Educational Needs and Opportunities in Additive Manufacturing: Summary and Recommendations from a NSF Workshop

Additive Manufacturing Education & Training

Final Workshop Report

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We are grateful to our sponsors who made this workshop possible:

![NSF Logo](image)

![America Makes Logo](image)

Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Workshop Summary

Additive Manufacturing (AM) is leading the rebirth of advanced manufacturing in the United States. While enthusiasm for AM has grown substantially recently, widespread use and industrial adoption of AM for production of end-use products has been tempered. Numerous workshops have been held to address AM’s technical challenges and research needs, but none have focused on the knowledge gaps and educational needs for the AM engineering workforce. Consequently, we held a 1.5-day workshop at the National Science Foundation (NSF) in Arlington, VA on April 10-11, 2014 to discuss the educational needs and opportunities in AM. The 66 participants spanned a variety of industries and OEMs as well as academic institutions, government labs, federal agencies, and non-profit organizations. The overall goal of the workshop was to identify (i) what should be taught to AM practitioners, (ii) the means by which it should be taught, and (iii) opportunities for novel partnerships for enhancing the AM workforce.

To help identify what should be taught to AM students and practitioners, seven invited speakers from industry shared their thoughts on the “ideal AM engineer.” Participants then engaged in small group discussions to identify topics and skillsets that are critical for educating the AM workforce. Five key themes emerged: (1) AM processes and process/material relationships, (2) engineering fundamentals with an emphasis on materials science and manufacturing, (3) professional skills for problem solving and critical thinking, (4) design practices and tools that leverage the design freedom enabled by AM, and (5) cross-functional teaming and ideation techniques to nurture creativity. All of the speakers’ slides can be found on the workshop website: http://www.enge.vt.edu/nsfamed/.

Eight invited speakers from universities and community colleges shared their “best educational practices” for teaching and using AM in the classroom, and nine invited speakers discussed national efforts and funding opportunities for AM education and training. Participants were then divided into small workgroups and tasked with developing concepts for novel partnerships for AM education. The resulting concepts included: (1) a lifelong “AM training pyramid” spanning K-12 through R&D that combines AM skill and knowledge acquisition with AM incubators and design competitions to grow and nurture AM communities; (2) a national network for AM education that leverages and expands NSF’s successful ATE programs; (3) a MAKE-brary initiative that seeks to create maker spaces in every community, (4) open source educational resources for AM; (4) after-hours AM training programs for incumbent workers and awareness programs for their families; (5) AM courses and curricula for K-5, middle school, high school, community colleges, and universities with cross-linkages across all levels; and (6) a series of small grant initiatives for initiating new AM educational partnerships, “Engineering Experiences for Undergraduates” programs, and student exchanges.

Based on these discussions, we offer the following recommendations to advance the AM workforce:

1. Ensure that AM curricula provide students with an understanding of (i) AM and traditional manufacturing processes to enable them to effectively select the appropriate process for product realization; (ii) the relationships between AM processes and material properties; and (iii) “Design for AM”, including computational tools for AM design as well as frameworks for process selection, costing, and solution generation that take advantage of AM capabilities.

2. Establishment of a national network for AM education that, by leveraging existing “distributed” educational models and NSF’s ATE Programs, provides open source resources as well as packaged activities, courses, and curricula for all educational levels (K-Gray).

3. Promote K-12 educational programs in STEAM (STEM plus the arts) and across all formal and informal learning environments in order to leverage the unique capabilities of AM in engaging students in hands-on, tactile, and visual learning activities.

4. Provide support for collaborative and community-oriented maker spaces that promote awareness of AM among the public and provide AM training programs for incumbent workers and students seeking alternative pathways to gain AM knowledge and experience.

Recommendations for scaling and coordinating these activities across local, regional, and national levels are also discussed to create synergies among the proposed activities and existing efforts.
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1. Motivation for the Workshop

Additive Manufacturing (AM), which began in the 1980s as a novel technology to assist rapid design prototyping, is leading the rebirth of advanced manufacturing in the United States. The hype and promise for AM has been driven as much by technological advances (e.g., the ability to manufacture fully-dense metal parts for production) as by the commodification of existing AM technologies (e.g., desktop-scale 3D printers). Many of these AM and 3D printing (3DP) advances lie on opposite ends of the Technology Readiness Scale, yet together they are generating unprecedented interest in this decades-old technology.

America Makes, the National Additive Manufacturing Innovation Institute (NAMII), is forging a national network to accelerate development and adoption of AM and 3DP technologies and increase our nation’s global manufacturing competitiveness\(^\text{1}\). Meanwhile, AM and 3DP systems are evolving rapidly, driven as much by government-funded research and industry investment as it is by new models for open innovation (e.g., \([\text{1}]\)) and sources for crowd-funding (e.g., Kickstarter campaigns for new 3D printers\(^\text{2}\)). Mergers and acquisitions are fueling industry growth and driving stock prices to unprecedented levels \([\text{2}]\), and the Maker Movement \([\text{3}]\) and open source 3DP efforts \([\text{4}]\) are creating a groundswell of interest in many fields of engineering, material science, and related technical areas. Moreover, the annual Wohlers Report \([\text{5}]\) and popular press articles (e.g., Wired\(^{\text{3}}\), Economist\(^{\text{4}}\)) are increasing awareness among the general public positively (e.g., low-cost 3D printed prosthetics\(^{\text{5}}\)) and negatively (e.g., 3D printed gun\(^{\text{6}}\)).

While enthusiasm for AM has grown substantially recently, widespread industrial adoption of AM for production of end-use products has been tempered. We attribute this sluggish adoption rate to (i) a lack of metrology and production standards for AM, (ii) ever-evolving technologies and materials, and (iii) the engineering workforce’s overall limited knowledge of the capabilities of AM technologies and how to appropriately design, communicate, and qualify products for them \([\text{6}]\). To address these issues, the Society of Manufacturing Engineering (SME) has defined a body of knowledge for AM and corresponding certification\(^{\text{7}}\) and is partnering with companies like 3D Systems to provide technical education and training\(^{\text{8}}\). Meanwhile, America Makes has partnered with Deloitte to create an online AM course for business leaders\(^{\text{9}}\) and is working with ASME to host their new Federal Fellowship in Advanced Manufacturing\(^{\text{10}}\).

Numerous workshops have been held in the past year to address AM’s critical research and technical challenges\(^{\text{11,12,13}}\). Specifically, these workshops have focused on (i) assisting newcomers in becoming familiar with the technology, (ii) presenting research opportunities to

\(^{1}\) \url{http://www.americamakes.us/}
\(^{3}\) \url{http://www.wired.com/design/2012/09/how-makerbots-replicator2-will-launch-era-of-desktop-manufacturing/}
\(^{6}\) \url{http://www.forbes.com/pictures/mh45ediiht/the-liberator/}
\(^{7}\) \url{http://www.sme.org/fam-certificate-program/}
\(^{8}\) \url{http://www.sme.org/MEMagazine/Article.aspx?id=81046&taxid=1459}
\(^{9}\) \url{http://dupress.com/articles/3d-opportunity-additive-manufacturing-course/}
\(^{10}\) \url{https://www.asme.org/about-asme/get-involved/advocacy-government-relations/federal-fellows-program/asme-advanced-manufacturing-fellowship}
\(^{11}\) \url{http://nsfam.mae.ufl.edu/}
\(^{12}\) \url{http://camal.ncsu.edu/research/ise-symposium-presentations/}
\(^{13}\) \url{http://advancedmanufacturing2013.northwestern.edu/}
those communities that have yet to interface with AM, and/or (iii) presenting updates on the
dynamically changing technologies. To date, none of these workshops have convened experts
from industry, academia, non-profit organizations, and government agencies to discuss the
specific educational needs and opportunities—and corresponding partnerships—for the AM
workforce. Advancing the understanding, utilization, and adoption of AM and 3DP will require
an interdisciplinary workforce that has the knowledgebase for synthesizing new materials,
integrating advanced process controls, establishing quality control standards, and formulating
new design and communication methodologies. The knowledge, skills, and abilities necessary
to work effectively with this AM technologies are not well understood—and are changing
quickly—given how rapidly the field is evolving.

