Completing the Circuit: Workforce Development for Advanced Building Construction and Grid-Interactive Efficient Buildings

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List of Acronyms

ABC	advanced building construction
AECORE	architecture, engineering, construction, building operations and real estate
AGC	Associated General Contractors of America
AI	artificial intelligence
BIM	building information management
BTO	Building Technologies Office
CAD	computer-assisted drawings
DER	distributed energy resource
DOE	U.S. Department of Energy
GEB	grid-interactive efficient building
HVACR	heating, ventilating, air conditioning, and refrigeration
ICT	information and communication technology
IPD	integrated project delivery
LCT	Legitimation Code Theory
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
SPT	Social Practice Theory

Executive Summary

Buildings function as objects in and around which life is conducted; they have functional value as shelter, aesthetic value, and even symbolic or social value within communities. However, recent technological advances are transforming buildings from static objects in the environment into active participants, with real-time impacts on personal health, regional energy systems, environmental sustainability, and the broader economy. This report explores how the shifting role of buildings is creating new demands on the workforce involved in the fields of architecture, engineering, construction, building operations, and real estate (AECORE).

The U.S. Department of Energy's Building Technologies Office is supporting this transformation through many areas of research and development, including the Advanced Building Construction (ABC) and Grid-Interactive Efficient Buildings (GEB) initiatives. ABC aims to expand access to innovative and affordable energy-efficient construction techniques. GEB focuses on combining energy efficiency and demand flexibility to transform buildings from an energy load to a clean and flexible energy resource.

The paper begins by describing changes in the building industry resulting from ABC and GEB technological advances. There are new software programs and data available to support building operations and automation, which has implications for professionals up and down the AECORE spectrum. Similarly, the adoption of robotics and automation in building construction and rehabilitation may change not only how buildings are built, but also how they are designed, engineered, and financed. Finally, increased financialization of the building industry is a result of buildings functioning not just as objects for investment, but also as incubators for these new technologies. What has emerged from this context is a division in the industry overall, between firms operating with the more historic view of buildings as objects, and firms navigating this new and evolving dynamism.

The third section of the paper explores current workforce challenges and identifies the skills gaps in each AECORE field based on expert interviews from professionals across the building industry. Workers all along the AECORE continuum now require greater critical thinking and technical skills related to data analytics, information, and communications technologies. There is also a greater need for a systemic understanding of climate and energy.

The next section of this report employs new strategies to address the gaps that are not purely technical. Using two tools of Social Practice Theory—the Circuit of Practice and Legitimation Code Theory—we explore the interconnection among social, environmental, and technical systems. The results reiterate how the changing role of buildings is blurring lines between traditional AECORE fields within the building industry.

The outcome of this research is a set of suggestions to facilitate the adoption of ABC and GEBs in both the emerging and existing branches of the building industry. Keys to success are breaking down industry silos and developing new, meaningful professional identities. An approach that focuses only on the development of technical skills would miss the opportunity to reshape the purpose and meaning of buildings. Repositioning building industry professions as high-tech, meaningful, and climate-positive can help grow the workforce needed to support ABC and GEBs.

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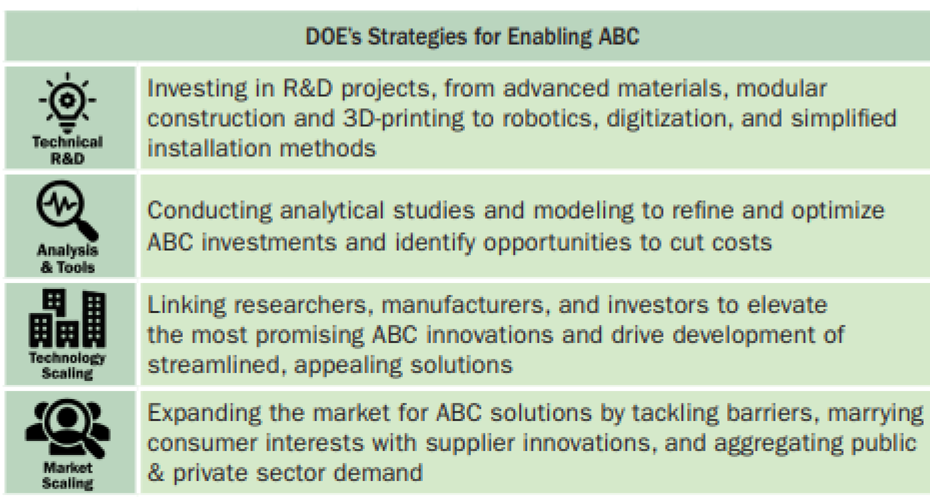
1 Introduction

The role that buildings play in society continues to evolve as climate change, housing costs, and indoor air quality become increasingly important. There is growing demand for today's buildings to be healthy, low-carbon, and affordable, in addition to being aesthetically pleasing and functional. These new expectations, in tandem with technological innovation, are shifting the way architects, engineers, builders, facilities managers, and real estate professionals deliver their products and services.

