MANUFACTURING
ADVANCED MANUFACTURING, 3D PRINTING, ADDITIVE MANUFACTURING, AUTOMATION, ROBOTICS, MATERIALS, MICRO- & NANO-MANUFACTURING, SUSTAINABILITY...

RESEARCH SURVEY
Advanced Manufacturing

This survey by MIT's Industrial Liaison Program identifies selected examples of MIT research and expertise related to advanced manufacturing and manufacturing broadly. Note that there is another survey on Manufacturing – Bio, Pharma; and a survey on Supply Chains/Logistics (2018).

According to Deloitte's 2020 Manufacturing Outlook (sourced 02/2020: https://www2.deloitte.com/us/en/pages/energy-and-resources/articles/manufacturing-industry-outlook.html), manufacturing industry trends to remain competitive include, “industrial companies getting their diversified ‘houses in order’; current business climate driving manufacturing companies to build digital muscle; manufacturers turning to partnerships for digital momentum; and manufacturers transitioning to renewable energy sources.”

MIT has deep expertise to address these areas and more. Some of the most recent and broad efforts to contribute to the expansion of manufacturing’s competitiveness, particularly in the US, include the following.

The Advanced Manufacturing Partnership (AMP), a national effort recommended by the President’s Council of Advisers on Science and Technology (PCAST) and announced by President Barack Obama in 2011, was chaired by MIT president Susan Hockfield and Dow Chemical CEO Andrew Liveris, and initially included a dozen large manufacturers and half a dozen major universities, including MIT. The AMP brought together industry, universities, and the federal government to invest in emerging technologies for the purpose of creating high quality manufacturing jobs and enhance our global competitiveness. See more: http://web.mit.edu/pie/amp/

The MIT Production in the Innovation Economy (PIE) project asked one big question: what production capabilities are needed to fuel innovation and to realize its benefits in good new jobs, new enterprises, and sustainable growth. PIE was a three-year long research project carried out by teams of MIT faculty and students which resulted in two books, Making in America: From Innovation to Market (MIT Press, 2013) by [Professor] Suzanne Berger and Production in the Innovation Economy (MIT Press, 2014) edited by [Professor] Richard M. Locke and Rachel L. Wellhausen. A Preview of the MIT Taskforce on Innovation and Production Reports from 2013 can be found here: https://web.mit.edu/pie/news/PIE_Preview.pdf

In addition, William Bonvillian, former head of MIT’s Washington DC office, is currently an advisor to the Workforce Project, a research project on workforce education at MIT’s Office of Open Learning. This study builds on ideas in his 2018 book (co-written with Peter L. Singer), Advanced Manufacturing–The New American Innovation Policies (MIT Press).

Research and expertise in various aspects related to manufacturing come from departments, programs, labs, and centers across the Institute, including the following:

- Aero / Astro
- Architecture
- Building Technology Program
- Civil and Environmental Engineering
- CSAIL
- EECS
- Industrial Performance Center
- Initiative on the Digital Economy
For more information on the following research and faculty and related work, please contact MIT’s Industrial Liaison Program at +1-617-253-2691.

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ADVANCED MANUFACTURING AT MIT

ADVANCED FUNCTIONAL FIBERS OF AMERICA (AFFOA) INSTITUTE
National Network for Manufacturing Innovation Institutes (NNMI Institutes)
Board Member: Maria Zuber, E. A. Griswold Professor of Geophysics & Vice President for Research at MIT, http://go.affoa.org/maria-zuber/#more-307

Advanced Functional Fabrics of America (AFFOA), is a non-profit Institute headquartered near MIT and is one of the latest members of the National Network of Manufacturing Innovation (NNMI) Institutes. AFFOA’s mission enables a manufacturing-based revolution—the transformation of traditional fibers, yarns, and textiles into highly sophisticated integrated and networked devices and systems.

At the heart of this revolution is a simple premise: highly functional textile-systems necessitate sophisticated fiber-device components. To pursue this mission, AFFOA addresses the spectrum of manufacturing challenges associated with volume manufacturing of revolutionary fibers and textiles from design to end products. AFFOA facilitates the transition of these revolutionary fiber and textiles from the laboratory through pilot production, delivering the functionality of semiconductor devices and systems at fiber length, uniformity, and cost. AFFOA leads the convergence of semiconductor technology into fiber and textile production to commercialize textile products that see, hear, sense, communicate, store and convert energy, regulate temperature, monitor health, and change color while delivering the conventional qualities of textiles to benefit the commercial consumer and warfighter...

AMERICAN INSTITUTE FOR MANUFACTURING INTEGRATED PHOTONICS (AIM PHOTONICS)
MIT is a Tier 1 member
CTO: Michael Watts, former MIT Professor of EECS/current Visiting Scientist; and CEO of Analog Photonics, http://www.aimphotronics.com/management-team

AIM Photonics is an industry driven public-private partnership that focuses the nation’s premiere capabilities and expertise to capture critical global manufacturing leadership in a technology that is both essential to National security and positioned to provide a compelling return-on-investment to the U.S. economy. The Institute’s goal is to emulate the dramatic successes experienced by the electronics industry over the past 40 years and transition key lessons, processes, and approaches to the photonic integrated circuit (PIC) industry. AIM Photonics supports Small and Medium Enterprises, providing practical access and technology on-ramps for U.S. industry, government, and academic communities. We are creating a National PIC manufacturing infrastructure, widely accessible and inherently flexible to meet the challenges of the marketplace with practical, innovative solutions...
MIMO has been established as an affiliate of MIT's Quest for Intelligence to translate the latest innovations in deep learning and machine learning to meet the needs in manufacturing and operations. In addition to the Quest, MIMO is also working closely with Operations Research Center, Leaders for Global Operations, CSAIL, and other MIT faculty in the Schwartzman College of Computing.

**Research:** MIMO research solves current problems using the latest in machine intelligence techniques and technologies. We take a hands-on, multi-disciplinary and results-oriented approach to increasing your competitiveness through innovation. Our faculty and students are interested in problems along the full manufacturing and operations value chain.

**Education:** MIMO has partnered with the Quest for Intelligence to address the educational gap between the theory behind the latest machine intelligence tools and the techniques and practices required to implement them. This Symposium Series is targeted at mid-career, mid-level executives with an engineering or science background that have or want to identify operational or manufacturing machine intelligence opportunities.

**Benchmark Data:** MIMO is building a data set of successfully trialed and implemented use cases; enabling technologies and processes; management best practices; and techniques to manage explainability, human interaction and address work force implications. We are surveying manufacturing and operations executives along the full manufacturing and operations value chain and in many industries.

**BOOK:** ADVANCED MANUFACTURING: THE NEW AMERICAN INNOVATION POLICIES  
By William B. Bonvillian and Peter L. Singer, MIT Press, December 2017  
https://mitpress.mit.edu/books/advanced-manufacturing

William B. Bonvillian is a Lecturer at MIT, former Director of MIT’s Washington, D.C., office, and the coauthor of Structuring an Energy Technology Revolution (MIT Press).

... In this book, William Bonvillian and Peter Singer explore how to rethink innovation and revitalize America’s declining manufacturing sector. They argue that advanced manufacturing, which employs such innovative technologies as 3-D printing, advanced material, photonics, and robotics in the production process, is the key.

Bonvillian and Singer discuss transformative new production paradigms that could drive up efficiency and drive down costs, describe the new processes and business models that must accompany them, and explore alternative funding methods for startups that must manufacture. They examine the varied attitudes of mainstream economics toward manufacturing, the post-Great Recession policy focus on advanced manufacturing, and lessons from the new advanced manufacturing institutes. They consider the problem of “startup scaleup,” possible new models for training workers, and the role of manufacturing in addressing “secular stagnation” in innovation, growth, the middle classes, productivity rates, and related investment. As recent
political turmoil shows, the stakes could not be higher.

LEARN: MASTER OF ENGINEERING (M.ENG) IN ADVANCED MANUFACTURING & DESIGN
https://manufacturing.mit.edu/
https://manufacturing.mit.edu/academics/industry-projects -- Project examples

The MEng degree combines in-depth, group-based graduate subjects and a project-based thesis experience at leading companies to accelerate students’ engineering and leadership skills. The capstone of the MEng degree is a three-month group project in a manufacturing company. These projects – done in groups of three students per site – form the basis of the thesis portion of the degree. Students work on-site under the supervision of an MIT faculty member typically solving near-term problems for their company.

A number of companies propose the projects in late fall and a selection process matches students with their project and MIT faculty advisors. Students begin their initial work at each company site in January followed by once-weekly meetings during the spring semester. From late May until mid-August the groups work on-site full-time to complete their projects. Students document his or her full contribution to the project thesis, which is submitted to their MIT advisor for approval.

LEARN (OPEN ENROLLMENT): MITX MICROMASTERS—PRINCIPLES OF MANUFACTURING
https://micromasters.mit.edu/pom/

Principles of Manufacturing MicroMasters® program credential, designed and delivered by MIT's #1-world ranked Mechanical Engineering department. The Principles of Manufacturing are a set of elements common to all manufacturing industries that revolve around the concepts of flow and variations. These principles have emerged from working closely with manufacturing industries at both the research and operational levels.

Targeted towards graduate-level engineers, product designers, and technology developers with an interest in a career in advanced manufacturing, the program will help you understand and apply these principles to product and process design, factory and supply chain design, and factory operations.

Curriculum Covers: The program is composed of 8 online courses and 4 final exams (the equivalent of 1 semester of coursework at MIT) ...the following subject areas:

- Supply Chain for Manufacturing: Operating and designing optimal manufacturing-centered supply chains.
- Management in Manufacturing: Understanding the uses and flow of business information to start up, scale up and operate a manufacturing facility.

All courses are open enrollment: You can participate in an entire course for free. To earn a certificate for your work you can verify and pay the course fee. Upon passing a course, you can
use your unique verified certificate as evidence of your effort. Enroll in individual courses, or if you're ready to jump in, you can purchase the whole program at one time.

LEARN: PROFESSIONAL CERTIFICATE PROGRAM IN DESIGN & MANUFACTURING
https://professional.mit.edu/programs/certificate-programs/professional-certificate-program-design-manufacturing

Focused on essential aspects of design, analysis, and manufacturing, this credential affords you the skill and insights to transform your processes. Equipped with these targeted strategies, you’ll be well prepared to reduce time to market while adapting the latest materials and technologies. Awarded upon successful completion of 4 qualifying Short Programs courses in Professional Education, this certificate equips you with the best practices and actionable knowledge needed to make a powerful impact on your organization’s innovation, design, and manufacturing efforts.

All programs are eligible for Continuing Education Units. The professional certificate program application fee is $325 (non-refundable). Each of the courses will be paid at the per-course rate. Select from the following Core courses:

Predictive Multiscale Materials Design—June 1-5, 2020
$4,500 (5 days): Discover the science, technology, and state-of-the-art computing methods being used to fabricate innovative materials from the molecular scale upwards.

Tribology: Friction, Wear, and Lubrication—June 22-26, 2020
$4,000 (5 days): Gain breakthrough insights into tribology, including an exploration of fundamental concepts as surface energy, elastic and elastoplastic deformation, micro-fracture, and surface interactions at the micro- and nano-scale.

Computational Design for Manufacturing: Creating a Pipeline for the Future of Production—July 13-17, 2020
$5,500 (5 days): Learn more about the new field of computational design, including advance manufacturing hardware considerations, methods for creative digital materials, and generative design workflows.

Additive Manufacturing: From 3D Printing to the Factory Floor—July 13-17, 2020
$5,500 (5 days): Gain a comprehensive understanding of additive manufacturing, its applications, and its implications both now and in the future.

Product Platform and Product Family Design: From Strategy to Implementation—July 13-17, 2020
$4900 (5 days): Explore how product architecture, platforms, and commonality can help a firm deploy and manage a family of products in a competitive manner.

LEARN: PROF. ED. DIGITAL PLUS COURSE—SMART MANUFACTURING: MOVING FROM STATIC TO DYNAMIC MANUFACTURING OPERATIONS (FEB OR MAY 2020)
February 4 - April 22, 2020 OR May 7 - July 23, 2020 (registration opens 12 Feb 2020)
10 weeks, online excluding orientation, 4-6 hours/week
Tuition: $2,800 (Flexible payment available; Special group enrollment pricing)
Advanced Manufacturing

Instructor: Dr. Brian Anthony (Associate Principal Research Scientist, MIT Institute of Medical Engineering & Science; Principal Research Scientist, MIT Mechanical Engineering; Director, Master of Engineering in Manufacturing Program, MIT; Co-Director, Medical Electronic Device Realization Center, Institute of Medical Engineering & Science; Director of MIT.nano)


Smart manufacturing is a convergence of modern data science techniques and artificial intelligence to form the factory of the future. Smart manufacturing is about increasing efficiency and eliminating pain points in your system. It’s characterized by a highly connected, knowledge-enabled industrial enterprise where all organizations and operating systems are linked, leading to enhanced productivity, sustainability, and economic performance.

MIT Professional Education’s Smart Manufacturing online program brings together cutting-edge technology like machine learning, Internet of Things, and data analytics to understand the current transformation of the manufacturing sector...

LEARN: SLOAN EXEC ED COURSE—IMPLEMENTING INDUSTRY 4.0: LEADING CHANGE IN MANUFACTURING & OPERATIONS (JUNE OR NOV 2020)

Program Dates: Jun 11-12, 2020 OR Nov 10-11, 2020
Tuition: $3,900 (excluding accommodations)
Instructors: Prof. John Van Maanen [link] and John Carrier [link]

https://horizon.mit.edu/

MIT Horizon, a new initiative within MIT Open Learning, is a content library with bite-sized content for everyone from the C-suite to the front line. MIT Horizon includes articles, illustrations, videos, podcasts, and live online events featuring industry and academic leaders. We provide every MIT Horizon customer with a dedicated Customer Success Manager to help ensure success, from smooth implementation to ongoing value.
3D PRINTING/ADDITIVE MANUFACTURING & DIGITAL FABRICATION

NEIL A. GERSHENFELD
Director, Center for Bits and Atoms, Professor of Media Arts and Sciences,
http://cba.mit.edu/

Prof. Neil Gershenfeld is the Director of MIT’s Center for Bits and Atoms. His unique laboratory is breaking down boundaries between the digital and physical worlds, from creating molecular quantum computers to virtuosic musical instruments. Technology from his lab has been seen and used in settings including New York’s Museum of Modern Art and rural Indian villages, the White House and the World Economic Forum, inner-city community centers and automobile safety systems, Las Vegas shows and Sami herds. He is the author of numerous technical publications, patents, and books including *Fab, When Things Start To Think, The Nature of Mathematical Modeling,* and *The Physics of Information Technology,* ... ...He is the originator of the growing global network of field fab labs that provide widespread access to prototype tools for personal fabrication, and directs the Fab Academy, the associated program for distributed research and education in the principles and practices of digital fabrication.

Research advances by Dr. Gershenfeld and his students and colleagues working at the boundary between physical science and computer science include: one of the first complete quantum computations, using nuclear spins in molecules; microfluidic bubble logic, with bits that transport materials as well as information; physical one-way cryptographic functions, implemented by mesoscopic light scattering; noise-locked loops that entrain on codes, which led to analog logic integrated circuits that use continuous device dynamics to solve digital problems; asynchronous logic automata to align hardware with software; Internet 0 for interdevice internetworking; microslot probes for ultra-small-sample structural studies; integrated 6-axis inertial measurement based on the dynamics of trapped particles; charge source tomography for electric field imaging and intrabody signaling; electropermanent actuators for high torque at low RPM with static holding; and additive assembly of functional digital materials that can be used in the highest modulus ultralight structures.

Center for Bits and Atoms
https://www.media.mit.edu/groups/center-for-bits-and-atoms-1/updates/
Projects: https://www.media.mit.edu/people/neilg/projects/
Pubs: http://cba.mit.edu/docs/papers/index.html

MIT’s Center for Bits and Atoms is an interdisciplinary initiative exploring the boundary between computer science and physical science. CBA studies how to turn data into things, and things into data. It manages facilities, runs research programs, supervises students, works with sponsors, creates startups, and does public outreach.

CBA was launched by a National Science Foundation award in 2001 to create a unique digital fabrication facility that gathers tools across disciplines and length scales for making and measuring things. These include electron microscopes and focused ion beam probes for nanostructures, laser micromachining and X-ray microtomography for microstructures, and multi-axis machining and 3D printing for macrostructures. These are supported by instrumentation for processing and characterizing materials and devices. CBA” tools are
available around the clock for its users working on projects that integrate these capabilities.

**Research:** CBA’s projects involve collaborations with researchers from across MIT’s campus and around the world. CBA personnel have participated in advances at the boundary between bits and atoms including what were among the first complete quantum computations, using nuclear spins in molecules; physical one-way cryptographic functions, implemented by mesoscopic light scattering; microfluidic bubble logic, with bits that transport materials as well as information; asynchronous logic automata, to align hardware with software; intelligent infrastructure, for energy efficiency; recoding the genome; coded folding, for programming matter; and the additive assembly of functional digital materials. CBA’s research is illustrated in this presentation (“i” for index).

*Assembler robots make large structures from little pieces: Systems of tiny robots may someday build high-performance structures, from airplanes to space settlements*

By David L. Chandler, October 2019, MIT News
https://www.media.mit.edu/articles/assembler-robots-make-large-structures-from-little-pieces/

Today’s commercial aircraft are typically manufactured in sections, often in different locations—wings at one factory, fuselage sections at another, tail components somewhere else—and then flown to a central plant in huge cargo planes for final assembly.

But what if the final assembly was the only assembly, with the whole plane built out of a large array of tiny identical pieces, all put together by an army of tiny robots?

That’s the vision that graduate student Benjamin Jenett, working with Professor Neil Gershenfeld in MIT’s Center for Bits and Atoms (CBA), has been pursuing as his doctoral thesis work. It’s now reached the point that prototype versions of such robots can assemble small structures and even work together as a team to build up a larger assemblies...

*Robotic Assembly of Discrete Cellular Lattices (Digital Materials)*

Digital Materials are a way of designing and manufacturing. Rather than building large, monolithic, single-use components, we discretize the material into simple, repeating, functional bits. A discrete set of base elements are combined to form cellular lattices with bulk material properties. This lets us cheat: we can maximize the performance of our material by assembling high-performance sub-elements, and their reversibility maximizes the sustainability and post-life reusability of the product. With all of these discrete units, assembly becomes a chore, and automation becomes crucial. The structured nature of the lattice enables assembler robots to use the geometry of the lattice for locomotion and error-correction. Further, the structured nature of the discretized lattice lends itself to novel design and simulation tools that exploit functional representations of the geometry to open the design space to previously unthinkable regimes of simulation, topological design and manufacture path-planning.
A JOHN HART
Associate Professor of Mechanical Engineering,
http://meche.mit.edu/people/faculty/ajhart@mit.edu
PUBS:
https://scholar.google.com/citations?hl=en&user=V7ZsMrMAAAAJ&view_op=list_works&sortby=pubdate

John Hart leads the MIT Center for Additive and Digital Advanced Production Technologies (APT), and the Mechanosynthesis Group, which aims to create new principles, machines, and processes for manufacturing of advanced materials. His work has been recognized by young investigator awards from NSF, ONR, AFOSR, DARPA, ASME, and SME; and he is the recipient of two R&D 100 awards.