The need to educate future design and manufacturing engineers was a core focus of the 2009
Roadmap for Additive Manufacturing [6,7], as unfamiliarity with AM technologies is a significant
hurdle for industrial adoption. The roadmap urges the development of university courses and
“programs for educating the general population to enhance the interest in AM applications and
generate some societal ‘pull’ for the technologies” [6]. Fundamentally, to realize the full
potential of AM, engineers must (i) fully understand AM technologies and AM materials, (ii)
know how to design products for fabrication via AM, (iii) be able to synthesize AM’s economic
and environmental impacts on a manufacturing value chain, and (iv) understand how to
effectively communicate and ultimately qualify AM parts. While some AM courses at the
undergraduate and graduate levels do exist (see, e.g., [8,9]), their limited quantity does not
match the recent interest in, and national importance of, AM technology. Recent textbooks on
AM (e.g., [10,11]) will satisfy some of this interest, but providing scalable hands-on experiences
to train thousands of students and incumbent workers is a challenge.

2. Overview of the Workshop

While there is clearly a need to educate a workforce that is capable of intelligently employing
AM technologies, the means for appropriately addressing this gap are not well defined. As
educators, what should we be teaching students about additive manufacturing? What do
graduate students need to know versus undergraduates? What technical training should be
offered at community colleges? What types of AM-related skills are needed in industry? How
best to capture and integrate the interdisciplinary knowledge needed to take full advantage of all
of AM’s capabilities? There are unlimited opportunities given the promise of AM, but what are
the real needs and subsequently, what are the knowledge, skills, and abilities that we should be
teaching our students to work in this rapidly changing environment?

To address these issues, we organized a 1.5-day workshop at the National Science Foundation
(NSF) in Arlington, VA on April 10-11, 2014. The objective of the workshop was to bring
together participants from academia, industry, and government agencies to actively engage in
discussions related to, and develop efforts for, enhancing the AM workforce through new and
novel educational and training partnerships. Specifically, workshop participants were asked:

1. What do we need to teach the AM workforce and why do we need to teach it?
2. Who is in the AM workforce – and what is their role in the AM workforce?
3. Where and how should the AM workforce be taught – and when?

Dr. Simpson and Dr. Williams co-organized the workshop and formed a Steering Committee to
help define the agenda and solicit speakers and participants to address these questions. The
following individuals participated on the Steering Committee, offering varying perspectives from
industry, academia, government agencies, and non-profit organizations involved with AM:
Working with the Steering Committee, workshop participants were solicited from a variety of sources and communities involved with AM education, research, and training. We compiled a list of approximately 150 possible participants for the workshop, which were emailed with an invitation to register for the workshop. A follow-up email invitation was sent two weeks later, and we actively recruited participants and speakers up to the week before the workshop using email and personal contacts. A total of 66 people attended the workshop: 27 from universities, 9 from community colleges, 19 from industry, and 11 people from government and non-profit agencies—see Appendix A for a complete list of participants and their affiliations.

The agenda for the workshop (see Appendix B) was structured around working group sessions that divided participants into small groups and tasked them with answering key questions for enhancing the AM workforce. Invited speakers presented brief “lightning” talks prior to each working group session to provide context to the discussions. Three working group sessions occurred over the course of the 1.5 day workshop.

i. **Working Group #1: What should we teach to the AM workforce and why?** Before tackling this question, invited speakers from industry discussed their AM workforce needs. Their presentations were framed around the question, “What are the characteristics of an ideal AM engineer?” to identify the “customer needs” for the future AM workforce. The working groups then elaborated on the knowledge and skills for the AM workforce and discussed the necessary concepts that an AM educational program should cover.

ii. **Working Group #2: To whom, where, and how should we teach AM?** The second day of the workshop began with a series of invited speakers from universities and community colleges who shared their “best AM educational practices”. This gave the participants insight into new ways to teach and use AM before they broke into their working groups to generate ideas for novel AM educational approaches.

iii. **Working Group #3: How should we partner for AM education and training?** To help the group identify means of implementing broad reaching educational programs, several speakers from government agencies and related organizations discussed national efforts and funding opportunities for AM education and training. Working groups were then formed, and participants were challenged with generating concepts for a novel, scalable AM workforce education and training programs.

The remainder of this report summarizes the speaker presentations and the results and recommendations of the small group discussions and working groups. All of the speakers’ slides can be found on the workshop website: [http://www.enge.vt.edu/nsfamed/](http://www.enge.vt.edu/nsfamed/).

### 3. Summary of Invited Speakers at the Workshop

We invited a total of 25 speakers to give presentations and “lightning talks” at the workshop. Mr. Ed Morris, Director of America Makes/NAMII kicked off the workshop by summarizing the national interest and investment in Additive Manufacturing (AM). He highlighted AM’s ability to effectively democratize manufacturing and to enable a new generation of entrepreneurs. Given this opportunity, Mr. Morris stressed the importance of educating the future workforce at all levels: public and K-12 (general awareness), workforce (non-degree through graduate), and
advanced AM research and education, especially since many other nations (e.g., Singapore, China, Taiwan, South Korea [12]) are investing significantly in these same areas.

Seven speakers then shared their perspectives on industry’s needs for AM education and training and outlined the characteristics of the “ideal AM engineer”. Section 3.1 provides a summary of these industry-focused presentations, and Section 3.2 summarizes the small group discussions that followed. After soliciting input from 20 participants prior to the workshop, eight speakers were selected to share their “best practices” for educating the AM workforce. These presentations are reviewed in Section 3.3. Finally, nine speakers were invited to discuss related national efforts and funding opportunities that might be leveraged for AM education. Section 3.4 summarizes highlights from these presentations, which set the stage for the novel partnerships outlined in Section 4 based on the small group discussions.

3.1. Industry Speakers: What Does the Ideal AM Engineer Need to Know?
Mr. Perry Morissette, the leader of the 3D Rapid Prototyping Capability Center (3DRPCC) at Boeing – Vertical Lift, started the industry session by sharing insight into Boeing’s use of AM, which includes visual aids, prototypes, shop-aids, parts to evaluate fit-check, parts for functional testing, and finally, “fly away” parts. He suggested that AM adoption is currently hampered by limited knowledge and access to AM technology. To address this, he presented three levels of AM workforce education and training: (i) general AM training, (ii) engineer, and (iii) equipment technician. The characteristics of each of these levels are presented in Figure 1 from his talk.

![Workforce Education and Training](image)

**Figure 1. Examples of Boeing’s AM workforce education needs (Source: P. Morissette)**

Mr. Morissette closed his talk with his vision for the “ideal AM engineer”, i.e., a person who (i) is excited about AM and seeks opportunities for educating and promoting AM, (ii) understands that “complexity is free” in AM, (iii) forgets the constraints of conventional fabrication and assembly,
and (iv) uses systems engineering, design of experiments, and root cause and corrective action (RCCA) methodologies in their projects. He also ended with a quote from one of his engineers stating that “AM will become less of a nicety and more of a necessity”, which captured where many felt AM is heading in the very near future.

Mr. Jay Beversdorf spoke on behalf of Stratasys—a large additive manufacturing OEM (Original Equipment Manufacturer). He shared insight into how Stratasys customers use AM to create jigs and fixtures, tooling, and end-use parts (see Figure 2). He then presented his perceived barriers to AM adoption, which include:

- **Poor understanding of AM capabilities**: Practicing engineers’ poor understanding of AM cause them to either immediately reject, or alternatively oversell, AM technologies. They are generally unfamiliar with AM application opportunities and do not understand AM “basics” (part orientation, material selection, etc.). This tends to lead to an ineffective use of AM, which can hinder future adoption.

- **AM not considered early on in product development**: Due to a perceived resistance to adopt new manufacturing technologies, AM is not well integrated into the product design cycle. As such, the resultant products are not designed for the full capability of AM.

To address these barriers, he suggested that an AM curriculum should provide students an understanding of traditional manufacturing processes as well as the fundamentals of AM. He stressed the importance of teaching students how to design parts for AM and using AM to solve engineering problems. He also offered that in addition to this knowledge, the ideal AM engineer would embrace innovation and be willing to try new opportunities and ideas.