Recognizing this shift, the U.S. Department of Energy (DOE) Building Technologies Office (BTO) is investing in many areas of building sector innovation, including understanding how technological advancements will impact the workforce. Two efforts, Advanced Building Construction (ABC) and Grid-Interactive Efficient Buildings (GEBs), represent system-level changes to the way we design, build, and operate buildings.

The ABC initiative provides funding for innovative solutions that address construction sector productivity and ability to scale advanced construction techniques. The ABC initiative aims to reduce the amount of time required for construction, improve building performance outcomes like comfort and indoor air quality, and reduce maintenance needs (DOE 2021). Part of this effort includes the ABC Collaborative, a network of building construction, real estate, and development stakeholders who are accelerating change by coordinating innovations across the building industry. Figure 1 shows DOE's multipronged approach to ABC.



DOE's Strategies for Enabling ABC	
Technical R&D	Investing in R&D projects, from advanced materials, modular construction and 3D-printing to robotics, digitization, and simplified installation methods
Analysis & Tools	Conducting analytical studies and modeling to refine and optimize ABC investments and identify opportunities to cut costs
Technology Scaling	Linking researchers, manufacturers, and investors to elevate the most promising ABC innovations and drive development of streamlined, appealing solutions
Market Scaling	Expanding the market for ABC solutions by tackling barriers, marrying consumer interests with supplier innovations, and aggregating public & private sector demand

Figure 1. DOE strategies for enabling ABC

Source: DOE (2021)

A parallel DOE effort is the GEB initiative, which is focused on combining energy efficiency and demand flexibility to transform buildings from an energy load to a clean and flexible energy resource. DOE defines GEBs as "energy efficient buildings with smart technologies characterized by the active use of DERs [distributed energy resources] to optimize energy use for grid services, occupant needs and preferences, climate mitigation, and cost reductions in a continuous and integrated way." GEBs can reduce greenhouse gas emissions by lowering overall energy use and increasing the demand flexibility of buildings, which will facilitate further integration of DERs on the grid (Satchwell et al. 2021).

GEB research is focused on valuing and understanding the technologies that make a building dynamic, such as smart appliances, thermostats, and advanced sensors and controls. The ABC and GEB workforce—ranging from equipment installers and repair technicians to architects and building operators—will need to understand how building technologies can be installed, operated, and maintained for optimal performance.

Advancements in building materials, technologies, and building processes will provide opportunities across the building industry workforce. This report describes some expected changes, and discusses their impact on the current and future workforce in architecture, engineering, construction, building operations, and real estate (AECORE). The intent of this study is to provide a foundation for understanding the context in which the workforce will need to operate to unleash the full potential of ABC and GEBs, identify workforce skill gaps, and introduce methods for addressing those gaps.

1.1 Methodology and Theoretical Frameworks

To gain perspective on these changes, we conducted a literature review and interviewed 22 building industry leaders. Interviewees were identified through our personal and professional networks, and included a wide range of professionals across the AECORE sectors, in both private industry and academia. Interview questions elicited reflection on the present and future state of the building industry and related workforce needs. We also conducted a literature review related to the broader topic of workforce development, including peer-reviewed and academic work. We applied a standard qualitative analysis method, known as Grounded Theory,[1] to conduct analysis, using the software tool ATLAS.ti. We analyzed the literature and interview results to develop a set of categories that guided analysis and subsequent findings. Several rounds of iterative analysis were applied to the data set to distill themes in the interviews and literature.

The analysis in this report is based on the sociotechnical perspective. This is a way of thinking that considers the interconnection between social, environmental, and technical systems. It holds that even a small change in one element of a system will inevitably have effects on others (Sovacool et al. 2020). This approach suggests that sociotechnical analysis, compared to modes that focus only on technology, can better account for unexpected outcomes. Research using the sociotechnical perspective has developed a wide range of tools for understanding the trajectories of change within a sociotechnical system.

This report engages Social Practice Theory, or SPT, which has been widely used in sociocultural analyses of energy and buildings. Some examples include studying the gap in heat pump performance (Gram-Hanssen et al. 2017), the role of infrastructure in automobility (Shove, Watson, and Spurling 2015), and the compartmentalization of knowledge in energy retrofits (Palm and Reindl 2016). SPT has been useful in developing a clearer understanding of the

[1] Grounded Theory, introduced by Glaser and Straus in 1967, includes collecting and analyzing data prior to drawing conclusions and developing a theory.

relationships between social dynamics and technical change (Hampton 2018). Through parallel consideration of technical innovation and social dynamics (Labanca and Bertoldi 2018), SPT highlights the greater opportunities that arise if institutions and markets are considered in parallel with other efforts.

In Section 4, we extend the insights of SPT by introducing a tool from the pedagogy literature with roots in practice theory called Legitimation Code Theory, or LCT. Its overarching goal is to overcome the fragmentation of knowledge that characterizes many fields of education and society. It provides a pathway for embedding a sociotechnical perspective in the emergent ABC and GEB industries through the intentional structuring of pedagogy and other workforce development efforts. LCT is especially relevant to efforts such as ABC, GEB, and others that require synthesis between previously separate areas of knowledge (Creutzig et al. 2018). LCT is a quickly growing area of research that has been applied to several different, AECORE-relevant disciplinary contexts, including physics (Georgiou and Sharma 2014), mechanical engineering (Wolmarans 2016), engineering, architecture, fashion, and digital media design (Carvalho, Dong, and Maton 2008), and settings where equity intersects with design (Shay and Steyn 2015).