MIT Center for Additive and Digital Advanced Production Technologies (APT)
http://apt.mit.edu/

The MIT Center for Additive and Digital Advanced Production Technologies (APT) aims to accelerate the implementation of AM and to invent its future. As such, APT convenes its members and MIT experts with a mission to: perform visionary research, continually and critically assess the status of AM technology, develop model-based decision tools and open strategic frameworks, build a vibrant academic-industry network including MIT students, and accelerate critical AM education initiatives for professional audiences. Taken together, these activities enable APT's members to implement process, product, and business model innovation and to leverage AM in tandem with the rapidly changing digital manufacturing infrastructure that includes robotics, advanced materials, and computational intelligence.

To complement its technical research, APT performs strategic analyses of the present and future capabilities of AM and of digitally-driven manufacturing systems. Broadly, we seek to identify the “scaling laws” of AM technologies and create insights that enable members to act decisively in this rapidly changing arena. These analyses include accurate, up-to-date cost models of AM, tools for value analysis, and a library of case studies derived from member interests. Key insights and detailed reports are shared with members far in advance of academic publication.

Mechanosynthesis Group

The Mechanosynthesis Group aims to advance the science and technology of manufacturing and its interplay with the sustainable growth of our world. Our focus areas include additive manufacturing, carbon nanomaterials, roll-to-roll processing, printed electronics, and resource-efficient sensing and diagnostic devices. Our work is multidisciplinary, spans from fundamental principles to applications, and engages a wide range of public and private sponsors and collaborators.

**Research:** Focus areas include additive manufacturing (spanning from nano to macro scales), carbon nanotubes and 2D materials, roll-to-roll processing, printed electronics, and resource-efficient sensors and diagnostics. These technical areas connect both to fundamental principles and applications in a variety of domains including lightweight structures, robotics, energy storage devices, optical materials, precision instrumentation, and medical devices. SEE: http://mechanosynthesis.mit.edu/research/
**Precision assembly of additively manufactured components using integral kinematic couplings**

R.W. Penny, A.J. Hart, 2019 Precision Engineering. 60: 104-116. 2019 DOI:
https://doi.org/10.1016/j.precisioneng.2019.04.011

The use of additive manufacturing (AM) in engineering applications is often confronted by process capabilities that limit component accuracy and surface finish. These limitations greatly complicate locating of parts for post-processing and/or assembly. Here, we describe the use of integral additively manufactured kinematic couplings (AM-KCs) for construction of modular AM assemblies. As a representative test geometry, classic Maxwell KCs are printed using four commonly used AM processes for plastics and metals. We study how coupling accuracy and repeatability are influenced by material properties, surface quality, and loading conditions. Under systematically controlled preload, as-built polymer AM-KCs are measured to have 1σ repeatability of 3.2-16.6 µm which depends on the layer thickness and material/process combination. Metal AM-KCs made by selective laser melting (SLM) are shown to repeat to 0.9µm. Finally, we demonstrate the use of AM-KCs in the fabrication of a modular, 3D printed optical assembly.

**Additive manufacturing of biomechanically tailored meshes for wearable and implantable devices.**

see also https://news.mit.edu/2019/3-d-print-mesh-ankle-knee-braces-0619

Additive manufacturing (AM) of medical devices such as orthopedic implants and hearing aids is highly attractive because of the potential of AM to match the complex form and mechanics of individual human bodies. Externally worn and implantable tissue-support devices, such as ankle or knee braces, and hernia repair mesh, offer a new opportunity for AM to mimic tissue-like mechanics and improve both patient outcomes and comfort. Here, it is demonstrated how explicit programming of the toolpath in an extrusion AM process can enable new, flexible mesh materials having digitally tailored mechanical properties and geometry. Meshes are fabricated by extrusion of thermoplastics, optionally with continuous fiber reinforcement, using a continuous toolpath that tailors the elasticity of unit cells of the mesh via incorporation of slack and modulation of filament–filament bonding. It is shown how the tensile mesh mechanics can be engineered to match the nonlinear response of muscle. An ankle brace with directionally specific inversion stiffness arising from embedded mesh is validated, and further concepts for 3D mesh devices are prototyped.

**Thesis: Integrating additive manufacturing into operations at middle market companies**

Thomas J. (Thomas James) Mangan, IV, 2019 M.B.A., MIT Sloan School of Management, and S.M., MIT Department of Mechanical Engineering, in conjunction with the Leaders for Global Operations Program at MIT
Advisors: Profs. John Hart (MechEng) and John F. Carrier (Sloan School)
https://hdl.handle.net/1721.1/122572

Ascent Aerospace's leadership recognizes the transformative potential of additive
manufacturing (AM) to the aerospace tooling industry. As a middle market company, Ascent required a deliberate approach to identifying areas with the highest potential for value creation. Without the research and development budget of an aerospace OEM, the best path forward for Ascent is to leverage existing AM technologies and those requiring minimal further development. The motivation for this project is to identify the best path forward for Ascent in leveraging AM as a value creation tool. Ascent had no AM capability at the beginning of this project, using a supplier when AM components when specifically requested by a customer. The thesis describes a methodology and results for identifying where to integrate AM into operations. It discusses the data and analysis used to find impact areas. The thesis also addresses some of the barriers impacting the adoption of AM. The analytical methods and organizational factors for additive adoption provide a holistic view of how to integrate AM into regular operations. Abstracted away from the case studies, the method should be actionable at any capital-constrained company to generate value through the adoption of AM. Recommendations on future work on how to approach the adoption of AM will be discussed, along with specific future work related to the thesis.

MIT Prof. Ed Course—Additive Manufacturing: From 3D Printing to the Factory Floor (July 13–17, 2020)

Lead Instructor: Prof. John Hart
July 13–17, 2020, $5500
https://professional.mit.edu/programs/short-programs/additive-manufacturing

The implications of additive manufacturing (AM) span the complete product life-cycle, from concept-stage design to service part fulfillment. Recent advances, including industrially viable high-speed AM processes, improved materials, and optimization software, now enable AM to be considered hand-in-hand with conventional production technologies. Moreover, the unprecedented design flexibility of AM allows us to invent products with new levels of performance, and to envision digitally-driven manufacturing systems that achieve rapid, responsive production with reduced cost and risk.

JEREMIAH A JOHNSON
Associate Professor of Chemistry, https://chemistry.mit.edu/profile/jeremiah-a-johnson/
Lab: http://web.mit.edu/johnsongroup

The Johnson laboratory seeks creative, macromolecular solutions to problems at the interface of chemistry, medicine, biology, and materials science. Materials synthesis is approached in an analogous manner to natural-products synthesis; an interesting target structure is chosen and a synthetic scheme is designed to access that structure as efficiently as possible. The targets are designed de novo from careful consideration of the specific needs of a given application and with a particular emphasis on function. The tools of traditional organic and organometallic synthesis, synthetic polymer chemistry, photochemistry, surface science, and biopolymer engineering are combined to realize the designs.

Just as natural-products chemists must often invent new reaction methodologies to access complex structures and their corresponding derivatives, the Johnson lab will seek to develop new methodologies for the construction and modification of complex material libraries. Iterative library synthesis, function-based screening, and design optimization will ultimately yield basic knowledge, such as structure-function relationships for materials in specific
applications, and new materials-based technologies that outperform current alternatives. Some examples of target material platforms and their associated applications are: (1) novel, nanoscopic branched-arm star polymer architectures for in vivo drug delivery and supported catalysis, (2) hybrid synthetic-natural hydrogels for correlation of the effects of network microstructure on cell response, and (3) new types of semiconducting organometallic polymers and polymer films for sensing, supported catalysis, and energy conversion.

**Light-controlled polymerization**


Developing well-controlled, light-mediated iniferter polymerizations using trithiocarbonates has allowed us to explore and reimagine additive manufacturing.

> Logic-controlled radical polymerization: multiple-stimuli switching of polymer chain growth through heat and light

> Living Additive Manufacturing (LAM) made possible by visible light photoredox catalysis

**Polymer Metal-Organic Cage Gels Based on Cu24L24 Cuboctahedra: Design, Synthesis, and Additive Manufacturing Enabled by Three-State Photoswitching**

Nathan J Oldenhuis, Peter Qin, Shu Wang, Hong-Zhou Ye, Eric Alt, Adam Willard, Troy Van Voorhis, Stephen Craig, Jeremiah Johnson, 2019 ChemRxiv


https://chemrxiv.org/articles/Polymer_Metal-Organic_Cage_Gels_Based_on_Cu24L24_Cuboctahedra_Design_Synthesis_and Additive_Manufacturing_Enabled_by_Three-State_Photoswitching/9162299/1

This manuscript presents a novel polyMOC network that can reversibly switch between three distinct states of mechanical and chemical properties, significantly extending the boundaries of stimuli-responsive materials. This triple switching phenomenon is enabled by a unique photoreduction mechanism that leverages Cu24L24 self-assembled metal-organic cages (MOCs) embedded in an elastic polymer gel. The properties of each material state can be used in a cooperative fashion to achieve advanced functions such as network toughening, metallic patterning, and additive manufacturing.

The merger of conformationally flexible macromolecules with the programmed self-assembly of metal-organic cages (MOCs) has enabled the design of hybrid polymer networks with properties that cannot be replicated in traditional gels/elastomers or crystalline frameworks alone. Herein, we report a new class of supramolecular polymer metal-organic cage (polyMOC) gels based on the assembly of Cu24L24 cuboctahedra. Leveraging the modularity of their high branch functionality junctions, and the photoredox chemistry of Cu (II) paddlewheel complexes, we demonstrate how these polyMOCs can be reversibly photoswitched between three oxidation states (Cu (II), Cu (I), and Cu (0)) that each give rise to unique mechanical, optical, and catalytic properties: the Cu (II) state is a high branch functionality, robust polyMOC with fast network dynamics, the Cu (I) state is a catalytically active fluid, and the Cu (0) state generates a copper suspension that can deposit metallic films. Reversible switching between these states allows their individual properties to be combined in a spatiotemporally patterned multi-material to achieve unprecedented functions. For example, extrusion of the Cu (II) polyMOC in the presence of polymeric azides and alkynes, where the mechanically robust polyMOC serves to
hold the solution of azides and alkynes in a printed shape, followed by photoswitching to the Cu (I) state and subsequent re-oxidation provides 3D-printed MOC-interpenetrating networks (MINs) with > 100-fold enhanced toughness compared to either parent network. Such complex functions, which cannot be accessed in traditional polymer networks, arise from ...

Visible-light-mediated, additive-free, and open-to-air controlled radical polymerization of acrylates and acrylamides


https://pubs.rsc.org/en/content/articlelanding/2019/py/c9py00022d#!divAbstract

Oxygen tolerance in controlled radical polymerizations has been an active field of study in recent years. Herein, we report a photocontrolled, additive-free iniferter polymerization that operates in completely open vials utilizing the “polymerizing through oxygen” mechanism. Trithiocarbonates are directly activated with high intensity 450 nm light to produce narrowly dispersed (Mw/Mn = 1.1–1.6) polycrylates and polyacrylamides. Living behavior is demonstrated through chain extension, block copolymer synthesis, and control over molecular weight through varying the monomer : iniferter ratio. A slight increase in induction period is observed for the open vial polymerization compared to the air-free reaction, but polymers with similar Mn and Mw/Mn values are produced after 30–60 minutes of irradiation. This system will provide a convenient platform for living additive manufacturing because of its fast reaction time, air tolerance, wide monomer scope, and lack of any additives beyond the monomer, iniferter, and DMSO solvent.

WOJCIECH MATUSIK
Professor of Electrical Engineering and Computer Science
https://people.csail.mit.edu/wojciech/
Group: http://cfg.mit.edu/

Wojciech Matusik is a Professor of Electrical Engineering and Computer Science at the MIT Computer Science and Artificial Intelligence Laboratory, where he leads the Computational Fabrication Group and is a member of the Computer Graphics Group. Before coming to MIT, he worked at Mitsubishi Electric Research Laboratories, Adobe Systems, and Disney Research Zurich. He studied computer graphics at MIT and received his PhD in 2003. He also received a BS in EECS from the University of California at Berkeley in 1997 and MS in EECS from MIT in 2001. His research interests are in computer graphics, computational design and fabrication, computer vision, robotics, and hci. In 2004, he was named one of the world's top 100 young innovators by MIT's Technology Review Magazine. In 2009, he received the Significant New Researcher Award from ACM Siggraph. In 2012, Matusik received the DARPA Young Faculty Award and he was named a Sloan Research Fellow. In 2014, he received Ruth and Joel Spira Award for Excellence in Teaching.

Computational Fabrication Group
http://cfg.mit.edu/
https://www.csail.mit.edu/research/computational-fabrication-group

Research at the Computational Fabrication Group at the MIT Computer Science and Artificial Intelligence Laboratory centers on digital manufacturing, 3D printing and computer graphics,
as well as computational photography and displays, and virtual humans and robotics.

**Knitting Skeletons: Computer-Aided Design Tool for Shaping and Patterning of Knitted Garments**

UIST 2019 Alexandre Kaspar, Liane Makatura, Wojciech Matusik,  
http://cfg.mit.edu/content/knitting-skeletons-computer-aided-design-tool-shaping-and-patterning-knitted-garments  
Project page: http://knitsskel.csail.mit.edu/  
See also: https://www.csail.mit.edu/news/computer-aided-knitting

This work presents a novel system for simple garment composition and surface patterning which aims to allow anyone to design customized knitted garments. Our tool combines ideas from CAD software and image editing: it allows the composition of (1) new parametric knitted primitives, and (2) stitch pattern layers with different resampling behaviours. The underlying course-based representation enables complex customization with automated layout and real-time patterning feedback. We show a variety of garments and patterns created with our tool, as well as our ability to transfer shape and pattern customizations across users. Finally, we make our design tool available to stimulate research in computational knitting.

**Neural Inverse Knitting: From Images to Manufacturing Instructions**

Alexandre Kaspar*, Tae-Hyun Oh*, Liane Makatura, Petr Kellnhofer, Jacqueline Aslarus, and Wojciech Matusik (* Equal contribution)  

Motivated by the recent potential of mass customization brought by whole-garment knitting machines, we introduce the new problem of automatic machine instruction generation using a single image of the desired physical product, which we apply to machine knitting. We propose to tackle this problem by directly learning to synthesize regular machine instructions from real images. We create a curated dataset of real samples with their instruction counterpart and propose to use synthetic images to augment it in a novel way. We theoretically motivate our data mixing framework and show empirical results suggesting that making real images look more synthetic is beneficial in our problem setup. We make our dataset and code publicly available for reproducibility and to motivate further research related to manufacturing and program synthesis.

**3D-Printed Organic Solar Cells**

Using our inkjet printer system, the goal of this project is to produce a light sensor / solar cell that is composed entirely of 3D printed materials.  

Being able to fully 3D print a solar cell unlocks a range of applications that were previously not possible for existing manufacturing techniques. All mature solar manufacturing technologies are limited to a single axis of curvature for their output solar cells, which means that they are unable to produce solar cells that could conformally coat an arbitrarily defined surface. 3D printed solar cells would thus be useful for coating objects such as drones, cars, robots, or any other application where weight or aerodynamics are especially important (which would preclude using a bulky form-altering scaffold to support a flat or single axis curved solar cell).
Patent: Adaptive material deposition for additive manufacturing
W Matusik, AS Park, JE Ramos, K Vidimce
US Patent 10,456,984, Publication date: 2019/10/29,

A closed-loop adaptive material deposition apparatus and method uses a scanning system to monitor an additively manufactured object as it is being fabricated and adapting the geometric shape and material composition of the subsequent layers based on the scan data. The scanning system repeatedly captures geometric and/or material information of a partially manufactured object with optional auxiliary objects inserted during the manufacturing process. Based on this information, the actual surface geometry and/or actual material composition is computed. Surface geometry may be offset and used as a slicing surface for the next portion of the digital model. The shape of the slicing surface may then be recomputed each time the system scans the partially fabricated object.

CAITLIN T MUELLER
Associate Professor of Architecture (Building Technology Program) and of Civil & Environmental Engineering, https://architecture.mit.edu/faculty/caitlin-mueller
https://cee.mit.edu/people_individual/caitlin-mueller/
Head, Digital Structures Group, http://digitalstructures.mit.edu/

Caitlin Mueller is a researcher, designer, and educator working at the interface of architecture and structural engineering. She is currently an Associate Professor in the Building Technology Program, where she leads the Digital Structures research group. As a researcher, Mueller focuses on developing new computational methods and tools for synthesizing architectural and structural intentions in early-stage design. She also works in the field of digital fabrication, with a focus on linking high structural performance with new methods of architectural making. In addition to her digital work, she conducts research on the nature of collaboration between architects and engineers from a historical perspective. Mueller also aims for interdisciplinary learning and integration in her teaching efforts, which include subjects in structural design and computational methods.

Digital Structures
http://digitalstructures.mit.edu/
Digital Structures is a research group at MIT working at the interface of architecture, structural engineering, and computation. We focus on the synthetic integration of creative and technical goals in the design and fabrication of buildings, bridges, and other large-scale structures. We are particularly interested in how digital techniques and tools can play an unexpected, collaborative role in these processes. Led by Professor Caitlin Mueller, the group is based in MIT’s Building Technology Program in the Department of Architecture, and also includes contributors from Civil and Environmental Engineering, and the Center for Computational Engineering.

Computational Structural Optimization and Digital Fabrication of Timber Beams
Structural optimization techniques offer means to design efficient structures and reduce their impact on the environment by saving material quantities. However, until very recently, the resulting geometrical complexity of an optimized structural design was costly and difficult to build. Today, fabrication processes such as 3D printing and Computer Numeric Control (CNC) machining in the construction industry reduces the complexity to produce complex shapes. This research aims to combine computational structural optimization and digital fabrication tools to create a new timber architecture. A key opportunity for material savings in buildings lies in ubiquitous structural components in bending, especially in beams. This research explores old and new techniques for shaping structural timber beams.

**Characterization of anisotropy in fused deposition modeling 3D printing**

http://digitalstructures.mit.edu/page/research#characterization-of-anisotropy-for-fdm-abs

The layer-based technique of the fused deposition modeling (FDM) additive manufacturing process creates anisotropy within printed parts, but the full quantitative characterization of this anisotropy is not yet available, making it difficult to predict structural performance of printed parts. This research studies the tensile strength of ABS plastic created by FDM in incrementally rotated orientations, to analytically and experimentally characterize the anisotropy of the material. The known relationship between strength and orientation can then be used to create a predictive model of the local material behavior in any FDM printed object.

**Robotic extrusion of architectural structures with nonstandard topology**


This paper presents a fast and flexible method for robotic extrusion (or spatial 3D printing) of designs made of linear elements that are connected in non-standard, irregular, and complex topologies. Nonstandard topology has considerable potential in design, both for visual effect and material efficiency, but usually presents serious challenges for robotic assembly since repeating motions cannot be used. Powered by a new automatic motion planning framework called Choreo, this paper’s robotic extrusion process avoids human intervention for steps that are typically arduous and tedious in architectural robotics projects. Specifically, the assembly sequence, end effector pose, joint configuration, and transition trajectory are all generated automatically using state-of-the-art, open-source planning algorithms developed in the broader robotics community. Three case studies with topologies produced by structural optimization and generative design techniques are presented to demonstrate the potential of this approach.

