSAs and related job roles as illustrated in the use cases in Table 6.

Table 6. Example Use Cases of Framework Definitions

Framework Level	Faculty Use Case (Curriculum)	Student Use Case (Career)
Competency (X.X)	Course Goal: "By the end of this semester, students will demonstrate the ability to model real-world challenges, such as resource allocation, using linear programming—a fundamental tool of operations management (4.2)."	Professional Identity: "I am qualified to work in operations and systems management."
Sub-competency (X.X.X)	Unit Topic: "This week we are covering statistical process control methods (4.5.11)."	Specialized Skill: "I understand the math behind monitoring industrial processes."
KSA	Learning Objective: "Students will be able to perform data collection and analysis (4.1.7)."	Resume Bullet: "Ability to collect and analyze production data for troubleshooting."

Connecting academic coursework and the associated skills can demonstrate how standard undergraduate mathematical instruction already cultivates skills that align with industry-validated competencies in advanced manufacturing. To this end, demonstrating how faculty can communicate alignment between courses and laboratories to students without altering course content, assessments, or learning objectives is important for student outcomes.

Each subsection below will discuss (i) what is already taught in a typical mathematics course, (ii) what habits of thinking and action this develops, (iii) how those habits appear in occupational contexts, and (iv) concrete ways faculty can articulate this to students. No manufacturing expertise is assumed or required.

4.2. Mapping Core Undergraduate Mathematics Courses to Competencies

The undergraduate courses listed below are based on both the guidance and recommendations on foundational and advanced coursework provided by the Mathematical Association of America through its Committee on the Undergraduate Program in Mathematics (CUPM) [24]and what is commonly taught in a four-year college as a part of a math major.

4.2.1. Algebra, Geometry, Precalculus, and Trigonometry

What faculty already teach: Students learn to work with functions as models. They analyze polynomial, exponential, logarithmic, and trigonometric functions; interpret graphs; solve equations and inequalities; and use identities and transformations to rewrite expressions into more useful forms. Trigonometry adds angle-based reasoning, periodicity, phase, geometric relationships, and parametric descriptions.

What this develops cognitively: These courses teach students to treat formulas as behavioral descriptions of a system, not just symbolic objects. Students also learn to recognize and interpret common functions and translate between representations such as equations, graphs, tables, and verbal descriptions.

How this appears occupationally: In technical areas such as robotics and manufacturing, much of the daily quantitative work begins before calculus: interpreting signals, trends, and functional patterns in process data; understanding cyclic behavior; choosing an appropriate model family; and periodic reasoning whenever a system has cycles (rotation, repeated operational states). These habits support early-career roles such as Production Analyst, Robotics Integrator, and more.

How a faculty member could frame it:

- When introducing function families: "*In advanced manufacturing, functions are the foundational rules used to program robotic movements, optimize material usage, and control product quality. Different function types aren't just arbitrary algebra categories; they represent distinct physical system behaviors: some grow quickly, some level off, some repeat. A crucial skill in advanced manufacturing is recognizing which mathematical behavior matches the real-world situation*."
- When emphasizing transformations and parameters: "*When we shift, stretch, or rescale a graph, we're learning how model parameters change behavior, similar to what a manufacturing engineer does when calibrating equipment, such as a machine for material thermal expansion*."
- When teaching periodicity and phase: "*Trigonometry isn't just about triangles—it's a way to describe repeating system behavior and timing (i.e., period, phase, amplitude) using mathematical language. It serves as the mathematical foundation that allows a robotic arm to understand and navigate three-dimensional space.*"

Table 7. Representative KSAs Developed: Algebra, Geometry, Precalculus, and Trigonometry

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.2 Technical Drawings and Schematics	Geometric dimensions and tolerances
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.4 Precision Measurement	Understand and use volumetric measurement instruments and techniques Understand and use mass measurement instruments and techniques
4.2.6 Automated Systems and Control Operations	Robot programming Operate, test, or maintain robotic equipment

4.2.2. Calculus Sequence (Single and Multivariable)

What faculty already teach: Across the calculus sequence, students learn to reason about change. They compute derivatives, interpret rates of change, solve optimization problems subject to constraints, and analyze monotonicity and curvature, gradients, Jacobians, and Hessians.

What this develops cognitively: These activities train students to reason about how system outputs respond to changing inputs, how to identify operating conditions that balance competing objectives, and how to reason locally about systems that are globally complex.

How this appears occupationally: In technical roles, systems rarely depend on a single factor. Decisions are made by asking: *If I adjust this input slightly, what changes the most? What is the cost of improvement in one dimension versus another?* This is sensitivity analysis and optimization under constraints, even when no calculus notation is visible. This is useful knowledge for occupations such as Process Engineer, Manufacturing Systems Analyst, Operations Analyst, and Production Analyst.

How a faculty member could frame it:

- When introducing derivatives: *"Manufacturing involves dynamic systems like robotics and assembly lines. Engineers apply derivatives for motion analysis, like calculating the velocity and acceleration of moving robotic arms and conveyor belts."*
- When solving optimization problems: *"To reduce manufacturing costs, scientists aim to use the least amount of material required to meet strength requirements. By expressing the volume of a part as a mathematical function, derivatives allow scientists to find the exact dimensions that minimize surface area or volume."*
- When teaching multivariable calculus: *"The gradient summarizes how a system responds to simultaneous changes. Real systems almost always behave this way."*

Table 8. Representative KSAs Developed: Calculus Sequence

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.2 Technical Drawings and Schematics	Knowledge and use of computer aided design (CAD)/computer-aided manufacturing (CAM) software
4.1.8 Research and Development	Process optimization
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.2 Systems	Understanding of mechanical systems
5.2 SMART MANUFACTURING TECHNOLOGY	
Sub-competency	**KSA**
Tools and Technologies	Understand and apply artificial intelligence/machine learning fundamentals

4.2.3. Linear Algebra

What faculty already teach: Students model systems using matrices, solve linear systems, and analyze eigenvalues and eigenvectors.

What this develops cognitively: This trains students to represent interconnected systems compactly, analyze whether repeated processes stabilize or diverge, and understand how information propagates across components.

How this appears occupationally: Complex systems are rarely isolated. They consist of interacting components whose behavior depends on collective structure. Stability, amplification, and coupling are central topics of inquiry. This is useful knowledge for occupations like Automation Engineer and Manufacturing Systems Engineer.

How a faculty member could frame it:

- When introducing matrices: *"A matrix isn't just an abstract object. It's a compact way to represent many interacting quantities such as employees, number of hours they work, the number of machines available, etc. Using tools of linear algebra that we will learn later in this course allows for the optimization of scheduling and production planning."*
- When introducing eigenvalues: "*When we analyze eigenvalues, we are studying whether repeated updates settle down, oscillate, or diverge. In advanced manufacturing, this can tell us whether a machine or production process settles into a stable operating condition, oscillates, or becomes unstable."*
- When teaching least squares: *"This is how we reconcile imperfect or inconsistent measurements into a best overall estimate. Manufacturing systems do not always give us perfect measurements. Least squares lets us turn noisy or inconsistent sensor measurements into the best estimate of what is actually happening in the process."*

Table 9. Representative KSAs Developed: Linear Algebra

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.9 Workflow Assessment	System simulation and modeling
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.6 Automated Systems and Control Operations	Robot programming
4.3 MAINTENANCE, INSTALLATION, AND REPAIR	
Sub-competency	**KSA**
4.3.2 General Skills	Knowledge of computer-aided manufacturing (CAM) software

5.2 SMART MANUFACTURING TECHNOLOGY	
Sub-competency	**KSA**
5.2.1 Tools and Technologies	Understand and apply artificial intelligence/machine learning fundamentals

4.2.4. Discrete Mathematics

What faculty already teach: Students work with logic, graphs, recurrence relations, and algorithms. They reason about ordering, feasibility, and complexity.

What this develops cognitively: This develops the ability to identify allowable sequence of actions (workflows), respect precedence and dependency constraints, and feasible procedure under limited resources.

How this appears occupationally: Many real systems are rule-bound. Certain steps must happen before others, resources are finite, and not all theoretically possible solutions are feasible in practice. This is useful knowledge for occupations like Supply Chain Analyst and Manufacturing Planner.

How a faculty member could frame it:

- When teaching graph theory: *"Any time we work with a graph or algorithm, we're studying what can happen, in what order, and at what cost. In advanced manufacturing, this kind of reasoning helps scientists design factory layouts, route materials and robots, schedule production steps, and optimize systems subject to constraints."*
- When analyzing algorithms: *"While Big Oh notation theoretically measures algorithm scalability as a problem grows, in advanced manufacturing, an algorithm is only useful if it works within the practical constraints of execution time, memory, and available hardware."*
- When working with recurrence relations: *"These capture how decisions compound over time. In advanced manufacturing, they can help model how production levels, inventory, machine wear, or process performance evolve from one step to the next."*

Table 10. Representative KSAs Developed: Discrete Mathematics

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.7 Testing/Troubleshooting	Knowledge and use of analytical or scientific software
4.4 PRODUCTION IN THE SUPPLY CHAIN/SUPPLY CHAIN LOGISTICS	
Sub-competency	**KSA**
4.4.10 Supply Chain Management	Understand and apply supply chain fundamentals

	Understand and utilize just-in-case supply chain resilience
5.3 INFORMATION TECHNOLOGY	
Sub-competency	**KSA**
5.3.1 Programming	Knowledge and use of programming skills
5.4 NICE FRAMEWORK/CYBERSECURITY	
Sub-competency	**KSA**
5.4.1 Cybersecurity Fundamentals	Understand and use cybersecurity fundamentals

4.2.5. Probability and Statistics

What faculty already teach: Students model random variation, estimate parameters, and make decisions under uncertainty using hypothesis testing and confidence intervals.

What this develops cognitively: This prepares students to distinguish normal variability from meaningful change and to assess risk when outcomes are uncertain.

How this appears occupationally: Real systems vary. The central question is not whether variation exists, but whether it indicates a real change or normal fluctuation. This is useful knowledge for occupations like Quality Engineer, Reliability Analyst, Data Analyst, and Process Analyst.

How a faculty member could frame it:

- When introducing the concept of randomness: *"A key question that statistical tools help us decide is whether an observed variation is expected or whether something has fundamentally changed. That reasoning underlies many quality, reliability, and decision-making roles."*
- When introducing distributions: *"A distribution describes how a single variable or multiple variables behave over time, not just a single outcome. By studying the characteristics of distributions, such as shape and spread, manufacturers can calculate the likelihood of anomalies before they happen."*

Table 11. Representative KSAs Developed: Probability and Statistics

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.7 Testing/Troubleshooting	Data collection and analysis
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.11 Production/Process Monitoring	Understand and execute test and measurement assays

	Participate in troubleshooting, trend analysis, and root-cause analysis of operations Documenting and reporting information and data Performance of analytic tests
4.5 QUALITY ASSURANCE AND CONTINUOUS IMPROVEMENT	
Sub-competency	**KSA**
4.5.12 Data Analysis and Presentation	Understand and ensure data quality Data visualization and reporting Data collection and reporting

4.2.6. Ordinary Differential Equations

What faculty already teach: Students analyze dynamic systems, equilibrium solutions, and stability.