1.2 Scope and Organization

This report provides a foundation for understanding the changing landscape of the built environment as ABC and GEBs emerge, as well as the impact of ABC and GEBs on AECORE professions. The scope of this study is limited to qualitative research to understand the broad implications of technological advancements on the building industry workforce. Quantitative assessment of workforce size, current and future labor shortages, and increases in worker productivity due to technological advancements are outside the scope of this study, but can be informed and contextualized using the findings and the theoretical frameworks offered here.

The report identifies skills that will be necessary for realizing the full potential of ABC and GEBs, and provides a tool for making long-term shifts in the education and training systems that prepare the workforce. The report concludes with a set of suggested activities to accelerate this evolution, and identifies areas for further research.

2 Context for ABC and GEBs

Conversations with industry leaders indicate several sources of uncertainty surrounding the future of the building industry. In general, our interviewees agreed that the building industry will see broad changes in the coming 5 to 10 years, but the cumulative outcome of these interconnected changes, and in particular their order, cannot be predicted. Cumulatively, the interviews identified five evolving areas that have implications for workforce development across all building industry professions. These areas will impact the way we design, construct, sell, and operate buildings:

1. Shifts in the role of buildings
2. Increased data availability and software capabilities
3. Greater adoption of robotics and automation
4. Financialization of the building industry
5. Bifurcation of the building industry.

2.1 Shifts in the Role of Buildings

As society gains a greater understanding of how buildings contribute to climate change, the technological advancements supported by DOE's ABC and GEB initiatives are paving the way to lessen the climate impact of the built environment. ABC supports innovations across the design and construction processes to scale low-carbon, affordable buildings. The GEB initiative is remaking buildings into energy resources that increase grid flexibility and reliability by combining energy efficiency and demand flexibility with smart appliances and communication technologies.

The ABC and GEB initiatives support a vision where buildings can deliver environmental and economic benefit while being healthy, energy-efficient, low-carbon, resilient, and affordable. Increased expectations for buildings necessitate an evolution and expansion of the current building workforce.

Workforce Implications

- Increasing our expectations of what buildings provide will lead to greater demand for building science and systems thinking across all phases of design, construction, and operation.
- Smarter buildings will require a workforce with information and communication technology (ICT) skills and an understanding of advanced sensors and controls, interconnected building systems, and the electricity grid.
- Skill deficiencies among a wide range of professionals can prevent high-performance buildings from delivering on their promise, adversely impacting their energy savings, indoor air quality, cost effectiveness, and long-term market adoption (Srivastava 2020).

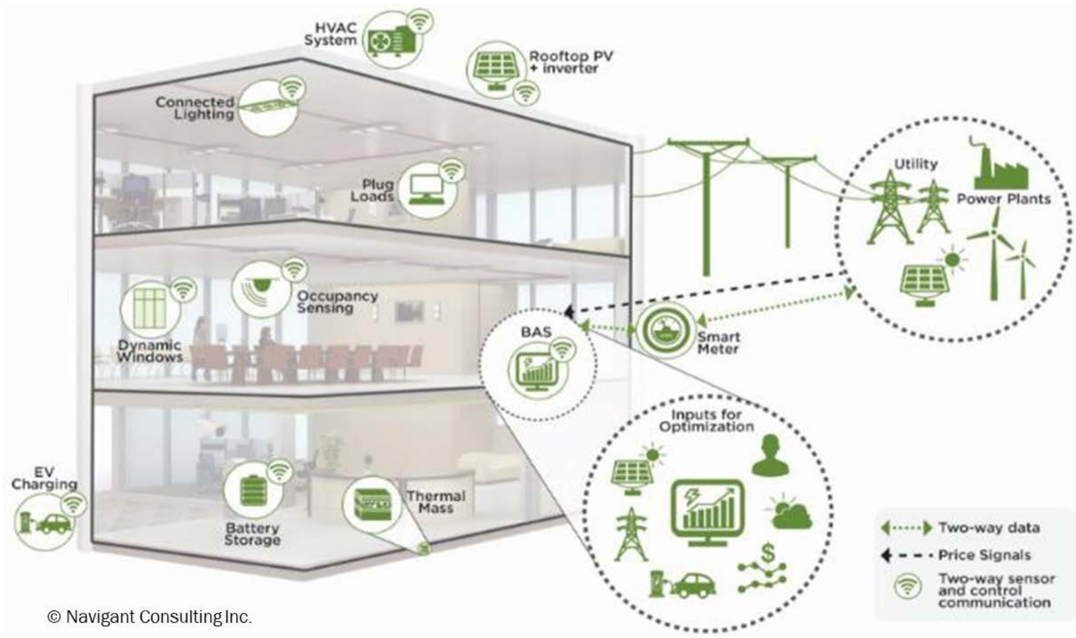


Figure 2. Illustration of a GEB

Source: Neukomm, Nubbe, and Fares (2019)

2.2 Increased Data Availability and Software Capabilities

The increasing use of software tools and data analytics provides a strong foundation for ABC and GEBs. GEBs in particular will utilize data that was previously unavailable in order to optimize a building's performance. Data analytics also underpins ABC applications. For example, building information management (BIM) tools now enable data to be shared across professions and throughout all phases of design, construction, and operation. The growing sophistication of tools to collect, share, and monitor data enables both ABC and GEBs.