**Sculpted Skeletons: Advanced Manufacturing of Structurally Optimized Concrete Housing in the Middle East**


Low-cost, safe, high-quality housing is a growing demand globally as populations expand and urbanize. In the Middle East and North Africa (MENA) region, reinforced concrete construction is typically being deployed to address this issue. However, conventional construction methods with this material are heavy and highly materially intensive, driving up costs, resource consumption, and carbon emissions. With emerging digital tools for optimized structural design, and new methods of advanced manufacturing and automated, roboticized construction,
a new housing typology can emerge, that allocates reinforced concrete as a structural material in intelligent, lightweight configurations. Foundations, slabs, beams, and columns can all take on sculpted, optimized forms that use only the material necessary to carry load. The result is a substantial reduction in material consumption, cost, embodied energy and carbon emissions, seismic loads, foundation systems, and construction complexity. For example, previous and ongoing work by the PI and her research group in India have shown that structurally shaped one-way floor systems can reduce their mass by 50% and embodied energy by 60%-70% compared to a flat slab with the same load capacity. The goal of this proposed work is to apply and extend these design and construction methods to the MENA housing sector, in collaboration with Dar Group and other local partners.

The specific new direction of the work seeking seed funding from this grant looks at large-scale 3D printing processes to produce low-cost, reusable, but highly customized inserts for concrete formwork. Printed from recycled and recyclable thermoplastic material, these reusable inserts will allow for a modular, structurally optimized construction logic to be materialized at scale for minimal complexity over existing construction methods, and ideally reduced cost. Alongside this new fabrication strategy, the project will develop a new design tool to be used by housing developers, designers, and occupants in the MENA region, harnessing the power of virtual reality to visualize these sculpted concrete housing systems in immersive three-dimensional environments. This allows for human input in the structural optimization process, resulting in designs that are materially efficient but also responsive to the holistic needs of people.

NERI OXMAN
Sony Corporation Career Development Associate Professor of Media Arts and Sciences,
https://www.media.mit.edu/people/neri/overview/
https://neri.media.mit.edu/neri-oxman.html
Group: https://www.media.mit.edu/groups/mediated-matter/overview/

Neri Oxman is the Sony Corporation Career Development Professor and Associate Professor of Media Arts and Sciences at the MIT Media Lab, where she founded and directs the Mediated Matter research group. Her team conducts research at the intersection of computational design, digital fabrication, materials science and synthetic biology, and applies that knowledge to design across disciplines, media and scales—from the micro scale to the building scale. Oxman’s goal is to augment the relationship between built, natural, and biological environments by employing design principles inspired and engineered by Nature, and implementing them in the invention of novel design technologies. Areas of application include architectural design, product design, fashion design, as well as the design of new technologies for digital fabrication and construction. Oxman coined the term, and pioneered the field of, Material Ecology, which considers computation, fabrication, and the material itself as inseparable dimensions of design. In this approach, products and buildings are biologically informed and digitally engineered by, with and for, Nature...

Mediated Matter Group
https://www.media.mit.edu/groups/mediated-matter/overview/
The Mediated Matter group focuses on Nature-inspired design and design-inspired Nature. We conduct research at the intersection of computational design, digital fabrication, materials science, and synthetic biology, and apply that knowledge to design across scales—from the micro
scale to the building scale. We create biologically inspired and engineered design fabrication tools and technologies and structures aiming to enhance the relation between natural and man-made environments. Our research area, entitled Material Ecology, integrates computational form-finding strategies with biologically inspired fabrication. This design approach enables the mediation between objects and environment; between humans and objects; and between humans and environment. Our goal is to enhance the relation between natural and man-made environments by achieving high degrees of design customization and versatility, environmental performance integration, and material efficiency. We seek to establish new forms of design and novel processes of material practice at the intersection of computer science, material engineering, and design and ecology, with broad applications across multiple scales.

**Printing objects that can incorporate living organisms: A 3D printing system that controls the behavior of live bacteria could someday enable medical devices with therapeutic agents built in**


A method for printing 3D objects that can control living organisms in predictable ways has been developed by an interdisciplinary team of researchers at MIT and elsewhere. The technique may lead to 3D printing of biomedical tools, such as customized braces, that incorporate living cells to produce therapeutic compounds such as painkillers or topical treatments, the researchers say.

The new development was led by MIT Media Lab Associate Professor Neri Oxman and graduate students Rachel Soo Hoo Smith, Christoph Bader, and Sunanda Sharma, along with six others at MIT and at Harvard University’s Wyss Institute and Dana-Farber Cancer Institute. The system is described in a paper recently published in the journal Advanced Functional Materials.

“We call them hybrid living materials, or HLMs,” Smith says. For their initial proof-of-concept experiments, the team precisely incorporated various chemicals into the 3D printing process. These chemicals act as signals to activate certain responses in biologically engineered microbes, which are spray-coated onto the printed object. Once added, the microbes display specific colors or fluorescence in response to the chemical signals.

In their study, the team describes the appearance of these colored patterns in a variety of printed objects, which they say demonstrates the successful incorporation of the living cells into the surface of the 3D-printed material, and the cells’ activation in response to the selectively placed chemicals....

**FIBERBOTS: Design of a multi-agent, fiber composite digital fabrication system**

The FIBERBOTS project was developed by the Mediated Matter group at the MIT Media Lab. Researchers include: Markus Kayser, Levi Cai, Christoph Bader, Sara Falcone, Nassia Inglessis, Barrak Darweesh, João Costa, and Prof. Neri Oxman (Founding Director).

Paper: [https://link.springer.com/chapter/10.1007/978-3-319-92294-2_22](https://link.springer.com/chapter/10.1007/978-3-319-92294-2_22)

[https://www.media.mit.edu/projects/fiberbots/overview/](https://www.media.mit.edu/projects/fiberbots/overview/)
FIBERBOTS is a digital fabrication platform fusing cooperative robotic manufacturing with abilities to generate highly sophisticated material architectures. The platform can enable design and digital fabrication of large-scale structures with high spatial resolution leveraging mobile fabrication nodes, or robotic "agents" designed to tune the material make-up of the structure being constructed on the fly as informed by their environment.

Some of nature’s most successful organisms collaborate in a swarm fashion. Nature’s builders leverage hierarchical structures in order to control and optimize multiple material properties. Spiders, for instance, spin protein fibers to weave silk webs with tunable local and global material properties, adjusting their material composition and fiber placement to create strong yet flexible structures optimized to capture prey. Other organisms, such as bees, ants and termites cooperate to rapidly build structures much larger than themselves.

**Making Data Matter: Voxel-printing for the digital fabrication of data across scales and domains**

We present a multimaterial voxel-printing method enabling the physical visualization of data sets commonly associated with scientific imaging. Leveraging voxel-based control of multimaterial 3D printing, our method enables additive manufacturing of discontinuous data types such as point cloud data, curve and graph data, image-based data, and volumetric data. By converting data sets into dithered material deposition descriptions, through modifications to rasterization processes, we demonstrate that data sets frequently visualized on screen can be converted into physical, materially heterogeneous objects.

Our approach alleviates the need to post-process data sets to boundary representations, preventing alteration of data and loss of information in the produced physicalizations. Therefore, it bridges the gap between digital information representation and physical material composition. We evaluate the visual characteristics and features of our method, assess its relevance and applicability in the production of physical visualizations, and detail the conversion of data sets for multimaterial 3D printing. We conclude with exemplary 3D printed datasets produced by our method pointing towards potential applications across scales, disciplines, and problem domains.

**Water-Based Additive Manufacturing**

This research presents water-based robotic fabrication as a design approach and enabling technology for additive manufacturing (AM) of biodegradable hydrogel composites. We focus on expanding the dimensions of the fabrication envelope, developing structural materials for additive deposition, incorporating material-property gradients, and manufacturing architectural-scale biodegradable systems. The technology includes a robotically controlled AM system to produce biodegradable composite objects, combining natural hydrogels with other organic aggregates. It demonstrates the approach by designing, building, and evaluating the mechanics and controls of a multi-chamber extrusion system. Finally, it provides evidence of large-scale composite objects fabricated by our technology that display graded properties and feature sizes ranging from micro- to macro-scale. Fabricated objects may be chemically stabilized or dissolved in water and recycled within minutes. Applications include the
fabrication of fully recyclable products or temporary architectural components, such as tent structures with graded mechanical and optical properties.

EMANUEL M SACHS
Professor of Mechanical Engineering, http://meche.mit.edu/people/faculty/sachs@mit.edu, https://lemelson.mit.edu/resources/emanuel-sachs

Emanuel “Ely” Sachs is a Professor of Mechanical Engineering at MIT. Professor Emanuel Sachs has spent his career moving back and forth between academia and industry. He has co-founded or otherwise been involved in seven start-up companies based on his inventions and co-inventions, including three that went public, one that was acquired by a public company, and three that are still private. Several of these companies are in the field of 3D Printing, which he helped to found, beginning in the late 1980s. Several of the companies are in Photovoltaics — solar cells. He has also contributed inventions in widespread use for process control for microelectronic fabrication. Professor Sachs is committed to teaching and has brought innovative methods to the teaching of invention, the engineering sciences, design, and manufacturing. He has received several teaching awards in conjunction with this work. He is a member of the National Academy of Engineering.

... His invention of string ribbon crystal growth makes it possible to manufacture photovoltaic cells and panels more efficiently and inexpensively than ever before. The process allows for the production of continuous thin strips of multi-crystalline wafers. In the past it was necessary to saw through a block of the substance to create these discs, a time-consuming and expensive process that also produces damaged material that needs to be culled from the final yield. String ribbon significantly reduces manufacturing cost for some types of solar panels, which in turn makes adoption of the technology on a wider scale more feasible. Sachs not only created the core process but also a method for seeding the growth of the necessary silicon material, as well as a method for continuous purification of the silicon during growth....

3D printing metals like thermoplastics: Fused filament fabrication of metallic glasses

Whereas 3D printing of thermoplastics is highly advanced and can readily create complex geometries, 3D printing of metals is still challenging and limited. The origin of this asymmetry in technological maturity is the continuous softening of thermoplastics with temperature into a readily formable state, which is absent in conventional metals. Unlike conventional metals, bulk metallic glasses (BMGs) demonstrate a supercooled liquid region and continuous softening upon heating, analogous to thermoplastics. Here we demonstrate that, in extension of this analogy, BMGs are also amenable to extrusion-based 3D printing through fused filament fabrication (FFF). When utilizing the BMGs’ supercooled liquid behavior, 3D printing can be realized under similar conditions to those in thermoplastics. Fully dense and amorphous BMG parts are 3D printed in ambient environmental conditions resulting in high-strength metal parts. Due to the similarity between FFF of thermoplastics and BMGs, this method may leverage the technology infrastructure built by the thermoplastic FFF community to rapidly realize and proliferate accessible and practical printing of metals.
Traditional and additive manufacturing of a new Tungsten heavy alloy alternative

A new class of rapid-sintering, fine-grained alloys recently developed is being commercially scaled through both traditional and additive manufacturing approaches. This paper discusses the scientific underpinnings of these new alloys and their processing, specifically for a W-based alloy as an alternative to Tungsten Heavy Alloy (WHA). This new alloy offers similar density and sintering temperatures to traditional WHA, but with a fine, thermally-stable microstructure that has the potential for higher temperature operation and significantly higher strength as compared to WHAs. The new alloy can be manufactured through established traditional approaches (e.g. press and sinter) and also through a recently developed 3D printing approach.

LAWRENCE SASS
Associate Professor of Architecture, Director, Digital Design Fabrication Group,
http://architecture.mit.edu/faculty/lawrence-sass
Group: http://ddf.mit.edu/
Pubs: https://scholar.google.com/citations?hl=en&user=CIl8F6cAAAAJ&view_op=list_works&sortby=pubdate

Larry Sass is an architectural designer and researcher exploring digital design and fabrication across scales. As an associate professor in the Department of Architecture at MIT, Larry has taught courses specifically in digital fabrication and design computing since 2002... Larry has published widely, and has exhibited his work at the Museum of Modern Art in New York City.

Larry’s research focused on digital delivery of housing for low income families. Main ideas are centered on discovery and development of new design tools that automated the production of design models and aid in fabrication of finished construction. He believes that hand crafted, hand operated construction will soon be a thing of the past, and that in the future, buildings will be printed with machines run by computers. Today in the age of manufacturing with information and new forms of machine intelligence more than ever designers will need new tools to produce their ideas. His latest obsession is development of fabrication-based software that helps designers and builders physical produce ideas from 3D computer models.

Design Fabrication Group
http://ddf.mit.edu/

The Design Fabrication Group explores the application of digital fabrication for Building Delivery. We aim to discover effective methods to apply computation to the design and production of buildings directly from 3D CAD models. The goal is to help people construct homes instantly using digital fabrication. Our systems make possible immediate manufacturing of structures as a kit of parts from a 3D model. We use a variety of manufacturing methods from additive to subtractive.

The theoretical framework of our system is based on generative modeling techniques found in evolutionary design. The system, guided by rules, decomposes an initial 3D shape into smaller
interlocking parts ready for CAD/CAM fabrication and assembly as a physical kit of parts. In theory, our evolutionary grammar can support delivery of any size building and any number of components.

**Digital Fabrication of Affordable Housing for Somerville, MA**
http://ddf.mit.edu/node/86
(2018) This three-family, Victorian style prototype demonstrates the potential of high precision, digitally fabricated, wood-frame construction. This model is 1/6th full scale, built of interlocking, laser cut and 3D printed components. This method of design, computing and fabrication is defined as Planar Modeling, a computer graphical method of 3D decomposition. The system decomposes a starting shape into modules first, followed by decomposition of each module into flat planes complete with interlocking joineries.

Affordability derives from the removal of any manual measuring and manual component manufacturing. Data for every component is generated by the computer. As software, Planar Modeling supplies the designer with measurements for material use, machine tool paths and time to assemble either by hand or robotic assistance. The advantage of Planar Modeling is that component geometry used to fabricate this prototype can also be used to fabricate a full-scale product using common CNC machines (computer numerically controlled) found frequently in cabinet making and woodworking shops.

**Generative computer-aided design: multi-modality large-scale direct physical production**

A rapid prototyping system for creating large-scale physical objects directly from computer models is introduced. Several production modalities incorporated in the system can be used to produce objects in different scales and types. Parts of the objects are generated by computational algorithms with appealing features that enable CNC manufacturing and facilitate manual assembly. Experiments have shown that man is an important factor of the production process even though the system has automated majority of part generation and fabrication. We show several large models created from the system, discuss problems associated with large-scale prototyping, and present potential applications of the proposed methods.

**SKYLAR TIBBITS**
Associate Professor of Design Research, https://architecture.mit.edu/faculty/skylar-tibbits
Co-director and Founder, Self-Assembly Lab
Lab: https://selfassemblylab.mit.edu/

Skylar Tibbits is a co-director and founder of the Self-Assembly Lab housed at MIT’s International Design Center. The Self-Assembly Lab focuses on self-assembly and programmable material technologies for novel manufacturing, products and construction processes. Skylar is an Associate Professor of Design Research in the Department of Architecture where he teaches graduate and undergraduate design studios and coordinate's MIT's Design Minor and Design Major programs. Skylar was recently named R&D Magazine's 2015 Innovator of the Year, 2015 National Geographic Emerging Explorer, 2014 Inaugural WIRED Fellow, 2014 Gifted Citizen, 2013 Fast Company Innovation by Design Award, 2013
Architectural League Prize, The Next Idea Award at Ars Electronica 2013, Visionary Innovation Award at the Manufacturing Leadership Summit, 2012 TED Senior Fellow and was named a Revolutionary Mind in SEED Magazine’s 2008 Design Issue.

Previously, he has worked at a number of renowned design offices including: Zaha Hadid Architects, Asymptote Architecture and Point b Design. He has designed and built large-scale installations at galleries around the world, has been published extensively in outlets such as the New York Times, Wired, Nature, Fast Company as well as various peer-reviewed journals and books.

**Self-Assembly Lab**

A research lab at MIT inventing self-assembly and programmable material technologies [https://selfassemblylab.mit.edu/](https://selfassemblylab.mit.edu/)

Self-Assembly is a process by which disordered parts build an ordered structure through local interaction. We have demonstrated that this phenomenon is scale-independent and can be utilized for self-constructing and manufacturing systems at nearly every scale. We have also identified the key ingredients for self-assembly as a simple set of responsive building blocks, energy and interactions that can be designed within nearly every material and machining process available. Self-assembly promises to enable breakthroughs across every application of biology, material science, software, robotics, manufacturing, transportation, infrastructure, construction, the arts, and even space exploration. The Self-Assembly Lab is working with academic, commercial, nonprofit, and government partners, collaborators, and sponsors to make our self-assembling future a reality.

**Design and Computational Modeling of a 3D Printed Pneumatic Toolkit for Soft Robotics**

Cosima du Pasquier, Tian Chen, Skylar Tibbits, and Kristina Shea, Soft Robotics Vol. 6, No. 5 Published Online: 4 Oct 2019 [https://doi.org/10.1089/soro.2018.0095](https://doi.org/10.1089/soro.2018.0095)

Soft and compliant robotic systems have the potential to interact with humans and complex environments in more sophisticated ways than rigid robots. The majority of the state-of-the art soft robots are fabricated with silicone casting. This method is able to produce robust robotic parts, yet its results are difficult to quantify and replicate. Silicone casting also limits design complexity as well as customization due to the need to make new molds. As a result, most designs are tailored for simple, individual tasks, that is, bending, gripping, and crawling. To address more complex engineering challenges, this work presents soft robots that are fabricated by using multi-material three-dimensional printing. Instead of monolithic designs, we propose a pneumatic modular toolkit consisting of a bending and an extending appendage, as well as rigid building blocks. They are assembled to achieve different tasks. We show that the performance of both appendages is (1) repeatable, that is, the same internal pressure results in the same rotation or extension across multiple specimens and repetitions, and (2) predictable, that is, the respective deformations can be modeled by using finite element analysis. Using multiple instances of both building blocks, we demonstrate the versatility of this toolkit by assembling and actuating a gripper and a crawling caterpillar. The reliability of the mechanics of the building blocks and the assembled robots show that this simple toolkit can serve as a basis for the next generation of soft robots.
From Self-Assembly to Evolutionary Structures

The Self-Assembly Lab at MIT is at the forefront of the move towards evolutionary construction processes. Three of the Lab’s members – doctoral researcher Athina Papadopoulou, co-director Jared Laucks and co-founder Skylar Tibbits – report on its recent experiments in macro-scale fabrication that relies on the reactions of specially designed material components, both among themselves and with their environment.

LUIS F. VELÁSQUEZ-GARCÍA
Principal Research Scientist, https://www.mtl.mit.edu/wpmu/lfv/about/principal-investigator
https://sense.mit.edu/people/luis-velasquez-garcia
Group: https://www.mtl.mit.edu/wpmu/lfv/
Pubs: https://scholar.google.com/citations?hl=en&user=UgYF_AIAAAJ&view_op=list_works&sortby=pubdate

Luis Fernando Velásquez-García received the Mechanical Engineer degree (valedictorian of the School of Engineering, magna cum laude) and the Civil Engineer degree (valedictorian of the School of Engineering, magna cum laude) from the Universidad de Los Andes, Bogotá, Colombia, in 1998 and 1999, respectively, and the M.S. degree and the Ph.D. degree in Department of Aeronautics and Astronautics of MIT, in 2001 and 2004, respectively.

