THE LEARNING FACTORY - A new approach to integrating design and manufacturing into engineering curricula

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Abstract

The **Learning Factory** integrates a practice-based curriculum and advanced manufacturing facilities. Its goal is to provide a new engineering educational experience that emphasizes the interdependency of design and manufacturing in a business environment. The Learning Factory offers a new approach to engineering education by providing balance between engineering science and practice. The key element in this approach is the combination of curriculum revitalization with coordinated opportunities for application and hands-on experience, thereby erasing the traditional boundaries between lecture and laboratory, academia and industrial practice. The Learning Factory is the product of the Manufacturing Engineering Education Partnership (MEEP). This partnership is a unique collaboration of three major universities with strong engineering programs (Penn State, University of Puerto Rico-Mayagüez, University of Washington), a premier high-technology government laboratory (Sandia National Laboratories), corporate partners covering a wide spectrum of U.S. Industries, and the federal government that is funding this project through the Technology Reinvestment Program (TRP). This paper describes our program and presents results from the first year of the partnership's existence.
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1. Introduction

The Need for Revitalizing Engineering Design Education: In order to understand engineering education today, it is informative to know something of its beginnings, and the continuous and sometimes cyclic evolution it has experienced over the past century. Lawrence Grayson provides an excellent history of engineering education in "The Making of an Engineer - An illustrated history of engineering education in the United States and Canada". A relevant excerpt follows:

The history of engineering education in the United States and Canada has been characterized by progressive tensions. During its early development, engineering educators were struggling for acceptability. The then traditional universities viewed engineering as too pragmatic and utilitarian for higher learning. The technical needs of the two nations required engineers with skills that often could be learned better through experience than through formal study. ... As the complexity of the technology increased, and the body of engineering knowledge became more codified, engineering education was more readily accepted as the basis for engineering practice and as an integral part of the university mission. Engineering became a full-fledged member of the education community with the passage of the Morrill Land Grant Act in 1862...
With acceptability, new tensions arose. There has been an ongoing debate over the appropriate balance between preparing graduates for immediate usefulness in the workplace and providing them with a more fundamental knowledge that would allow them to continue their education and be more useful in the long run...
After World War I, the demands of industry for graduates with immediate utility forced more and more specialization, and the number of engineering disciplines expanded rapidly. ... the laboratory became the place for teaching current industrial techniques. World War II helped swing the balance in the other direction. The war highlighted the shortcomings of engineering education, as people trained in physics were better suited to perform many of the tasks of new weapons development. Engineering education rapidly moved toward a much more fundamental approach, and in many cases the curricula became the study of engineering science. The movement toward science continued until recent problems in the competitive position of many American companies in global markets has shown the disadvantage of neglecting industrial applications. There once again is movement in the schools to reemphasize engineering practice, including manufacturing techniques, and concepts such as quality and reliability of the product. [1]

Taken in this historical perspective, the title of this paper - "A new approach to integrating design and manufacturing into engineering curricula" is not wholly accurate. This approach is not really "new", but is part of that movement to reemphasize engineering practice. While the content of curricula, as well as the balance between theory and practice has dramatically changed over the decades, the predominant delivery method in most engineering schools today - the lecture - is relatively unchanged from that of a century ago. Lecture is a time honored, efficient technique for delivering large quantities of analytical information. In recent years, new findings in cognitive processes[2 3] and behavioral psychology[4] have demonstrated the limits of lecture, and alternatives to augment its effectiveness have been proposed[5], including laboratories and cooperative learning.

Lectures encourage passivity in students, leading them to expect the instructor to provide all required knowledge. Lectures are geared toward the verbal learner, and do not take into account the varied learning styles of our students. Many engineers are in reality "visual learners", much better served by active, visual and tactile teaching methods[6]. Many students who have the intelligence and creativity to be excellent engineers find little fulfillment or stimulation in the rigid confines of the lecture hall, and drop out of formal engineering programs as a result. They do not see the relevance of their required courses to the actual practice of engineering. Too often these are promising minority or female students, to whom this lack of relevance and stimulation is sometimes "the straw that breaks the camel's back". Just as one cannot learn to drive without getting behind the wheel; or to swim without getting wet; entry into the profession of engineering, particularly in the area of design, requires far more than sitting in a lecture hall.