What this develops cognitively: This builds intuition for how systems evolve over time, their long-term behavior versus short-term transients, and whether they return to normal after disturbances.

How this appears occupationally: Many systems operate continuously. The key questions are whether they settle, oscillate, or fail when perturbed. This is useful knowledge for occupations like Process Modeling Engineer and Energy Systems Analyst.

How a faculty member could frame it:

- When discussing equilibrium: *"An equilibrium solution represents a steady operating condition. These questions matter any time a system runs continuously."*
- When analyzing stability: *"Stability tells us whether small disruptions fade away or grow. This is critical when modeling physical processes such as temperature, vibration, pressure, or motion, where a small disturbance can either be absorbed by the system or amplified into a failure."*
- When solving initial-value problems: *"Initial value problems capture what happens when a system starts from a particular state. This lets us model startup and transient behavior, such as how a machine heats up, a robotic arm begins moving, or a manufacturing process reaches its operating condition, rather than looking only at its long-term behavior."*

Table 12. Representative KSAs Developed: Ordinary Differential Equations

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	System simulation/modeling

4.1.7 Testing/Troubleshooting	Advanced fault finding on actual equipment Investigate equipment failures or difficulties to diagnose faulty operation and to recommend remedies
4.1.9 Workflow Assessment	System simulation/modeling
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.6 Automated Systems and Control Operations	Understand and use factory automation technologies
5.3 INFORMATION TECHNOLOGY	
Sub-competency	**KSA**
5.3.1 Programming	Knowledge and use of programming skills

4.2.7. Numerical Analysis

What faculty already teach: Students approximate solutions, analyze errors, and study convergence.

What this develops cognitively: This trains students to judge how much approximation error is acceptable, how computational choices affect reliability, and how to understand the limits of computational models.

How this appears occupationally: When exact solutions are unavailable, decisions depend on how much error is acceptable. This is useful knowledge for careers like Manufacturing Simulation Engineer and Test Engineer.

How a faculty member could frame it:

- When discussing truncation error: *"Every approximation introduces error. What we study here is how much error we can tolerate and how fast it accumulates. That judgement is essential whenever models replace exact solutions."*
- When studying convergence: *"Convergence tells us whether repeated numerical approximations are moving toward a reliable solution. When computations are used to simulate or control a physical process, convergence is what gives us confidence that the numerical result is trustworthy."*
- When comparing numerical methods: *"Choosing a numerical method is itself a design decision; the right method balances accuracy, speed, stability, and computational cost required to model and control a physical system"*

Table 13. Representative KSAs Developed: Numerical Analysis

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**

4.1.1 Critical Work Functions	System simulation/modeling
4.1.7 Testing/Troubleshooting	Data collection/analysis Knowledge and use of analytic or scientific software
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.5 Manufacturing Tool and Equipment Operations	Systems analysis and evaluation
5.3 INFORMATION TECHNOLOGY	
Sub-competency	**KSA**
5.3.1 Programming	Knowledge and use of programming skills

4.2.8. Operations Research

What faculty already teach: Students solve optimization problems under constraints and analyze trade-offs. Typical topics include linear programming, integer programming, and duality.

What this develops cognitively: This develops structured decision-making when resources are limited and objectives compete.

How this appears occupationally: The mathematical structure of optimization models mirrors how real systems are managed. Objectives are negotiated, constraints are unavoidable, and trade-offs must be made explicit. This is useful knowledge for careers like Operations Manager and Industrial Engineer.

How a faculty member could frame it:

- When teaching queuing theory: "*In advanced manufacturing processes, dynamic scheduling uses queuing theory to reroute jobs (which can be customers, data, or raw materials) based on real-time data to minimize idle time or prevent bottlenecks.*"
- When teaching linear programming: *"Optimization isn't about finding a perfect answer. It's about choosing the best option given limits. That logic applies to any situation where you can't have everything at once."*

Table 14. Representative KSAs Developed: Operations Research

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.8 Research and Development	Process optimization
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**

4.2.13 Project Management and Execution	Select material quantities or processing methods needed to achieve efficient production
4.4 PRODUCTION IN THE SUPPLY CHAIN/SUPPLY CHAIN LOGISTICS	
Sub-competency	**KSA**
4.4.4 Detailed Scheduling and Planning	Select material quantities or processing methods needed to achieve efficient production
4.4.10 Supply Chain Management	Understand and apply supply chain fundamentals Understand and utilize just-in-case supply chain resilience

4.2.9. Graph Theory

What faculty already teach: Students study vertices and edges, paths and cycles, connectivity, flows, matchings, and network structure. They analyze shortest paths, maximum flows, cuts, and connectivity under removal of nodes and edges.

What this develops cognitively: The course develops the ability to represent complex systems as interconnected components; reason about reachability, dependency, and propagation; and identify points whose failure disproportionately affects the whole system. Students learn to see structure.

How this appears occupationally: Many real-world systems consist of interconnected activities, resources, or information channels. The need for these skills appears whenever practitioners must understand how delays or failures propagate through a system, which components are critical to overall functionality, and how to route limited resources efficiently through a network. This is useful knowledge for occupations like Supply Chain Analyst, Manufacturing Systems Engineer, and Operations Analyst.

How a faculty member could frame it:

- When introducing graphs: *"We are modeling a system where some actions depend on others. The edges encode those dependencies allowing us to determine what happens first, what can happen in parallel, and how a change in one step can affect the rest of the system."*
- When teaching shortest paths: *"This is about finding the most efficient way to move through a constrained system. The same reasoning can determine how a robot moves across a factory floor, how materials are routed between workstations, or how components move through a production process while minimizing distance."*
- When discussing cuts or connectivity: *"Removing certain nodes has much larger impact than others. Identifying them reveals potential bottlenecks and single points of failure, helping engineers design production systems that are more resilient to equipment failures, disruptions, or maintenance."*

Table 15. Representative KSAs Developed: Graph Theory

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.7 Testing/Troubleshooting	Advanced fault finding on actual equipment Investigate equipment failures or difficulties to diagnose faulty operation and to recommend remedies
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.1 Critical Work Functions	Monitor industrial processes and systems
4.2.11 Production/Process Monitoring	Participates in troubleshooting, trend analysis, and root-cause analysis of operations
4.4 PRODUCTION IN THE SUPPLY CHAIN/SUPPLY CHAIN LOGISTICS	
Sub-competency	**KSA**
4.4.10 Supply Chain Management	Understand and apply supply chain fundamentals

4.2.10. Combinatorics

What faculty already teach: Students count configurations, analyze permutations and combinations, and reason about feasibility under constraints. They study recurrence relations and existence arguments.

What this develops cognitively: The course builds the ability to enumerate feasible possibilities under rules, distinguish what is theoretically possible from what is practically feasible, and reason about complexity and growth of solution spaces.

How this appears occupationally: In many occupational settings, decisions involve selecting feasible configurations from a large space of possibilities subject to constraints. The challenge is determining which configurations are allowed, how quickly possibilities grow as systems scale, and when brute-force exploration becomes impossible. This is useful knowledge for occupations like Manufacturing Planner and Quality Analyst.

How a faculty member could frame it:

- When counting configurations: *"This tells us how many valid ways a system can be arranged or operated once rules and constraints are imposed. This reasoning can determine the number of feasible production sequences, or assembly options available when safety, capacity, and process requirements must all be satisfied."*
- When analyzing growth rates: *"This explains why some problems become infeasible as systems scale. As the number of components, machines, or possible configurations increases, the number of possible choices can grow quickly making it impractical to evaluate every possible configuration."*

- When teaching knowledge graphs: *"Modern factories generate vast amounts of interconnected data from machines, sensors, production systems, and other sources. Knowledge graphs provide a structured map of these relationships, while combinatorial reasoning helps us navigate the enormous number of possible connections by identifying viable paths and efficiently eliminating irrelevant ones".*

Table 16. Representative KSAs Developed: Combinatorics

4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.6 Automated Systems and Control Operations	Use computers, computer-interfaced equipment, robotics or high-technology industrial applications to perform work duties
4.2.7 Manufacturing Process Applications and Operations	Review instructions to determine operational methods or sequences
4.2.9 Industrial Productions	Use computers, computer-interfaced equipment, robotics or high-technology industrial applications to perform work duties
4.3 MAINTENANCE, INSTALLATION AND REPAIR	
Sub-competency	**KSA**
4.3.27 Programmable Logic Controlled Industrial Equipment M/I/R	Robotic programming
5.3 INFORMATION TECHNOLOGY	
Sub-competency	**KSA**
5.3.1 Programming	Advanced robot programming

4.2.11. Real Analysis

What faculty already teach: Students work with limits, continuity, convergence, measure, integration, and rigorous reasoning about functions and sequences.

What this develops cognitively: This develops precision in reasoning, careful handling of assumptions, and the ability to reason about behavior in limiting or extreme cases.

How this appears occupationally: In technical environments, reliability depends on understanding when approximations are valid, when assumptions break down, and how small errors accumulate. This mode of reasoning supports roles that require validation, verification, and reliability analysis across complex systems and can lead to jobs such as Quality Managers or Failure Analysis Technicians.

How a faculty member could frame it:

- When discussing limits and continuity: *"Rigorous reasoning about limits is how we ensure system behavior remains predictable as we approach extreme operating*

conditions. In reliability engineering, knowing exactly where a continuous process might break down is the difference between transient and catastrophic failure."

- When studying sequences and convergence: *"Analyzing the convergence of functions isn't just an exercise in rigor; it is the mathematical foundation for verification and validation. In other words, we are practicing how to prove that our models truly reflect reality even when small errors begin to accumulate."*
- When handling epsilon-delta proofs: *"This level of precision is about managing sensitivity and tolerance. When you work with these bounds, you are practicing the same skills used to diagnose whether system deviations are within acceptable quality standards or if the underlying assumptions have failed."*

Table 17. Representative KSAs Developed: Real Analysis

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	System simulation/modeling
4.1.7 Testing/Troubleshooting	Data collection/analysis
4.1.8 Research and Development	Technoeconomic analysis
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.5 Manufacturing Tool and Equipment Operations	Systems analysis and evaluation
4.3 MAINTENANCE, INSTALLATION, AND REPAIR	
Sub-competency	**KSA**
4.3.33 Reliability and Maintainability	Failure analysis
4.5 QUALITY ASSURANCE AND CONTINUOUS IMPROVEMENT	
Sub-competency	**KSA**
4.5.11 Probability and Statistics/Statistical Process Control Methods	Statistical process control (SPC) methods

4.2.12. Complex Analysis

What faculty already teach: Students study analytic functions, contour integration, series representations, and transform-based methods.

What this develops cognitively: This builds the ability to exploit structure, symmetry, and alternative representations to simplify complex structures.

How this appears occupationally: Many engineering and manufacturing problems rely on transform methods, frequency-domain reasoning, and system response analysis. The underlying reasoning can support signal analysis, system stability, and response

characterization. That connects naturally to roles performing process control, automation, diagnostics, and information technology (IT)/operational technology (OT) integration such as Robotics Technician.