In 2004, after completing his studies, Dr. Velásquez-García became a Postdoctoral Associate with the Microsystems Technology Laboratories (MTL), where he was appointed Research Scientist in 2005, and Principal Scientist and Core Member of MTL in 2009. Dr. Velásquez-García is an expert in micro- and nanofabrication technologies, and his research focuses in the application of micro- and nano-technology to multiplexed scaled-down systems to attain better performance. He has conducted research in micro- and nanotechnology applied to a wide range of topics including electrospray, field electron devices, 3-D HV packaging, mass spectrometry, propulsion, and chemical reactors. He has authored more than 37 journal publications and 60 peer-reviewed conference proceedings, and he is the holder of 7 patents on MEMS technologies. Dr. Velásquez-García is a senior member of the Institute of Electrical and Electronics Engineers (IEEE), senior member of the American Institute of Aeronautics and Astronautics (AIAA), and full member of the honor research society Sigma Xi.

Patent: Vacuum pumps and methods of manufacturing the same
Inventors: Luis Fernando Velásquez-García, Anthony Park Taylor

Techniques for manufacturing miniaturized diaphragm pumps using additive manufacturing techniques, such as polyjet printing, are provided, as are the pumps and systems that result from using such techniques to produce the pumps. The provided pumps include a compression chamber that has a first surface, a second opposed surface, and a conical outer wall that extends between the first surface and the second surface and that has a bowed configuration in which the outer wall has a generally concave shape. A diaphragm is disposed proximate to the compression chamber, and the pump also includes one or more valves that control the flow of
fluid between the compression chamber and one more fluid ports. Fluid can be selectively vacuumed into and exhausted out of the compression chambers. Various manufacturing techniques for fabricating the pumps are also provided.

**Fully 3D-Printed, Monolithic, Mini Magnetic Actuators for Low-Cost, Compact Systems**  

We report the design, fabrication, and experimental characterization of the first fully 3D-printed, multi-material miniature magnetic actuators for compact systems in the literature. The actuator design integrates a bonded hard magnet made of NdFeB microparticles embedded in a Nylon 12 matrix (55% by volume) with structural and support elements made of pure Nylon 12. The device is a 10 mm-diameter, 1.2 mm wall-thick, and 9 mm tall cylindrical frame that mounts on an off-the-shelf solenoid and a 10 mm diameter, 100 μm-thick, leak-tight membrane connected at its center to a 4 mm diameter, 4.95 mm tall hard magnet. The actuators are monolithically printed in layers as thin as using -wide strokes via fused filament fabrication (FFF) –a low-cost 3D printing technology capable of processing high-performance thermoplastics to create monolithic objects made of a plurality of distinctive feedstock. The average surface ...

**THESIS: ASSESSING THE OPPORTUNITY TO PRODUCE NITINOL MEDICAL DEVICE COMPONENTS USING ADDITIVE MANUFACTURING**  
Arvind R. (Arvind Rama) Kalidindi, 2019 M.B.A., MIT Sloan School of Management  
Advisors: Profs. Thomas Roemer and Christopher A. Schuh  
https://hdl.handle.net/1721.1/122273

Nitinol is an important alloy for medical device applications due to its exceptional combination of strength and elasticity. Most Nitinol is produced in wire form and then braided or laser cut into the complex geometries needed for medical device applications. These manufacturing processes are costly and can be labor-intensive. Additive manufacturing, or 3D printing, offers a tantalizing alternative to the status quo of Nitinol manufacturing as the desired part can be printed to shape, greatly simplifying the operations and cost of producing medical device components. Working with Boston Scientific in Clonmel, Ireland, roughly 100 Nitinol samples were additively manufactured to determine whether quality parts could be printed. Through a design of experiment procedure, the 3D printing parameters were optimized to develop settings for parts with high relative density, low internal defects, and low impurity concentrations, meeting the ASTM F2063 standards for medical device-grade Nitinol. The main challenge from an engineering perspective is the loss of Ni during printing, which could require either higher power lasers or sourcing high Ni content powder to reach the desired properties. Operationally, a cost accounting model was developed to match the expected operational setup for additively manufacturing Nitinol, with smaller components comparing favorably cost-wise to traditionally manufactured Nitinol components. The engineering and business analyses were combined to determine the best applications considering Nitinol properties used (superelasticity, shape memory, and ductility) and the opportunity for 3D printing (prototyping, replacing existing Nitinol parts, developing new Nitinol parts). The best opportunities in the short-term for this technology were identified to be prototyping and developing new Nitinol components targeting ductility and shape memory Nitinol applications.
LEARN: MIT XPRO—ADDITIVE MANUFACTURING FOR INNOVATIVE DESIGN AND PRODUCTION (FEB 2020)
24 Feb 2020—>11 weeks, Online, $1950 (MIT ILP discount 15%)

This course is intentionally designed to be accessible to the beginner, with pathways for deep technical understanding for experienced professionals. Past learner job roles have included engineers, designers, and executives.

MATERIALS, AND MICRO- & NANO-MANUFACTURING

DUANE BONING
Clarence J. LeBel Professor in Electrical Engineering, and Professor of Electrical Engineering and Computer Science; Engineering Faculty Co-Director of the Leaders for Global Operations (LGO) Program, http://www-mtl.mit.edu/wpmu/researchgroupsboning/boning/
https://quest.mit.edu/people/principal-investigators/duane-boning/
Group: https://www-mtl.mit.edu/wpmu/researchgroupsboning/

Dr. Duane S. Boning is the Clarence J. LeBel Professor in Electrical Engineering, and Professor of Electrical Engineering and Computer Science in the EECS Department at MIT. He is affiliated with the MIT Microsystems Technology Laboratories, and serves as MTL Associate Director for Computation and CAD. He is also the Engineering Faculty Co-Director of the MIT Leaders for Global Operations (LGO) program, serving in that role since September 2016. From 2004 to 2011, he served as Associate Head of the EECS Department at MIT. From 2011 through 2013 he was the Director/Faculty Lead of the MIT Skoltech Initiative, and from 2011 through July 2018, he was the faculty Director of the MIT/Masdar Institute Cooperative Program....

His research interests include the modeling and control of variation in IC, photonics, and MEMS processes, devices, and circuits. Particular emphasis is on statistical characterization and design for manufacturing of devices and circuits in advanced technologies, and the modeling of chemical mechanical polishing (CMP), spin-on coatings, plasma etch, and nanoimprint/embossing processes.

Statistical Metrology Group
https://www-mtl.mit.edu/wpmu/researchgroupsboning/

The Statistical Metrology Group focuses on the understanding and reduction of variation in advanced micro- and nano-fabrication processes, devices, and circuits, particularly in integrated circuit, photonic and MEMS technologies. We develop new methods and approaches to measure, model, and mitigate the wide range of deviations observed in manufactured devices.

One branch of our work is closely tied to important semiconductor fabrication processes, and emerging processes in MEMS and nanofabrication technologies.... The second major branch of our work is tied to the design implications of manufacturing variation. We develop novel test circuits to measure variation, particularly to gather the large numbers of measurements to enable modeling of not only mean but also variance dependencies. We develop new approaches to model these variations, ranging from spatial correlation models, to systematic layout models,
to random and other variation models in compact model form. We study the impact of variations in parameters such as \( V_t \), \( I_d(sat) \), and leakage on circuit and system (e.g. multicore) design. Finally, we consider yield optimization, circuit compensation and self-healing approaches to mitigate these variations.

**Thesis: Machine learning for automated anomaly detection in semiconductor manufacturing**

Michael D DeLaus, 2019 M.Eng., Department of Electrical Engineering & Computer Science
Advisor: Prof. Duane Boning
https://hdl.handle.net/1721.1/123017

In the realm of semiconductor manufacturing, detecting anomalies during manufacturing processes is crucial. However, current methods of anomaly detection often rely on simple excursion detection methods, and manual inspection of machine sensor data to determine the cause of a problem. In order to improve semiconductor production line quality, machine learning tools can be developed for more thorough and accurate anomaly detection. Previous work on applying machine learning to anomaly detection focused on building reference cycles, and using clustering and time series forecasting to detect anomalous wafer cycles. We seek to improve upon these techniques and apply them to related domains of semiconductor manufacturing. The main focus is to develop a process for automated anomaly detection by combining the previously used methods of cluster analysis and time series forecasting and prediction. We also explore detecting anomalies across multiple semiconductor manufacturing machines and recipes.

**Nicholas X. Fang**
Professor of Mechanical Engineering, http://meche.mit.edu/people/faculty/nicfang@mit.edu
Group/Lab: https://web.mit.edu/nanophotonics/
https://scholar.google.com/citations?hl=en&user=PcoqNjgAAAAJ&view_op=list_works&sortby=pubdate

Nicholas X. Fang arrived at MIT in Jan 2011 as Associate Professor of Mechanical Engineering. Prior to MIT, he worked as an assistant professor at the University of Illinois Urbana-Champaign. Professor Fang’s areas of research look at nanophotonics and nanofabrication. His recognitions include the ASME Chao and Trigger Young Manufacturing Engineer Award (2013); the ICO prize from the International Commission of Optics (2011); an invited participant of the Frontiers of Engineering Conference by National Academies in 2010; the NSF CAREER Award (2009) and MIT Technology Review Magazine’s 35 Young Innovators Award (2008).

Professor Fang seeks to bridge new frontiers in nanophotonics and nanomanufacturing. His research group concentrates on creating devices for focusing photon and sound into nanometer scale and using them for imaging and nanofabrication. These devices and technologies could lead revolutionary methods of diagnosing living cells at molecular scale details, without the use of an electron microscope, and open the door for the non-destructive screening of drugs and other biological materials.

**Nanophotonics and 3D Nanomanufacturing Laboratory**
https://web.mit.edu/nanophotonics/
Our research efforts concentrate on focusing photon and sound into sub-wavelength scales. While we emphasize on new insights of material and device design from fundamental approaches, we also actively pursue the applications of our technology in the areas of energy conversion, communication, and biomedical imaging.

At one end, we study basic wave-material interactions from excitation of basic building blocks. Our work at this end of the spectrum has led to the invention of new class of functional metamaterials, such as optical metamaterials with aims of breaking the diffraction limit, and acoustic metamaterials of negative stiffness, for bending and trapping sound and elastic waves in engineered spaces.

At the other end of the spectrum, we develop new micro/nanofabrication and characterization processes that are needed for these novel metamaterials. Our research effort in this area includes invention of nanoscale ionic manufacturing methods, coupled with computation models of ionic transport in the solid electrolyte. We also explore these novel materials and nanofabrication processes to a range of important applications, such as: thin film optical metamaterials for photochemical energy conversion, as well as acoustic metamaterials for manipulation of shock waves.

Micro and Nano Manufacturing
https://web.mit.edu/nanophotonics/research.htm#Manufacturing

Metal Investment Casting: Metal investment casting is a process of converting a plastic or wax pattern into a metal replica. We are exploring the limits of this technology by closely studying each step of this process in order to determine the current obstacles in the production of arbitrary metal geometries in terms of parts complexity, resolution, volume, or finish. The use of metal investment casting is suited for demanding applications where metallurgic or surface smoothness properties are critical and not addressable by direct metal additive manufacturing techniques. We work at the frontline of plastic additive manufacturing to produce high resolution parts for use in investment casting tests. We also tackle upstream issues with geometry creation and downstream issues with investment handling, firing and cleaning for a holistic study of this process.

3D-printed microarchitected materials for efficient heat and mass transfer: Efficient transport and reaction for catalytic reactors are desirable in a broad array of implications for biological and environmental applications, or the automotive and power plant industry. Porous substrates with thinner cell/pore walls and higher cell/pore density enable faster activation of the catalyst due to low-heat capacity, larger catalytic surface area, and lower hydrodynamic resistance of working fluids. However, manufacturing of well-engineered structures with thin wall and higher cell/pore density remained a challenge. To overcome the limitations, we study manufacturing-friendly structural design and additive manufacturing process for microarchitected ceramic substrates with both a high surface area to volume ratio and low-heat capacity. Our central idea for achieving efficient ceramic substrates is leveraging on the geometrical benefits of 3D microlattices of thin-walled hollow-tubes.

Scalable additive manufacturing via integral image formation
Additive manufacturing techniques enable the fabrication of functional microstructures with mechanical and chemical properties tailored to their intended use. One common technique is stereolithography, which has recently been augmented in response to modern demands to support smaller features, larger build areas, and/or faster speeds. However, a limitation is that such systems typically utilize a single-aperture imaging configuration, which restricts their ability to produce microstructures at large volumes due to the tradeoff between the image resolution and image field area. In this paper, we demonstrate three versatile imaging functions based on the coupling a planar lens array, namely, parallel image transfer, kaleidoscopic superposition, and integral reconstruction, the combination of which is termed integral lithography. In this approach, the individual microlenses in the planar lens array maintain a high numerical aperture and are employed in the creation of digital light patterns that can expand the printable area by the number of microlenses (10^3-10^4). The proposed lens array-based integral imaging system provides the concurrent ability to scale-up and scale-down incoming image fields, thereby enabling the scalable stereolitographic fabrication of three-dimensional features that surpass the resolution-to-area scaling limit. The proposed system opens up new possibilities for producing periodic microarchitectures spanning four orders of magnitude from micrometers to centimeters that can be applied to biological scaffolds, metastructures, chemical reactors, and functional surfaces.

**Rapid multi-material 3D printing with projection micro-stereolithography using dynamic fluidic control**

Daehoon Han, Chen Yang, Nicholas X Fang, Howon Lee (2019) Additive Manufacturing, 27, 606-615, May 2019, [https://doi.org/10.1016/j.addma.2019.03.031](https://doi.org/10.1016/j.addma.2019.03.031)

Mask projection stereolithography is a digital light processing-based additive manufacturing technique that has various advantages, such as high-resolution, scanning-free parallel process, wide material sets available, and support-structure-free three-dimensional (3D) printing. However, multi-material 3D printing with mask projection stereolithography has been challenging due to difficulties of exchanging a liquid-state material in a vat. In this work, we report a rapid multi-material projection micro-stereolithography using dynamic fluidic control of multiple liquid photopolymers within an integrated fluidic cell. Highly complex multi-material 3D micro-structures are rapidly fabricated through an active material exchange process. Material flow rate in the fluidic cell, material exchange efficiency, and the effects of energy dosage on curing depth are studied for various photopolymers. In addition, the degree of cross-contamination between different materials in a 3D printed multi-material structure is evaluated to assess the quality of multi-material printing. The pressure-tight and leak-free fluidic cell enables active and fast switch between liquid photopolymers, even including micro-/nano-particle suspensions, which could potentially lead to facile 3D printing of multi-material metallic/ceramic structures or heterogeneous biomaterials. In addition, a multi-responsive hydrogel micro-structure is printed using a thermo-responsive hydrogel and an electroactive hydrogel, showing various modes of swelling actuation in response to multiple external stimuli. This new ability to rapidly and heterogeneously integrate multiple functional materials in three-dimension at micro-scale has potential to accelerate advances in many emerging areas including 3D metamaterials, tissue engineering, and soft robotics.

**SANG-GOOK KIM**

Professor of Mechanical Engineering, [http://meche.mit.edu/people/faculty/sangkim@mit.edu](http://meche.mit.edu/people/faculty/sangkim@mit.edu)
Sang-Gook Kim is a professor in the Department of Mechanical Engineering. He held positions at Axiomatics Co., Cambridge, MA (1986) and Korea Institute of Science and Technology (1986-1991). Then he became a corporate executive director at Daewoo Corporation, Korea, and directed the Central Research Institute of Daewoo Electronics Co. until 2000 when he joined MIT. He is currently the Micro/Nano Area Head of the Department of Mechanical Engineering at MIT.

Prof. Kim’s research has been in the field of product realization throughout his career at both the industry and academia. His recent research includes piezoelectric MEMS energy harvesting, micro ultrasonic transducers and nano-engineered energy conversion for carbon neutrality and solar water splitting systems. He is a fellow of CIRP (International Academy for Production Engineering), fellow of ASME, and overseas member of Korean National Academy of Engineering.

Park Center for Complex Systems: Micro Nano Systems Laboratory (MNSL)
https://micronanosystems.mit.edu/
MNSL has been working on how to better design and manufacture products with micro- and nano-scale components and structures.

**AI for design: Virtual design assistant**

Sang-Gook Kim, Sang Min Yoon, Maria Yang, Jungwoo Choi, Haluk Akay, Edward Burnell (2019) CIRP Annals, Volume 68, Issue 1, 2019, Pages 141-144
https://doi.org/10.1016/j.cirp.2019.03.024
https://micronanosystems.mit.edu/

Engineering faces many wicked problems: irreducibly interdisciplinary with multiple competing objectives, and of such large scale and complexity that will require processes to deeply rely on human insights and power of computation. The resurgence of machine learning offers the possibility for new forms of human/computer collaboration where each fuels hybrid intelligence in complementary ways. A concept of virtual design assistant (VDA) is developed as a platform to bring the hybrid intelligence in solving complex design challenges. A deep learning-based abstraction process is developed to provide VDA a function to extract structured functional requirements from fragmental design specifications and customer needs.

**BRIAN L WARDLE**
Professor of Aeronautics and Astronautics, Raymond L. Bisplinghoff Faculty Fellow, Director, necstlab and Nano-Engineered Composite aerospace Structures Consortium
https://aeroastro.mit.edu/brian-wardle

Specialization and Research Interests: Nano-engineered composites, composite and layered materials; hybrid nanocomposite systems; MEMS power devices and energy harvesting; structural health monitoring systems; active materials and devices; finite-element modeling; structural response and testing; buckling mechanics

**Necstlab**
http://necstlab.mit.edu/
The necstlab (pronounced ‘next lab’) research group explores new concepts in engineered materials and structures, and is directed by Prof. Wardle (Aeronautics & Astronautics). The group’s mission is to lead the advancement and application of new knowledge at the forefront of materials and structures understanding, with research contributions in both science and engineering. Applications of interest include enhanced (aerospace) advanced composites, multifunctional attributes of structures such as damage sensing, and also microfabricated (MEMS) topics. A significant effort over the past decade has been to use nanoscale materials to enhance performance of advanced aerospace materials and their structures through the industry supported NECST Consortium.

The necstlab group has interests that span fundamental materials synthesis questions through to structural applications of both hybrid and traditional materials. This includes longstanding projects in MEMS and now bioNEMS/MEMS. While not all-encompassing, much of the group’s work supports the efforts of the NECST Consortium, an aerospace industry-supported research initiative that seeks to develop the underlying understanding to create enhanced-performance advanced composites using nanotechnology. Beyond the NECST Consortium Members, necstlab research is supported by industry, AFOSR, ARO, NASA, NIST, NSF, ONR, and others.

**A new approach to making airplane parts, minus the massive infrastructure:**
*Carbon nanotube film produces aerospace-grade composites with no need for huge ovens or autoclaves*


A modern airplane’s fuselage is made from multiple sheets of different composite materials, like so many layers in a phyllo-dough pastry. Once these layers are stacked and molded into the shape of a fuselage, the structures are wheeled into warehouse-sized ovens and autoclaves, where the layers fuse together to form a resilient, aerodynamic shell.