Workforce Implications

- The ever-increasing ability to monitor and collect data from buildings and interconnected appliances will increase demand for data analysts, software engineers, and tech-savvy building operators.
- Increasing the use of data-centric software, such as BIM tools and digital twins, will require greater knowledge of a range of software programs and platforms, in addition to requiring increased interoperability of software and data.
- Energy modeling and benchmarking will also be in greater demand, enabled by the increasing sophistication of software and data tools.

2.3 Greater Adoption of Robotics and Automation

> "There will be a need for construction engineers who are not only savvy with BIM-driven processes and tools, but are also competent at using artificial intelligence (AI)-driven tools and understanding their underlying mechanisms. I foresee a near future where one can get a master's degree in AI in construction. Regardless, skills in computer science (such as data science in forms of data sensing, analytics, and visualization), human-computer interaction, as well as cybersecurity will all be critical."
> -Mani Golparvar-Fard, National Institute of AI in Construction

The perception of robotics and automation as "job creators" or "job killers" varied among those we interviewed. Interviewees recognized that a transition is happening out of pure necessity to mitigate the impacts of worker shortages and accommodate new business practices due to the COVID-19 pandemic. Some believed that lower-skilled, repetitive jobs could be taken over by robots, but that any job requiring agility, dexterity, or judgement would be retained by humans. Robots and automation have the potential to reduce repetitive labor and augment the physical capacity of human workers, which could make some jobs more appealing and less punishing on the human body.

Forrester, a major research and consulting firm, notes, "we can't produce enough robots fast enough to have a material effect on job numbers. Machines can't replicate human agility at costs that make sense. While you can train a human to put a bolt in a different spot in a second, programming this change into a robot would be very expensive" (International Federation of Robotics 2017; Le Clair, Gownder, and Higgins 2020).

Workforce Implications

- Adoption of robotics and automation in the construction industry will require more people with computer and mechanical skills to operate and maintain the machines and systems that are helping people construct buildings.
- Moving construction into a factory setting (i.e., modular building) requires a workforce with trade skills and manufacturing expertise. However, interviewees differed in their opinions on what skills are needed for modular building. Some believe tradespeople will simply transfer and apply their existing skills in a factory environment. Others believe that we need an entirely different workforce attuned to the culture of high-quality manufactured products, pointing out that the focus on increasing volume and cutting costs is prevalent across nearly all sectors of the building industry and that this focus contributes to a widely held assumption that quality is unaffordable and therefore unattainable.

2.4 Financialization of the Building Industry

Broader shifts within the economy have repositioned the building industry as an asset class and source of profit. Financialization is defined as "the increasing dominance of financial actors, markets, practices, measurements, and narratives, at various scales, resulting in a structural transformation of economies, firms (including financial institutions), states, and households" (Aalbers 2019). The knowledge that the construction industry has been slow to adopt productivity-gaining technologies has led to a wave of speculative capital that is reshaping the sector. For example, McKinsey reports that "from 2014 to 2019, investors poured $25 billion into engineering and construction technology, up from $8 billion over the previous five years"

(Blanco et al. 2020). Large sums of venture capital can distort markets and disadvantage smaller businesses, especially if a well-capitalized larger business is able to operate at a loss for years or prevent competition by locking down supplies of key materials. The scale of these investments can also fuel regional or national boom-and-bust cycles.

The increasing importance of climate change, resilience, and healthy buildings to consumers and policymakers may counterbalance the short-term outcomes of financialization. Changes in the way that buildings are valued and sold could result from reconfigurations of value made possible by ABC and GEBs.

Workforce Implications

- New business models can accelerate financialization by changing the business dynamics of an industry. Emerging business models, such as energy efficiency as a service, and new methods of construction, such as modular construction, will require employees to learn new sales and business approaches.
- Financialization generally sees labor as a cost to be reduced, rather than a source of value. Mechanisms are needed to account for the economic, social, and environmental value that will be delivered by the ABC and GEB workforce and to offset the increased precarity of work associated with financialization.