How a faculty member could frame it:

- When studying transform-based methods: *"Complex analysis allows us to move seamlessly between equivalent representations of the same phenomenon. This habit of switching viewpoints mirrors how engineers interpret system behavior through transforms and frequency-domain responses."*
- When studying analytic functions: "*When a function is analytic, its symmetry and a few special points (e.g., poles) can tell you how the whole system behaves, just like engineers use frequency plots and sensor data to spot resonances or instability and adjust the controls."*

Table 18. Representative KSAs Developed: Complex Analysis

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	System simulation/modeling
4.1.3 Engineering Concepts	Understanding of electrical systems
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.6 Automated Systems and Control Operations	Robot programming
5.2 SMART MANUFACTURING TECHNOLOGY	
Sub-competency	**KSA**
5.2.2 IT/OT Integration	Cuber-Physical Systems (CPS)

4.2.13. Abstract Algebra

What faculty already teach: Students study groups, rings, finite fields, symmetric structures, and invariant properties.

What this develops cognitively: This develops structural reasoning, the ability to work within logical constraints, and identifying what remains invariant under transformation.

How this appears occupationally: The rigorous structural reasoning developed in this course is directly applied to designing secure data architectures, implementing cryptographic protocols for cybersecurity, and ensuring structural integrity across integrated IT/OT platforms. This is useful knowledge for occupations like Cybersecurity Analyst and Industrial Engineer.

How a faculty member could frame it:

- When introducing group theory: "*Groups and symmetric structures are more than just abstract ideas; they represent the logical constraints that govern complex systems. In cybersecurity, these invariant structures are what allow us to create secure, encrypted communication channels that remain robust against interference*."
- When teaching finite fields: "*Finite fields provide the mathematical foundation that makes encryption possible and keeps data secure. When we study these structures, we are learning the specific logic needed to design data integrity protocols that protect manufacturing operations from unauthorized access or cyber threats*."
- When discussing homomorphisms and isomorphisms: "*These mappings show us how information preserves its structure even when it changes form. Seeing this structural equivalence is how IT and OT integration specialists ensure that high-level software commands are translated accurately into, for example, physical robotics actions.*"

Table 19. Representative KSAs Developed: Abstract Algebra

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.7 Testing/Troubleshooting	Advanced fault finding on actual equipment
5.3 INFORMATION TECHNOLOGY	
Sub-competency	**KSA**
5.3.2 Databases and Applications	Proficient understanding of Structured Query Language basics
5.4 NICE FRAMEWORK/CYBERSECURITY	
Sub-competency	**KSA**
5.4.1 Cybersecurity Fundamentals	Understand and use cybersecurity fundamentals Cybersecurity processes
5.4.4 Operating Technology (OT) Security	Understand IT/OT Integration security

4.2.14. Summary Framing for Math Faculty

As evidenced by the analysis presented in Sections 4.2.1 -4.2.13, many topics taught in undergraduate mathematics courses map to Tier 4 and Tier 5 competencies. This mapping demonstrates that math curricula aligns with both technical skills and occupation-specific demands in advanced manufacturing. Table 20 provides examples of concrete mathematical activities for each of the mathematics courses listed above and a selection of sub-competencies and associated KSAs.

Table 20. Mapping Core Undergraduate Mathematics Courses to Representative Competencies, Sub-competencies, KSAs with an Operational Description, and Concrete Mathematical Activities

Undergraduate Math Course	Example Tier 4 /5 Competency: Sub-Competency	Representative KSAs Developed (Operational Description)	Concrete Mathematical Activity
Algebra, Geometry, Precalculus, Trigonometry	Operations Management: Automated Systems and Control Operations (4.2.6)	Representing quantitative relationships, translating between symbolic, graphical, and geometric representations	Interpreting slope and rate from linear models; using trigonometric relationships to understand forces, angles, and periodic behavior
Calculus Sequence	Manufacturing Process Design: Design Lifecycle and Concepts (4.1.5)	Sensitivity analysis; constrained optimization	Partial derivatives; constrained extrema
Calculus Sequence	Operations Management: Production/Process Monitoring (4.2.11)	Monitoring response to parameter changes	Monotonicity and curvature analysis
Linear Algebra	Operations Management: Automated Systems and Control Operations (4.2.6)	System modeling; stability and convergence	Matrix modeling of a system; eigenvalue analysis
Linear Algebra	Manufacturing Process Design: Workflow Assessment (4.1.9)	Interdependence and coupling analysis	Solving coupled linear systems
Linear Algebra	Smart Manufacturing Technology: IT/OT Integration (5.2.2)	Understanding distributed interaction in cyber-physical systems	Transformation matrices and vector space projections for multi-input systems
Discrete Math	Production in the Supply Chain/Supply Chain Logistics: Supply Chain Management (4.4.10)	Scheduling and precedence reasoning	Boolean logic for rule bound systems; recurrence relations
Discrete Math	NICE Framework/Cybersecurity: Cybersecurity Fundamentals (5.4.1)	Shared responsibility; Implementing logical constraints throughout the DevSecOps lifecycle	Logic circuits; algorithm complexity analysis; graph-based network security
Probability & Statistics	Quality Assurance and Continuous Improvement: Probability and Statistics/Statistical Process Control Methods (4.5.11)	Variability detection, trend identification	Control charts; hypothesis testing
Probability & Statistics	Quality Assurance and Continuous Improvement:	Data quality; reporting accuracy	Estimation; confidence intervals

Undergraduate Math Course	Example Tier 4 /5 Competency: Sub-Competency	Representative KSAs Developed (Operational Description)	Concrete Mathematical Activity
	Data Analysis and Presentation (4.5.12)		
Ordinary Differential Equations	Manufacturing Process Design/Development: Testing/Troubleshooting (4.1.7)	Dynamic system behavior analysis	Equilibrium and stability analysis
Numerical Analysis	Manufacturing Process Design/Development: Testing/Troubleshooting (4.1.7)	Approximation accuracy; numerical reliability	Convergence and stability of algorithms
Operations Research	Operations Management: Manufacturing Process Applications and Operations (4.2.7)	Optimization under constraints	Linear programming; dual analysis
Operations Research	Operations Management: Project Management and Execution	Resource optimization	Linear programming; dual analysis for resource trade-offs
Graph Theory	Production in the Supply Chain/Supply Chain Logistics: Supply Chain Management (4.4.10)	Network reasoning; dependency and flow analysis	Shortest paths; max-flow algorithms
Graph Theory	Operations Management: Production/Process Monitoring (4.2.11)	Identification of critical paths and failure points	Network connectivity analysis
Combinatorics	Operations Management: Manufacturing Process Applications and Operations (4.2.7)	Feasibility reasoning under constraints	Counting valid configurations
Combinatorics	Manufacturing Process Design/Development: Workflow Assessment (4.1.9)	Constraint interaction analysis	Inclusion-exclusion; recurrence relations
Real Analysis	Maintenance, Installation, and Repair: Reliability and Maintainability (4.3.33)	Precision in handling underlying assumptions and reasoning about system behavior in limiting or extreme cases	Working with limits, continuity, and measure to handle edge cases
Complex Analysis	Operations Management: Automated Systems and Controls (4.2.6)	Signal and frequency characterization; Interpreting system behavior through	Contour integration; transform based methods; series representations

Undergraduate Math Course	Example Tier 4 /5 Competency: Sub-Competency	Representative KSAs Developed (Operational Description)	Concrete Mathematical Activity
		transforms and resonances	
Abstract Algebra	NICE Framework/Cybersecurity: Cybersecurity Fundamentals (5.4.1)	Applying cryptographic structures and algorithms	Study of groups, rings, and finite fields for encryption protocols

The occupations listed in the tables above were derived directly from the MFG USA Competency Framework by identifying occupations that explicitly reference the Tier 4 and Tier 5 KSAs developed through undergraduate mathematics. Only occupations that appear across multiple institutes or technology sectors were included. The developed KSAs, as seen in the Operational Description Column of Table 20 do not reproduce framework language verbatim. Instead, the table translates selected Tier 4 and Tier 5 KSAs from the MFG USA Competency Framework into descriptions of the mathematical actions through which those KSAs are instantiated in the undergraduate coursework. This translation preserves the framework's functional intent while rendering the competencies interpretable and actionable for mathematics and physics faculty.

4.3. Mapping Core Undergraduate Physics Courses to Competencies

Much like mathematics, physics and astronomy courses offer many skills related to future advanced manufacturing workforce needs. From high school through postsecondary education, educators must help students and upskilling workers understand how the knowledge and skills they are developing connect to real occupations and workplace capabilities. Physics and astronomy courses from high school through university postsecondary education offer many skills related to future workforce needs. Putting courses and training programs in context for students can help them show their value to hiring managers and employers, recall information more quickly, and better perceive their future career pathway options. This section demonstrates how standard high school and undergraduate physics courses cultivate critical thinking, analytic and experimental skills, and systems-level competencies that are clearly aligned with industry-validated Tier 4 and Tier 5 KSAs and manufacturing roles. Without changing course or degree content, pedagogy, or learning goals, it is possible to better highlight the value of physics education to those within industry. This work helps show how knowledge and skills learned in physics and astronomy educational programs apply to a wide range of occupations and career pathways.

In the subsections below, physics courses typically taught from high school through college will be connected to the skills and tasks needed for future-looking advanced manufacturing occupations. In this report it is assumed that such students have experience with the scientific method, fractions and estimation, and a primary and secondary school understanding of materials within Tier 2 of the DOL Advanced Manufacturing Competency Model. By placing

these courses in the context of potential careers of importance through 2030 and the associated skills needed, faculty can support both hiring managers and students.

While specific KSAs identified by industry and Manufacturing USA institutes are associated with individual courses, the mappings are suggestions and do not include all course content which could be mapped to dividual courses. Specific KSAs are provided as examples and are not intended to be prescriptive. Individual course mapping to the KSAs of this report should be done by individual departments on a regular basis, as there is significant course variation among institutions and professors. Linkages are also nested, meaning that the KSAs taught in lower-level courses are reinforced or expanded upon in upper-level courses. Additionally, potentially ubiquitous skills such as programming or measurements can be present in any number of courses; connection to specific courses is provided as an example. The courses listed below were obtained by performing a survey of common physics courses taught across the United States as a part of an undergraduate curriculum.

4.3.1. Introductory Physics I (Kinematics and Mechanics)

What faculty already teach: Students often study Newton's laws, kinematics, work–energy, momentum, conservation laws, rigid body motion, oscillations, and basic modeling of physical systems.

What this develops cognitively: Kinematics develops spatial reasoning and abstract thinking through visualization and development of models using mathematical relationships. Physics I is a foundational course designed to teach learners how to apply math to the world around them. This course develops core analytical problem-solving skills through physical motion examples, such as teaching how to decompose complex movements into measurable components like displacement, velocity, and acceleration. Ultimately, Physics I trains the brain to predict physical outcomes based on theoretical inputs, bridging the gap between mathematical logic and real-world observation. This course develops the ability to model systems from first principles; identify motion, forces, rotation, momentum, and energy; reason about equilibrium, motion, and mechanical systems; learn how to make physical assumptions; and translate physical situations into models, including energy and momentum.