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**Examples of Advanced AM Uses**

- **Jigs and Fixtures**
  - Inspection fixtures
  - Assembly fixtures
  - Nesting fixtures
  - Transportation
  - 5-S organizers

- **Tooling**
  - Silicone Molding
  - Vacuum Forming
  - Sand Casting
  - Lay-up Tooling
  - Injection Molding
  - Blow Molding
  - Sheet Metal Forming

- **End Use Parts**
  - End of arm tooling
  - Low volume production
  - Prosthetics
  - Customized Products

*Figure 2. Examples of AM uses by Stratasys’s customers (Source: J. Beversdorf)*
Dr. Shawn Kelly, the Director of the Additive Manufacturing Consortium at EWI, formerly Edison Welding Institute, stated that the technical barriers to AM adoption include insufficient quality, lack of qualification and certification approaches, lack of AM-specific design considerations, and material science issues. Poor understanding of AM process limitations and an overall lack of AM training are additional barriers. Even though AM provides considerable design freedom compared to existing manufacturing processes, he stressed that downstream considerations (e.g., inspection, certification, quality control, material properties) warrant a more “holistic view of AM” (see Figure 3). Given his expertise in laser-based AM processes, he stressed the need for an enhanced knowledgebase of welding metallurgy, materials science, and heat transfer (and related material distortion). He stated that the ideal AM engineer not only understands the AM manufacturing chain and process capabilities, but also understands materials science and metallurgy, how the process affects the material quality and properties, and engineering design.

Figure 3. A “Holistic view of AM” topics (Source: S. Kelly)

Mr. Philip Lane presented on behalf of ExOne and shared the OEM’s needs for future AM engineers. He expressed a need for an AM workforce that featured materials science researchers, engineers for part design and analysis, and technicians for post-processing, part testing, printing, and part inspection, verification and validation. The specific needs for each of these positions is presented in Figure 4 from his talk. Mr. Lane stressed that the ideal AM engineer understands and takes advantage of the relationships between materials, part design, and the selected AM process.
Mr. Bill Flite, Senior Manager for Advanced Manufacturing at Lockheed Martin, highlighted some of the company’s advanced uses of AM, which include titanium fuel tanks for spacecraft. In addition to an overall lack of ubiquitous knowledge and awareness of AM technologies, Mr. Flite suggested that barriers to AM implementation include a lack of closed-loop process control, insufficient material design allowables, and lack of aerospace-qualified materials and processes. He stressed that “Design for AM” techniques, which include design and analysis guides and methods for selecting (and costing) appropriate AM technologies, need to be prominent in future AM curricula. He also suggested that, in addition to training the future workforce, we re-train and re-educate both experienced engineers and shop-floor technicians in how to design for, and support, AM. For Lockheed Martin, the “basic” knowledge required to be an AM engineer lies in the topics of design for manufacturing, CAD, and AM process basics. Advanced skills include polymer chemistry, metallurgy, and topology optimization. In addition to these skills, the ideal AM engineer would have a “maker” mentality and see value in iterative design.

Mr. Andrew Lucibello, the East Area Sales Manager for EOS, discussed the OEM’s customers’ use of AM in this talk. Their customers use both EOS’s polymer and metal AM systems in their applications, which entail medical applications including dental, orthopedic devices, and surgical implants as well as aerospace applications involving jet engine fuel injection systems, air ducts for plane cabins, and unmanned air vehicles (see Figure 5). He shared that their worldwide installed base is about 1600 systems (1/3 metal, 2/3 polymer), with the majority (67%) installed in Europe (versus 15% in North America and 18% in the Asia-Pacific region). Mr. Lucibello drew from these examples to inform the audience that the future AM engineering workforce needs to be made aware of the expanded possibilities AM offers to its users including expanded design freedom, enhanced productivity (via rapid prototyping), reduced cost (via integrated functionality and assembly reduction), and product customization.
Dr. Ola Harrysson, an Associate Professor and Fitts Fellow in Biomedical Manufacturing at North Carolina State University, presented on behalf of Arcam, an OEM that produces Electron Beam Melting (EBM) equipment. In addition to the current technical limitations of absence of adequate part validation, insufficient understanding of material properties, and overall high costs, Dr. Harrysson also stated that the need for engineers and technicians with sufficient AM skills were barriers to AM adoption. Dr. Harrysson delineated educational requirements for four AM-related careers:

- **Machine operators**: Their task is to operate the machine and post-process the resultant parts. Operators would require a technical degree that would be focused primarily in customer interactions and providing extensive experience with the machine.

- **Application engineers**: Application engineers work with customers to enhance their use of AM for their specific application. This position would require a M.S. degree and would provide the engineer with a good understanding of technical skills, materials knowledge, and the necessary software tools (e.g., CAD, file preparation, and build preparation).

- **Service technicians**: Their task is to service the machine, which can include tasks such as repair and software and equipment upgrades. This position would require a BS in engineering, which would provide them knowledge of the necessary software tools for the AM build cycle (e.g., CAD, file preparation, and build preparation).

- **Research & Development**: This position is tasked with enhancing the overall AM process and material portfolio. This would most likely require a Ph.D. in various fields of engineering and science.

Dr. Harrysson closed his talk by suggesting that the ideal AM engineer would be a well-rounded engineer that had good technical skills and a good understanding of material behavior—and was meticulous and very safety conscious.
The invited industry speakers represented a range of OEMs and end users (i.e., customers). Despite their different contexts, many similar themes existed across their presentations. To synthesize these themes, we created a Wordle based on the text in their slides. The resulting word cloud, which displays words that appeared more frequently with greater prominence in the graphic, is presented in Figure 6. As can be seen in the figure, speaker topics in design, engineering, process, manufacturing, technologies, and materials appeared repeatedly in the presentations, providing a common point for the small group discussions that followed.

3.2. Working Group #1: What Should We Teach the AM Workforce and Why?
Using the industry speakers’ presentations as a foundation, participants were asked to respond to the following question: “What should we teach to the AM workforce, and why?” Specifically, participants were tasked with identifying a list of topics that were relevant to an AM curriculum. Participants were strategically placed into small groups of 6-8 people to ensure that each group had representation from industry, academia, and the government (see Appendix C). The participants worked in their groups to ideate relevant topics and create a mind map (see Figure 7) using any combination of small and large Post-It® notes. They were encouraged to identify specific topics and skill-sets across all levels and domains.
The resulting mind maps—created by mapping clusters of individual topics together on large pieces of paper as seen in Figure 8—were then posted on walls around the room for sharing via a “gallery” viewing. This approach gave each participant an opportunity to offer their input, observe their colleagues’ thoughts, and engage in discussion and reflection about the presented ideas; it also helped document each participant’s thoughts on AM curriculum content.

Following the small group discussions, we surveyed and tallied all of the items on each of the group’s mind maps to identify reoccurring topics and themes. The result of this synthesis is summarized in Table 1. The participants’ suggested topics are listed along with a count of the frequency that each topic was listed across all of the mind maps.

As seen in Table 1, all of the individual topics can be broadly grouped into five key themes (listed in order of highest frequency count, which is indicated in parentheses):

- **Additive Manufacturing** (96): Participants placed significant importance on educating students on the basics of all AM processes and the AM process/materials relationships so that they may be able to effectively select AM processes for a variety of applications.
- **Engineering Fundamentals** (59): Several participants expressed a need to continue to educate students in the fundamentals of engineering analysis, but with added emphasis on material science (to be able to better understand process/material interactions) and on manufacturing technologies (to be able to better select amongst traditional and additive manufacturing processes).
- **Professional Skills** (45): Participants expressed a need to educate students in problem solving and critical thinking skills so as to enable them to better address the needs of this advanced manufacturing technology. In addition, participants suggested that future AM curricula include content related to entrepreneurship and technology transfer.
- **Design** (44): Recognizing that AM significantly reduces the design constraints that are typically imposed by conventional manufacturing technologies, several participants...
stressed the need for integrating design into the curriculum. Many participants stressed the need for advancing students’ understanding of CAD, FEA, and topology optimization software, as well as the overall design process.

- **Creative Skills** (12): Related to design education, many participants suggested that opportunities for nurturing students’ creativity be included in a curriculum by teaching creativity techniques and by integrating industrial design content.