Now MIT engineers have developed a method to produce aerospace-grade composites without the enormous ovens and pressure vessels. The technique may help to speed up the manufacturing of airplanes and other large, high-performance composite structures, such as blades for wind turbines.

The researchers detail their new method in a paper published today in the journal Advanced Materials Interfaces (see next item).

“If you’re making a primary structure like a fuselage or wing, you need to build a pressure vessel, or autoclave, the size of a two- or three-story building, which itself requires time and money to pressurize,” says Brian Wardle, professor of aeronautics and astronautics at MIT. “These things are massive pieces of infrastructure. Now we can make primary structure materials without autoclave pressure, so we can get rid of all that infrastructure.”

Wardle’s co-authors on the paper are lead author and MIT postdoc Jeonyoon Lee, and Seth Kessler of Metis Design Corporation, an aerospace structural health monitoring company based in Boston....

**Void-Free Layered Polymeric Architectures via Capillary-Action of Nanoporous**
Films
Jeonyoon Lee, Seth S. Kessler, Brian L. Wardle, Advanced Materials Interfaces
First published: 13 January 2020  https://doi.org/10.1002/admi.201901427

Here, a nanomaterial with morphology-controlled nanoscale capillaries is utilized to overcome manufacturing challenges in layered polymeric architectures. It is demonstrated that the capillary pressure from a nanoporous film replaces the need for applied pressure to manufacture void-free layered polymeric architectures. Manufacturing of aerospace-grade advanced carbon fiber composites is performed for the first time without utilizing pressure from an autoclave. Combined with a conductive curing approach, this work allows advanced composites to be manufactured without costly oven or pressure vessel infrastructure. The nanomaterial-enabled capillary pressure is quantified as 50% greater than typical pressures used in such processing, and is anticipated to overcome the limitations imposed by the requirement of high applied pressure in many other applications such as adhesive joining of various bulk materials including metals, press forming, and closed-mold infusion processing of layered composites and polymers.

See also: Advanced carbon fiber composite out-of-autoclave laminate manufacture via nanostructured out-of-oven conductive curing
J. Lee, X. Ni, F. Daso, X. Xiao, D. King, J. S. Gómez, T. B. Varela, S. S. Kessler, B. L. Wardle

Unique material innovations reduce costs in manufacturing

This year the Massachusetts Institute of Technology and Metis Design Corp. collaborated to demonstrate an “out-of-oven” composite curing process that addresses the limitations of conventional oven- and autoclave-based processes. Those drawbacks include poor energy efficiency, high operational cost, long cure times and geometrical constraints on the components to be cured. In August, the team demonstrated carbon nanotube heaters for conductively curing composite structures without an oven, achieving equivalent thermophysical and mechanical performance to conventionally cured composites, while reducing cure time by 60% and energy consumption by two orders of magnitude. The team believes that this process contributes to the design and manufacturing of next-generation multifunctional architectures by leveraging nanoengineered laminate capabilities such as sensing, structural health monitoring and ice protection systems.

(PROJECT) INTERACTIVE MANUFACTURING ENABLED BY SIMULTANEOUS SENSING AND RECOGNITION
Prof. Jeehwan Kim (Mechanical Engineering, and Materials Science & Engineering),
http://jeehwanlab.mit.edu/
Jeehwan Kim, associate professor with a dual appointment in mechanical engineering and materials science and engineering, proposes an ultra-sensitive sensor system using neuromorphic chips to improve advanced manufacturing through real-time monitoring of machines. Machine failures compromise productivity and cost. Sensors that can instantly process data to provide real-time feedback would be a valuable tool for preventive maintenance of factory machines.

Kim’s group, also part of RLE, aims to develop single-crystalline gallium nitride sensors that, when connected to AI chips, will create a feedback loop with the factory machines. Failure patterns would be recognized by the AI hardware, creating an intelligent manufacturing system that can predict and prevent failures. These sensors will have the sensitivity to navigate noisy factory environments, be small enough to form dense arrays, and have the power efficiency to be used on a large number of manufacturing machines.

**ROBOTICS, AUTOMATION**

**H. HARRY ASADA**
Ford Professor of Engineering, Singapore Research Professor of Mechanical Engineering, Director, d’Arbeloff Lab for Information Systems & Technology,
http://meche.mit.edu/people/faculty/asada@mit.edu
http://darbelofflab.mit.edu/

Professor Asada was a research scientist at Carnegie Mellon University before coming to MIT in 1982 as an assistant professor. He was promoted to associate professor in 1985, then spent three years at Kyoto University before returning to MIT, where he attained the rank of full professor in 1990. He is the author of three books, has received best-paper awards seven times, and holds nine patents. In 1998 he was awarded the ASME (American Society of Mechanical Engineering) Dynamic Systems and Control Outstanding Investigator Award. The award is given to a Dynamic Systems and Control Division member "who has demonstrated sustained outstanding research contributions, either basic or applied, as a mechanical engineering professional to fields of interest to the DSCD."

Professor Asada is a specialist in robotics and control and he is director of the d’Arbeloff Laboratory for Information Systems and Technology.

**MIT d’Arbeloff Lab**
http://darbelofflab.mit.edu/

The focus of the Bio-Robotics group in the Brit and Alex d'Arbeloff Laboratory for Information Systems and Technology is science and technology of robotic systems motivated by both practical applications and scientific interests. Biological systems have long been a metaphor of robotic systems as well as sources of inspiration for conceiving novel functionality and creating physical embodiments that perform diverse tasks. We in the d’Arbeloff Laboratory extend the traditional bio-mimetic robotics to new frontiers of robotics science and technology for:

- Seeking effective solutions to socially and economically challenging problems,
- Developing key enabling technologies, such as novel actuators, sensors, and
communication technology, and
- Exploring the possibility of using live cells and organelles as components of robots.
- These research activities are seamlessly integrated into graduate and undergraduate education.

**Patent: Extending robotic arm**

Inventors: Haruhiko Harry Asada, Abbas Munir Shikari
2020-01-09: Application status is Pending

Embodiments described herein relate to expandable robotic arms. According to some embodiments, the robotic arm may include a series of expandable segments connected to each other. Further, each of the expandable segments may be individually controlled to expand and/or tilt with one or two tilt degrees of freedom. In operation, the robotic arm may expand sequentially segment by segment from a proximal most segment to a distal most segment to reach a target position and orientation from an initial position and orientation. A variety of methods and algorithms for pathfinding and otherwise operating such a robotic arm are also described.

**Patent: Wearable robotic systems for supporting a load**

Inventors: Haruhiko Harry Asada, Daniel J Gonzalez

Wearable robotic systems including robotic limbs for supporting a load while a user moves through an environment and their methods of use are described. In one embodiment, a robotic system includes robotic limbs with first and second robotic limb segments that are movable between different configurations to support a load while a user is standing or crawling. In another embodiment, a robotic system includes first and second robotic limbs that are substantially located within a plane parallel to a frontal plane of a user when the robotic system is worn. In another embodiment, a wearable robotic system includes first and second robotic limbs and an associated base that is attachable to a user's torso. The first and second robotic limbs may include a plurality of actuators and associated robotic limb segments to couple the robotic legs to the base and control their movement.

**Supernumerary Robotic Limbs (SRL)**

Corresponding author: Federico Parietti

The Supernumerary Robotic Limbs (SRL) is a wearable robot which provides a human user with two additional robotic arms. The SRL is being used to assist wearers in complex tasks, to compensate for their weight while working in uncomfortable positions, and to augment their balance during walking. The robot has a wide range of applications, including the aircraft manufacturing industry, construction sites, elderly assistance and gait rehabilitation.

Design: The Supernumerary Robotic Limbs (SRL) is composed of four main parts. First, it is
equipped with a harness that forms a comfortable yet firm interface with the human body. The harness is attached to the robot base, which follows the shape of the user’s hip and contains control electronics and power storage units. Lastly, two robotic limbs – each with three degrees of freedom – are connected to the base. The most important feature of the SRL is the independence of the robotic limbs from the natural limbs of the user. Unlike conventional exoskeletons, the SRL is not constrained to follow the kinematic configuration of the wearer. Independence allows the SRL to provide assistance by following optimal control laws and not simply by blindly following human motions. The SRL also enables the user to execute tasks that would be impossible to realize using only two arms or two legs. In this sense, the SRL can increase the range of motor skills available to the user. This represents a new form of human augmentation.

... The first aircraft manufacturing task in which the SRL has been used to support the user is drilling. This task is challenging, because it requires high positional accuracy and in some cases coordination between different workers. If two human workers are collaborating to perform a task, one will assume the role of the leader and the other one will be the follower. By recording the motion and the forces involved in this collaborative task, it is possible to develop a control strategy that enables the SRL to act as the follower, compensating for the weight of a part while the wearer drills a hole in it [Llorens-Bonilla 2012]. It is also possible to combine the bracing strategy with the drilling assistance function [Parietti 2014]. In this case, the SRL grasps the environment with one robotic limb and compensates part of the weight of the user. At the same time, the other robotic limb indicates to the worker the exact drilling location, and guides the drill bit by precisely positioning and firmly holding a bushing on the aircraft structure.

Additional studies have characterized in detail the bracing strategy, fully revealing its potential to enhance the safety and reduce the workload of aircraft manufacturing and construction workers....

ALBERTO RODRIGUEZ
Associate Professor of Mechanical Engineering,
https://meche.mit.edu/people/faculty/ALBERTOR@MIT.EDU
Lab/Group: http://mcube.mit.edu/

Alberto Rodriguez is an Associate Professor at the Mechanical Engineering Department at MIT. Alberto graduated in Mathematics (‘05) and Telecommunication Engineering (‘06) from the Universitat Politecnica de Catalunya, and earned his PhD (‘13) from the Robotics Institute at Carnegie Mellon University. He leads the Manipulation and Mechanisms Lab at MIT (MCube) researching autonomous dexterous manipulation, robot automation, and end-effector design. Alberto has received Best Paper Awards at conferences RSS’11, ICRA’13, RSS’18, IROS’18, and RSS’19, and has been finalist for best paper awards at conferences IROS’16 and IROS’18. He has lead Team MIT-Princeton in the Amazon Robotics Challenge between 2015 and 2017, and has received the Amazon Research Award in 2018 and 2019, and the 2018 Best Manipulation System Paper Award from Amazon.

MCube Lab (Manipulation and Mechanisms Laboratory)
http://mcube.mit.edu/
Projects: http://mcube.mit.edu/projects.html
Autonomous robotic manipulation comes from an effective use of materials, modeling, perception, planning, control and design. The MCube Lab brings those disciplines together for the problem of mastering contact. Our goal is to develop technologies to bring reliable autonomous physical interaction closer to reality.

**TossingBot: Learning to Throw Arbitrary Objects with Residual Physics**

A. Zeng, S. Song, J. Lee, A. Rodriguez and T. Funkhouser, 2020 TRO


YouTube: [https://www.youtube.com/watch?v=f5Zn2Up2RjQ](https://www.youtube.com/watch?v=f5Zn2Up2RjQ)

We investigate whether a robot arm can learn to pick and throw arbitrary objects into selected boxes quickly and accurately. Throwing has the potential to increase the physical reachability and picking speed of a robot arm. However, precisely throwing arbitrary objects in unstructured settings presents many challenges: from acquiring reliable pre-throw conditions (e.g. initial pose of object in manipulator) to handling varying object-centric properties (e.g. mass distribution, friction, shape) and dynamics (e.g. aerodynamics). In this work, we propose an end-to-end formulation that jointly learns to infer control parameters for grasping and throwing motion primitives from visual observations (images of arbitrary objects in a bin) through trial and error. Within this formulation, we investigate the synergies between grasping and throwing (i.e., learning grasps that enable more accurate throws) and between simulation and deep learning (i.e., using deep networks to predict residuals on top of control parameters predicted by a physics simulator). The resulting system, TossingBot, is able to grasp and throw arbitrary objects into boxes located outside its maximum reach range at 500+ mean picks per hour (600+ grasps per hour with 85% throwing accuracy); and generalizes to new objects and target locations.

**What are the Important Technologies for Bin Picking? Technology Analysis of Robots in Competitions based on a Set of Performance Metrics**


Bin picking is still a challenge in robotics, as patent in recent robot competitions. These competitions are an excellent platform for technology comparisons since some participants may use state-of-the-art technologies, while others may use conventional ones. Nevertheless, even though points are awarded or subtracted based on the performance in the frame of the competition rules, the final score does not directly reflect the suitability of the technology. Therefore, it is difficult to understand which technologies and their combination are optimal for various real-world problems. In this paper, we propose a set of performance metrics selected in terms of actual field use as a solution to clarify the important technologies in bin picking. Moreover, we use the selected metrics to compare our four original robot systems, which achieved the best performance in the Stow task of the Amazon Robotics Challenge 2017. Based on this comparison, we discuss which technologies are ideal for practical use in bin picking robots in the fields of factory and warehouse automation.
Accurate Vision-based Manipulation through Contact Reasoning

Planning contact interactions is one of the core challenges of many robotic tasks. Optimizing contact locations while taking dynamics into account is computationally costly and in only partially observed environments, executing contact-based tasks often suffers from low accuracy. We present an approach that addresses these two challenges for the problem of vision-based manipulation. First, we propose to disentangle contact from motion optimization. Thereby, we improve planning efficiency by focusing computation on promising contact locations. Second, we use a hybrid approach for perception and state estimation that combines neural networks with a physically meaningful state representation. In simulation and real-world experiments on the task of planar pushing, we show that our method is more efficient and achieves a higher manipulation accuracy than previous vision-based approaches.

NICHOLAS ROY
Professor of Aeronautics and Astronautics, https://aeroastro.mit.edu/nicholas-roy
https://www.csail.mit.edu/person/nicholas-roy
Robust Robotics Group: http://groups.csail.mit.edu/rrg/index.php
https://www.csail.mit.edu/research/robust-robotics-group

Nicholas Roy’s research has focused specifically on the problems that result from uncertainty in the world, such as sensor noise or unpredictable action outcome. Probabilistic, decision-theoretic models have proven to be ideally suited for state estimation in the face of uncertainty; I believe that such models can be equally useful for planning. For example, I have formulated algorithms for a class of planning models called Partially Observable Markov Decision Processes (POMDPs). The POMDP framework is a general model for planning with incomplete information, however, it suffers from substantial computational intractability. My contribution has been an approach for finding approximate policies for large (and currently unsolvable) POMDP models that are relevant to real world systems...
https://www.csail.mit.edu/person/nicholas-roy

Robust Robotics Group
https://www.csail.mit.edu/research/robust-robotics-group
Our research goals are to build unmanned aerial vehicles (drones) that can fly without GPS through unmapped indoor environments, robots that can drive through unmapped cities, and to build social robots that can quickly learn what people want without being annoying or intrusive.

Such robots must be able to perform effectively with uncertain and limited knowledge of the world, be easily deployed in new environments and immediately start autonomous operations with no prior information. This engineering challenge requires algorithmic advances in decision-theoretic planning, statistical inference, and artificial intelligence. We focus on problems of planning and control in domains with uncertain models, using optimization, statistical estimation and machine learning to learn good plans and policies from experience...
Inferring 3D Shape Distributions for Robot Perception and Planning


For a mobile robot to operate autonomously in an unknown environment, it must actively construct a representation of space. To do so, the robot needs to position its sensors to gather information and reason about objects, while coping with occlusions and sensor noise. In this work, we propose a distributional spatial representation based on 3D geometric shapes (such as cylinders and cuboids), which captures the structure of volumetric information compactly and provides a meaningful abstraction for reasoning about objects and viewpoints in the face of uncertainty. We develop methods for inferring shape parameters from point clouds, predicting viewpoint information over shapes, and robustly grasping objects.

Real-Time Human-Robot Communication for Manipulation Tasks in Partially Observed Environments

http://www.rohanpaul.in/content/Papers/2018ISER-interacti.pdf

Effective human-robot teams coordinate activities via communication to optimally perform tasks. In human teams, visual and auditory cues are often used to communicate information about the task and/or environment that may not otherwise be directly observable. Analogously, robots that primarily rely on visual sensors cannot directly observe some attributes of objects that may be necessary for reference resolution or task execution. Algorithms that fuse information communicated by humans about hidden states of objects with information obtained from physical interactions with those objects, such as force measurements and/or joint torques, enable robots to more robustly perform tasks when posed with inaccurate or insufficient information. Also, minimizing latency in understanding language is crucial for human-robot teams because latency in communication reduces mission tempo and limits the effectiveness of collaboration. A robot with a language model that can anticipate a subset of utterances that a human collaborator will likely communicate can leverage idle system time to proactively generate and ground those expressions in the context of its current world model, thus minimizing the latency between receiving an utterance and understanding its meaning. The experiments in this paper address natural language interaction in human-robot teams for tasks where multi-modal (eg visual, auditory, haptic, etc) observations are necessary for robust execution. Contemporary approaches to probabilistic language understanding in partially known environments deal with uncertainty in both physical locations and semantic labels that is resolved upon observation with visual sensors...

DANIELA L RUS
Director, Computer Science and Artificial Intelligence Laboratory (CSAIL), Andrew (1956) and Erna Viterbi Professor of Computer Science and Engineering, Deputy Dean of Research for Schwarzmann College of Computing, Associate Director of MIT’s Quest for Intelligence Core
Group / lab: https://www.csail.mit.edu/research/distributed-robotics-laboratory

Daniela Rus is the Andrew (1956) and Erna Viterbi Professor of Electrical Engineering and Computer Science; Director of the Computer Science and Artificial Intelligence Laboratory
(CSAIL); and Deputy Dean of Research for Schwarzmann College of Computing at MIT. Rus’ research interests are in robotics, artificial intelligence, and data science.

The focus of her work is developing the science and engineering of autonomy, toward the long-term objective of enabling a future with machines pervasively integrated into the fabric of life, supporting people with cognitive and physical tasks. Her research addresses some of the gaps between where robots are today and the promise of pervasive robots: increasing the ability of machines to reason, learn, and adapt to complex tasks in human-centered environments, developing intuitive interfaces between robots and people, and creating the tools for designing and fabricating new robots quickly and efficiently. The applications of this work are broad and include transportation, manufacturing, agriculture, construction, monitoring the environment, underwater exploration, smart cities, medicine, and in-home tasks such as cooking, to serve as director of CSAIL, and its predecessors the AI Lab and the Lab for Computer Science,...


**M-Blocks Modular Robotics**

Creating modular robotic systems which can reconfigure themselves in order to create new robots.

https://www.csail.mit.edu/research/m-blocks-modular-robotics
http://web.mit.edu/johnrom/www/design/
http://web.mit.edu/johnrom/www/design/cube/

The vision of the field of Modular Self-Reconfigurable Robotics (MSRR) is to create swarms of robots which are able to connect to each other and to be able to change their configuration in order to create new robots or structures. The M-Blocks projects introduces a novel hardware system using pulses of angular momentum and magnetic hinges in an attempt to simplify the practical challenges involving modules moving on a substrate of other modules.