How this appears occupationally: Advanced manufacturing relies on the ability to translate physical systems and mechanical systems into predictable models. This concept appears often in the workplace as a need to perform root-cause analysis on mechanical systems. This can appear as distinguishing between intended motion or actions and energy loss such as friction, air resistance, or thermal heating. This course content also appears in the application of metrology, which is a foundational concept for many occupations. A student's understanding of equilibrium and dimensions is used to ensure parts meet strict geometric tolerances, data is correctly measured, and even the size of things from time to distance. For example, whether calibrating a robotic arm or documenting a workflow via standard operating procedures (SOPs) involving physical systems, a worker is essentially applying first-principles reasoning to ensure repeatability and system stability. This course is critical for entire classes of occupations, such as technicians, engineers, maintenance leads, and analysts. It is directly related to occupations within electronics, materials, and even biomanufacturing.

How a faculty member could frame it:

- When introducing free-body diagrams: "*This is about identifying what actually influences a system and what can be ignored. That filtering step is critical in any complex technical system. It lets us translate real-world measurements to a model which can help us predict how the system will behave*."
- When teaching energy and momentum conservation laws: "*Conservation of energy and momentum let us predict outcomes even when we can't know every internal detail.*"
- When teaching kinematics: "*Physical systems that focus on motion and energy can be modeled to predict future behavior within documented limitations and using assumptions.*"

Table 21. Representative KSAs Developed: Introductory Physics I (Kinematics and Mechanics)

T4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	Electrical, optical, thermal, and mechanical modeling and simulation
4.1.3 Engineering Concepts	Analyze problems to see how mechanical and thermal devices might help solve a particular problem Understanding of thermal, mechanical, and optical material properties
4.1.7 Testing/Troubleshooting	Data collection/analysis
4.1.9 Workflow Assessment	Follow SOPs and provide documentation
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.2 Systems	Understanding of mechanical systems
4.2.4 Precision Measurement	Measurement/metrology
4.2.5 Manufacturing Tool and Equipment Operations	Set up, adjust, calibrate, clean, maintain, and troubleshoot laboratory and field equipment

4.3.2. Introductory Physics II (Electricity and Magnetism)

What faculty already teach: Students often study electrostatics, electric and magnetic fields, circuits, AC and DC circuits, induction, and electromagnetic waves.

What this develops cognitively: Physics II develops conceptual visualization and abstract reasoning by requiring students to model fields and electromagnetic forces that cannot be directly observed in many cases. This course strengthens the ability to think in multiple dimensions, teaching learners to synthesize complex relationships between electricity, magnetism, and light through vector calculus and theoretical frameworks. Ultimately, Physics II

trains the brain to perceive the interconnectedness of energy and matter, bridging the gap between intangible mathematical abstractions and the functional technology of the modern world. This course trains students to apply mathematical models, such as fields, to physical systems; understand electromagnetic phenomena; reason about electrical circuits, motors, and basic thermodynamics; and understand signals and electrical power, as well as how to apply systems logic such as Kirchhoff's laws to physical systems.

How this appears occupationally: Advanced manufacturing relies on the ability to model and control the movement of energy and information through electrical and magnetic (E&M) systems. In the workplace, this commonly appears as the need to analyze how electrical signals propagate through a system without degradation, which often involves distinguishing between the intended signal and noise or interference. Understanding the foundation of electricity and magnetism is critical when working with materials, high-precision sensors, electronics, and even automated controllers. This course content appears in the application of electromagnetic principles to manage materials at both the macro and microscopic level, such as in semiconductor fabrication or air filtration systems. Much like in mechanical systems, a student's understanding of circuit components and E&M field theory is used to ensure that electrical parts are manufactured within strict tolerances to maintain signal integrity and prevent system failure. For example, when designing a power distribution layout for a factory floor or troubleshooting a faulty sensor in a cyber-physical system, a worker is applying systems logic to ensure reliable electrical performance and signal transmission. This course is critical for entire classes of occupations, including Electrical Technicians, Systems Engineers, and Automation Specialists, and is directly related to sectors such as optoelectronics, energy systems, motors, sensors, IT/OT, and smart manufacturing.

How a faculty member could frame it:

- When introducing charge and fields: "*Electric fields let us reason about how charged particles would propagate through space and are essential to understanding semiconductors, air filtration, and electrical and electrical heating processes.*"
- When building and analyzing circuits: "*Electrical signals are created, measured, and altered using circuits. This lets us model circuit system response, delay, and feedback*."
- When discussing resistance and capacitance: "*While precise, these circuit components are manufactured within given tolerances. Understanding these variances is what allows us to maintain signal integrity*."

Table 22. Representative KSAs Developed: Physics II (Electricity and Magnetism)

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	Electrical, optical, thermal, and mechanical modeling and simulation
4.1.2 Technical Drawings and Schematics	Reading and interpreting schematics, blueprints, and technical and non-technical documents and drawings

4.1.3 Engineering Concepts	Basic understanding of electrical and optical principles Understanding of optics/electromagnetics Understanding of electrical systems
4.1.7 Testing/Troubleshooting	Knowledge and use of analytical or scientific software
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.4 Precision Measurement	Measurement/metrology
4.2.5 Manufacturing Tool and Equipment Operations	Set up, adjust, calibrate, clean, maintain, and troubleshoot laboratory and field equipment

4.3.3. Introductory Physics III (Waves and Optics)

What faculty already teach: Students often study superposition, interference, diffraction, geometric optics, waves, sound, interference, and resonance.

What this develops cognitively: Physics III develops a more advanced understanding of wave-particle duality and photons, challenging students to visualize how both light and sound propagate through different media. This course enhances spatial and analytical reasoning by teaching learners to model interference, diffraction, and refraction using geometric and trigonometric relationships. Ultimately, Physics III trains the brain to reconcile the overlap between particle behavior and wave motion, bridging the gap between classical physical observations and the fundamental nature of light and sound. Students learn to analyze wave properties such as intensity, frequency, wavelength, and propagation; review how wave systems interact with physical matter; and understand optics, resolution, limits, and measurement constraints.

How this appears occupationally: Advanced manufacturing relies on the ability to use wave properties and optical phenomena as high-precision diagnostic tools in many occupations. In the workplace, this appears as the use light microscopes and when interference and diffraction patterns are used to measure features that are too small for traditional mechanical probes. This utilizes the behavior of light to detect nanometer-scale variations in thickness or surface roughness, which is critical for production of semiconductors, precision coatings, and optical lenses. This course content also appears in the application of polarization and resonance to analyze the internal health of a system. For example, using polarized light to visualize internal mechanical stresses in a transparent component allows a worker to identify a potential point of failure before the part ever leaves the factory. Signal transmission and reception also rely heavily on this course content. Whether using a laser interferometer for ultra-precise alignment or managing the resolution limits of an imaging system, a worker applies wave-behavior models to ensure product quality and measurement accuracy. This course is critical for entire classes of occupations and roles, including Optical Technicians, Quality Assurance Engineers, opto-electronics, 3D printing Engineers, Machinists, and Materials Analysts, and is directly related to

sectors such as biomanufacturing, aerospace, mechanical engineering, and photonic device production.

How a faculty member could frame it:

- When discussing thin-film interference: "*This isn't just about the colors on a soap bubble; it's the physics behind precision coating. In advanced manufacturing, we use these interference patterns to measure the thickness of a lubricant or a semiconductor layer down to a few nanometers*."
- When discussing resolution limits: "*Every measurement system has fundamental limits. Understanding those limits is part of any system design that includes cameras*."
- When teaching polarization: "*Polarization is a powerful tool for stress analysis, optics, and data filtering. By looking at how light twists through a transparent plastic or glass component, we can examine internal mechanical stresses before the part ever fails in the field*."

Table 23. Representative KSAs Developed: Introductory Physics III (Waves and Optics)

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	Electrical, optical, thermal, and mechanical modeling and simulation
4.1.3 Engineering Concepts	Basic understanding of electrical and optical principles Design new ways to use electrical power to develop or improve products Understanding and application of materials science Understanding of thermal, mechanical, and optical material properties Understanding of thermal, mechanical, and optical reliability
4.1.7 Testing/Troubleshooting	Knowledge and use of analytical or scientific software
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.4 Precision Measurement	Measurement/metrology
4.2.5 Manufacturing Tool and Equipment Operations	Set up, adjust, calibrate, clean, maintain, and troubleshoot laboratory and field equipment

4.3.4. Modern Physics (Introduction to Quantum and Relativity)

What faculty already teach: Students learn special relativity, wave–particle duality, atomic structure, Schrödinger equation, tunneling, and quantization.

What this develops cognitively: Modern Physics helps learners develop a higher level of conceptual flexibility by exploring physical situations in which intuitive classical assumptions often fail, in favor of quantum and relativistic frameworks. This course strengthens abstract reasoning as learners grapple with paradoxical concepts such as time dilation, wave-function collapse, and the quantization of energy. Ultimately, Modern Physics bridges the gap between macroscopic experience and the fundamental, probabilistic laws that govern the universe. This course develops comfort with probabilistic models, acceptance of fundamental uncertainty and limits, reasoning under non-classical constraints, and interpretation of models that are predictive but non-intuitive

How this appears occupationally: Advanced manufacturing relies on the ability to apply probabilistic and non-classical models to the behavior of materials at the atomic and subatomic levels. In the workplace, this appears as the need to manage and predict the behavior of electrons in semiconductors or the properties of photons in laser systems. This often involves reasoning about quantum tunneling and energy bands to optimize the efficiency of a microchip or the precision of a sensor, where classical physics no longer provides accurate predictions. This course material is essential for all semiconductor and advanced optics occupations. This course content also appears in the development of next-generation materials, where understanding the probabilistic nature of particles allows for the design of components with specific electrical or thermal properties. For example, when analyzing the performance of a quantum-dot display or a high-efficiency solar cell, a worker is applying non-intuitive models to ensure that the device operates within its intended specifications. This course is critical for a variety of occupations and roles, including Materials Scientists, Semiconductor Engineers, Research Scientists, Quantum Scientists, Hybrid Electronics Technical Leads, and Nanotechnology Specialists, and is directly related to sectors such as electronics, quantum computing, materials science, composites, and advanced biophotonics.