The National Science Foundation has recognized the deficiencies in engineering education and is providing impetus to change by sponsoring several major education initiatives and coalitions[7] including the partnership described in this paper.

A Short History of MEEP:

The Manufacturing Engineering Education Partnership (MEEP) consists of Penn State, The University of Puerto Rico- Mayagüez, the University of Washington, Sandia National Labs, and 36 industrial affiliates. The MEEP partnership owes its existence and its success to four factors:

1. Firm belief in the need for increased emphasis on practice in engineering education, particularly for engineering design
2. Ground breaking activities at Penn State and the University of Washington by the NSF ECSEL Coalition.[8]
3. The 1993 ARPA Technology Reinvestment Program (TRP) Solicitation
4. A common purpose and an unusual attitude of cooperation among the partners.

On July 15, 1994, MEEP received funding from the ARPA TRP to support a two year experiment. The goals and expectations of this experiment are the subject of this paper.

MEEP Objectives:

The specific objectives of our partnership are, to develop:

1) A practice-based engineering curriculum which balances analytical and theoretical knowledge with manufacturing, design, business realities, and professional skills;
2) Learning Factories at each partner institution, integrally coupled to the curriculum, for hands-on experience in design, manufacturing, and product realization;
3) Strong collaboration with industry;
4) Outreach to other academic institutions, government and industry.

The Partners:

The Manufacturing Engineering Education Partnership (MEEP) brings together three major universities with strong engineering programs (Penn State, University of Puerto Rico-Mayagüez, University of Washington), a premier high-technology government laboratory (Sandia National Laboratories) and corporate partners covering a wide spectrum of US. Industries. The partnership draws on the special strengths of each member and provides a unique opportunity to share physical and intellectual resources and explore diverse educational approaches. Students at these institutions come from a wide range of geographic, socio-economic and cultural backgrounds. Together, these schools graduated 2,384 B.S. engineering professionals in the 1992-1993 academic year, all with the potential for significant impact on our nation's industrial competitiveness.

Penn State (PSU) is a land grant university with over 38,000 students drawn primarily from the urban/industrial Northeast. The College of Engineering at Penn State, established in 1896, has a long tradition as one of the country's leading educators of engineers. Approximately one in fifty engineers in the United States with a bachelor's degree in engineering earned that degree from Penn State. As part of its land grant tradition, Penn State Engineering achieves a balance of engineering education, research and service activities, including:

- A graduate education and research program with an enrollment of more than 1,300 master's and doctoral degree students and an annual research expenditure of $33 million;
- vigorous partnerships with US. industry -- ranking second among American universities in industrially supported research and development activities;
- the first Industrial Engineering Department to be established in the US, and ranked among the top five programs nationally.

The ***University of Washington*** (UW) is the oldest and largest single campus on the West Coast. It is a large urban university dedicated to excellence in teaching and research that enrolls over 34,000 undergraduate and graduate students and has over 230 faculty members engaged in both teaching and research. The University's proximity to high technology firms in aerospace, biomedical processes, and electronics provides the partnership with unique opportunities for industrial interaction. The College of Engineering celebrated its centennial in 1994 and is the largest college of engineering in the Pacific Northwest.

The University of Puerto Rico - Mayagüez (UPRM) is primarily a teaching university set in a multicultural area with close ties to Central and South America and their emerging markets and industries. It is a land/sea/space grant institution established in 1911 as part of the University of Puerto Rico system. UPRM serves a population of approximately 10,000 in the Colleges of Agriculture, Arts and Sciences, Business and Engineering. Each year the college graduates about 550 engineering students and approximately 25% are women. UPRM is the largest institution in graduating Hispanic engineers in the US and is the premier institution in technological development in Puerto Rico, with strong ties to the manufacturing sector, in the electronics, pharmaceutical, food processing, chemical and textile industries.