<table>
<thead>
<tr>
<th>Table 1. Summary of AM topics and frequency of appearance on participants’ mind maps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Topic</strong></td>
</tr>
<tr>
<td>Terms, processes &amp; technologies, pros &amp; cons</td>
</tr>
<tr>
<td>Business considerations: supply Chain, economics, lifecycle analysis &amp; sustainability</td>
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<tr>
<td>Design for AM; File formats</td>
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<tr>
<td>AM Materials &amp; Material-Process relationships</td>
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<tr>
<td>Knowledge about applications, successes &amp; careers</td>
</tr>
<tr>
<td>Material science; computational mechanics; metallurgy; material selection; polymer chemistry</td>
</tr>
<tr>
<td>Manufacturing technologies: overview of traditional processes (machining), nano</td>
</tr>
<tr>
<td>Metrology, Quality Control, Testing and inspection, Verification &amp; validation</td>
</tr>
<tr>
<td>Engineering modeling, analysis, &amp; statistics</td>
</tr>
<tr>
<td>Systems thinking</td>
</tr>
<tr>
<td>Math</td>
</tr>
<tr>
<td>Vocational / hands-on skills</td>
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<tr>
<td>Mechatronics</td>
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<tr>
<td>Engineering economics</td>
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<td>Programming</td>
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<td>Biomedical</td>
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<tr>
<td>Safety</td>
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<tr>
<td>Problem solving &amp; critical thinking</td>
</tr>
<tr>
<td>Teaming &amp; collaboration; Cultural awareness</td>
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<tr>
<td>Entrepreneurship, technology transfer; Customer service &amp; marketing</td>
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<tr>
<td>Learning how to “Fail Forward”</td>
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<tr>
<td>Achieving breadth and depth: a “T-shaped” engineer or a “da Vinci”</td>
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<tr>
<td>Decision making</td>
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<tr>
<td>Teaching skills</td>
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<tr>
<td>Communication</td>
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<tr>
<td>Adaptability</td>
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<tr>
<td>Computer Aided Design Software</td>
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<td>Design Process</td>
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<td>Topology Optimization</td>
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<td>Finite Element Analysis</td>
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<td>Quality Functional Deployment</td>
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<td>Geometric dimensioning &amp; tolerancing</td>
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<tr>
<td>Reverse engineering</td>
</tr>
<tr>
<td>Art, Industrial Design, STEAM, art for designers</td>
</tr>
<tr>
<td>Ideation / creativity techniques / design thinking</td>
</tr>
</tbody>
</table>

The small group discussions, in concert with the industry speakers’ presentations, suggested that an AM curriculum should provide students an understanding of:

i. both AM and traditional manufacturing processes to enable them to effectively select the appropriate process for product realization;

ii. a formalized “Design for AM” process that includes both AM-specific computational tools (e.g., CAD, FEA, topology optimization) and frameworks for process selection, process costing, and generating novel solutions that take advantage of AM capabilities; and

iii. the relationships between manufacturing processes and material properties.

In addition to these technical topics, an AM curriculum would prepare students to work well as part of a team, provide a breadth of knowledge to be able to adapt to new challenges as they arise, and encourage them to take risks and learn from design iterations that leverage AM.
3.3. Best Practices in Education: How Might We Educate the AM Workforce?

Having worked collaboratively to ideate what we should teach the AM workforce, the next task was to identify how we should educate and train the workforce. To accomplish this objective, academic speakers were invited to give “lightning talks” on “best practices” for delivering AM education. Due to time constraints, only eight speakers were invited to speak; however, a total of 12 academic participants submitted 1-2 PowerPoint slides that highlighted their work in the classroom. All of these slides can be found on the workshop website14.

Dr. Carolyn Seepersad, an Associate Professor in Mechanical Engineering at the University of Texas-Austin, began by providing an overview of AM educational activities at UT Austin. The core of their AM offering is an undergraduate/graduate AM course that provides students an understanding of (i) alternative AM processes, capabilities, and limitations, (ii) economics and sustainability of AM, and (iii) a design process for AM, including applications and emerging trends. The course is based on a project- and problem-based pedagogy and culminates in a semester-long “Design for AM” project, in which students are tasked with designing a product specifically for AM. Further details about this course, which is orchestrated in collaboration with Chris Williams at Virginia Tech, have been detailed in a prior publication [13]. In addition to the AM course, UT-Austin has created an “Innovation Station” (a 3D Printing vending machine) and a designer’s guide for SLS (e.g., rules of thumb for design, including quantitative guidelines on feature sizes and tolerances). Dr. Seepersad closed her remarks by suggesting that “Design for AM” knowledge might be more critical than AM process knowledge, as parts that make effective use of the technologies’ capabilities can further drive demand for AM use.

Dr. Rahul Rai, an Assistant Professor in Mechanical & Aerospace Engineering at the University at Buffalo-SUNY, presented the concept of educating students about AM by having them investigate the functional components of AM through dissection of a system (see Figure 9) and by developing process-flow software. In the undergraduate/graduate elective course on Additive Manufacturing, students work on developing an AM embedded system; as a result, the students become exposed to both hardware and software issues related to AM. Learning objectives of the course include: providing understanding of the basic AM principles and underlying process physics, comparing and selecting AM processes, and developing hands-on, teamwork, and problem solving skills by applying AM techniques in a design problem.

Dr. David Rosen, the Associate Chair for Administration and Morris M. Bryan, Jr. Professor of Mechanical Engineering at Georgia Tech, discussed Georgia Tech’s AM educational initiatives, which feature both formal (e.g., a dedicated AM class) and informal (e.g., the “Invention Studio” maker space) learning environments. GT’s Invention Studio is a student-led maker space (5 rooms; ~2000 ft²) that features multiple digital fabrication tools (e.g., ~20 3D printers, 3 laser cutters, a water-jet cutter, CNC, etc.), as seen in Figure 10. The Invention Studio, which aims to (i) inspire innovation, design and “making”, (ii) provide opportunities for student leadership and (iii) provide fabrication resources for senior capstone design projects, serves over 700 students per semester. It has demonstrated the capability to feed a culture of entrepreneurship and innovation across the campus.

14 http://www.enge.vt.edu/nsfamed/
Dr. Rosen also shared information on their AM course’s learning objectives. Specifically, upon completing their AM course, students should be able to: (i) select the appropriate AM technology, (ii) analyze AM processes to determine the effects of changing process variables, (iii) understand the unique capabilities of AM technologies and demonstrate the ability to take advantage of them, (iv) apply AM technologies appropriately in an engineering design-manufacture context, (v) demonstrate the ability to design process chains that include AM technologies, and (vi) understand the state-of-the-art in AM research.
Dr. Krishnan Suresh, an Associate Professor in Mechanical Engineering at the University of Wisconsin-Madison, highlighted his work to develop a new topology optimization software, PareTOWorks, to create optimal designs for structural problems. The software is integrated into SolidWorks for ease of use, and the output STL file is directly 3D printable. As part of his presentation, he showed a video that demonstrated the software interface and use (see Figure 11). PareTOWorks can be downloaded free from their website, and the software is currently being deployed in over two dozen universities across the world. In the future, Dr. Suresh and his team plan to integrate this and related design software into a summer-school course that focuses on “Digital Design and Manufacturing”, targeting graduate students, post-docs, and faculty as well as practicing engineers. The course will provide the fundamentals of digital design tools, include hands-on workshops, and discuss open research opportunities in AM.

Dr. Richard A. Wysk, the Dopaco Distinguished Professor in Industrial & Systems Engineering at North Carolina State University, and and Dr. Ola Harrysson discussed the organization and sequencing of engineering design instruction and education at NC State. Driven by a changing digital paradigm for manufacturing, NC State has developed a new manufacturing course sequence. The overall goals and topics of each of the three courses is presented in Figure 12. The course sequence features a “flipped classroom” (i.e., students watch pre-taped lectures out-of-class and spend in-class time solving problems, case studies, and open-ended design problems) and hands-on laboratories. In addition to this undergraduate three-course sequence, NC State features a graduate-level introductory course in manufacturing, which provides the necessary background to take more advanced courses in additive manufacturing, medical-related manufacturing, micro/nano manufacturing, automation, and production engineering.

15 http://www.sciartsoft.com
Course 1
- This course will teach the students the process of going from a product idea to a functional prototype
- Topics to be covered
  - Market research, voice of the customer, QFD, and concept generation and selection
  - Basic detailed design using Solidworks and other appropriate software
  - Geometrical Dimensioning and Tolerancing, Metrology
  - The use of Additive Manufacturing technologies to fabricate conceptual and functional prototypes
  - Metrology/Qualification

Course 2
- The following course will teach the students about the different manufacturing processes that can be used to mass-produce the product
- Topics to be covered
  - Modern manufacturing processes
    - CNC, Injection Molding, Micro and Nano fabrication
  - Process limitations, costs and DFX
  - Automation necessary for modern manufacturing
  - Geometric tolerancing

Course 3
- Manufacturing Systems Engineering: design of contemporary manufacturing systems
- Topics to be covered
  - Elements of lean manufacturing
  - Automation and control
  - Integrate manufacturing processes with automation for part handling and inspection
  - Hands on projects for system design and implementation

Figure 12. NC State’s undergraduate three-course sequence in manufacturing (Source: R. Wysk)

Dr. Karen Wosczyna-Birch, the Executive Director for the NSF ATE Center for Next Generation Manufacturing, presented an overview of their AM initiatives targeting students at both K-12 and community college levels:

- **AM Manufacturing Certificate**: This program consists of four courses targeted at training community college students in AM. Courses feature an overview of AM technology and processes, and detail the process parameters needed to ensure a high-quality part.