How a faculty member could frame it:

- When introducing quantum probability: "*Some systems are inherently probabilistic. The goal is not certainty but reliable prediction. This is common in semiconductors and optics*."
- When discussing models: "*A good model doesn't need to be intuitive. It needs to be accurate and useful*."
- When teaching uncertainty: "*Limits on precision are not experimental failures. They are properties of the system.*"

Table 24. Representative KSAs Developed: Modern Physics

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.2 Technical Drawings and Schematics	Technology design/system design
4.1.3 Engineering Concepts	Analyze problems to see how mechanical and thermal devices might help solve a particular problem

	Understanding of thermal, mechanical, and optical material properties Understanding and application of materials science
4.1.7 Testing/Troubleshooting	Knowledge and use of analytical or scientific software
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.4 Precision Measurement	Measurement/metrology
4.2.7 Manufacturing Process Applications and Operations	Fiber/waveguide coupling and assembly Prepare and assemble components and equipment
5.2 SMART MANUFACTURING TECHNOLOGY	
Sub-competency	**KSA**
5.2.1 Tools and Technologies	Statistical Process Control (SPC), analytics, artificial intelligence/machine learning Understand and apply artificial intelligence/machine learning fundamentals

4.3.5. Thermodynamics and Introduction to Statistical Mechanics

What faculty already teach: Students learn the laws of thermodynamics, entropy, heat engines, phase transitions, ensembles, and macroscopic behavior emerging from microscopic rules.

What this develops cognitively: Thermodynamics and Statistical Mechanics aims to develop the ability to scale cognitive perspectives, teaching students to transition between the macroscopic behavior of bulk matter and the microscopic chaos of individual particles. This course strengthens probabilistic reasoning and systems thinking as learners model how energy distribution and entropy drive the direction of physical processes. Students develop the ability to reason about energy efficiency and loss, understand irreversible chemical and physical processes, connect micro-level physics to macro-level behavior, and consider thermodynamic limitations for engines and physical systems.

How this appears occupationally: Advanced manufacturing relies on the ability to model the flow of energy and the transition of states to maximize system efficiency. In the workplace, this appears as the need to manage heat dissipation and energy loss in high-power machinery or chemical processing plants. This often involves distinguishing between theoretical maximum efficiency and actual operational output, allowing a worker to identify where energy is being wasted or heat flow is being limited. This course content also appears in the study of phase transitions and material stability, which is critical for processes like additive manufacturing (3D printing), composites, and the synthesis of biopharmaceuticals. For example, when designing a cooling system for a high-speed computer numerical control (CNC) machine or analyzing the thermal cycle of a smelting furnace, a worker applies thermodynamic laws to ensure the system remains stable and cost-effective. This course is critical for a variety of occupations, such as

Thermal Engineers, Additive Engineers, Process Analysts, Quantum Computing Engineers, and Energy Auditors, and is directly related to sectors such as energy systems, mechanical and electrical engineering, aerospace, material science, and advanced materials production.

How a faculty member could frame it:

- When analyzing efficiency: "*Every system has unavoidable losses. Engineering and industry focus on managing them*."
- When connecting micro to macro: "*Large-scale behavior emerges from many small interactions*."
- When teaching heat engines and cycles: "*Most industrial processes are a cycle. By analyzing these as thermodynamic loops, we can calculate the theoretical maximum throughput and efficiency, giving us a benchmark for the 'perfect' factory line*."

Table 25. Representative KSAs Developed: Thermodynamics and Introduction to Statistical Mechanics

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	Electrical, optical, thermal, and mechanical modeling and simulation
4.1.2 Technical Drawings and Schematics	Design or redesign mechanical and thermal devices or subsystems, using analysis and computer-aided design
4.1.3 Engineering Concepts	Analyze problems to see how mechanical and thermal devices might help solve a particular problem Understanding of thermal, mechanical, and optical material properties Understanding and application of materials science Understanding of thermal, mechanical, and optical reliability
4.1.7 Testing/Troubleshooting	Knowledge and use of analytical or scientific software
5.3 INFORMATION TECHNOLOGY	
Sub-competency	**KSA**
5.3.1 Programming	Knowledge and use of programming skills (Python, C++)

4.3.6. Experimental Physics and Advanced Laboratory

What faculty already teach: Students study experimental design, instrumentation, data acquisition, uncertainty analysis, calibration, error propagation, reporting, and presentation.

What this develops cognitively: Experimental Physics and Advanced Laboratory courses help learners develop the ability to bridge theoretical abstraction and physical reality, translate mathematical models into measurable observables, and apply scientific and engineering principles to complex, real-world processes and equipment. These courses strengthen critical thinking, scientific synthesis, and iterative problem-solving as learners navigate the tension between idealized physics and the systemic uncertainties of real-world instrumentation. This course builds laboratory and engineering skills; experimental design, testing, and prototyping; equipment troubleshooting and data analysis; technical communication and documentation; and entrepreneurship.

How this appears occupationally: Advanced manufacturing relies on the ability to design, execute, and validate experiments to ensure that theoretical models and designs translate into reliable physical products and processes. This course is foundational for research scientists and engineers. In the workplace, this appears as the need to establish the accuracy and reliability of data through rigorous calibration and uncertainty analysis. This often involves distinguishing between a true system failure and a measurement error caused by sensor noise or environmental interference or statistics, which is critical for maintaining quality control in high-precision environments. This course content also appears in the development of SOPs and the creation of test fixtures used to stress-test components before they are deployed. For example, whether calibrating a high-precision laser sensor or performing a root-cause analysis on a defective batch of materials, a worker applies experimental methodology to ensure that the data collected is an honest reflection of physical reality. This course is critical for a variety of occupations and roles, such as Engineering, Research Scientists, Quality Assurance Managers, and Laboratory Technicians, and is directly related to any experimental sectors such as aerospace, biomanufacturing, additive manufacturing, robotics, opto-electronics, materials processing, and semiconductor fabrication.

How a faculty member could frame it:

- When discussing uncertainty: "*Every tool and measurement has a quantifiable uncertainty which needs to be reported.*"
- When teaching calibration: "*Sensors are only as good as their last calibration. It's not just 'zeroing' a scale, it's establishing a mathematical relationship between signals and a trusted, physical reality. Flawed calibration is meaningless data."*
- When teaching signal filtering/noise*:* "*Most environments are electrically or mechanically noisy. Understanding how to filter out a 60 Hz noise or vibrations from sensors can make all the difference for many processes."*
- When analyzing oscillations: "*Oscillatory behavior shows up whenever systems are pushed away from equilibrium; it happens in many technical systems such as CNC milling or robotics*."

Table 26. Representative KSAs Developed: Experimental Physics and Advanced Laboratory

T4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT

Sub-competency	KSA
4.1.1 Critical Work Functions	Electrical, optical, thermal, and mechanical modeling and simulation
4.1.2 Technical Drawings and Schematics	Design or redesign mechanical and thermal devices or subsystems, using analysis and computer-aided design
4.1.7 Testing/Troubleshooting	Knowledge and use of analytical or scientific software Data collection and analysis Prepares test articles, fixtures, and data collection devices to perform various tests
4.2 OPERATIONS MANAGEMENTS	
Sub-competency	**KSA**
4.2.11 Production/process Monitoring	Documenting and reporting information and data Follow SOPs and provide documentation Tool calibration
4.2.4 Precision Measurement	Measurement/metrology Verify dimensions of parts using precision measuring instruments
5.3 INFORMATION TECHNOLOGY	
Sub-competency	**KSA**
5.3.1 Programming	Knowledge and use of programming skills (Python, C++)
5.3.2 Databases and Applications	Industrial Internet of Things (IIoT), data capture, and data platforms

4.3.7. Computational Physics

What faculty already teach: Students study numerical solutions of physical systems, simulation, algorithm selection, validation, visualization, and performance trade-offs.

What this develops cognitively: Computational Physics develops the ability to model continuous and complex physical phenomena. Students can translate complex physics systems into differential equations and algorithmic architectures. This course strengthens algorithmic thinking and numerical intuition as learners navigate the trade-offs between computational efficiency, stability, and the convergence of simulated models toward physical truth. Students learn to replace analytic solutions with computational models; utilize numerical integration and simulations, such as Monte Carlo; evaluate model fidelity and stability, such as finite element analysis; balance accuracy, speed, and resource constraints; and validate simulations against reality.

How this appears occupationally: Advanced manufacturing relies on the ability to replace costly physical prototypes with high-fidelity computational models and simulations. In the workplace, this appears as the need to predict how a system will behave under different variables before a single part is ever manufactured. Ability modeling is a core function in advanced manufacturing. This often involves distinguishing between a model's theoretical output and its real-world fidelity, ensuring that the numerical approximations used are accurate enough to guarantee safety and performance. Many powerful tools commonly use this approach in finite element analysis. This course content also appears in the creation of digital twins, where real-time data from the factory floor is fed into a simulation to predict when a machine will fail or where a bottleneck will occur. For example, whether simulating the thermal stress on a 3D-printed aerospace component or using Monte Carlo methods to optimize a supply chain's resilience, a worker applies computational reasoning to reduce risk and accelerate production. This course is critical for a variety of occupations, including Engineering, Data Analysts, Systems Architects, Quantum Scientists, and Research Scientists, and is directly related to sectors such as smart manufacturing, aerospace, and additive manufacturing.

How a faculty member could frame it:

- When validating simulations: "*A simulation is only useful if we understand its limits and assumptions*."
- When discussing discretization: "*Numerical choices are design decisions*."
- When visualizing data: "*Visualization is part of analysis, not decoration*."
- When teaching Numerical Integration: "*There is rarely a perfect formula for a real-world part. Numerical methods are used to calculate volumes, centers of mass, thermal and electrical properties, and structural loads for shapes that are far too complex for standard calculus."*
- When teaching simulation (Monte Carlo/stochastic): "*Advanced manufacturing uses digital twins to predict failures before they happen and improve processes. By running thousands of simulated shifts with slight random variations, we can predict exactly when a machine will need maintenance before it actually breaks down*."

Table 27. Representative KSAs Developed: Computational Physics

4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	Electrical, optical, thermal, and mechanical modeling and simulation
	System simulation/modeling
4.1.2 Technical Drawings and Schematics	Design or redesign mechanical and thermal devices or subsystems, using analysis and computer-aided design Knowledge and use of computer-aided design (CAD)/computer-aided manufacturing (CAM) software

	Radio-frequency/very-large-scale integration/photonic integrated circuit design, modeling, layout
4.1.7 Testing/Troubleshooting	Knowledge and use of analytical or scientific software Data collection and analysis
4.5 QUALITY ASSURANCE AND CONTINUOUS IMPROVEMENT	
Sub-competency	**KSA**
4.5.12 Data Analysis and Presentation	Data collection and reporting Data visualization and reporting Understand and ensure data quality Understanding and execution of data quality fundamentals and control
5.3 INFORMATION TECHNOLOGY	
Sub-competency	**KSA**
5.3.1 Programming	Knowledge and use of programming skills (Python, C++)

4.3.8. Upper-Division Theoretical Physics and Astrophysics (Classical Mechanics, EM, Quantum)

What faculty already teach: Students study Lagrangians, Hamiltonians, symmetry, conservation laws, variational principles, and advanced mathematical structures.

What this develops cognitively: Upper-Division Theoretical Physics and Astrophysics develops a student's ability to construct rigorous formalisms from first principles, distill complex physical phenomena into universal mathematical symmetries and laws, and model real-world systems. These courses strengthen high-level analytical synthesis and abstract reasoning as learners master the transition from intuitive descriptions to the sophisticated language of tensors, operators, symmetries, and equations. This coursework develops structural reasoning across systems; boundary value problems related to electrical, mechanical, and statistical systems; abstraction and simplification that unify disparate problems; and long-range analytic planning and system modeling.