**Self-transforming robot blocks jump, spin, flip, and identify each other**

Developed at MIT’s Computer Science and Artificial Intelligence Laboratory, robots can self-assemble to form various structures with applications including inspection


Swarms of simple, interacting robots have the potential to unlock stealthy abilities for accomplishing complex tasks. Getting these robots to achieve a true hive-like mind of coordination, though, has proved to be a hurdle.

In an effort to change this, a team from MIT’s Computer Science and Artificial Intelligence Laboratory (CSAIL) came up with a surprisingly simple scheme: self-assembling robotic cubes that can climb over and around one another, leap through the air, and roll across the ground....

... While the mechanism is quite intricate on the inside, the exterior is just the opposite, which enables more robust connections. Beyond inspection and rescue, the researchers also imagine using the blocks for things like gaming, manufacturing, and health care....
Using Muscle Signals to Lift Objects with Robots

When envisioning robot assistants of the future helping people around the house or in factories, they work as a team with their human partners as fluidly as if they were another person. Since the key to good teamwork is always good communication, we need a way to seamlessly convey desired goals and commands to our robot helpers. Moving towards such a goal, this project looks at the person's muscle activity to inform the robot about how it should move to best assist the person while they collaborate. By using the muscles already involved in performing the task, the robot could almost become like an extension of yourself that can be controlled intuitively.

This represents a step towards building a vocabulary for communicating with a robot assistant in a more natural way. As we continue to enrich this vocabulary, adding more continuous motion estimation as well as more gestures, the human and robot can accomplish more complex manipulations.

This robot helps you lift objects — by looking at your biceps
CSAIL system can mirror a user's motions and follow nonverbal commands by monitoring arm muscles.

... researchers at MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) recently showed that a smoother robot-human collaboration is possible through a new system they developed, where machines help people lift objects by monitoring their muscle movements.

Dubbed RoboRaise, the system involves putting electromyography (EMG) sensors on a user's biceps and triceps to monitor muscle activity. Its algorithms then continuously detect changes to the person’s arm level, as well as discrete up-and-down hand gestures the user might make for finer motor control...

... The team used the system for a series of tasks involving picking up and assembling mock airplane components. In experiments, users worked on these tasks with the robot and were able to control it to within a few inches of the desired heights by lifting and then tensing their arm. It was more accurate when gestures were used, and the robot responded correctly to roughly 70 percent of all gestures.

Graduate student Joseph DelPreto says he could imagine people using RoboRaise to help in manufacturing and construction settings, or even as an assistant around the house.

“Our approach to lifting objects with a robot aims to be intuitive and similar to how you might lift something with another person — roughly copying each other’s motions while inferring helpful adjustments,” says DelPreto, lead author on a new paper about the project with MIT Professor and CSAIL Director Daniela Rus....
Sanjay Sarma is the Vice President for Open Learning at MIT, which includes the Office of Digital Learning, the MIT Integrated Learning Initiative and the Abdul Latif Jameel World Education Lab. He is also the Fred Fort Flowers (1941) and Daniel Fort Flowers (1941) Professor of Mechanical Engineering at MIT.

A co-founder of the Auto-ID Center at MIT, Sarma developed many of the key technologies behind the EPC suite of RFID standards now used worldwide. He was the founder and CTO of OATSystems, which was acquired by Checkpoint Systems (NYSE: CKP) in 2008, and he has worked at Schlumberger Oilfield Services in Aberdeen, UK, and at the Lawrence Berkeley Laboratories in Berkeley, California. His research includes sensors, the Internet of Things, cybersecurity and RFID.

...Author of more than 200 academic papers in computational geometry, sensing, RFID, automation, CAD, learning engineering, the science of learning and education reform, Sarma has two upcoming books: one on the science of learning and a second on the future of work. Sarma is the recipient of numerous awards for teaching and research, including the MacVicar Fellowship, Business Week’s eBiz Award, and InformationWeek's Innovators and Influencers Award...

**Learning Gestures Using A Passive Data-Glove With RFID Tags**


Hand gesture recognition enables non-tactile interfaces for human-machine interactions. Cameras are currently powerful tools to recognize these gestures, however, use of cameras is constrained by privacy concerns and need for well-lit, line of sight implementation. In this study, we propose an alternate method to recognize gestures using a passive data-glove augmented with passive RFID tags. We envision passive tags-based gesture recognition will have applications in improving operator safety around machines, activity monitoring in factories and sign to speech recognition, etc. Low-level reader information (RSSI, Phase and Doppler frequency) can be used to capture changes to the tags in the environment, therefore generating enough information to infer gestures. In this paper, we present a technique to enable fast feature recognition using low-level reader data by correcting for inconsistencies in phase data due to frequency hopping. We experimented with four different classifiers on the low-level reader data and our Fully-Connected Neural Network (FCCN) classifier is able to learn gestures from tag-data with 98% accuracy.

Hand gesture recognition using everyday safety gloves augmented with passive RFID tags enable us to create low-cost “connected-gloves” for industrial activity and safety monitoring applications.
Julie Shah is an Associate Professor in the Department of Aeronautics and Astronautics at MIT and leads the Interactive Robotics Group of the Computer Science and Artificial Intelligence Laboratory. Shah received her SB (2004) and SM (2006) from the Department of Aeronautics and Astronautics at MIT, and her PhD (2010) in Autonomous Systems from MIT. Before joining the faculty, she worked at Boeing Research and Technology on robotics applications for aerospace manufacturing. She has developed innovative methods for enabling fluid human-robot teamwork in time-critical, safety-critical domains, ranging from manufacturing to surgery to space exploration. Her group draws on expertise in artificial intelligence, human factors, and systems engineering to develop interactive robots that emulate the qualities of effective human team members to improve the efficiency of human-robot teamwork. In 2014, Shah was recognized with an NSF CAREER award for her work on “Human-aware Autonomy for Team-oriented Environments,” and by the MIT Technology Review TR35 list as one of the world’s top innovators under the age of 35. Her work on industrial human-robot collaboration was also recognized by the Technology Review as one of the 10 Breakthrough Technologies of 2013, and she has received international recognition in the form of best paper awards and nominations from the International Conference on Automated Planning and Scheduling, the American Institute of Aeronautics and Astronautics, the IEEE/ACM International Conference on Human-Robot Interaction, the International Symposium on Robotics, and the Human Factors and Ergonomics Society.

Interactive Robots Group

https://www.csail.mit.edu/research/interactive-robotics-group
http://interactive.mit.edu/

The Interactive Robotics Group (IRG) designs models and algorithms that enable robots to infer human cognitive state and learn implicit constraints and preferences of human team members from listening, watching, and practicing/training with human teams. Through this process, robots and machines learn “unwritten rules of the game” for working with teams of people in complex organizations and can collaborate to strengthen team plans. We also develop algorithms that enable robots to make fast adjustments to team plans in response to disturbances — to “play the game” with people. This work has been translated to enable new forms of human-machine teaming in manufacturing assembly lines, healthcare applications, transportation, and defense.

Predicting Human Motion for Fluid Human-Robot Teaming


Our project focuses on developing a general human motion prediction framework that can be applied in a variety of domains, ranging from manufacturing to space robotics, in order to improve the safety and efficiency of human-robot interaction.

...The aim of this work, therefore, is to build upon prior work in the field of human intent
prediction in order to develop a data-driven approach that can learn from given task data and automatically synthesize a prediction solution that is generalizable and robust.

Namely, given a variety of data encoding how the person moves in the shared environment and how he or she performs the tasks, we have developed a method that automatically selects a favorable combination of prediction methods to accurately predict occupancy at various future timeframes. We then use these predictions as an input to robot motion planning algorithms in order to allow robots to reason about where co-located people will be in the future and select paths and motions that allow for safe and efficient sharing of the space.

**Semi-Supervised Learning of Decision-Making Models for Human-Robot Collaboration**


We consider human-robot collaboration in sequential tasks with known task objectives. For interaction planning in this setting, the utility of models for decision-making under uncertainty has been demonstrated across domains. However, in practice, specifying the model parameters remains challenging, requiring significant effort from the robot developer. To alleviate this challenge, we present ADACORL, a framework to specify decision-making models and generate robot behavior for interaction. Central to our approach are a factored task model and a semi-supervised algorithm to learn models of human behavior. We demonstrate that our specification approach, despite significantly fewer labels, generates models (and policies) that perform equally well or better than models learned with supervised data. By leveraging pre-computed performance bounds and an online planner, ADACORL can generate robot behavior for collaborative tasks with large state spaces (> 1 million states) and short planning times (< 0.5 s).

**Activity recognition in manufacturing: The roles of motion capture and sEMG+ inertial wearables in detecting fine vs. gross motion**


In safety-critical environments, robots need to reliably recognize human activity to be effective and trustworthy partners. Since most human activity recognition (HAR) approaches rely on unimodal sensor data (eg motion capture or wearable sensors), it is unclear how the relationship between the sensor modality and motion granularity (eg gross or fine) of the activities impacts classification accuracy. To our knowledge, we are the first to investigate the efficacy of using motion capture as compared to wearable sensor data for recognizing human motion in manufacturing settings. We introduce the UCSD-MIT Human Motion dataset, composed of two assembly tasks that entail either gross or fine-grained motion. For both tasks, we compared the accuracy of a Vicon motion capture system to a Myo armband using three widely used HAR algorithms. We found that motion capture yielded higher accuracy than the wearable sensor for gross motion recognition (up to 36.95%), while the wearable sensor yielded higher accuracy for fine-grained motion (up to 28.06%). These results suggest that these sensor modalities are complementary, and that robots may benefit from systems that utilize multiple modalities to simultaneously, but independently, detect gross and fine-grained motion. Our findings will help guide researchers in numerous fields of robotics including learning from demonstration and grasping to effectively choose sensor modalities that are most suitable for their applications.
Consider the Human Work Experience When Integrating Robotics in the Workplace

Worldwide, manufacturers are reimagining the future of their workforce and its connection to technology. Rather than replacing humans, Industry 5.0 explores how humans and robots can best complement one another's unique strengths. However, realizing this vision requires an in-depth understanding of how workers view the positive and negative attributes of their jobs, and the place of robots within it. In this paper, we explore the relationship between work attributes and automation goals by engaging in field research at a manufacturing plant. We conducted 50 face-to-face interviews with assembly-line workers (n=50), which we analyzed using discourse analysis and social constructivist methods. We found that the work attributes deemed most positive by participants include social interaction, movement and exercise, (human) autonomy, problem solving, task variety, and building with their hands. The main negative work attributes included health and safety issues, feeling rushed, and repetitive work. We identified several ways robots could help reduce negative work attributes and enhance positive ones, such as reducing work interruptions and cultivating physical and psychological well-being. Based on our findings, we created a set of integration considerations for organizations planning to deploy robotics technology, and discuss how the manufacturing and HRI communities can explore these ideas in the future.

BRIAN C. WILLIAMS
Professor of Aeronautics and Astronautics, https://aeroastro.mit.edu/brian-c-williams
https://www.csail.mit.edu/person/brian-williams
Group: http://groups.csail.mit.edu/mers/

Professor Williams worked at the Xerox Palo Alto Research Center and NASA Ames Research Center, prior to joining the faculty at MIT. He is a pioneer in the fields of qualitative reasoning, model-based diagnosis and autonomous systems. He received a NASA Space Act Award for Remote Agent, the first fully autonomous, self-repairing space explorer, demonstrated onboard the NASA Deep Space One probe in May, 1999. He was a member of the Tom Young Blue Ribbon Team in 2000, assessing future Mars missions in light of the Mars Climate Orbiter and Polar Lander incidents, and is currently a member of the Advisory Council of the NASA Jet Propulsion Laboratory at Caltech. He has won four best paper prizes for his research in diagnosis, qualitative algebras, propositional inference and soft constraints. He is a fellow of AAAI, has served as guest editor of the Artificial Intelligence Journal and has been on the editorial boards of the Journal of Artificial Intelligence Research, and MIT Press...

Prof. Williams' research concentrates on model based-autonomy -- the creation of long-lived autonomous systems that are able to explore, command, diagnose and repair themselves using fast, commonsense reasoning. Current research focuses on model-based programming and cooperative robotics: Model-based programming embeds commonsense within robotic explorers and everyday devices by incorporating model-based deductive capabilities within traditional embedded programming languages. Cooperative robotics extends model-based autonomy to robotic networks of cooperating space, air and land vehicles, on Earth or other planets. Applications include deep space explorers, distributed satellites, unmanned air vehicles, Mars rovers, intelligent offices and automobiles. Research interests include reasoning at reactive time scales, cooperative and space robotics, intelligent embedded systems, model-
based programming, model-based reactive planning, execution and diagnosis, data-driven exploratory modeling, and hybrid system control.

**Model-Based Embedded and Robotics Systems Group (MERS)**

We are working to elevate robots from mechanical creations controlled by low-level scripts with a considerable amount of human guidance to truly cognitive robots.

http://groups.csail.mit.edu/mers/

There are three main thrusts to the research in the Model-Based Embedded and Robotics Systems (MERS) group: goal-driven interaction with robots, natural human/robot teaming, and robotic reasoning about the environment. When combined, these research topics allow us to create cognitive robots that can be talked to like another human, can work with a team member to finish a task, can recover from many failures without assistance, and can collaborate with a human to recover from a failure that the robot cannot solve alone. We enable these cognitive robot abilities by using model-based techniques. At the heart of these techniques are engineering models of how the robot works and models of how the robot’s environment behaves. On top of these models, we have developed algorithms that enable the robot to reason over how it believes the world works, much like humans do.

**Robots Adapting to Human Intent**

Our goal is to develop algorithms for allowing robots to adapt intelligently to humans when they are working together as a team.

https://www.csail.mit.edu/research/robots-adapting-human-intent

There has been much prior work on getting robots to adapt to disturbances in their environment, and also much work on recognizing human intent. This work aims to fuse the two together, for the case in which we have flexible plans for the human-robot team. By analyzing the structure of the plan -- including the actions and their requirements, timing constraints, and allowable choices for the humans and robots -- we can provide a single framework that allows a robot to adapt to its human teammate’s intent.

**PhD Thesis 2019: Risk-bounded Coordination of Human-Robot Teams through Concurrent Intent Recognition and Adaptation**

Steven J. Levine, 2019 PhD MIT EECS,
Advisors: Profs. Brian Williams and Leslie Kolodziejski

There is an ever-growing demand for humans and robots to work fluidly together in a number of important domains, such as home care, manufacturing, and medical robotics. In order to achieve this fluidity, robots must be able to (1) recognize their human teammate’s intentions, and (2) automatically adapt to those intentions in an intelligent manner. This thesis makes progress in these areas by proposing a framework that solves these two problems (task-level intent recognition and robotic adaptation) concurrently and holistically, using a single model and set of algorithms for both.

The result is a mixed-initiative human-robot interaction that achieves the team’s goals. The robot is able to reason about the action requirements, timing constraints, and unexpected
disturbances in order to adapt intelligently to the human.

We extend this framework by additionally maintaining a probabilistic belief over the human's intentions. We develop a risk-aware executive that performs concurrent intent recognition and adaptation. Our executive continuously assesses the risk associated with plan execution, selects adaptations that are safe enough, asks uncertainty-reducing questions when appropriate, and provides a proactive early warning of likely failure. Finally, we present an extension to this work which enables the robot to save time by ignoring potentially many, vanishingly-unlikely scenarios. To achieve this behavior, we frame concurrent intent recognition and adaptation as a constraint satisfaction problem, and compactly represent their associated solutions and policies using compiled structures that are updated online as new observations arise. Through the use of these compiled structures, the robot efficiently reasons about which actions to perform, as well as when to perform them – thereby ensuring decision making consistent with the team’s goals.

SEE THE E-WASTE! TRAINING VISUAL INTELLIGENCE TO SEE DENSE CIRCUIT BOARDS FOR RECYCLING


The state-of-the-art semantic segmentation and object detection deep learning models are taking the leap to generalize and leverage automation, but have yet to be useful in real-world tasks such as those in dense circuit board robotic manipulation. Consider a cellphone circuit board that because of small components and a couple of hundred microns gaps between them challenges any manipulation task. For effective automation and robotics usage in manufacturing, we tackle this problem by building a convolutional neural networks optimized for multi-task learning of instance semantic segmentation and detection while accounting for crisp boundaries of small components inside dense boards. We explore the feature learning mechanism, and add the auxiliary task of boundary detection to encourage the network to learn the objects' geometric properties along with the other objectives. We examine the performance of the networks in the visual tasks (separately and all together), and the extent of generalization on the recycling phone dataset. Our network outperformed the state-of-the-art in the visual tasks while maintaining the high speed of computation. To facilitate this globally concerning topic, we provide a benchmark for Ewaste visual tasks research, and publicize our collected dataset and code, as well as demos on our in-lab robot at https://github.com/MIT-MRL/recybot.

SUSTAINABILITY

TIMOTHY GUTOWSKI
Professor of Mechanical Engineering, http://meche.mit.edu/people/faculty/GUTOWSKI@MIT.EDU
LAB: http://web.mit.edu/ebm/www/
Tim Gutowski is currently a Professor of Mechanical Engineering at MIT, where he has been on the faculty since 1981. From 1994 to 2004 he was the director of the Laboratory for Manufacturing and Productivity, and from 2001 to 2005 he was the associate head of the Department of Mechanical Engineering. His research interests have ranged from polymer processing, to advanced composites manufacturing, to manufacturing systems, to his current area of study - manufacturing and the environment. He has over 150 technical publications, three books, and seven patents and patent applications. His most recent books are: Advanced Composites Manufacturing, Wiley 1997 and Thermodynamics and the Destruction of Resources, (with Bhavik Bakshi and Dusan Sekulic ) Cambridge University Press 2011.

His current area of study is focused the climate change consequences of engineered systems including; manufacturing, transportation and buildings. His publications can be found at the website http://web.mit.edu/ebm/www/publications.htm

Environmental BENIGN ManufaCturing
http://web.mit.edu/ebm/www/projects.htm

The EBM group is focused on examining the environmental effects associated with manufacturing and products. Research areas include: the thermodynamic, economic, and life cycle assessment of manufacturing processes and systems, products and recycling systems. Additional work looks at the environmental effects from the consumption side of the issue.

Additive manufacturing: Tracking the energy use of emerging technology
http://web.mit.edu/ebm/www/projects.htm#pjt5

This project focuses on the energy and resource efficiency of “additive manufacturing” technologies. By categorizing and studying different additive manufacturing methods, we will compare it with conventional manufacturing and evaluate the feasibility of its application in injection molding tooling. To fully assess the environmental impact of additive technologies, the analysis will include pre- and post-processing.

Prospective environmental analyses of emerging technology: a critique, a proposed methodology, and a case study on incremental sheet forming.

Prospective environmental assessment of emerging technology is necessary in order to inform designers of beneficial changes early in a technology’s development, and policy makers looking to fund projects and nudge manufacturers toward the most sustainable application of a technology. Existing analyses often have shortcomings such as failing to consider the environmental impacts in all stages of a product’s life cycle; implicitly assuming that the emerging technology will be cost-effective wherever it is technically viable; and assuming optimistic application scenarios that discontinue long-established trends in human behavior. In this article, we propose a new approach, complementary to the prospective and anticipatory life cycle assessment literature, addressing the above concerns and attempting to make sense of the large uncertainties inherent in such analyses by using distributions to model all the inputs. The paper focuses on emerging manufacturing technologies, such as incremental sheet forming...
(ISF), but the issues examined are also applicable to new end-use products, such as autonomous vehicles. This paper makes use of approaches (such as Bass modeling and product cannibalization considerations) familiar to those in the business community who anticipate market diffusion of a new technology and the effect on existing technology sales. The proposed methodology is demonstrated by estimating the potential environmental impacts in the U.S. car industry by 2030 of an emerging double-sided ISF process. Energy and cost models of ISF and drawing are used to estimate potential mean savings of around 100 TJ/primary and 60 million U.S. dollars per year by 2030.