2.5 Bifurcation of the Building Industry

The fifth driver of uncertainty identified in this research is the sense that the building industry is in the process of separating into two distinct entities: one focused on high-value, high-cost construction, and the other focused on providing the lowest-cost product possible. Most see the potential for uptake of ABC and GEB innovation in high-value, high-cost construction. The rate at which building codes and software tools are standardized across the industry and the country will influence how quickly ABC and GEBs are adopted. However, our interviewees pointed out that no single player in the industry, including state or local governments, exerts enough control to unilaterally determine how future events will unfold. Our interviewees noted that the rate at which individual companies embrace ABC and GEBs could accelerate the bifurcation of the market into two entities, split by cost and value of construction. This possibility, raised by several of our expert interviewees, identified a possible outcome of ABC and GEB initiatives that is not apparent in the literature.

Our interviewees see the bifurcation of the building market in the context of macroeconomic trends relating to capital and investment, organized labor, and geographic and social mobility. The prediction that the market will split into two sectors stems from the pragmatic observation that innovations in the context of the American economy are unlikely to be taken up evenly. This is not necessarily a pessimistic scenario; our interviewees noted that, given the current need for housing and the importance of retrofitting existing buildings to meet climate and carbon goals, the potential to grow the AECORE workforce is nearly boundless. However, our interviewees noted that this growth would not be evenly distributed with respect to geographic location or demographic factors. One interviewee made a helpful distinction between what we will call the "traditional approach" and the "ABC/GEB approach." As adoption of ABC and GEBs increases, current construction and building practices will continue, and no matter what, constructing, maintaining, renovating, and retrofitting these buildings will require a sizable workforce.

Workforce Implications

- The new ABC/GEB paradigm suggests a need for a new category within the workforce—one that equips workers across all fields and levels of the AECORE professions to work collaboratively to quickly deliver significantly improved outcomes through ABC and GEBs.
- Upskilling the existing workforce to improve the efficiency of existing buildings represents a significant opportunity for professional development and increased earnings in the short- to medium-term. Because buildings are fixed in geographic location, workforce development programs focused on existing buildings can help support urban and rural economies across the United States.
- Workers in an ABC factory may need to learn machine language to control the equipment on the production line. Even though the output is similar—a building component—the type of work and knowledge needed to control a machine is fundamentally different from the bulk of skilled labor now performed on construction sites. For example, Judith Sheine of the TallWood Design Institute identified the need for timber product manufacturers to bring on people who can translate computer-assisted drawings (CAD) to the machine programming language used to mill mass timber building components.
- The workforce responsible for generating innovations in GEBs will require a deep understanding of the complex relationship between supply and demand on the electric grid—and this equation is ever-changing as more renewables come online (Bakke 2016). Programs that create bridges between the traditional building industry and the emergent ABC and GEB industry would allow for the transformation and expansion of existing skill sets to these new contexts.

3 Understanding and Overcoming ABC and GEB Workforce Gaps

Today's building industry workforce will need to grow and acquire new skills to make ABC and GEBs a reality.

3.1 Current Challenges and Gaps

The challenges described here are not specific to ABC and GEBs, but rather represent a spillover from the larger construction and building operations sectors. However, ABC and GEBs will not reach their full potential if we do not address challenges in the broader sectors.

3.1.1 Negative Perception of and Low Interest in Building Industry Careers

Critical fields for the success of ABC and GEBs have struggled to attract and retain the people needed to meet the nation's workforce needs, especially in construction and building operations. To measure the effect of this shortage on construction firms, Associated General Contractors of America (AGC)/Autodesk surveyed 2,500 construction industry members nationwide in 2018. They found that 80% of contractors reported having trouble finding craft workers, nearly 50% reported having to raise their prices, and 46% reported having to push out construction deadlines to deal with the shortage (AGC 2018). Unfortunately, the younger generation of digital natives[2] has been hesitant to join the construction industry, and the construction workforce is consequently aging (Stern 2019).

Building operations is facing a similar situation. The average age of a building operator is 49.5 years, and only 15.6% of the workforce is 34 or younger (BLS). That suggests that a majority of building operators nationwide are set to retire in the next 15 years. This is particularly critical because 92% of building industry members believe that operations and maintenance (O&M) skills are vital for transitioning to an energy-efficient and resilient built environment (Srivastava et al. 2020).

While automation and robotics may help address some of these shortages, the impending "tsunami of retirements" means that we need to heavily recruit people to these fields (Stern 2019). People working in these fields need to have pathways to gaining the skills needed to advance in their careers, and investment needs to be made in engaging with young people to give them compelling pathways for success in construction, operations, and the broader AECORE fields.

3.1.2 Insufficient Skills To Effectively Advance ABC and GEBs

The current workforce will need to gain new skills to realize the full potential of ABC and GEBs. We drew on qualitative analysis of our expert interviewee responses to identify four groups of skills that will underpin the development of ABC and GEBs. These are:

[2] The Oxford dictionary defines a "digital native" as "a person born or brought up during the age of digital technology and therefore familiar with computers and the internet from an early age."

1. Systemic understanding of buildings, climate, and energy with respect to occupants and others
2. Critical thinking and problem solving
3. Data analytics
4. ICT and technical skills.

The skills are described in more detail below.