How this appears occupationally: Advanced manufacturing relies on the ability to use high-level abstraction and structural reasoning to unify disparate physical phenomena into a single, manageable system. In the workplace, more theory-based courses in physics appear as the need to model complex, multicomponent systems not as a series of individual forces but as a single energy landscape to be optimized; examples are 7-axis robotic arms or complex phase diagrams for material synthesis. This often involves distinguishing between a system's superficial behavior and its underlying invariant properties, allowing a worker to predict how a change in one variable will propagate across an entire integrated platform. This course content also appears in the design of cutting-edge technology, where perturbation theory is used to

account for real-world imperfections, such as identification impurities in a semiconductor, to ensure the device still functions as intended. These types of courses also apply when using Lagrangian mechanics to program the fluid motion of an automated assembly line or applying Maxwell's equations to design induction heating for metal forging; in each instance, an engineer applies advanced theoretical frameworks to solve problems that are too complex for basic intuition. This course is critical for occupations including Principal Engineers, Research Scientists, Quantum Scientists, Hybrid Electronic Technical Leads, and System Architects, and is directly related to sectors such as quantum computing, aerospace, artificial intelligence, materials science, electronics, and advanced robotics.

How a faculty member could frame it:

- On Lagrangian mechanics: *"Instead of individual force vectors, by looking at the total energy of a system, we can derive the equations of motion for a 7-axis robotic arm in one go. This is the math that powers the physics engines used in industrial simulation*."
- On Maxwell's equations (in matter): "*We aren't just talking about vacuum physics—this is how we design induction heating for metal forging or understand how a high-power laser interacts with a specific polymer during subtractive manufacturing*."
- On Quantum Perturbation Theory: "*Real-world materials are never perfect. They have impurities and defects and noise. This allows us to predict how those perturbations change the electrical mobility or thermal dissipation of a semiconductor wafer*."

Table 28. Representative KSAs Developed: Classical Mechanics, EM, Quantum

T4.1 MANUFACTURING PROCESS DESIGN/DEVELOPMENT	
Sub-competency	**KSA**
4.1.1 Critical Work Functions	System simulation/modeling
4.1.3 Engineering Concepts	Analyze problems to see how mechanical and thermal devices might help solve a particular problem Mechanical engineering Understanding and application of materials science Understanding of optics/electromagnetics Understanding of thermal, mechanical, and optical material properties
4.1.8 Research and Development	Develop and test device prototypes
4.2 OPERATIONS MANAGEMENT	
Sub-competency	**KSA**
4.2.7 Manufacturing Process Applications and Operations	Fiber/waveguide coupling and assembly Fiber/waveguide coupling, assembly, and validation Understanding of electronics and controls
5.3 INFORMATION TECHNOLOGY	

Sub-competency	KSA
5.3.1 Statistical data analysis	Statistical data analysis

4.3.9. Summary Framing for Physics Faculty

Across undergraduate physics curriculum, students repeatedly practice:

- Modeling complex systems
- Reasoning under uncertainty and comparing to real systems
- Analyzing stability, efficiency, and trade-offs
- Designing, validating, and interpreting experiments and equipment
- Working fluently between theory, computation, and data
- Examining physical material properties and engineered systems

The above physics courses map directly to industry-wide Tier 4 competencies, including process design, operations, quality, and safety. They also strongly connect to Tier 5 competencies (e.g., materials, smart systems, experiments, and testing), even when no manufacturing context is present, because the foundational information is integrated into these courses. The required pedagogical intervention is not curricular change but explicit naming and placing learning in the context in which they will experience the need for it. While incomplete, the above courses provide some context for students and advanced manufacturing workers.

Table 29. Mapping Core Undergraduate Physics Courses to Representative Competencies, Sub-competencies, KSAs with an Operational Description, and Concrete Physics Activities

Undergraduate Physics Course	Example Tier 4/5 Competency: Sub-competency	KSAs Developed (Operational Description)	Concrete Physics Activity
Introductory Physics I (Kinematics and Mechanics)	Manufacturing Process Design: Engineering Concepts (4.1.3)	Modeling system behavior from first principles; identifying dominant forces; metrology	Free-body diagrams; equation-of-motion; metrology
Introductory Physics I (Kinematics and Mechanics)	Quality Assurance: Process Control (4.5.11)	Measurement validation; uncertainty analysis	Error propagation and calibration labs
Introductory Physics II (Electricity and Magnetism)	Manufacturing Process Design: Engineering Concepts (4.1.3)	Apply mathematical models to electric and magnetic fields; reason about electric signals and power	Model, design, and build electric circuits and motors; analyze circuit components

Undergraduate Physics Course	Example Tier 4/5 Competency: Sub-competency	KSAs Developed (Operational Description)	Concrete Physics Activity
Introductory Physics II (Electricity and Magnetism)	Materials Design & Production: Electronic Materials (5.7.4)	Test and design electronic circuits	Measurement of electronic circuit components
Introductory Physics III (Waves and Optics)	Manufacturing Process Design: Process Optimization (4.1.5)	Trade-off analysis between efficiency, output, and loss	Heat engine design and efficiency
Experimental Physics and Advanced Laboratory	Experiments, Tests, and Analyses: Experimental Design (5.5.3)	Designing experiments to sense, test, and evaluate	Controlled parameter experiments
Experimental Physics and Advanced Laboratory	Operations Management: Control and Feedback (4.2.6)	Analysis of coupled systems and feedback loops	Circuit transient analysis (RC, RLC)
Experimental Physics and Advanced Laboratory	Quality Assurance: Data Analysis & Presentation (4.5.12)	Distinguishing signal from noise; resolution limits	Interference and diffraction analysis
Experimental Physics and Advanced Laboratory	Operations Management: Monitoring & Diagnostics (4.2.11)	Frequency-domain interpretation of system behavior	Fourier analysis of waveforms
Computational Physics	Manufacturing Process Design: Modeling & Simulation (4.1.7)	Replacing analytic models with validated simulations	Numerical integration; Monte Carlo simulations; thermal finite element analysis
Computational Physics	Operations Management: Predictive Monitoring (4.2.11)	Predicting system evolution over time	Time-stepped simulations
Upper-Division Theoretical Physics (Classical Mechanics, EM, Quantum)	Manufacturing Process Design: System Integration (4.1.9)	Modeling distributed systems and interactions	Optoelectronics and semiconductor field and flux calculations

Undergraduate Physics Course	Example Tier 4/5 Competency: Sub-competency	KSAs Developed (Operational Description)	Concrete Physics Activity
Upper-Division Theoretical Physics (Classical Mechanics, EM, Quantum)	Operations Management: Manufacturing Process Applications and Operations (4.2.7)	Modeling electromagnetic wave propagation	Waveguides and fiber optics
Upper-Division Theoretical Physics (Classical Mechanics, EM, Quantum)	Manufacturing Process Design: Constraint-Based Design (4.1.9)	Quantum systems and physical constraints	Quantum confinement and tunneling models

4.3.10. Faculty Use Cases: From Mapping to Practice

The mappings outlined above are intended to support faculty practice in concrete ways:

- At the syllabus level, instructors can identify relevant competencies alongside traditional learning objectives.
- At the unit level, instructors can contextualize topics in terms of system behavior, variability, or optimization.
- At the problem level, instructors can frame abstract exercises as instances of broader analytic reasoning used in real systems.

For students, this translation enables clearer professional narratives. A learning objective such as *analyze stability of equilibrium solutions* becomes *evaluate operating conditions in dynamic systems*. A homework assignment in statistical inference becomes evidence of competency in process monitoring and quality control.

The result is not a change in what is taught, but a change in how learning is framed, communicated, and understood.

In short, Section 4 demonstrates that undergraduate mathematics and physics curricula already align strongly with industry-wide Tier 4 and Tier 5 competencies essential to advanced manufacturing. By making these connections explicit, faculty can help employers recognize analytic capability and strengthen the workforce pipeline without compromising academic autonomy.

Building on the evidence in Sections 4.2.1–4.2.13 and Sections 4.3.1-4.3.8 that undergraduate mathematics and physics aligns with Tier 4 and Tier 5 workforce competencies in advanced manufacturing, Appendix A provides additional faculty framing language and resume-ready student takeaways to make these technical links explicit.

5. Pedagogical Implications: High Impact, Low Overhead

Aligning undergraduate mathematics and physics curricula with advanced manufacturing competencies does not require creating new courses, introducing vocational content, or departing from disciplinary rigor. Instead, the primary intervention is intentional framing: making explicit the connections between existing course material and the competencies students will be expected to demonstrate in professional settings.

As noted above, many of the Tier 4 and Tier 5 competencies emphasized by the MFG USA Competency Framework such as process monitoring, data analysis, optimization, and system modeling are already embedded in standard undergraduate coursework. Calculus, linear algebra, probability and statistics, differential equations, numerical analysis, and upper-level theory courses all cultivate analytical behaviors that map directly to industry-wide technical competencies. The pedagogical challenge is not what is taught but how it is contextualized and communicated.

5.1. Making Competencies Explicit

A small but impactful shift is to explicitly identify relevant competencies and KSAs within course materials. For example, a syllabus learning objective such as *analyze differential equations and assess stability* can also be framed as *develop competency in modeling dynamic processes and evaluating system robustness*, which aligns directly with operations management and process design roles. This framing preserves mathematical precision while increasing occupational legibility.

Importantly, this does not require replacing theoretical problems with application-heavy ones. Even abstract exercises can be contextualized through brief framing statements that indicate how similar analytic reasoning appears in real-world settings. Over time, these cues help students internalize how mathematical thinking transfers beyond the classroom.

5.2. Isolated Interventions

Isolated interventions within a single course are unlikely to produce lasting impact. Students encounter mathematics and physics as a sequence of disconnected requirements unless departments adopt a shared approach to translating skills. For this reason, competency alignment is most effective when treated as a department-wide effort rather than the responsibility of individual instructors.

When multiple courses consistently reinforce the idea that mathematical skills accumulate into professional competencies, students begin to recognize patterns across the curriculum. This cumulative signaling helps students articulate coherent narratives about their preparation, rather than viewing each course as an isolated hurdle.

5.3. Explicit Communication to Students is Essential

One of the most consistent findings across workforce studies is that students do not infer relevance on their own. Faculty cannot assume that students will automatically recognize how mathematical abstraction applies to manufacturing, engineering, or technology roles. These connections must be stated clearly and repeatedly, using language students can later reuse. For example, faculty can directly point to the key areas identified in Table 1 and Table 2, such as aerospace, defense, data science and tech, and explicitly explain how advanced manufacturing careers are embedded within all of them.

Simple practices, such as briefly discussing career-relevant competencies when introducing a topic, highlighting how a particular method supports real-world decision-making, or modeling resume-ready descriptions of skills, can substantially improve students' ability to translate their training into professional contexts. These conversations benefit all students, including those pursuing graduate study, by reinforcing conceptual clarity and communication skills.