Sandia National Laboratories is a multiprogram R&D laboratory of the United States Department of Energy, managed and operated by Martin Marietta Corporation. Established in 1949, Sandia's original mission was the weaponization of nuclear devices. In the intervening decades, other mandated responsibilities have included national security, energy and environment, technology transfer and industrial competitiveness. Each of these areas binds Sandia to the US. manufacturing industry. As the premier "engineering" laboratory of the DOE, Sandia uses it's R&D resources to support three major thrusts: Advanced Manufacturing Technologies, Advanced Information Technologies, and Electronics and Photonics. Sandia's role in MEEP is to provide advanced capabilities in rapid prototyping, precision manufacturing, virtual reality, and electronic outreach.

2. Combining Theory and Practice into One Curriculum

Our "new" curriculum is based on the direct linkage of theoretical studies with practice-based design and problem solving activities. **The Learning Factory**, in combination with the curriculum enables students to integrate design and manufacturing issues. Together, these developments will produce an engineer ready for the 21st century, with the following qualities:

- Strong foundation in engineering science fundamentals;
- Well versed in the big picture of manufacturing and product realization, including the design process and business realities;
- Knowledgeable of current technologies and tools, and most importantly, their management and application to solve new problems;
- An effective team player;
- Adept at communication (oral, written, electronic); and
- Equipped and motivated for future learning.

This interdisciplinary curriculum will be available as a minor or a degree option at the participating schools. Several departments at each school are cooperating in this development, including: Mechanical, Industrial, Chemical, Electrical Engineering and Business. The curriculum, as shown in Figure 1, consists of a progression of manufacturing/design courses, approximately one per term, and allows students to practice engineering science fundamentals in the solution of real problems.

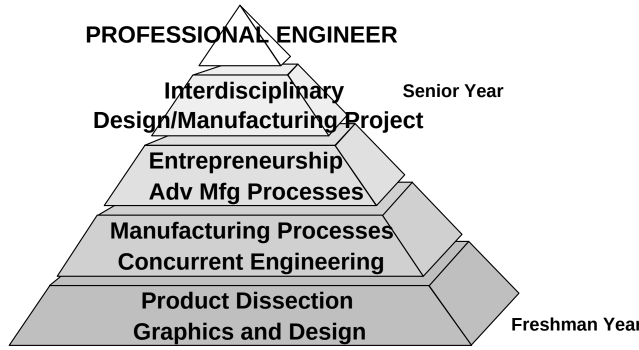

Figure 1. The courses in the Learning Factory option build a firm foundation for a productive engineering career in manufacturing, design, and product realization

This curriculum makes extensive use of case studies, active learning techniques, and computer technologies in the classroom, and provides previously unavailable opportunities for hands-on engineering experience in the Learning Factory. As part of the new curriculum, several new courses are in development across the partnership. As the Learning Factory develops and its benefits are demonstrated, other courses will naturally begin to use its facilities. The courses currently being developed by MEEP are:

Product Dissection: This course examines the way in which products and machines work: their physical operation, the manner in which they are constructed, and the design and societal considerations that determine the difference between success and failure in the marketplace. Students, working in interdisciplinary teams, will dissect several common products to discover their internal functions and to critique their design, manufacturing methods, materials selection and disposability.

Concurrent Engineering: This course presents the origin and meaning of the term *concurrent engineering* and discusses its role in modern engineering companies. The effect of concurrent engineering practices on other product life cycle issues such as safety, reliability, maintainability and product disposal are examined. Additionally, case studies from various industries are presented and speakers from local industries present a practical perspective.

Entrepreneurship: This course, developed in conjunction with the Business School, focuses on the process of starting, financing and managing a new business. It also focuses on the management of existing enterprises and includes such topics as risk, product/markets, objectives and goals, business plans, control, staffing and financing.

Process Quality Engineering: This course exposes students to the importance of statistical and probabilistic methods in the current TQM culture. Students learn to apply probability models and statistical tools to engineering problems. The course provides a laboratory experience, where students design their own experiments, collect data, and apply appropriate statistical analysis tools to that data.