- **3D Manufacturing by Design Curriculum**: Targeted at high school and community college students, this curriculum provides students an understanding of how to design, make, and market 3D models via AM. The course features a design project that challenges students to create a 3D printed object that meets a need or solves a common problem found in the home.

- **CPEP Ventures**: A middle school initiative focused on engaging urban-under-represented students that uses desktop 3D printers to stimulate research, development, and manufacturing experience.

Dr. Wosczyna-Birch ended her presentation by recommending that AM can move forward by targeting both science, community college, and university faculty and students in the areas of science, technology, engineering, arts, and math (STEAM).

Dr. Christopher Williams, an Associate Professor in Mechanical Engineering and Engineering Education at Virginia Tech discussed Virginia Tech’s AM educational initiatives, which, similar to Georgia Tech, take place in both formal and informal learning environments. AM has been integrated into much of VT’s engineering curriculum. AM is used to support first-year and senior capstone design projects and is the subject of a dedicated undergraduate/graduate course (similar to that described by Dr. Seepersad). Dr. Williams highlighted two initiatives that occur in an informal learning environment: (1) a 3D printing vending machine and (2) a large extracurricular design competition (see Figure 13).

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16 [http://nextgenmfg.org/](http://nextgenmfg.org/)
17 [http://nextgenmfg.org/course/view.php?id=13](http://nextgenmfg.org/course/view.php?id=13) (Click “Login as a guest”; No PW Required)
VT’s “DreamVendor” (shown on left of Figure 13) is a 3D Printing vending machine that provides broad access to 3D Printing. This free-to-use interactive kiosk allows students to fabricate parts for their personal and course-based design projects. The DreamVendor has engaged students at all levels (including faculty and staff) from departments across the university. In addition to this initiative, VT has hosted an extracurricular design competition that challenged students to design remote-control air and ground vehicles that can be fabricated completely by AM. The challenge, which is inspired by a shared vision of deployable AM for military and civilian applications, engaged over 200 students across the university in its pilot offering.

Dr. Ismail Fidan, a faculty associate at Tennessee Tech University (TTU), closed the session by sharing his team’s development and assessment of a remotely accessible AM laboratory at TTU. The goals of their program are to enhance students’ interest in manufacturing engineering, to share manufacturing resources with other institutions, and to engage students in “real world” problems using AM. Using cutting-edge servers and network cameras, Dr. Fidan and his team were able to provide web-based access to TTU’s AM facilities. In addition, RPIDS, Moodle, WebCT, and D2L were used to deliver instructional content to students across several institutions. From this work, which was sponsored by grants from NSF, almost 50 higher education students have accessed and used the remote laboratory. Dr. Fidan concluded his talk by suggesting that distance learning provides a great potential for AM education; advanced technological tools can allow distance students to engage with AM technology, and might be a way to alleviate the burden of high capital costs for smaller universities.

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18 [http://www.dreams.me.vt.edu/dreamvendor](http://www.dreams.me.vt.edu/dreamvendor)
3.3. National Efforts & Opportunities: Who Might We Partner with for AM Education?
The final nine speakers at the workshop were invited specifically to discuss related national efforts, programs, and funding opportunities to promote and advance additive manufacturing. These ranged from activities supported by NSF and other government agencies to efforts by industry and non-profit organizations. A brief summary of each speaker’s presentation follows; their slides can be found on the workshop website for more detailed information.

NSF Program Director, V. Celeste Carter, kicked off the session with an overview of several programs funded through NSF’s Division of Undergraduate Education (DUE) that could be leveraged for AM education, training, and workforce development. Many existing education and workforce training efforts have been supported by NSF’s Advanced Technological Education (ATE) Program, which was established 20 years ago\(^\text{20}\). The ATE program provides funding for community colleges to partner with industry and economic development organizations to educate science and engineering technicians for new and cutting edge industries (e.g., nanotechnology, additive manufacturing). One of the common challenges when creating such programs is understanding the pathways that students may take through different length curricula, and examples were shown to illustrate how different programs might be integrated and provide transitions to certificates and more advanced degrees (e.g., Florida’s Advanced Technology Education, FLATE, Curriculum Map\(^\text{21}\)). Two well-established ATE Programs, namely, RapidTech and NACK, were introduced and highlighted by other speakers in the session. Workshop participants were also informed of the new Improving Undergraduate STEM Education (IUSE) program that is in development at NSF\(^\text{22}\) and NSF Scholarships that are available for STEM students\(^\text{23}\). Participants were also reminded that they could receive supplements to active NSF SBIR and STTR Phase II awards to engage community colleges in the effort; these supplements provided up to $40,000 with 75% budget allocated for the community college engaged in the research.

Established in 2007, the mission of NSF’s RapidTech Program is to assist industry and educators with the adoption of rapid technologies such as 3D printing and additive manufacturing\(^\text{24}\). Ed Tackett, Director of RapidTech, which is now hosted by the University of California-Irvine, discussed the differences in career pathways for high school, community college, and university students and shared how RapidTech provides “stackable and latticed” certificate programs and Associate of Science degrees to meet the different needs of these different students (see Figure 14). Five colleges are partnered in the effort (i.e., Westmoreland Community College, Edmonds Community College, Portland Community College, Orange Coast College, and Lorain County Community College), and national workshops have engaged nearly 100 high schools, colleges, and universities in their educational efforts (see Figure 15). Interestingly, few institutions in the mid-west and central U.S. have shown interest in the program as seen in the figure, and Ed challenged the audience to find ways to engage them. Meanwhile, almost 150 organizations have been involved with their industry workshops and workforce training programs.

\(^\text{20}\) https://atecentral.net/ate20/book
\(^\text{21}\) http://www.fl-ate.org/flip/etdegree/
\(^\text{22}\) http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504976
\(^\text{23}\) http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5257
\(^\text{24}\) http://www.rapidtech.org
Figure 14. Stackable and latticed certificates and degrees via RapidTech (Source E. Tackett)

Figure 15. Attendees of RapidTech’s national workshops by institution (Source: E. Tackett)
RapidTech is planning to create the Advanced Manufacturing Project for Learning in Focused Innovation (AMPLiFI). AMPLiFI will create a flexible technician education framework that draws on the experience of the National Network for Manufacturing Innovation (NNMI) institutes to prepare the nation’s technical workforce for the advanced manufacturing technical occupations of the future. The proposed framework will be developed and piloted for curricula focused on Additive Manufacturing (AM) in a manner that it is broadly applicable to technician education programs in other technical areas. The framework and associated knowledge, skills, and competencies will be developed around accepted national and international standards (e.g., ASTM, ISO, etc.) to ensure broad industry recognition and acceptance using the instructional models and mapping and assessment strategy show in Figure 16.

![Model for instructional material][1]
![Mapping and assessment of knowledge and skills][2]

**Figure 16. Framework for curriculum development in AMPLiFI program (Source: E. Tackett)**

**NSF’s Nanotechnology Applications and Career Knowledge Network** (NACK) was discussed by Dr. Osama Awadelkarim, Professor of Engineering Science & Mechanics at Penn State and Co-Director of the NSF ATE’s NACK Program. The mission of NACK is to enable nanotechnology education at two-year community and technical colleges in partnerships with four-year universities. These partnerships enable resource sharing (e.g., courses, programs, laboratory facilities, staff), which eases the staff and cost burden at community technical colleges that cannot afford high-end nanotechnology and creates educational pathways through and across institutions for student development. NACK engages research universities and community and technical colleges in 18 states (see Figure 17) and provides resources and services through a shared web portal (see Figure 18). Course materials and assessment rubrics are developed by university and industry practitioners, and lectures are available through the web in multiple formats (e.g., PowerPoint, video). Based on proximity and travel support, students from community and technical colleges can travel to university “hubs” for hands-on laboratories and capstone coursework; remote web access and videos of equipment operation are made available to those who cannot travel. More than 1,200 educators and industry practitioners have completed nanotechnology workshops, and more than 135 companies have hired students into micro/nanotechnology jobs.