5.4. Benefits Beyond Workforce Alignment

While this paper focuses on workforce preparation, the pedagogical benefits of competency framing extend beyond employment outcomes. Making learning objectives explicit improves student outcomes by helping students understand not only what they are learning but also why it matters. Framing mathematical tools as transferable analytic capabilities can deepen engagement, reduce attrition, and support wider worker participation by broadening students', parents, and current workers sense of possible futures. This approach also clarifies the intellectual power of mathematics and physics by positioning abstraction as a strength rather than a barrier.

In short, aligning undergraduate mathematics and physics education with advanced manufacturing competencies is a low-overhead, high-impact intervention, requiring no curricular overhaul, new degree programs, or compromise of academic autonomy. What it does require is a shared commitment to helping students see how the analytic skills they are developing connect to meaningful, high-impact work beyond the classroom.

6. Existing Academic Efforts Bridging Mathematics and Physics Education to Industry

Academia has not been idle in addressing concerns about the relevance of undergraduate mathematics and physics education to the workforce. Over the past two decades, a range of initiatives have emerged that aim to expose students to real-world problems, interdisciplinary collaboration, and new modes of thinking. These efforts demonstrate both recognition of the translation challenge and the feasibility of addressing it within existing academic structures. However, adoption remains uneven and these efforts are rarely framed in the language of nationality defined manufacturing competencies.

Key academic efforts that already help to bridge undergraduate mathematics and physics training to industry-relevant practice include:

- Society for Industrial and Applied Mathematics (SIAM) affiliated programs. There are several programs operated by SIAM [25] for undergraduate math students, including the Simons Undergraduate Summer Research Program, which is devoted to research and learning in applied mathematics and computational science.
- Preparation for Industrial Careers in Mathematical Sciences (PIC Math). This program[26], sponsored jointly by the MAA and SIAM, is one of the most direct efforts to connect undergraduate mathematics education with industrial practice. PIC Math partners faculty and students with external organizations to work on authentic, open-ended problems drawn from industry, government, and non-profit contexts. It allows students to work on industry-relevant problems inside a classroom, reinforcing the idea that the core curriculum already supports workforce-relevant competencies when appropriately contextualized.
- Research Experiences for Undergraduates (REU). This program [27], sponsored by the National Science Foundation, provides undergraduate students with hands-on research opportunities across all areas of STEM. While REU are often viewed as a gateway to graduate school, they can be exceptionally valuable for students entering the workforce directly as they can bridge the gap between classroom theory and industrial application.
- Other ways academia prepares students for the workforce include hiring faculty with industrial expertise (professor of practice), creating interdisciplinary majors, offering capstone projects, and partnering with local companies for internships.

Together, these initiatives demonstrate that academia already recognizes the need to connect undergraduate mathematics and physics education to real-world occupations. However, these programs have different goals, do not necessarily have a shared vocabulary linking academic work to occupational competencies, and are optional for students. Therefore, a more uniform approach connecting coursework to occupations could be implemented in the classroom across all faculty to make it a department-wide effort.

Tables 30 and 31 below list the top careers pursued by mathematicians and physicists. These occupations demonstrate that the skills and knowledge students develop in coursework prepare them for roles across industry, including engineering, analytics, computing, and advanced manufacturing. The tables help reinforce the idea that students should understand

their coursework not only as a sequence of classes but also as preparation for a wide range of professional trajectories.

Table 30 lists the top four careers for math occupations in 2024 along with their median pay [28].

Table 30. Top Math Occupations

Occupation	2024 Median Pay
Actuaries	$125,770
Data Scientists	$112,590
Mathematicians and Statisticians	$104,350
Operations Research Analyst	$91,290

Table 31 lists the top careers for physics majors during 2020-2022 along with their median starting salary. [29]

Table 31. Top Physics Occupations

Occupation	Median Starting Salary
Engineering	$70,000
Computer Software	$70,000
Data and Business Analysis	$65,000–$75,000
Technical Support	$41,000
Government Scientist	$67,500

Some occupations listed in the tables, such as Data Science, Quantitative Analyst, and Operations Research Analyst, may initially seem to sit outside traditional ideas of manufacturing positions. However, advanced manufacturing is no longer only defined by physical production but also shaped by data, computation, automation, and systems-level optimization. Manufacturing environments now generate large volumes of information through sensors, process controls, machine logs, inspection systems, and supply chain networks. Professionals who can analyze this data are essential for improving reliability, throughput, quality, forecasting, and operational efficiency. The occupations identified above are thus not peripheral to advanced manufacturing but integral to it. These roles support predictive maintenance, anomaly detection, process optimization, robotics, computer vision for inspection, and data-driven decision-making across design, production, and logistics.

6.1. Resources for Faculty to Explore

A growing set of publicly available workforce and competency resources can support faculty who wish to make undergraduate mathematics and physics curricula more transparent to industry pathways without altering disciplinary content. When used thoughtfully, these

resources help faculty understand how employers describe technical capability and help students see how their coursework connects to real-world occupational roles. The value of these resources lies in providing context, validation, and a shared language among faculty, students, and employers.

6.1.1. RoboticsCareer.org

Created by the ARM (Advanced Robotics for Manufacturing) Institute—a Department of War-funded consortium of industry, government, and academia that is part of the Manufacturing USA network—this website [30] hosts several tools including a searchable database that students and faculty can reference for available jobs in the field of robotics.

The website's News and Events page [31] illustrates how mathematics is a core enabling language for robotics, spanning everything from programming and motion planning to sensing and optimization. It explicitly ties robotics practice to mathematical foundations, naming topics like algebra, trigonometry, calculus, linear algebra, and probability and statistics as tools people use to reason about robot motion, forces, angles and distances, modeling, and sensor data.

For faculty, this is a useful site because it provides an employer-facing narrative that validates what the core curriculum already develops. In practice, faculty can use RoboticsCareer.org as a reference when writing course descriptions, introducing a topic, or advising a student, since the website provides concrete language that links course concepts to robotics roles. For example, the website highlights how math strengthens students aiming for roles such as Robotics Integrators, while also noting how Robotics Technicians use math for programming, operation, and maintenance on the manufacturing floor.

For students, the website helps reduce two common barriers: the belief that robotics requires only expensive advanced degrees and uncertainty about what preparation entails. One article [32] outlines an accessible training pathway and the skill stack employers look for, including mechanical aptitude, math and science familiarity, communication skills, and basic software/programming literacy. Robotics.Career.org can serve as a bridge between coursework and career translation.

6.1.2. NICE Workforce Framework for Cybersecurity

The NICE Workforce Framework [33] for Cybersecurity provides one of the clearest examples of how academic preparation translates into role-based capability. The NICE framework breaks cybersecurity work into categories, specialty areas, tasks, and KSAs. Roles are not defined by academic majors but by what someone will need to do in a specific role.

For faculty, the value of the NICE framework lies in its structure. [34] It shows how abstract preparation—linear algebra, cryptography, discrete mathematics, and systems modeling—becomes operational capability in areas such as secure system design, threat analysis, risk modeling, and network monitoring. Even if a department does not teach cybersecurity, NICE shows how mathematical reasoning maps to real-world functions without requiring curricular changes. Faculty can use the framework to translate course learning outcomes into

competency language or to advise students who express interest in security, defense, or infrastructure resilience.

For students, the NICE framework is powerful because it clarifies that careers are grounded in skills developed through coursework.[35] A student who has studied probability and statistics is developing a risk analysis capability. A student who has taken abstract algebra or number theory may be building a foundation relevant to encryption systems. By reviewing NICE role descriptions, students can see how analytic thinking aligns with national workforce priorities and extract resume-ready language that reflects actual tasks and responsibilities.

6.1.3. Massachusetts Technology Collaborative (MassTech)

Resources such as MassTech [36] illustrate how institutions have integrated workforce awareness into technical coursework while preserving academic rigor. These materials [37] include shared competency language, rubrics, and common embedded performance assessments designed to evaluate student mastery.

For faculty, reports from MassBridge (a workforce initiative housed within MassTech's Center for Advanced Manufacturing) show that small adjustments such as adding competency language to a syllabus, contextualizing a unit with industry-relevant framing, and designing a capstone project aligned with real-world skills can be implemented relatively easily. Reviewing these materials can also provide practical ideas for aligning terminology across a department, reinforcing coherence from introductory through upper-division courses.

For students, consistency across an institution builds and sends an important signal. When competency-oriented language appears in multiple syllabi, students begin to recognize how analytic skills accumulate into professional capacity. This strengthens professional identity formation. Instead of viewing courses as isolated requirements that need to be fulfilled to earn a degree, students see a structured pathway.

6.1.4. O*NET OnLine

O*NET OnLine [38] is an occupational database that provides detailed descriptions of job roles using structured categories such as tasks, work activities, and KSAs. Developed to create a common workforce language, O*NET offers a continuously updated view of how employers define capabilities across industries, including advanced manufacturing, robotics, engineering, and data-intensive roles.

For faculty, O*NET serves as a practical translation tool. By reviewing occupation profiles such as Manufacturing Engineer or Process Analyst, instructors can identify recurring competencies that align directly with existing mathematics and physics coursework.

For students, O*NET profiles provide language that students can adapt for resumes and interviews, helping them articulate how their academic preparation supports a particular occupation title.

6.1.5. Manufacturing x Digital (MxD)

MxD [39] strengthens U.S. manufacturing competitiveness through technology innovation, workforce development, and cybersecurity preparedness.

Students can use MxD's virtual training center to enroll in online courses to prepare for jobs in cybersecurity, artificial intelligence/machine learning, digital manufacturing, supply chain, operations and other fields.

Faculty and students can also explore MxD's workforce readiness guides that outline future-focused job roles and career pathways to navigate the manufacturing landscape.

6.1.6. MAA Career Center

The MAA Career Center [40] offers faculty a practical way to help students explore careers in the mathematical sciences. Beyond job listings, the Career Center provides career resources that can support advising and enable faculty and students to explore how mathematical training aligns with a broad range of professional opportunities.

6.1.7. American Institute of Physics (AIP) Statistical Research Center

AIP [41] offers data-rich resources on education and employment in physics and related fields. These materials can help faculty and students engage in career conversations grounded in evidence and illustrate the broad range of professional pathways available to physics majors.

7. Conclusion

The Manufacturing USA Advanced Manufacturing Occupation and Competency Framework provides an industry-validated articulation of the capabilities required across advanced manufacturing occupations. This paper demonstrates that undergraduate mathematics and physics programs already cultivate many of these competencies, particularly at the Tier 4 and Tier 5 levels, through their emphasis on modeling, abstraction, analysis, uncertainty quantification, and reasoning skills. The central challenge facing the manufacturing workforce pipeline is therefore not curricular inadequacy but invisibility.

By framing undergraduate coursework in competency language alongside course learning outcomes, institutions can strengthen the link between academic preparation and workforce expectations. Explicitly mapping mathematics and physics curricula to Tier 4 and Tier 5 competencies makes the analytic capabilities developed in these subjects visible to students and interpretable by employers, improving signaling without requiring new courses or a programmatic overhaul.

Importantly, this approach preserves the intellectual integrity of mathematics and physics education. Translation does not imply simplification. On the contrary, making competencies explicit clarifies the power of coursework in undergraduate mathematics and physics.