1. **Systemic Understanding of Buildings, Climate, and Energy**

   Together, the external environment, building materials and components, the power grid, and occupants act as an entire system. The emergent ABC and GEB workforce needs skills built on an understanding of buildings, climate, energy, and occupants as interconnected. These skills would leverage knowledge of high-performance building design principles and building physics, knowledge of buildings' role in climate change, and knowledge of the relationship between energy generation and demand. It is also important to understand how occupant behavior is driven by and responds to the indoor environment, and the impact of occupant behavior on buildings as a system.

2. **Critical Thinking and Collaborative Problem Solving**

   The ABC and GEB workforce also needs a robust set of soft skills. As ABC and GEBs approaches scale, a focus on communication, teamwork, and leadership development will be essential. These skills are especially important for ABC and GEBs due to the complex, cross-disciplinary nature of teams and projects. Creating a culture of continuous learning will also be necessary as innovation in ABC continues, and as GEBs adjust to the evolving role of buildings and the grid.

3. **Data Analytics**

   The ability to work both with and on data sets, large and small, will underpin nearly every aspect of ABC and GEB deployment. Even if the calculative aspects of data analytics are handled by software or automated machines, operators will need a high-level understanding of what kind of data is being used to achieve a given objective. For those charged with using data to make decisions or create algorithms, the ability to critically use data in combination with calculative abilities will be essential to achieving outcomes that are both profitable and equitable.

4. **ICT and Technological Skills**

   Near-term advancement in ABC and GEBs is reliant on specialized technological skills that are expanding in number. Current processes require labor-intensive transformations between different software programs and platforms (for example, design, energy modeling, and manufacturing all require separate, but coordinated, software and platform-specific computer files). In the long term, consolidation may provide a common language for control and operation, but further technological development is likely to increase the number of specialized technical tools used across AECORE.

Table 1 shows examples of skills that the workforce will need to use to support ABC and GEBs, as mentioned in our interviews. Many of these skills are present in today's workforce, but they are segmented or siloed, rather than shared across occupations. To support the development of ABC and GEBs, these skills will need to be embedded deeply and shared widely across occupations in the future. Equipping new entrants with these skills and enabling them to work across existing AECORE boundaries will be dependent on a shift in our educational system to accommodate interdisciplinary learning and problem-solving across occupations.

Table 1. ABC and GEB Skills

Systemic Understandings			***Applied Skills***		
Buildings	***Climate***	***Energy***	***Critical Thinking and Collaborative Problem Solving***	***Data Analytics***	***ICT and Technological Skills***
Examples: • Detail, construct, and test building envelopes • Design and install HVAC systems • Apply passive design principles • Use energy modeling to inform design	**Examples:** • Build with low-carbon design and materials • Design for disassembly and reuse • Design and build for resilience	**Examples:** • Design, install, and maintain building-scale energy storage and generation systems • Program connected appliances and buildings for demand flexibility • Optimize building performance with real-time data	**Examples:** • Manage complex, collaborative, and cross-disciplinary teams and projects • Develop communication and teamwork abilities in individuals and organizations • Pursue continuous learning as systems and goals evolve	**Examples:** • Conduct energy benchmarking • Assess embodied and operational carbon and life cycle • Utilize BIM, internet of things data, and digital twins to improve design, construction, and operation	**Examples:** • Integrate tools and platforms (i.e., CAD, virtual reality, 3D printing) into design, construction, and operation • Operate and program automated equipment, robots • Operate drones for assessment and construction

3.1.3 Lack of Alignment and Shared Knowledge Across AECORE Professions

An overarching theme throughout our interviews was the need for more connection between professionals and workers in existing AECORE segments, highlighting the importance of shared understanding to the transformation of practices. This point is illustrated by the following examples from our interviews:

- Les Goldberg and Marty Doscher, who lead a team working on city infrastructure at Dassault Systèmes, note how they have flattened the social structure of the workplace so those in engineering and production are working together instead of under project managers. They explain, “we didn’t want to drive transformation away from people with hard hats.” They’ve created in-house programs to train architects, engineers, civil engineers, and construction managers to take a critical approach to new manufacturing processes and fabrication tools. They note that although “the industry needs people to know how to use digital tools, it’s not just about the software.” An understanding of intent and outcome—one that stems from systemic understanding—is needed because each task is inherently different. This calls for a workforce that can “work with data to make data-driven decisions, work outside of traditional professional silos, and understand life cycle costs, which should be included in every designer's skillset."