Figure 17. NACK provides a working, productive nanotechnology development network involving U.S. research universities and community and technical colleges (Source: O. Awadelkarim)

Figure 18. NACK resources and services online via http://nano4me.org (Source: O. Awadelkarim)

Mike Hripko, the new Deputy Director for Workforce and Educational Outreach at America Makes\textsuperscript{26}, focused his talk on mechanics that America Makes is creating to help to pool resources (and risk) in support of cooperative development of training, assessment, and case studies for AM education. America Makes is working to leverage community knowledge in support of cooperative development of material specifications and databases, process specifications, design rules, and application guidelines through public-private funded and crowd-funded projects. They soon plan to start packaging and proliferating workforce and educational outreach initiatives that are developed by these projects, and they are also organizing focused workshops, working groups, and projects to foster and accelerate AM adoption. They are actively seeking partnerships for educational innovation that combine the expertise of America Makes industry and corporate members with those in academia. As an example, they are now offering short courses on the fundamentals of additive manufacturing materials and processes\textsuperscript{27}, and they plan to broadly socialize these and related educational resources for students, faculty, and industry as their offerings grow.

\textsuperscript{26} http://www.americamakes.us
\textsuperscript{27} https://americamakes.us/news-events/events/event/12-fundamentals-of-additive-manufacturing-materials-processes
NSF’s Additive Manufacturing Research Experiences for Undergraduate (REU) Program was run by Missouri University of Science & Technology (NSF Grant EEC-1004839). Dr. Robert Landers, Professor of Mechanical Engineering and PI on the grant, gave an overview of the REU program, which engaged numerous companies through industry visits and targeted projects that leverage their AM capabilities. The program provides stipends, housing, meals, and travel support for 11 undergraduate students each summer (8 from across the country, 3 from MS&T) and also offers them a chance to attend conferences such as the International Solid Freeform Fabrication Symposium as part of their experience. The program has been successful in attracting students from under-represented groups (42% female, 9% minorities), and student ratings of the program have been positive, particularly in terms of mentoring and learning about applications of AM to real-world problems. Student knowledge about AM has also been shown to increase substantially via the program.

Dr. Paul Witherell, Project Lead, Systems Integration for Additive Manufacturing at the National Institute of Standards and Technology (NIST), provided an overview of the ongoing efforts in measurement science for additive manufacturing within NIST’s Engineering Laboratory. NIST recognizes that AM is a multidisciplinary effort, and they are engaging numerous inter-agency working groups, federal agencies/labs, non-governmental organizations (NGOs), public-private partnerships (e.g., America Makes), universities, and industries in their work. NIST is currently focusing on four areas critical for AM adoption: (1) characterization of AM materials; (2) real-time control of AM processes; (3) qualification of AM materials, processes, and parts; and (4) systems integration for additive manufacturing. They offer several opportunities for undergraduate, graduate, and post-graduate training grants through programs such as NIST’s Summer Undergraduate Research Fellowship (SURF), which provides financial support and housing for the students. NIST is also involved in AM standards development through the American Society for Testing and Materials (ASTM) F42 Committee on AM Technologies.

American Society of Mechanical Engineers (ASME) is also developing new ways to engage its 130,000 members in support of additive manufacturing and advanced manufacturing technologies. Brandy Smith, Program Manager for Emerging Technologies at ASME, shared information on the Advanced Design & Manufacturing Impact Forum that ASME organized to coincide with the 2014 ASME International Design Engineering Technical Conferences in Buffalo, NY. Senior-level leaders and CEOs from MakerBot, Stratasys, Sciaky, Optomec, SLM Solutions, Solid Concepts, and many more shared their insights on the business of 3D printing and AM’s future while companies like Honeywell, Lockheed Martin, and Boeing discussed the challenges of adopting AM in their industry. ASME had previously developed video podcasts and assessment-based courses in support of nanotechnology education through their Nanotechnology Institute, and they welcome ideas for developing similar materials, including webinars and training workshops, for additive manufacturing that they can help host and distribute globally through their membership.

Evan Malone, President of NextFab, explained how his “gym for innovators” leverages its 3D printing and fabrication capabilities to provide AM education and training to a variety of audiences. Their mission is to make the public aware of AM, to make hands-on users

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28 [http://isc.mst.edu/reu](http://isc.mst.edu/reu)
31 [http://www.astm.org/COMMITTEE/F42.htm](http://www.astm.org/COMMITTEE/F42.htm)
33 [https://community.asme.org/nanotechnology_institute/w/wiki/4783.nanotechnology-institute-home.aspx](https://community.asme.org/nanotechnology_institute/w/wiki/4783.nanotechnology-institute-home.aspx)
34 [http://nextfab.com](http://nextfab.com)
independent operators of AM, and to help manufacturing professionals know when to use AM. Toward this end, they provide complimentary 1-2 hour courses to engage the general public to learn about their equipment and offer paid memberships to access and use their equipment, similar to TechShop\(^{35}\) and other “gym membership” models. Hands-on users (e.g., makers, designers, entrepreneurs) of the facility can sign up and pay for software and hardware tutorials that range from a few hours to a few days to gain proficiency with a desired technology. Finally, manufacturing processional, particularly from small/mid-size enterprises, can pay a small fee to send groups of individuals to 2-4 hour short courses to see hardware and software demos and talk to NextFab staff about related technical and business issues. NextFab is currently seeking partners to help develop intensive AM courses to cover the SME AM Certification Rubric and create “Certified AM Machinists” with the depth of knowledge to apply AM for commercialization and in new applications.

Surprisingly, many companies still struggle to find the “business case” for 3D printing within their company. Bob Fiori, Managing Partner of the 3D Printing Alliance, shared their vision for helping companies in the mid-Atlantic region understand “the business of 3D printing” and the associated educational and training needs for its adoption and use within an organization\(^{36}\). Their mission is to “stimulate economic development in the region by commercializing innovation, enabling startups, creating jobs, securing funds, attracting international companies, and accelerating corporate adoption of 3D Printing”. Toward this end, they engage OEMs and distributors of 3D printing equipment and software providers as well as companies, universities, and economic development organizations interested in being involved in 3D printing and promoting related business opportunities within their region. They are also starting to organize events to educate and promote 3D printing, including an event in the Capitol Rotunda in Harrisburg, PA to make legislators aware of 3D printing and its applications.

4. Novel Partnerships for Educating & Training the AM Workforce

The workshop concluded with participants being divided into seven teams, each tasked with developing a proposal (in a 3-minute “pitch” presentation format) that detailed an innovative new program for additive manufacturing education and/or workforce training. This activity sought to synthesize all of the speaker presentations, mind mapping, and small group discussions into a set of recommendations for novel models for AM education and workforce development. A list of the members in each workgroup can be found in the participant list in Appendix D.

4.1. Additive Manufacturing (AM) Training Pyramid (Team 1)

Team 1 developed an education model that connects the entire educational spectrum, from K-12, to non-engineering students, to AM research and development (R&D) activities (see Figure 19). Starting with K-12 students, the curriculum would focus on understanding and implementing 3DP capabilities, targeted to both STEM and non-STEM students. Following completion of this core curriculum, those seeking to become Engineers and Digital Artists would continue forward in an AM Learning Incubator environment, with a structured “Design for Additive Manufacturing” program. Subsequently, a Systems Engineer might study the Process/Supply Chain for Additive Manufacturing. Engineers and Technicians would continue to learn about operation, repair, and troubleshooting of AM equipment. Finally, R&D experts would seek to discover and advance new hardware, software, and materials for AM.

\(^{35}\) [http://techshop.ws]
\(^{36}\) [http://3dprintalliance.org/]
Key to the “AM Training Pyramid” is AM support communities, which might be in the form of an AM Tech Shop or Incubator at the early stages of learning, evolving to a research laboratory/incubator setting for R&D professionals. This Learning Incubator is envisioned as providing an immersive learning environment, short on lecture and long on project-based learning in collaboration with industry. Design/build, developer, and hacker competitions would be used to engage people in each community and promote broader awareness of AM.

![AM training pyramid](image)

Figure 19. AM training pyramid linking AM communities and learning (Source: Team 1)

A second key to the AM Training Pyramid is the establishment of smooth pathways from apprentice to mastery in each of three paths:
- Designer
- Maker
- Operations Manager

Also included in this lifelong learning model are a series of skill challenges and competitions, ever increasing in skill requirements and expertise.