For faculty, the implications are practical and achievable. Small shifts in framing—naming competencies, contextualizing examples, and reinforcing transferability across courses—can signal subject matter relevance to real-world employment opportunities. For students, this coherence supports clearer professional identity formation and a more confident articulation of skills. For employers, it improves understanding of academic credentials as indicators of capability.

At the national level, aligning undergraduate mathematics and physics education with the MFG USA Competency Framework strengthens the advanced manufacturing workforce in a durable and scalable way. Mathematics and physics departments play a critical role in sustaining U.S. leadership in advanced manufacturing by showing their students how their coursework is relevant to technical roles in advanced manufacturing, helping students articulate how foundational coursework translates to industry demands.

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Appendix A. A Faculty Guide to Translating Mathematics and Physics Coursework into Workforce Relevant Competencies

This appendix is designed as a **practical reference for math and physics faculty** who want to help students articulate the workforce relevance of their coursework—particularly for advanced manufacturing, engineering, and technical industry roles—**without altering course content, assessments, or academic standards**.

The guidance here operationalizes the mappings presented in Section 4 by offering concrete language, examples, and low-overhead practices faculty can adopt immediately. No knowledge of manufacturing processes or workforce frameworks is assumed. **Math and physics courses already develop industry-relevant competencies.** The suggested step is making those competencies *explicit* to students.

A.1. What This Appendix Is (and Is Not)

This appendix is:

- A translation guide between math and physics instruction and occupational competencies
- A resource for syllabus language, lecture framing, and student communication
- Discipline-respecting and evergreen

This appendix is not:

- A proposal for curricular reform
- A call to add vocational content
- A requirement to teach manufacturing examples
- An evaluation tool

The goal is **visibility**, not modification.

A.2. The Translation Principle

Students encounter physics as a sequence of topics:

Mechanics → E&M → Waves → Thermodynamics → Modern Physics → Labs

Employers encounter capability as a set of competencies:

System modeling, monitoring, optimization, experimentation, data interpretation

The translation gap occurs when students are never shown how the first becomes the second.

Faculty can close this gap by consistently naming **what kind of thinking** a topic develops, not just **what topic** is being taught.

A.3. A Three-Layer Translation Faculty Can Use Immediately

Every topic can be framed at three levels:

1. Topic Level (Traditional)

"*What is being taught*"

Example: Stability of equilibrium solutions

2. Capability Level (Faculty Framing)

"*What kind of thinking this develops*"

Example: Evaluating whether a system returns to steady operation after disturbance

3. Competency Level (Student Articulation)

"*How this shows up in professional settings*"

Example: Diagnosing whether operating conditions are robust or prone to failure

Faculty do **not** need to introduce all three layers every time. Even occasional explicit framing has cumulative impact.

A.4. Sample Faculty Language by Course Type

The examples below are intentionally brief and adaptable.

Introductory Mechanics

Faculty framing language

- "*This problem is about identifying which forces matter and which can be ignored*."
- "*We're modeling how a system responds when conditions change*."
- "*Stability analysis tells us whether small disturbances grow or disappear*."

Student takeaway (Example resume language)

- "*I can model physical systems and predict how they respond to changing conditions*."

Electricity & Magnetism

Faculty framing language

- "*Fields let us analyze distributed influence across a system*."
- "*Circuits are controlled environments for studying feedback and response time*."
- "*Coupled equations describe how subsystems interact*."

Student takeaway

- "*I can analyze interconnected systems with feedback and signal flow.*"

Waves and Optics

Faculty framing language

- "*Superposition explains how multiple effects combine in real systems*."
- "*Fourier analysis helps us understand complex signals*."
- "*Resolution limits are fundamental constraints, not experimental flaws.*"

Student takeaway

- "*I can distinguish signal from noise and understand system limits*."

Thermodynamics

Faculty framing language

- "*Efficiency always involves trade-offs*."
- "*Irreversibility tells us what cannot be recovered*."
- "*Macroscopic behavior emerges from many small interactions*."

Student takeaway

- "*I can analyze efficiency, losses, and constraints in complex systems*."

Experimental Physics / Advanced Laboratory

Faculty framing language

- "*Uncertainty determines how much confidence we place in results*."
- "*Troubleshooting is part of experimental reasoning*."
- "*Clear reporting is a technical skill*."

Student takeaway

- "*I can design experiments, evaluate data quality, and communicate results*."

Computational Physics

Faculty framing language

- "*Numerical methods are design choices*."
- "*A model must be validated, not just computed*."
- "*Accuracy, speed, and stability must be balanced*."

Student takeaway

- "*I can build and validate computational models of real systems*."

Algebra, Geometry, Precalculus, and Trigonometry

Faculty framing language

- "*A system can be represented mathematically in different forms. An equation, a graph, and a table are multiple ways of seeing one relationship.*"
- "*Transformations help us understand how changing parameters changes the behavior of a system, whether that means shifting, reflecting, or changing the timing of a repeated pattern.*"

Student takeaway

- "*I can represent quantitative relationships in multiple ways and move between symbolic, graphical, and numerical forms*."

Calculus Sequence

Faculty framing language

- "*We are studying how accumulated change can be measured and interpreted*."
- "*Many problems involve understanding how small incremental effects combine over time*."
- "*This method lets us estimate behavior even when we cannot compute exact values directly*."

Student takeaway

- "*I can analyze how system outputs change when conditions or parameters vary*."

Linear Algebra

Faculty framing language

- "*Vectors allow us to represent multiple quantities within a single structured framework*."
- "*Linear transformations describe how one set of quantities systematically affects another*."
- "*Working with bases helps us express complex relationships in simpler coordinate systems.*"

Student takeaway

- "*I can represent complex relationships between many variables in a structured mathematical form*."

Discrete Mathematics

Faculty framing language

- "*Logical structures help us determine whether statements are universally valid*."
- "*Discrete structures allow us to analyze systems that evolve in steps rather than continuously*."
- "*Proof techniques establish whether a conclusion must follow from given assumptions*."

Student takeaway

- "*I can analyze systems governed by logical rules and discrete structures*."

Probability and Statistics

Faculty framing language

- "*Probability models allow us to reason about outcomes when results cannot be predicted exactly.*"
- "*Sampling gives us a way to learn about large systems using limited observations*."
- "*Statistical summaries help reveal patterns that are not visible in individual measurements*."

Student takeaway

- "*I can interpret uncertain outcomes using probabilistic models and data summaries.*"

Ordinary Differential Equations

Faculty framing language

- "*This equation describes how a quantity changes relative to its current state*."
- "*Solutions describe entire families of possible system behaviors*."
- "*Initial conditions determine which behavior a specific system follows*."

Student Takeaway

- "*I can describe and analyze processes where the rate of change determines future behavior.*"

Numerical Analysis

Faculty framing language

- "*Some problems cannot be solved symbolically, so we approximate solutions to them computationally*."
- "*Iterative methods refine solutions step by step*."
- "*Understanding how approximation error behaves is part of solving the problem*."

Student takeaway

- "*I can approximate solutions to complex problems and evaluate the reliability of those approximations*."

Operations Research

Faculty framing language

- "*Many real decisions involve balancing competing objectives within fixed limits*."
- "*Mathematical models help make complex decisions transparent and testable*."
- "*Structured decision models allow us to evaluate alternative strategies systematically*."

Student takeaway

- "*I can build mathematical models that support structured decision-making*."

Graph Theory

Faculty framing language

- "*Graphs help us represent relationships between many connected elements*."
- "*Paths show how something moves through a network of connections*."
- "*Connectivity tells us whether parts of a system remain linked when components are removed*."

Student takeaway

- "*I can analyze networks and understand how relationships between components affect system behavior*."

Combinatorics

Faculty framing language

- "*Counting methods help determine how many configurations satisfy a set of rules*."
- "*Constraints limit which arrangements are possible*."
- "*Growth rates reveal how quickly possibilities expand as systems become larger*."

Student takeaway

- "*I can determine how many valid configurations exist under defined constraints*."

Real Analysis

Faculty framing language

- "*Precise definitions allow us to determine exactly when mathematical reasoning is valid*."
- "*Limits formalize how quantities behave as they approach boundary conditions*."
- "*Rigorous arguments ensure that conclusions hold under clearly stated assumptions*."

Student takeaway

- "*I can construct rigorous arguments and evaluate when mathematical conclusions are justified*."

Complex Analysis

Faculty framing language

- "*Complex representations often reveal patterns that are difficult to see in real-valued formulations*."
- "*Transforming a problem into a different domain can make its structure easier to analyze*."
- "*Analytic structure allows global behavior to be inferred from local information*."

Student takeaway

- "*I can use alternative mathematical representations to analyze system behavior*."

Abstract Algebra

Faculty framing language

- "*Algebraic structures can reveal patterns that remain unchanged under transformation*."
- "*Operations can be studied independently of the specific objects involved*."
- "*Structure provides a way to understand families of systems through shared rules*."

Student takeaway

- "*I can analyze systems through their underlying structural rules and invariants*."

A.5. Syllabus-Level Integration (Low Overhead)

Faculty who wish to go one step further can add **one sentence** to a syllabus or course description.

Example Additions (Optional)

- *"This course develops skills in system modeling, stability analysis, and quantitative prediction used in operations, process design, and technical analysis roles."*
- *"Students will develop competencies in experimental design, data validation, and uncertainty analysis applicable to quality and test engineering contexts."*

These statements **do not replace** learning objectives; they complement them.

A.6. Helping Students Articulate Their Skills

Students often list course titles on resumes because they lack alternative language. Faculty can help model translation explicitly.

Example Translation

Course: Advanced Laboratory in Experimental Physics

Resume-ready articulation:

- Designed and executed experiments with controlled variables
- Analyzed measurement uncertainty and validated data quality
- Troubleshot complex instrumentation systems
- Communicated technical results in written and oral formats

Course: Numerical Analysis

Resume-ready articulation:

- Built numerical models to approximate system behavior when closed-form solutions were impossible
- Assessed numerical stability and error propagation to ensure reliable results for simulation-driven decisions
- Implemented and compared iterative solvers to balance accuracy, compute time, and robustness under varying input conditions
- Documented assumptions, validated outputs against benchmarks, and communicated findings in clear technical summaries

Explicit modeling like this helps students internalize how to communicate their preparation.

A.7. Department-Level Impact

Isolated interventions help, but **consistency across courses matters more**.

Students begin to recognize patterns across the curriculum rather than viewing each course as disconnected when multiple faculty:

- Use similar framing language
- Reinforce transferable competencies
- Connect abstract reasoning to system behavior

This coherence supports:

- Stronger professional identity formation
- Improved student confidence
- Clearer employer signaling
- Better alignment with advanced manufacturing and technical workforce needs

A.8. Key Takeaway for Faculty

Faculty are already teaching what industry needs.

The intervention required is not new content but **naming**

- The kind of reasoning students are practicing
- How that reasoning transfers
- Competencies students can carry forward

Doing so strengthens the workforce pipeline **without compromising disciplinary rigor, autonomy, or academic intent**.