Interdisciplinary Senior Design Project: This capstone course provides students with the opportunity to practice the design of products, processes and enterprises from conceptualization to actualization. Students collaborate with partners at other MEEP schools and work in interdisciplinary teams on open-ended hardware-oriented projects provided by industry. This project activity ideally spans a full academic year.

The educational objectives of our curriculum, i.e. the desired skills which we want our students to develop, are listed in Table 1 as well as their level of integration into the MEEP courses.

Table 1. Distribution of Skills and Knowledge Through New Courses

CURRICULUM THEMES	Product Dissection	Concurrent Engineering	Entrepreneurship	Quality
Engineering Science Fundamentals	P	P	P	P
Design/Synthesis	B	B	B	B
Probability Methods	N/A	N/A	N/A	A
Materials (Selection, Non-Traditional)	B	P	P	O
Creativity	B		O	O
Manufacturing Processes	O	P	P	O
Communication Skills	B	A	A	B
Team Skills	B	A	A	A
Problem Solving Skills	B		P	B
Total Quality	N/A	A	A	B
Business Concerns	O	B	B	O
Project Management	O	A	A	N/A
Cross-Disciplinary Industrial Projects	N/A	A	A	O
Analysis	B	O	O	A
Self Awareness, Awareness of Others and Environment	B	A	A	N/A
Integration of Product/Process	B	A	A	O

Legend:
- O Overview
- B Basic
- A Advanced
- P Prerequisite
- N/A Not Applicable

Modular, Electronic Curriculum

Curriculum and laboratory development are time consuming and costly processes. The partners are dedicated to the philosophy that sharing of resources and ideas, avoiding redundant efforts, utilization of new technologies for communication, and achieving consensus on curriculum content are critically important. Our mission is to jointly develop curriculum materials that are easily transportable and utilized among the MEEP partners, and exportable to the academic community at large. Ultimately, all course materials will be available on Internet over the World Wide Web.

Each curriculum module will be developed using the same basic eleven part template:

1. Laboratory Worksheet
2. Instructor's Guide
3. Lab Preparation Assignment Handout for Students
4. Associated Lecture Notes
5. Reading Assignments
6. Homework Assignments and Solutions
7. Reference List
8. "To Explore Further" Section
9. Videotape of a Typical Session (where possible)
10. Assessment Tools for the Student and Course Evaluation
11. Expected Outcomes (student abilities) from this Module

Course Development Process

Course development consists of a four part process:

1) Planning - coordinators from each school agree on overall course objectives and content and how that course fits into the balance of the curriculum
2) Piloting - one school takes the lead role in developing the course specifics and offering it on a trial basis
3) Publication - The piloting school makes all course materials available in electronic format (preferably over the Internet) for use by other schools.
4) Deployment - The remaining schools apply the course materials and offer the courses, making whatever modifications are necessary to satisfy unique institutional requirements.

The development process is shared over the partnership as shown in Table 2.

Table 2. Sharing of curriculum development efforts across the MEEP partnership

Course	Piloting Institution	Pilot Offering	Offering across MEEP	Export
Product Dissection	Penn State	August 94	Fall 95	Summer 96
Concurrent Engineering	Washington	September 94	Fall 95	Summer 96
Entrepreneurship	Puerto Rico	January 95	Fall 95	Summer 96
Process Quality Engineering	Penn State	January 95	Fall 95	Summer 96

3. The Integrated Learning Factory

Physical facilities for manufacturing and product realization, located at each partner institution, are the cornerstone of our efforts. Across our coalition, over 14,000 square feet of new and remodeled facilities, equipped with state-of-the-art equipment, are being devoted to this activity. The basic principle of the Learning Factory is integration — integration of design and manufacturing experiences into the undergraduate curriculum; integration of equipment and materials into manufacturing systems; and integration of people from several engineering and business disciplines into effective teams that design and produce products and processes.