**Performance evaluation of material separation in a material recovery facility using a network flow model**


In this paper, we model the recycling process for solid waste as performed in a material recovery facility. The intent is to inform the design and evaluation of a material recovery facility (MRF) in order to increase its profit, efficiency and recovery rate. We model the MRF as a multi-stage material separation process and develop a network flow model that evaluates the performance of the MRF through a system of linear equations. We estimate the parameters of the network flow model from historical data to find the best fit. We validate the model using a case-study of a light-packaging recovery section of an MRF in Spain. Additionally, we examine how uncertainty in the input material composition propagates through the system, and conduct a sensitivity analysis on the model parameters.

**Claiming Sustainability: Requirements and Challenges**


Despite the strong desire to find solutions that enable sustainable development, understanding of the requirements that methods must satisfy to guide technological development toward sustainability is still quite limited. We address this challenge based on a meta-principle for sustainability: human activities should not exceed critical ecosystem capacity, and by translating this principle into six specific requirements that sustainability assessment methods should satisfy. These necessary but not sufficient requirements are to ensure that decisions made by these methods do not demand more from ecosystems than can be supplied, and actions meant to reduce environmental impact do not shift the problem outside the system boundary. By applying these requirements to existing methods, we identify their benefits and shortcomings, and use this insight to suggest a multidisciplinary path forward. This path requires integration of methods for engineering design, with methods for considering spatial effects, socio-economic interactions, and human-natural system interactions. Such integration poses challenges and opportunities for multidisciplinary research toward solutions for sustainable development.

**Rapid Freeform Sheet Metal Forming: Technology Development and System Verification**

The objective of this project is to develop a transformational RApid Freeform sheet metal Forming Technology (RAFFT) in an industrial environment, which has the potential to increase manufacturing energy efficiency up to ten times, at a fraction of the cost of conventional technologies. The RAFFT technology is a flexible and energy-efficient process that eliminates the need for having geometry-specific forming dies. The innovation lies in the idea of using the energy resource at the local deformation area which provides greater formability, process control, and process flexibility relative to traditional methods. Double-Sided Incremental Forming (DSIF), the core technology in RAFFT, is a new concept for sheet metal forming. A blank sheet is clamped around its periphery and gradually deformed into a complex 3D freeform part by two strategically aligned stylus-type tools that follow a pre-described toolpath. The two tools, one on each side of the blank, can form a part with sharp features for both concave and convex shapes. Since deformation happens locally, the forming force at any instant is significantly decreased when compared to traditional methods. The key advantages of DSIF are its high process flexibility, high energy-efficiency, low capital investment, and the elimination of the need for massive amounts of die casting and machining. Additionally, the enhanced formability and process flexibility of DSIF can open up design spaces and result in greater weight savings.

ELSA OLIVETTI
Atlantic Richfield Associate Professor of Energy Studies, https://dmse.mit.edu/people/elsa-a-olivetti
LAB: https://olivetti.mit.edu/

Professor Olivetti’s research focuses on improving the environmental and economic sustainability of materials in the context of rapid-expanding global demand. Her research addresses two major problems where solutions could yield significant environmental benefits: Improving the sustainability of materials through increased use of recycled and renewable materials, recycling-friendly material design, and intelligent waste disposition; and Understanding the implications of substitution, dematerialization and waste mining on materials markets. Her research spans three levels of materials production: operational-level, industrial network-level and market-level strategies.

The Olivetti Group
http://olivetti.mit.edu/

The group focuses on quantifying the impact of and providing strategies for increasing the resource, economic, and environmental effectiveness of materials in the context of rapidly expanding global markets. In particular, we build analytical models to understand how the characteristics of a system drive the design of materials and processes and how the characteristics of a material or process drive the design of systems. Through collaboration with experimentalists and industrial research partners, our work links information around fundamental materials structure/property relationships with scaled economic and environmental impact.

Assessing the resource impact of recycling and material substitution: The goal of this research is to employ a systems perspective to strengthen decision-makers’ ability to predict the impacts of corporate and governmental policy in the materials substitution and recycling arenas.
Predicting impact of novel materials and processes: This work centers on assessing the environmental and economic impact of materials and processes as early in their development as possible. We leverage information along the trajectory from lab bench synthesis to prototype processing to final scaled manufacturing.

Beneficial Use of Non-hazardous Industrial Byproducts in Building Materials: The increased use of secondary (i.e. recycled) and renewable resources will likely be key in achieving sustainable materials use. Unfortunately, these strategies share a common barrier to economical implementation—increased quality variation compared to their primary and synthetic counterparts.

Design parameters and environmental impact of printed wiring board manufacture

The environmental life cycle impact of electronics continues to be of interest within the life cycle arena. Previous work has shown the majority of burden can be attributed to the use phase as well as the manufacturing impact of components. This study leverages primary data from an industrial facility to provide an assessment of the cradle-to-gate global warming potential for printed wiring board (PWBs) components used in electronics equipment. There has not been as much evolution in the technology for PWBs as compared to other components such as integrated circuits. A newer technology, high-density interconnect (HDI) PWBs, is evaluated in addition to conventional boards based on various representative designs for consumer products. The results show that the board impact for handheld devices, notebooks and desktops range from to around 0.6 to 10 kgCO2e/board. The cradle-to-gate global warming potential is dominated by the manufacturing energy to fabricate the board as well as the board laminate materials (80% of the total impact). The study demonstrates that environmental impact varies by design parameters other than layer count and board area. The research also assesses the water use and chemical hazard associated with PWB manufacture.

The Role of Manufacturing Variability on Environmental Impact

Additive manufacturing (AM) especially metal additive manufacturing (MAM) is expected to disrupt many industries. Besides being very flexible and allowing bespoke parts with little to no setup time, AM technology is able to fabricate parts with geometries which were previously impossible to create. This allows for dramatically better designs by making the product lighter or more efficient. However, despite these numerous and significant benefits, the uptake of functional additive manufactured parts is slow. A major barrier to expedited uptake of this technology is process control. It is not certain what the most important process parameters or the ideal process windows are and how this changes for different process/material combinations. As of yet, there is not a set process to certify an AM part or process. This makes quality assurance prohibitively longwinded and expensive. Furthermore, to ensure safety under such uncertain conditions, a high safety factor and therefore thicker parts must be used. As a result, uncertainty is also tied to increased material consumption and therefore higher
environmental impact. We need to better understand the nature of variability in AM in order to alleviate some of these problems. This manuscript presents several examples of the influence of variability in manufacturing and its potential impact on environmental performance.

**Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review**


As one quarter of global energy use serves the production of materials, the more efficient use of these materials presents a significant opportunity for the mitigation of greenhouse gas (GHG) emissions. With the renewed interest of policy makers in the circular economy, material efficiency (ME) strategies such as light-weighting and downsizing of and lifetime extension for products, reuse and recycling of materials, and appropriate material choice are being promoted. Yet, the emissions savings from ME remain poorly understood, owing in part to the multitude of material uses and diversity of circumstances and in part to a lack of analytical effort. We have reviewed emissions reductions from ME strategies applied to buildings, cars, and electronics. We find that there can be a systematic trade-off between material use in the production of buildings, vehicles, and appliances and energy use in their operation, requiring a careful life cycle assessment of ME strategies. We find that the largest potential emission reductions quantified in the literature result from more intensive use of and lifetime extension for buildings and the light-weighting and reduced size of vehicles. Replacing metals and concrete with timber in construction can result in significant GHG benefits, but trade-offs and limitations to the potential supply of timber need to be recognized. Repair and remanufacturing of products can also result in emission reductions, which have been quantified only on a case-by-case basis and are difficult to generalize. The recovery of steel, aluminum, and copper from building demolition waste and the end-of-life vehicles and appliances already results in the recycling of base metals, which achieves significant emission reductions. Higher collection rates, sorting efficiencies, and the alloy-specific sorting of metals to preserve the function of alloying elements while avoiding the contamination of base metals are important steps to further reduce emissions.

**Thesis: Manufacturing variability; effects and characterization through text-mining**

Advisors: Prof. Elsa Olivetti and Prof. Duane Boning
https://hdl.handle.net/1721.1/122216

Researchers and developers of new materials and processes often underestimate or neglect the effects of manufacturing variability and, as a result, make overly optimistic assumptions about their technologies. In this thesis, I explore the effects of manufacturing variability and find ways to characterize the manufacturing variability of emerging manufacturing processes. I develop a framework that connects manufacturing variability to environmental impact and economic costs through the concept of overdesign. I study examples using this framework and find that around 19% of concrete production is used solely to overcome issues of manufacturing variability, and that reducing the variability when producing fiber composite parts for a Boeing 787 reduces fuel consumption by millions of dollars and saves ktons of CO₂ from entering the
atmosphere. I further explore the effects of manufacturing variability by considering its impacts on the commercialization process of new technologies.

I consider Additive Manufacturing (AM), a promising technology, and argue that this technology has not reached commercial traction in great part due to our lack of understanding of the uncertainty associated with this process. I draw parallels to fiber composites, which faced similar issues in the 1980s before a collaborative effort, through the Advanced Composite Technology (ACT) and Advanced General Aviation Technology Experiments (AGATE) programs, was able to solve many of these challenges. Finally, I consider the volumes of data available in published documents and analyze whether it is possible to extract this information using text mining techniques, and to use these data to characterize the manufacturing variability of upcoming technologies. Some important challenges obstruct our ability to extract all the important information from these documents, but important steps are made to remove some of these challenges and I demonstrate that useful information can be extracted.

Manufacturing engineers view processes as stochastic rather than deterministic. I ultimately argue for this view to also be adopted by environmentalists, materials researchers, and decision makers. I also further develop methods to extract and utilize manufacturing variation information.

DESIREE L. PLATA
Gilbert W. Winslow (1937) Career Development Professor in Civil Engineering,
https://cee.mit.edu/people_individual/desiree-plata/
Group/Lab: http://platalab-dev.mit.edu/

Research Interests: environmental chemistry, environmentally and economically sustainable design, industrially-important processes and materials, energy technologies (fossil and low-carbon), advanced materials synthesis and manufacture

Plata Lab
Environmentally Sustainable Innovation / Innovation for Environmental Sustainability
http://platalab-dev.mit.edu/

...In particular, the group focuses on unlocking the potential of carbon-based nanomaterials for energy storage and water treatment by enabling scalable, tunable, environmentally sustainable nanomanufacturing. To do so, we use trace organic chemical analysis to interrogate emissions formed during lab-scale representations of industrial synthetic methods. The analytical tools we have developed rely on pre-concentration methods that offer 6-order-of magnitude improvements over typical emissions testing approaches. This detailed chemical information sheds light on bond-building steps in nanocarbon formation, illuminating routes to reduce unwanted byproducts and improve the material and energy budget during nanomaterial fabrication. The preferred route for carbon nanomaterial synthesis at scale is catalytic chemical vapor deposition, which has a complex gas mixture and gas-catalyst interactions that are difficult to study in situ. The Plata lab houses a unique device that enables us to simulate the complex reaction atmosphere molecule-by-molecule, probing different reaction intermediates and pathways, and monitor nanocarbon formation during nanotube growth via a variety of spectroscopic methods. Finally, nano-enabled devices in our lab are being developed to demonstrate that material performance is not sacrificed using sustainable synthetic routes. In
this way, our work spans all the way from fundamental chemical mechanisms to providing applied solutions to pressing real-world problems.

**Life Cycle Assessment of Aerogel Manufacture on Small and Large Scales: Weighing the Use of Advanced Materials in Oil Spill Remediation**


Recent studies demonstrated that advanced aerogel composites (Aspen Aerogels® Spaceloft® [SL]) have the potential to transform oil remediation via high oil uptake capacity and selectivity, excellent reusability, and high mechanical strength. Understanding the life cycle environmental impacts of advanced aerogels can enable a more holistic decision-making process when considering oil recovery technologies following a spill. Here, we perform a cradle-to-grave streamlined life cycle assessment (LCA) following International Organization for Standardization (ISO) 14040 2006 for SL weighed against the conventional oil sorbent material, polyurethane foam. The model included alternative use and disposal scenarios, such as single or multiple uses, and landfill, incinerator, and waste-to-energy (WTE) approaches for cleaning 1 cubic meter (m3) of light crude oil. Results showed that the ideal case for SL application was comprised of multiple use and WTE incineration (68% reduction in material use, approximately $7 \times 10^3$ megajoules [MJ] of energy recovery from WTE), but SL offered energy and materials savings even when used once and disposed of via traditional means (i.e., landfill). In addition to evaluating these already-scaled processes, we performed an anticipatory LCA for the laboratory-scaled aerogel fabrication process that might inform the sustainable design of next-generation aerogels. In particular, the model compared rapid supercritical extraction (RSCE) with two conventional supercritical extraction methods—alcohol and carbon dioxide supercritical extraction (ASCE and CSCE, respectively)—for silica aerogel monoliths. Our results showed that RSCE yielded a cumulative energy savings of more than $76 \times 10^3$ and $100 \times 10^3$ MJ for 1 m3 of monolithic silica aerogel manufacturing compared to ASCE and CSCE, respectively.

**Patent: Electrochemical separation and recovery of metals**

Inventors: Megan O’Connor, Desiree PLATA

The invention provides a novel filtration apparatus for the selective separation of metals from a mixture thereof. The invention also provides a method for the separation and isolation of metals from a sample using electrochemical precipitation.

... in order to create a secondary supply of these metals, novel materials management strategies and supporting technologies will be needed to enhance reuse and recycling at the end-of-life and in the manufacturing stages. Such systematic changes will not only secure the supply of metals for the requisite technologies, but also have the ancillary benefit of further reducing emissions by reducing mining and refining of primary metal.

While there are no standard recovery technologies (i.e., commercialized and readily integrated onto an assembly line) available to manufacturers seeking to remove valuable materials from their own waste streams, end-of-life waste management strategies currently recycle 20% of global municipal solid waste and less than 1% of RESE (Reck & Graedel, Science 2012, 337, 690-695). These low recycling rates result from many interrelated factors including consumer...
behavior, government policy, and lack of infrastructure. In addition, there are few recycling technologies sufficiently advanced to reclaim the critical materials or separate the metals from one another for reuse.

**DECARBONIZING THE MAKING OF CONSUMER PRODUCTS**

Researchers are devising new methods of synthesizing chemicals used in goods from clothing, detergents, and antifreeze to pharmaceuticals and plastics.


Most efforts to reduce energy consumption and carbon emissions have focused on the transportation and residential sectors. Little attention has been paid to industrial manufacturing, even though it consumes more energy than either of those sectors and emits high levels of CO2 in the process.

To help address that situation, Assistant Professor Karthish Manthiram, postdoc Kyoungsuk Jin, graduate students Joseph H. Maalouf and Minju Chung, and their colleagues, all of the MIT Department of Chemical Engineering, have been devising new methods of synthesizing epoxides, a group of chemicals used in the manufacture of consumer goods ranging from polyester clothing, detergents, and antifreeze to pharmaceuticals and plastics.

“We don’t think about the embedded energy and carbon dioxide footprint of a plastic bottle we’re using or the clothing we’re putting on,” says Manthiram. “But epoxides are everywhere!”

As solar and wind and storage technologies mature, it’s time to address what Manthiram calls the “hidden energy and carbon footprints of materials made from epoxides.” And the key, he argues, may be to perform epoxide synthesis using electricity from renewable sources along with specially designed catalysts and an unlikely starting material: water.

The challenge

Epoxides can be made from a variety of carbon-containing compounds known generically as olefins. But regardless of the olefin used, the conversion process generally produces high levels of CO2 or has other serious drawbacks.

To illustrate the problem, Manthiram describes processes now used to manufacture ethylene oxide, an epoxide used in making detergents, thickeners, solvents, plastics, and other consumer goods. Demand for ethylene oxide is so high that it has the fifth-largest CO2 footprint of any chemical made today.

The top panel of Figure 1 in the slideshow above illustrates one common synthesis process. The recipe is simple: Combine ethylene molecules and oxygen molecules, subject the mixture to high temperatures and pressures, and separate out the ethylene oxide that forms.

However, those ethylene oxide molecules are accompanied by molecules of CO2 — a problem, given the volume of ethylene oxide produced nationwide. In addition, the high temperatures
and pressures required are generally produced by burning fossil fuels. And the conditions are so extreme that the reaction must take place in a massive pressure vessel. The capital investment required is high, so epoxides are generally produced in a central location and then transported long distances to the point of consumption.

Another widely synthesized epoxide is propylene oxide, which is used in making a variety of products, including perfumes, plasticizers, detergents, and polyurethanes. In this case, the olefin — propylene — is combined with tert-butyl hydroperoxide, as illustrated in the bottom panel of Figure 1. An oxygen atom moves from the tert-butyl hydroperoxide molecule to the propylene to form the desired propylene oxide. The reaction conditions are somewhat less harsh than in ethylene oxide synthesis, but a side product must be dealt with. And while no CO2 is created, the tert-butyl hydroperoxide is highly reactive, flammable, and toxic, so it must be handled with extreme care.

In short, current methods of epoxide synthesis produce CO2, involve dangerous chemicals, require huge pressure vessels, or call for fossil fuel combustion. Manthiram and his team believed there must be a better way....

THESIS: MATERIAL SUBSTITUTION IN ELECTRIC VEHICLE MANUFACTURING: COMPARING ADVANCED HIGH STRENGTH STEEL AND ALUMINUM
Joshua Thomas Jameson Burd, 2019 S.M. in Technology and Policy, MIT School of Engineering, Institute for Data, Systems, and Society
Advisor: Dr. Richard Roth
https://hdl.handle.net/1721.1/122162

In electric vehicle production, the high cost of battery manufacture motivates investment in energy efficient and lightweight vehicle designs. A common lightweighting strategy is to substitute Advanced High Strength Steel (AHSS) or aluminum in place of traditional mild steel. Aluminum is a lighter weight than AHSS, leading to greater reduction of battery and motor costs. However, it is more expensive to manufacture the vehicle body using aluminum compared to AHSS. This thesis is an attempt to answer the question of which material is less expensive from a total vehicle cost point of view, and how that might change as technological learning affects the various vehicle subsystems. A fully designed vehicle with an Advanced High Strength Steel (AHSS) body serves as the basis for an aluminum "comparator" design.

For each design, the cost of manufacturing each part in the body structure and closures, the cost of each assembly joining step, and the cost of painting the assembled body is calculated using process-based cost modeling. Assembled and painted body and closures manufacturing cost for the steel design is $923 and $1798 for aluminum due to higher aluminum material costs and more expensive aluminum part manufacturing, assembly and paint process costs. Lighter body structures require smaller motors, batteries, chassis, and other subsystems in the rest of the vehicle. Secondary weight savings factors derived from statistical mass benchmarking studies are used to calculate changes in curb mass based on the difference in body mass between the steel and aluminum designs. For a 23% weight saving assumption, the aluminum design was 58 kg lighter in the body and closures, and 93 kg lighter in the full curb weight.