- Although much of the industry has now adopted BIM, there are still sizeable gaps. Salla Eckhardt, Director of Innovation & Digital for Microsoft, notes two in particular: "BIM is being utilized for construction, although there are not enough building owners asking for BIM." In particular, Eckhardt says, "there's opportunity for more cross-pollination and leveraging professional and citywide organizations to allow for learning from each other."
- Julia Day, director of the Integrated Design and Construction Lab at Washington State University, has observed a disconnect in the way her students use and understand BIM. Day says, "Our construction management students usually have to completely remake the architectural models because they do not contain the correct information (or sometimes any information at all). For instance, architectural students may lean heavily on the massing tools and not use or apply the 'information' part of the model, thereby making it impossible for construction management teammates to pull accurate schedules or estimates. We've heard from industry partners that this is commonplace beyond school as well."
- Kimberly Llewellyn, senior product manager of emerging markets at Mitsubishi Electric Trane US, states that there is a "disparity in how we appreciate academic and theoretical knowledge over experiential knowledge." She adds, "Field reality is much more complex than what can be represented in a model. For example, a skilled mason can inform design decisions and predict building performance based on degradation or resilience of different materials and assemblies from having laid eyes and hands on the building elements themselves. So often modelers are making guesses about material properties and other inputs. We are more inclined to trust the models of inexperienced, tech-savvy designers than we are to trust the experienced field professionals. This inclination is dangerous."
- Stacy Smedley, executive director of building transparency and director of sustainability at Skanska USA, emphasized the role of "hands-on" experience, as did many other interviewees. Smedley pointed out that tradespeople have outsized influence in adopting new materials, such as low-carbon concrete, especially if they have not worked with it before. Smedley adds that concerns are usually raised at a point in the building process when budget and timely project delivery can easily override the desire to use new materials.

These examples point to the need for an approach to ABC and GEB skills that acknowledges the potential for alignment and collaboration among the fields responsible for designing, constructing, selling, and operating buildings. To successfully scale ABC and GEBs, professionals across AECORE must be aligned around a shared understanding of building science basics, principles of energy flow, and software tools used to move projects between professionals.

Identifying a shared base of knowledge across AECORE professionals will smooth the process of designing, constructing, selling, and operating high-performance buildings and will ultimately increase adoption of these new building technologies.

3.2 Current Status and Future Needs: ABC and GEB Skills

The following five subsections provide an overview of the current status and outline future trajectories for the development of skills related to ABC and GEBs within each of the AECORE professions.

3.2.1 Architecture

Architects are educated in problem-solving and design thinking (Boland and Collopy 2004). This can be attributed to the embrace of a design attitude, which puts a focus on reframing problems and questioning assumptions. This focus contrasts with a decision attitude, which focuses on choosing between predetermined solutions. Whereas the decision attitude flounders in conditions of uncertainty, the design attitude flourishes, able to make new connections and further innovation. Other researchers have used the related concepts of design thinking (Dorst 2011) and wicked problems (Buchanan 1992) to characterize the ability to simultaneously work and rework problem and solution (Day and Orthel 2017). This general approach fits well with the emergent nature of ABC and GEBs.

Some elements of architectural culture, however, are less compatible with ABC and GEBs. For example, there has been a long-standing recognition that high-quality and high-performance projects benefit from integrated project delivery (IPD).[3] Yet despite IPD's clear benefits, adoption has been slow (Kent and Becerik-Gerber 2010). One reason is architectural education, which explicitly and implicitly trains architects to expect the ultimate position of leadership on a project (Stevens 1998). This is reflected in calls for architectural education to incorporate leadership training (Bilek-Golias 2014) and in a broader orientation to issues of good design and beauty, which are seen as critical judgements that only architects are qualified to make. This has repercussions for what is taught to architects in training. As Lindsay Baker of the International Living Future Institute points out, "architectural education is very consciously *not* interested in the mechanics of the profession so much as it is in the theory of the profession. So people tend not be taught how to use data, [or] how to use technology." User experience, including questions related to health and productivity, likewise do not fit the conventional frame of architectural education.

Approaches to teaching thermodynamics in architecture culture link thermodynamics to the creation of novel form (Moe 2017) or, more commonly, are disconnected from the core curriculum, sending a message that thermodynamics is not important. In the profession, energy modeling tasks are typically handled by specialists. Because architects tend to have a limited understanding of energy flows and energy modeling tools, trust in these tools is diminished, limiting their application in the early stage of the design process, when they can have the most impact on reducing carbon emissions (Alsaadani and Bleil De Souza 2018).

An example of how this paradigm will need to shift to support ABC and GEBs is mass timber buildings, which are often modular. Mass timber buildings require teams of architects, mechanical and structural engineers, and manufacturers to work together from the very beginning of the project. According to Judith Sheine, professor of architecture at the University of Oregon and director of design at the TallWood Institute, this context "compels architects and engineers to start thinking about things really differently from the very beginning—particularly architects."

[3] The American Institute of Architects defines IPD as a project delivery approach that integrates people, systems, business structures, and practices into a process that leverages the talents and insights of all participants to optimize project results.

3.2.2 Engineering

Today's engineers have skills using data and are trained to solve bounded problems, often using specific technical tools. Engineering is differentiated from architecture through its diverse and formally articulated organizational structure, with clearly differentiated fields and subfields underpinned by distinct bodies of knowledge, certifications, and standards. Another important difference is the social relationship embedded in the field; whereas architects are explicitly and implicitly taught to be leaders who buck the system by creatively questioning assumptions, engineers are taught to follow procedures, respect authority, and provide plenty of room for error. In the United States, engineering firms also shoulder much of the liability for complex building projects, a contractual arrangement not common in other countries.