The Learning Factory differs from the traditional, highly focused, disciplinary labs that are tied to specific courses. As illustrated in Figure 3, the Learning Factory is the focal point of the product and process realization activities in design and manufacturing and draws on the specialized resources of the disciplinary labs where appropriate to support the courses. It is “dynamic” or agile, in that the student activities define its use and structure. For instance, the Product Dissection course uses Learning Factory facilities (model shop, design studio, CAD/CAM, Metrology, Manufacturing Processes) as well as disciplinary labs (Electronics, Computing, Materials and Mechanics, Composites Processing).

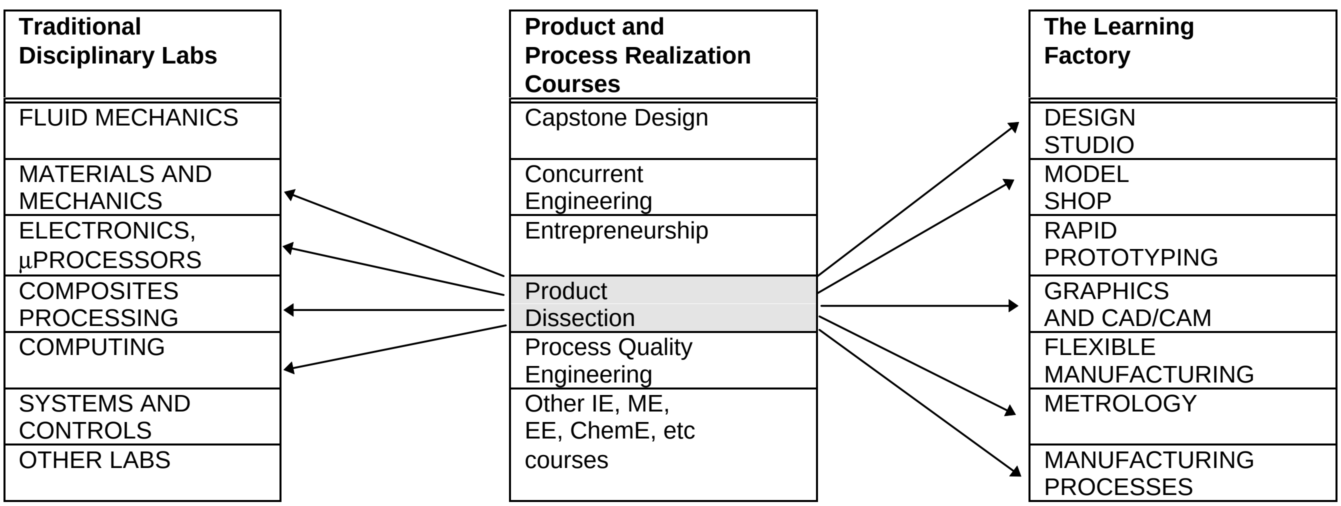

Figure 3. Relationship between Learning Factory, Product Realization Curriculum, and Traditional Laboratories

In the Learning Factory, students actively experience the product realization process in its entirety, from design concept to finished hardware. Our vision is a facility where students continually seek to implement their ideas, hone their skills and practice engineering in an environment similar to an industrial setting. We seek an experience where every semester (or quarter), students participate in a course that uses the Learning Factory as an integral part of its syllabus. For example, in the freshman year, students in Product Dissection benchmark products, document designs using CAD equipment, perform measurements, critique manufacturing and design decisions and use prototyping facilities to implement their ideas for product improvement. Sophomores and Juniors are likely to be found honing their basic manufacturing process skills, and directly experiencing the interdependency of design and manufacturing covered in Concurrent Engineering.

Seniors in the design projects class work in cross-disciplinary product teams on a wide variety of projects requiring the use of advanced design and manufacturing concepts and facilities. The needs of our industrial affiliates are a prime source of these projects. Other projects may revolve around student design competitions sponsored by the various professional societies, or student inventions resulting from the entrepreneurship class or independent studies. Typical activities in the Learning Factory are illustrated in Figure 4. Also shown is an example of the layout of a typical Learning Factory (the 3,500 square feet PSU facility).