The lighter vehicle weight was used to scale costs of batteries, motors, and chassis. In total, the cost of these subsystems was $12,467 in the steel design and $11,754 in the aluminum design.
This base case result found that the full vehicle cost of the steel design was $330 less expensive than the aluminum design. Sensitivity and variation of parameters found that the cost advantage of the steel design shrinks with larger assumed weight savings or larger assumed battery sizes. An analysis of how costs are likely to change with time shows that decreasing battery and motor costs will likely outpace decreasing aluminum manufacturing costs such that the steel design may be as much as $500 less than the full cost of the aluminum design by 2030.

**THESIS: MANUFACTURING FOOTPRINT STRATEGY FOR PRODUCT LINE EXPANSION**
Brian C. (Brian Christopher) Martin, 2019 M.B.A., MIT Sloan School of Management and S.M., MIT Department of Civil and Environmental Engineering, in conjunction with the Leaders for Global Operations Program at MIT
Advisors: Profs. Retsef Levi (Sloan) and Franz-Josef Ulm (CEE)
https://hdl.handle.net/1721.1/122579

To reach its long term revenue targets, EDSCO Fasteners must expand its smooth bar anchor bolt product line to increase revenue generation. In order to maximize profit during this expansion, an operational strategy must be developed to minimize total landed cost. This project will assess the current manufacturing processes and develop a realistic and practical model of the supply chain. Using data collected through pilot project implementation the model's parameters are calibrated and the model accuracy is validated. By developing this model as a linear optimization program it can be used as a decision support tool to inform the operational strategy. Likely expansion scenarios and decision points (consolidation, acquisition, capital expenditures, etc.) are considered as decision variables in the supply chain optimization model to minimize total landed cost. These results are used to inform a recommended scenario based strategy for product line expansion.

**RELATED**

**CRYPTOGRAPHIC “TAG OF EVERYTHING” COULD PROTECT THE SUPPLY CHAIN**
Tiny, battery-free ID chip can authenticate nearly any product to help combat losses to counterfeiting


To combat supply chain counterfeiting, which can cost companies billions of dollars annually, MIT researchers have invented a cryptographic ID tag that’s small enough to fit on virtually any product and verify its authenticity.

A 2018 report from the Organization for Economic Co-operation and Development estimates about $2 trillion worth of counterfeit goods will be sold worldwide in 2020. That’s bad news for consumers and companies that order parts from different sources worldwide to build products.

Counterfeiters tend to use complex routes that include many checkpoints, making it challenging to verifying their origins and authenticity. Consequently, companies can end up with imitation parts. Wireless ID tags are becoming increasingly popular for authenticating assets as they change hands at each checkpoint. But these tags come with various size, cost, energy, and
security tradeoffs that limit their potential.

Popular radio-frequency identification (RFID) tags, for instance, are too large to fit on tiny objects such as medical and industrial components, automotive parts, or silicon chips. RFID tags also contain no tough security measures. Some tags are built with encryption schemes to protect against cloning and ward off hackers, but they’re large and power hungry. Shrinking the tags means giving up both the antenna package — which enables radio-frequency communication — and the ability to run strong encryption.

In a paper presented yesterday at the IEEE International Solid-State Circuits Conference (ISSCC), the researchers describe an ID chip that navigates all those tradeoffs. It’s millimeter-sized and runs on relatively low levels of power supplied by photovoltaic diodes. It also transmits data at far ranges, using a power-free “backscatter” technique that operates at a frequency hundreds of times higher than RFIDs. Algorithm optimization techniques also enable the chip to run a popular cryptography scheme that guarantees secure communications using extremely low energy.

“We call it the ‘tag of everything.’ And everything should mean everything,” says co-author Ruonan Han, an associate professor in the Department of Electrical Engineering and Computer Science and head of the Terahertz Integrated Electronics Group in the Microsystems Technology Laboratories (MTL). “If I want to track the logistics of, say, a single bolt or tooth implant or silicon chip, current RFID tags don’t enable that. We built a low-cost, tiny chip without packaging, batteries, or other external components, that stores and transmits sensitive data.”

Joining Han on the paper are: graduate students Mohamed I. Ibrahim, Muhammad Ibraheem Wasiq Khan, and Chiraag S. Juvekar; former postdoc associate Wanyeong Jung; former postdoc Rabia Tugce Yazicigil; and Anantha P. Chandrakasan, who is the dean of the MIT School of Engineering and the Vannevar Bush Professor of Electrical Engineering and Computer Science...

BUILDING MANUFACTURING FLEXIBILITY WITH STRATEGIC SUPPLIERS AND CONTINGENT EFFECT OF PRODUCT DYNAMISM ON CUSTOMER SATISFACTION


María Jesús Sáenz, Executive Director, MIT SCM Blended Master's Program, and Director, MIT Digital Supply Chain Transformation, https://ctl.mit.edu/about/bio/maria-jesus-saenz

A critical capability sought by an increasing number of firms is manufacturing flexibility, because it allows to effectively respond to dynamic markets. Grounded upon a supply chain perspective, this paper aims to assess antecedents of manufacturing flexibility that stem from the upstream relationships with strategic suppliers. Additionally, it is one of the first to analyze the contingent effect of product dynamism on the impact of manufacturing flexibility on downstream customer satisfaction. We apply structural equation modeling to a sample of 155 companies in order to analyze our hypotheses. Results strongly indicate that buyer-supplier collaboration facilitates inter-organizational learning that in turn allows organizations to...
develop manufacturing flexibility and increase customer satisfaction. Approaching manufacturing flexibility from a broader supply chain view thus pays off. Moreover, we apply multi-group confirmatory factor analysis to explore the contingent effect of product dynamism on the relationship between manufacturing flexibility and customer satisfaction. Results suggest a stronger impact of manufacturing flexibility on performance in the context of higher product dynamism in companies’ customer markets, confirming the importance of a contingency view to flexibility.

MIT INITIATIVE ON THE DIGITAL ECONOMY (IDE)
http://ide.mit.edu/

The MIT Initiative on the Digital Economy (IDE) explores how people and businesses will work, interact, and prosper in an era of profound digital transformation.

Toward Understanding the Impact of Artificial Intelligence on Labor

Rapid advances in artificial intelligence (AI) and automation technologies have the potential to significantly disrupt labor markets. While AI and automation can augment the productivity of some workers, they can replace the work done by others and will likely transform almost all occupations at least to some degree. Rising automation is happening in a period of growing economic inequality, raising fears of mass technological unemployment and a renewed call for policy efforts to address the consequences of technological change. In this paper we discuss the barriers that inhibit scientists from measuring the effects of AI and automation on the future of work. These barriers include the lack of high-quality data about the nature of work (e.g., the dynamic requirements of occupations), lack of empirically informed models of key microlevel processes (e.g., skill substitution and human–machine complementarity), and insufficient understanding of how cognitive technologies interact with broader economic dynamics and institutional mechanisms (e.g., urban migration and international trade policy). Overcoming these barriers requires improvements in the longitudinal and spatial resolution of data, as well as refinements to data on workplace skills. These improvements will enable multidisciplinary research to quantitatively monitor and predict the complex evolution of work in tandem with technological progress. Finally, given the fundamental uncertainty in predicting technological change, we recommend developing a decision framework that focuses on resilience to unexpected scenarios in addition to general equilibrium behavior.

Automation and New Tasks: How Technology Displaces and Reinstates Labor

We present a framework for understanding the effects of automation and other types of technological changes on labor demand, and use it to interpret changes in US employment over the recent past. At the center of our framework is the allocation of tasks to capital and labor—the task content of production. Automation, which enables capital to replace labor in tasks it
was previously engaged in, shifts the task content of production against labor because of a
displacement effect. As a result, automation always reduces the labor share in value added and
may reduce labor demand even as it raises productivity. The effects of automation are
counterbalanced by the creation of new tasks in which labor has a comparative advantage. The
introduction of new tasks changes the task content of production in favor of labor because of a
reinstatement effect, and always raises the labor share and labor demand. We show how the role
of changes in the task content of production—due to automation and new tasks—can be inferred
from industry-level data. Our empirical decomposition suggests that the slower growth of
employment over the last three decades is accounted for by an acceleration in the displacement
effect, especially in manufacturing, a weaker reinstatement effect, and slower growth of
productivity than in previous decades.

INDUSTRIAL PERFORMANCE CENTER (IPC)
Faculty Co-Chair: Richard Lester
Executive Director: Elisabeth B. Reynolds
http://ipc.mit.edu/, http://ipc.mit.edu/research

With a particular interest in Innovation, Productivity and Competitiveness, the IPC brings
together teams of researchers in engineering, science, management and the social sciences at
MIT and beyond to carry out innovative, applied research in the following areas:
Advanced Manufacturing; Energy; Globalization; Innovation; Work of the Future.

MIT Work of the Future
https://workofthefuture.mit.edu/

The MIT Task Force on the Work of the Future is conducting research in key domains such as
mobility, skills and education, manufacturing, and more. Research looks at topics of technology,
work, and society through both macro- and micro-lenses to assess broad factors as well as the
experience of firms, institutions, individuals, and communities. This collaborative research
effort implements expertise from a range of disciplines and departments, aiming to develop
policy-relevant ideas and insights.

2019, David Autor, David A. Mindell, Elisabeth B. Reynolds
https://workofthefuture.mit.edu/report/work-future
https://workofthefuture.mit.edu/sites/default/files/2019-
09/WorkoftheFuture_Report_Shaping_Technology_and_Institutions.pdf

The world now stands on the cusp of a technological revolution in artificial intelligence and
robotics that may prove as transformative for economic growth and human potential as were
electrification, mass production, and electronic telecommunications in their eras. New and
emerging technologies will raise aggregate economic output and boost the wealth of nations.
Will these developments enable people to attain higher living standards, better working
conditions, greater economic security, and improved health and longevity? The answers to these
questions are not predetermined. They depend upon the institutions, investments, and policies
that we deploy to harness the opportunities and confront the challenges posed by this new era.

How can we move beyond unhelpful prognostications about the supposed end of work and
toward insights that will enable policymakers, businesses, and people to better navigate the disruptions that are coming and underway? What lessons should we take from previous epochs of rapid technological change? How is it different this time? And how can we strengthen institutions, make investments, and forge policies to ensure that the labor market of the 21st century enables workers to contribute and succeed? To help answer these questions, and to provide a framework for the Task Force’s efforts over the next year, this report examines several aspects of the interaction between work and technology.

**Research area: Advanced Manufacturing**

Manufacturing is perhaps the earliest adopter of automation, beginning with industrial robotics in the late 1960s and early 1970s. Today, new technologies like additive manufacturing and collaborative robotics are redesigning the production process as well as where production occurs. The MIT Work of the Future initiative approaches this topic through several lenses to understand both upstream questions about how new technology is designed and developed, to downstream questions regarding the adoption of new technologies and how they are changing the nature of manufacturing work and the skills required to succeed in manufacturing-related industries...

**MIT PORTUGAL: DIGITAL TRANSFORMATION IN MANUFACTURING**
Co-Directors: Profs. Dava Newman and Doug Hart
[https://www.mitportugal.org/industry](https://www.mitportugal.org/industry)

The MIT Portugal Program (MPP) is a strategic international partnership between Portuguese universities and research institutions, MIT, the Portuguese government, as well as partners from industry and other non-academic institutions.

The third phase of the program—MIT Portugal Partnership 2030 (MPP2030)—was launched in June of 2018 and funded by the Fundação para a Ciência e Tecnologia (FCT). MPP2030 will continue to uphold MIT’s strong commitment to collaborate with Portuguese institutions with the goal of strengthening Portugal’s knowledge base and international competitiveness through strategic investments in research, people, and ideas...

Within the scope of the new partnership, MPP2030 focuses on developing research in four strategic areas: Climate Science & Climate Change, Earth Systems: Oceans to Near Space, **Digital Transformation in Manufacturing**, and Sustainable Cities—all of which include data science intensive approaches and methodologies...

**MIT STARTUP EXCHANGE**
[https://startupexchange.mit.edu/](https://startupexchange.mit.edu/)

MIT Startup Exchange actively promotes collaboration and partnerships between MIT-connected startups and industry, principally members of MIT’s Industrial Liaison Program (ILP). “MIT-connected” startups are based on licensed MIT technology, or are founded by MIT
faculty, staff, or alumni. Over 1,700+ startups are registered with MIT Startup Exchange and monthly additions are helping to shape and define an innovative and entrepreneurial community.

**ADDEATION**  
John Hart (Co-Founder, MIT Faculty), Cambridge, MA, [https://www.addeation.com/](https://www.addeation.com/)

Addeation is a consultancy that focuses on design strategy and additive manufacturing for accelerated product development. Our team helps business leaders harness the value of 3D printing/additive manufacturing and integrate digital tools for design, development, and rapid commercialization into their business model for a sustainable competitive advantage.

**BMF PRECISION TECHNOLOGY CO. LTD.**  
STEX25 2019, Shenzhen City CHINA  
Spin-off company from the 3D Nano-manufacturing and Nano-photonics group led by Professor Nicholas Fang at MIT, who is also a cofounder and chief scientist of the company [http://bmftec.com/](http://bmftec.com/)

We focus on the design, development and production of micro/nano-scale 3D printing systems and micro/nano-scale functional composite materials.

**DESKTOP METAL**  

Desktop Metal is accelerating the transformation of manufacturing with end-to-end metal 3D printing solutions. Founded in 2015 by leaders in advanced manufacturing, metallurgy, and robotics, the company is addressing the unmet challenges of speed, cost, and quality to make metal 3D printing an essential tool for engineers and manufacturers around the world. The Studio System™ is the first office-friendly metal 3D printing system for rapid prototyping and is 10 times less expensive than existing technology today. To manufacture metal 3D printed parts at scale, Desktop Metal also debuted the only 3D printing system for mass production of high resolution metal parts today, the Production System™.

**DUST IDENTITY**  

DUST -- the Diamond Uncloneable Security Tag -- is a proprietary technology which utilizes nanodiamonds to create an unclonable identity layer on any object. An optical scanner and cloud-based infrastructure provides an interface to the object identity and provenance. DUST ensures that trusted data and verifiable products are used and traced across their full lifecycle.

**EVERACTIVE**  
Santa Clara, CA, [https://everactive.com/](https://everactive.com/)

Operating without batteries, Everactive wireless sensors generate a new class of data for the analytics of the future Industrial IoT.
FORMLABS
STEX25 2019, Somerville MA
https://formlabs.com/

Formlabs designs and manufactures powerful and accessible 3D printing systems. Headquartered in Boston with offices in Germany, Japan, and China, the company was founded in 2011 by a team of engineers and designers from the MIT Media Lab and Center for Bits and Atoms. Formlabs is establishing the industry benchmark for professional 3D printing for engineers, designers, and manufacturers around the globe, and accelerating innovation in a variety of industries.

INKBIT
STEX25 2019
Prof. Wojciech Matusik (Co-Founder, MIT Faculty), Cambridge, MA,
http://inkbit.launchrock.com/

Inkbit is MIT-trained scientists and engineers inventing the future of manufacturing. The team combines expertise in industrial systems, design software and material science to identify and seize opportunities for mass-market additive manufacturing.

NVBOTS
AJ Perez (Chairman, Founder; Alum), Chris Haid (General Manager, Founder; MIT Alum) (2 other MIT alum/founders), Boston, MA, https://nvbots.com/

NVBOTS® creates automated, enterprise 3D printing solutions that fix some of the industry’s toughest problems. Entirely dedicated to disruptive innovation, our research and development program NVLABS ecently developed the only 3D printing technology that can print multiple metals in the same build, supporting a growing list of metals that includes stainless steel, titanium, nickel, copper nickel, aluminum, zirconium, silver and palladium. NVBOTS was founded by 4 MIT alumni who won the Lemelson prize. We also licensed the technology from MIT TLO (automated 3D printing).

REALTIME ROBOTICS
Boston, MA, https://rtr.ai/

Realtime Robotics was founded with the goal of transforming how robots and autonomous vehicles move. Our initial invention was a proprietary computer processor that quickly solved how to get a robot or vehicle to its desired target without collisions. This solved the problem of conventional motion planning which has been too slow for robot and AV applications in dynamic environments. Realtime Robotics has continued to transform automation, with products that provide trailblazing features like risk-aware driving, high-productivity multi-robot workcells and automated robot vision that continuously calibrates itself.

POLY6 TECHNOLOGIES

Our process intelligent materials offer digital manufacturing solutions to existing production
within some of the world’s largest and most complex industries. Poly6’s intelligent materials advance engineering design capabilities and increase system efficiency for established production processes. Poly6 is a Boston-based advanced materials and manufacturing company that came out of MIT’s Langer Lab in 2016. Through materials innovation, Poly6 enables businesses to advance function, efficiency and quality in scaled manufacturing processes within biotechnology, aerospace, electronics and other industries.

RIGHTHAND ROBOTICS
STEX25 2019, Somerville MA
https://www.righthandrobotics.com/

RightHand Robotics (RHR) is a leader in providing end-to-end solutions that reduce the cost of e-commerce order-fulfillment of electronics, apparel, grocery, pharmaceuticals, and countless other industries. Unlike traditional factory robots that can be complex to set up and are singly purposed, RHR solutions are simple to integrate and adaptable to improve the utilization of many different customer workflows, such as sorting batch-picked items, picking items from an ASRS, inducting items to a belt sorter, and order quality assurance.

SIMPRINT NANOTECHNOLOGIES
Duane Boning (Co-Founder, MIT Faculty), Hayden Taylor (Co-Founder, MIT Alum), Bristol, UK, http://simprintnanotech.com/pg/home

Simprint Nanotechnologies provides software tools and simulation services to users of nanoimprint lithography (NIL). We offer an extremely fast way of simulating the nano-scale transformation of material involved in NIL. Our software allows semiconductor, photonics, and data-storage manufacturers to use nanoimprint reliably and with greatly reduced development costs. Simprint software helps users to build intuition about the physics of the nanoimprint process, making it invaluable in nanoimprint lithography research.

TAKTILE [FORMERLY ABSTRACT LLC]
Cambridge MA https://www.taktilemfg.com/

Taktile leverages IoT machine vision and power monitoring sensors to show discrete custom-goods manufacturers and distribution centers why variance occurs in their manual and semi-automated production processes. Our solution includes hardware (cameras, instrumented power cables), AI-powered software that automatically classifies labor and legacy machine status, and a user-facing production console that delivers automated supervision and auditing of the operation.

ZAIPUT FLOW TECHNOLOGIES
Andrea Adomo (Co-Founder, CEO, MIT Alumnus), Timothy Jamison (Advisor, MIT Faculty), Cambridge, MA, https://www.zaiput.com/

Zaiput Flow Technologies is a start-up company launched to bring innovative tools for continuous flow chemistry to the market. Devoted to excellence, innovation and outstanding customer service, the company offers devices focused on separation and extraction. Our products include liquid-liquid separators and back pressure regulators that are scalable,
modular, and continuous. Whether you work in academia or industry, if you work with continuous flow, we believe that our products will help to streamline your work, enable new approaches and allow you to harvest the power of continuous flow.