4.2. A National Network for Additive Manufacturing (AM) Education (Team 2)

Inspired by NSF’s NACK Program, Team 2 proposed that a national network for AM education be established that integrates across three sub-networks comprised of virtual, physical, and human resources. The national network for AM will provide a central clearinghouse for AM curricula, programs, and education resources. Education suppliers would be able characterize their offerings based on a variety of attributes (e.g., student age, class year, specific knowledge sought, format, location, cost), enabling an education consumer to view the various education product offerings. These educational suppliers could offer links to further course details, and the website could provide a “ratings” feature identifying those programs that were deemed to be most valuable by the students. Furthermore, the suppliers could share resources for both
educational content as well as physical labs and machines. Content is envisioned to be in the form of MOOCs, videos, seminars, and courses with powerful search engine and website design features to enable those looking for AM educational content to select from amongst a wide variety of attributes. The network would be established for both formal and informal learning environments across the education spectrum (K-Gray). Strong partnerships are envisioned with industry, industry-government consortia (e.g., America Makes), professional organizations (e.g., ASME, SME), community colleges, K-12 schools, and universities.

This national network AM would be inclusive of all AM educational initiatives in relevant STEM, art, architecture, and design programs, and it would encourage collaboration between STEM and non-STEM disciplines (i.e., STEAM37). A schematic for the proposed network is shown in Figure 20 to illustrate the relationships among students, education providers, curricula, facilities, and learning objectives. The team also envisioned integration of AM into a broad academic curriculum for K-12 students that would be coupled with after-school activities such as “The 3DP Club”, Technology Student Association (TSA), Girl and Boy Scouts, FIRST Robotics, and other related existing organizations. Industry would be solicited for technical support, and successful educational and delivery models from NSF’s ATE programs (e.g., NACK, RapidTech, Center for Next Generation Manufacturing) could be used to accelerate adoption.

![Figure 20. Schematic for a National Network for Additive Manufacturing (Source: Team 2)](image)

4.3. MAKE-braries (Team 3)
Team 3 proposed combining maker spaces and libraries to createMAKE-braries, a 21st century counterpart to Andrew Carnegie’s leadership to establish libraries for every community in the late 19th and early 20th centuries. Each MAKE-brary would provide a funded community maker space in every community, equipped with a range of modern manufacturing tools (e.g., additive, subtractive, scanning, traditional shop tools). The facility itself could be new or re-purposed or make an active facility available during “off-peak hours” similar to what TechShop established in Arizona State University’s Chandler Innovation Center38. The target audiences would be educational (e.g., primary, secondary, university, community college) and advanced/production (e.g., NextFab, TechShop, Hive 76, etc.).

4.4. AM...to Infinity and Beyond: Open Source for AM (Team 4)
Team 4 advocated for open source educational opportunities for AM for all Americans to complement the growing popularity and pervasiveness of open source 3D printers [4]. The concept is to provide lifelong learning opportunities available to all persons in all disciplines. Such an initiative is viewed as inclusive and would possibly involve a fundamental educational restructuring, with very close ties to regional businesses.

4.5. AM Educational Programs (Team 5)
All-inclusive exposure to AM was the key pillar behind Team 5’s educational initiative. Their initiative starts with teaching “3D Thinking”, including courses introducing spatial concepts, the functional requirements of design, AM production techniques, and the introduction of design for multi-functional products. The logic behind their initiative is that the realization of tomorrow’s next-generation products, much like today’s smart phones, will likely have multi-functional purposes while optimizing functionality, material use, weight, space, and features. A new generation of engineers and designers will be required to design multi-functional products, leveraging AM technologies, and creating new economies of scale.

4.6. Enhancing My Current Workforce with AM “After Hours” (Team 6)
Team 6 sought to incorporate AM learning for current/incumbent workers, primarily professional engineers, designers, as well as their family members. Offering a mix of educational incentives, the intent would be to infuse AM into the organization via champions and provide immediate corporate value.

Initially, the goal is to collect and share a company’s manufacturing challenges with all of its employees. An AM “after-hours” build/use workshop, featuring a broad spectrum of desktop printers, located on or near the company premises would promote technology awareness and basic familiarity. Coupled with Lunch/Learn sessions, a company could familiarize employees with additive manufacturing with little investment and little to no employee training cost. Moreover, the best AM solutions developed in the lab could be rewarded and incentivized with employee time off, pay bonus, or access to more low/no cost training.

Multiple organizations from non-competing businesses could potentially share the “After Hours” lab space to minimize cost and promote new collaborations and different perspectives. A supplier/customer collaboration was also suggested as a novel, alternative model. To optimize the investment, the space could be shared with the employee family members, the general public, or select student groups after hours.

4.7. Integrated AM Activities for K-12 and Community Education (Team 7)
Team 7 advocated that AM education is inherently interdisciplinary, is at the forefront of national interest, provides a unique interconnectedness between STEM and the arts, is affordable, and offers good career prospects. As such, AM education provides a learning thread for lifetime education for all Americans, and Team 7 proposed activities spanning K-5 through parents. They proposed that the K-5 focus would be on how things are made and how things work. Middle school students would develop creative thinking skills, and study AM software, hardware, chemistry, and materials. High school curriculum would include 3D printing tools, industry standards, and the business modeling required to understand when to employ an AM solution. Community colleges would teach factory skill for manufacturing to multiple-level users. Finally, AM education and awareness for parents is a critical educational component, to ensure support for students pursuing advanced manufacturing careers.

Several AM educational programming ideas were proposed by the team. Specifically, this group proposed a series of $50k projects that would be directed by a program manager. The intent would be for teams of students to quickly provide solutions that incorporate emerging knowledge and technology. Separately and simultaneously, distance learning or onsite training might be offered to incumbent workers.

- University students might collaborate with regional community college students via shared facilities, and collaboration on capstone projects.
AM collaborations which involve institutional exchanges of students and faculty tend to be naturally supportive of diversity objectives, by combining students, faculty, and engineering professionals.

Engineering Experiences for Undergraduates (EEU) might be developed as a counterpart to the successful Research Experiences for Undergraduate (REU) program.

Competitions that uncover new and innovative AM applications could also be developed. Though perhaps not a complete solution in and of themselves, their idea was to provide seed funding to identify feasible solutions that might be detailed by engineering professionals.

5. Recommendations & Closing Remarks

Additive manufacturing is clearly poised to have broad impact not only in how companies design and produce parts in a wide range of industries (aerospace, medical, energy, oil and gas, to name a few), but also in how we educate and train students and practitioners for careers in design, engineering, manufacturing, visual arts, architecture, education, or any application area. AM technology is evolving rapidly, but we must find novel ways to collaborate and collectively advance this technology and its adoption along with the supporting educational infrastructure to utilize AM’s full capabilities. Based on the invited presentations and small group discussions at the workshop, we offer the following recommendations to enhance the AM workforce:

1. Ensure that AM curricula provide students with an understanding of (i) AM and traditional manufacturing processes to enable them to effectively select the appropriate process for product realization; (ii) the relationships between AM processes and material properties; and (iii) “Design for AM”, including computational tools for AM design as well as frameworks for process selection, costing, and solution generation that take advantage of AM capabilities.

2. Establishment of a national network for AM education that, by leveraging existing “distributed” educational models and NSF’s ATE Programs, provides open source resources as well as packaged activities, courses, and curricula for all educational levels (K-Gray).

3. Promote K-12 educational programs in STEAM (STEM plus the arts) and across all formal and informal learning environments in order to leverage the unique capabilities of AM in engaging students in hands-on, tactile, and visual learning activities.

4. Provide support for collaborative and community-oriented maker spaces that promote awareness of AM among the public and provide AM training programs for incumbent workers and students seeking alternative pathways to gain AM knowledge and experience.

A vision for “layering” these national, regional, and local efforts for AM education and training as shown in Figure 21. This layered approach is based on an analogy to NSF’s I-Corps vision to create a national “fabric” to foster innovation and promote research commercialization [18]. The NSF I-Corps program offers support for individual teams to commercialize their research and connect with mentors from across the country. Regional I-Corps sites are being established to enable local teams and provide additional resources and support, and a national network of I-Corps nodes offer immersion curriculum and engage in research about commercialization.

Analogous to these NSF I-Corps programs, many organizations at the workshop (and many not in attendance) are already engaging in multiple efforts that support multiple “layers” of this AM E&T vision. The challenge lies in connecting them into a coherent network to create synergies that address the pressing and growing need for AM E&T, and the team suggestions discussed in Section 4 provide a means for cross-linking these efforts across multiple layers as shown in the figure. Specifically, the workshop outcomes from the teams are grouped by their use at the national, regional, and local levels to establish a national AM network that links regional sites for
AM E&T, which tap into local AM experts in industry and academia that engage individuals and teams locally in integrated AM E&T activities from K-Gray.