4. Industrial Partnership

Industrial involvement is essential for ensuring that these efforts result in a fully integrated, practice-based approach to engineering education that is beneficial both to students and to their future employers. Feedback from industry keeps attention focused on the necessary skills and knowledge base that students require, and how these elements should be integrated into the academic experience.

Students will work at the university or industrial sites in cross-disciplinary teams on real-world problems. Industry-supplied projects provide these problems, and in the process, help shape the careers of a new generation of professional engineers. Industry partners directly benefit from this partnership by:

- Availability of well-prepared engineering graduates who understand the product realization process;
- Opportunities to evaluate potential employees through internships, collaborative projects and classroom interactions;
- Direct assistance in product and process design problems through sponsorship of senior design projects;
- Professional development of industry personnel through teaching, learning factory and curriculum development;
- Technology transfer through Industrial-Academic exchanges - industry engineers in the classroom, and faculty internships in industry; and the
- Opportunity to influence and improve the education of engineers well into the next century.

The members of our industrial partnership span the spectrum from large multi-national corporations to small family-owned businesses. Represented industries include aerospace, automotive, electronics, pharmaceuticals, chemicals, computers, machine tools and consumer products. Each member brings with it a unique perspective and a valuable contribution. These members form the project's Industrial Advisory Committee and meet quarterly to critique the progress of the Learning Factory and offer strategic guidance. The current industrial affiliates of this project are:

Table 3. Industrial Partners of MEEP

Allegheny Valve	AMP	AT&T
Baxter	Bently Systems	Boeing
D/E Associates	DEC	DuPont
ELDEC	ExtrudeHone	Fluke
Foundry Education Foundation	General Electric	General Motors
Hewlett Packard	IBM	Industrial Modernization Center (PA)
JLG Industries	K2	Kennemetal
Kodak	Motorola	Muncy Machine Tool
Murata Electronics	New Holland	PACCAR
Precision Components	Proctor and Gamble	Rolodex
Stryker/Arroyo	Techno-Plastics	Telecomm Solutions
Textron Lycoming	Washington Technology Center	Westinghouse

These partners contribute in several critical ways, providing physical and personnel resources including:

- Manufacturing/design student projects
- Engineers in the classroom
- Opportunities for faculty experiences in industry
- Donations and loans of equipment
- Direct financial support
- Summer student internships
- Expertise to develop Learning Factory
- Tours of industrial facilities for students and faculty
- Case histories
- Advice and feedback on MEEP activities

5. Outreach

The MEEP partnership is dedicated to changing engineering education and ensuring that the benefits of those changes are available to all students. Our approach will attract outstanding students who wish to supplement the traditional lecture environment with real-world experiences in the Learning Factory. The approach will also help retain those students who are not stimulated by the traditional lecture environment, but who have the intellectual and creative abilities to become exceptional engineers. The partnership will develop virtual manufacturing facilities and will provide electronic access to these extensive and capital intensive facilities from remote locations, including those that serve historically under-represented groups. Our curriculum materials will be modular, transportable and available to the academic community at large. Extensive use will be made of electronic techniques for communication and curriculum export, such as satellite transmission, multi-media computer tools, the National Information Infrastructure, and video conferencing.

6. Summary

A unique partnership of universities, industries, and the federal government has been formed to revitalize design and manufacturing engineering education. This partnership is developing an integrated curriculum and physical facilities for product realization at each university, with the full cooperation and assistance of 36 industrial partners. The primary products and benefits of this coalition to students, industry and faculty will be:

- Superior engineering graduates who are well prepared to impact overall business productivity;
- A new paradigm for engineering education based on a balance among analysis, design, processing and integration;
- Model practice-oriented engineering education curriculum elements, packaged as tested teaching modules;
- Greater prestige for manufacturing and design education in university curricula;
- Opportunities for students, faculty and engineers to exchange location, technology, ideas and products across a wide geographic and cultural spectrum.

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