Figure 21. A vision for “layering” AM E&T based on an analogy to NSF I-Corps programs

To complete the analogy and realize the proposed vision, the National Network for Additive Manufacturing (proposed by Team 2) would (i) link “nodes” of AM E&T established by national organizations such as America Makes, ASME, SME, NIST, and others; (ii) leverage insights from NSF ATE programs like NACK; and (iii) utilize manufacturing demonstration facilities (MDFs) established by DARPA (CIMP-3D at Penn State\(^{39}\)) and DOE (i.e., Oak Ridge National Laboratory\(^{40}\)). The open source for AM (Team 4) and AM educational programs (Team 5) would be made available and be deployed through this national AM network, feeding regional and local efforts and activities like those discussed by RapidTech, the Center for Next Generation Manufacturing, EWI, and NextFab at the workshop. The AM training pyramid (Team 1) provides a model for a regional effort that creates AM experts while nurturing and sustaining local efforts through its apprenticeships and AM E&T engagements. The Make-braries (Team 3) and AM “After Hours” (Team 6) at local companies provide local efforts that deploy AM into the community by connecting AM experts in industry and academia to help train the incumbent workforce while also exciting the next generation of designers, engineers, artists, architects, and entrepreneurs through STEAM competitions, hands-on activities, Maker Faires\(^{41}\), etc. that utilize AM. The integrated AM activities for K-12 and community education (Team 7) then solidify the foundation, draw from the national AM network, and are customized through the regional AM E&T activities, and tailored to each local community.

Additive manufacturing requires a truly integrated and interdisciplinary approach, and the quicker we can get everyone working together on this exciting technology, the more exciting the advancements and outcomes will be. We believe that the proposed vision for “layering” AM E&T provides the cross-linkages and collaborations that are needed to not only advance AM technology but also prepare the current and future workforce to harness AM’s potential. We hope that these recommendations, in concert with the countless other AM initiatives and activities currently underway, will help AM achieve the hype it is being given.

\(^{39}\) [http://www.cimp-3d.org](http://www.cimp-3d.org)

\(^{40}\) [http://www.crnl.gov/user-facilities/mdf](http://www.crnl.gov/user-facilities/mdf)

\(^{41}\) [http://makerfaire.com/](http://makerfaire.com/)
References Cited:


## Appendix A. Workshop Participants and Affiliations

<table>
<thead>
<tr>
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<td>Jiahua</td>
<td>Zhu</td>
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Appendix B. Workshop Agenda

**Thursday, April 10, 2014 (Day 1)**
NSF, Stafford I, Room 375

12:00 – 1:00  Working Lunch: Welcome & Workshop Introductions
Tim Simpson, Penn State University
Chris Williams, Virginia Tech

Spotlight Address:
“Additive Manufacturing Education – Partnering for Success”
Ed Morris, America Makes

1:00 – 2:00  Industry Talks:
What does the ideal Additive Manufacturing Engineer look like?
Perry Morissette, Boeing
Jay Beversdorf, Stratasys
Shawn Kelly, EWI
Phil Lane, ExOne
Bill Flite, Lockheed Martin
Andy Lucibello, EOS
Ola Harrysson, NC State/Arcam

2:00 – 2:30  Discussion Break: Small Group Discussions with Industry Speakers

2:30 – 4:00  Working Group #1: *What should we teach the AM workforce and why?*

4:00 – 4:45  Working Group #1: Report Out

4:45 – 5:00  Day 1 Synthesis & Homework Assignment: *How do others teach AM?*
Tim Simpson, Penn State University
Chris Williams, Virginia Tech

5:30 – 7:00  Group Networking Reception (Sponsored by America Makes)
*Rock Bottom Brewery*
4238 Wilson Boulevard
(Ballston Common Mall)
Friday, April 11, 2014 (Day 2)
NSF, Stafford I, Room 375

8:00 – 8:50 Working Breakfast: Share Homework Findings
   Tim Simpson, Penn State University
   Chris Williams, Virginia Tech

8:50 – 9:00 Day 2 Welcome & Opening Remarks: George Hazelrigg, NSF

9:00 – 10:00 Lightning Talks: Best Practices in AM Education and Training
   Carolyn Seepersad, University of Texas – Austin
   Rahul Rai, SUNY Buffalo
   David Rosen, Georgia Tech
   Suresh Krishnan, Wisconsin
   Richard Wysk, NC State
   Karen Wosczyna-Birch, NCATC
   Chris Williams, Virginia Tech
   Ismail Fidan, Tennessee Tech University

10:00 – 10:30 Discussion Break: Small Group Discussions with Lightning Talk Speakers

10:30 – 12:00 Working Group #2: To whom and where should we teach AM?

12:00 – 1:30 Working Lunch: National Efforts & Related Opportunities
   V. Celeste Carter, NSF
   Michael Hripko, America Makes
   Brandy Smith, ASME
   Evan Malone, NextFab Studio
   Robert Landers, Missouri S&T
   Paul Witherell, NIST
   Bob Fiori, 3D Printing Alliance
   Osama Awadelkarim, Penn State University
   Ed Tackett, RapidTech, UC Irvine

1:30 – 3:00 Working Group #3: How should we partner for AM education and training?

3:00 – 4:00 Working Groups #2 & #3: Report Out

4:00 – 4:30 Closing Comments
   Tim Simpson, Penn State University
   Chris Williams, Virginia Tech
### Appendix C. Workgroup Assignments for Day 1 (Mind Mapping)

#### Team 1
- Ed Morris
- Carolyn Seepersad
- Patricia Godin
- Kaye Ebelt
- Samia Suliman
- James McGuffin-Cawley
- Jiahua Zhu

#### Team 2
- Perry Morissette
- Douglas Jensen
- Henry Kelly
- Barry Fell
- Stephanie Adams
- Mohammad Elahinia
- Yong Huang

#### Team 3
- Ola Harrysson
- David Rosen
- Mrunalini Pattarkine
- Nathaniel Wurst
- Bob Fiori
- Rahul Rai
- ZJ Pei

#### Team 4
- Bill Flite
- Chris Williams
- Carol Adukaitis
- Susan Singer
- Richard Martukanitz
- Osama Awadelkarim
- David Saint John

#### Team 5
- Bill Cowan
- Richard Wysk
- Henry Kelly
- Ohad Meyuhas
- Tim Simpson
- Dominic Ju
- Andrew Lucibello

#### Team 6
- Raj Manchanda
- Craig McAtee
- Evan Malone
- Karen Wosczyna-Birch
- NathanCrane
- Krishnan Suresh
- Chang Ye

#### Team 7
- Shawn Kelly
- Mary Kocak
- Brandy Smith
- Michael Tinkleman
- Brent Stucker
- Ben Wittbrodt
- Forrest Sheng Bao

#### Team 8
- Phil Lane
- Katie Feldman
- Norman Riddle
- Michael Hripko
- Robert Landers
- Yalin Dong
- Arun Muley

#### Team 9
- Shelly Linor
- Paul Witherell
- Steven Brown
- Lucinda Curry
- Susan Finger
- Tirumalai Srivatsan
- Sanjay Joshi

#### Team 10
- Jay Beversdorf
- Ed Tackett
- Brennan Hogan
- Patricia Scaramuzzo
- Ismail Fidan
- Horea Ilies
- Shannon Munro
Appendix D. Workgroup Assignments for Day 2 (Novel Educational Partnerships)

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Sanjay Joshi  
Ohad Meyuhas  
Lucinda Curry  
Craig McAtee  
Arun Muley  
Nathan Crane  
Carol Adukaitis | David Rosen  
Bill Flite  
Forrest Sheng Bao  
Michael Hripko  
Shelly Linor  
Ben Wittbrodt  
Mary Kocak  
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Brandy Smith  
Brennan Hogan  
Ed Morris  
Ola Harrysson | Bob Fiori  
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Osama Awadelkarim  
Richard Wysk  
Norman Riddle  
Paul Witherell  
Leena Pattarkine | Krishnan Suresh  
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Jiahua Zhu  
Karen Wosczyna-Birch  
Perry Morissette  
Shannon Munro  
Michael Tinkleman |

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Samia Suliman  
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Nathaniel Wurst  
James McGuffin-Cawley  
Tirumalai Srivatsan |