One opportunity posed by ABC and GEBs is the potential to expand the ability of engineers to apply their problem-solving abilities to larger and more complex problems. This could be accomplished by moving the role of the engineer upstream in the process, as is the case with IPD. In current modes of practice, the problem-solving capacities of engineers have been constrained by their position downstream from architects in the design process. New roles and different organizational structures are needed to coordinate or design the interface between different roles in the design and construction process. By the time an engineer is engaged, it is often too late to redefine the problem that needs to be solved, so the engineer figures out the best way to solve it within the given constraints. In contrast, ABC and GEBs present a significant opportunity for engineers to shape project outcomes, especially with regard to new materials and technologies unfamiliar to architects and designers. As Stacy Smedley points out, "on the professional side, engineers are excited because they have a larger role to play." When carbon accounting is brought into the picture, the engineer's role becomes even more critical. As Smedley explains, "the highest carbon impact materials are all ones that the engineers are detailing and drawing." These possibilities are amplified when IPD is used or when architects and engineers collaborate closely—that is, when "architects lean on the structural engineers for choosing different concrete mixes and smaller steel beams, while the architects focus on the envelope and interior materials."

The ABC and GEB workforce may also benefit from unbundling technical skills that were once performed by engineers but have since been offloaded to others. These skills should be taught with respect to the first principles that govern the systemic relationship between buildings, energy, and environment. A disconnect in the mechanical skills needed for high-performance buildings illustrates this. For example, Peter Schneider of VEIC, who is working on a high-performance modular project in Maine, found it difficult to find a contractor who could "do a detailed duct design—moving beyond the rule of thumb, getting into low-load homes, ducted heat pumps, ventilation equipment." For ABC and GEBs to have efficient HVAC systems that deliver comfort and good air quality, mechanical engineers need to reclaim aspects of problem-solving and design that have been bundled with system installation. This is especially important because the long-standing shortage of workers in the HVAC industry (Electric & Gas Industries Association 2018), when interlocked with the dominance of conventional systems, creates little incentive for changes in practice (Lutzenhiser 1994). Bundling skills into prescriptive rules for system sizing limits the rate of change, as prescriptive rules have to be unlearned and also obscure the first principles governing fundamental design decisions. Likewise, software, automation, and codes can have a similar effect, locking in conventional approaches and making it difficult to apply new methods of calculation and design.

3.2.3 Construction

Demands on today's tradespeople—electricians, mechanical engineers, sheet metal workers, and others—will grow as ABC and GEBs evolve. ABC and GEB construction will rely both on expanded knowledge of buildings, climate, and energy and on the development of field-specific technical skills, such as the operation of robots and automated assembly lines. Labor organizations are in an excellent position to support upskilling today's organized trades.

Looking forward, continuing labor shortages may drive the adoption of modular construction (McKinsey & Company 2019). ICT and technology will continue to grow across the construction industry as an important means of augmenting and amplifying a scant labor supply. While some predict that automation could lead to the loss of 2.7 million construction workers by 2057 (Manzo, Manzo IV, and Bruno 2018), others see the emergence of ABC and GEBs as an opportunity to refocus existing and future workers on higher-quality outcomes. Two of our interviewees observed that speed, not quality, is valued on most conventional construction sites, as well as in off-site manufacturing plants. While ABC does aim to increase productivity, an equally important aim is to improve the quality and performance of buildings.

As Kimberly Llewellyn points out, "there is a ton of work on our existing building stock and even on new construction that doesn't get done adequately because we have devalued skill sets and therefore we don't have the labor." Ivan Rupnik, from Northeastern University's School of Architecture, cites evidence from Sweden and Japan, where the modular industry employs "higher skilled, better paid labor" than site-built construction. Others see a decline in the demand for and value of low-skilled, low-wage jobs, such as drywall and painting, but point out that these jobs will be difficult to replace with current robotic technology.

3.2.4 Operations

The building operations workforce will see a significant shift from current tasks that involve problem-solving and the application of manual technical skills to roles centered in data analytics and ICT.

ABC and, in particular, GEBs, may require building operators to be knowledgeable about energy flows and the operation of the grid and to be comfortable making data-driven decisions and using ICT and technical systems. A significant obstacle to this potential change is the attitude toward technology within the current operations industry. As Lindsay Baker recalled from her time at a building automation startup, "software of any kind is perceived as a job killer… I literally had guys tell me, 'I don't want to install your software because I'd have to fire somebody, and if I had to fire somebody what am I going to say to his wife and kids?'" Some in the field do not feel like they have the time to learn new software, a problem amplified by the lack of standardization and the resulting path dependency of competing building control systems. Cybersecurity is also a stumbling block, with building operators hesitant to connect any building systems to the internet for fear of hacking, ransomware, and other attacks.

3.2.5 Real Estate

Problem solving and other soft skills are core to the present operation of real estate development and investment, along with a constrained set of data analytics tools. Broadly speaking, ICT and technical skills are limited to those tools needed to facilitate transactions, though operations that hold real estate in the long term are increasingly turning to specialized tools to automate tenant interactions and monitor building operation and maintenance needs.

Real estate development and investment is characterized by the dominance of financial metrics such as capitalization rate, net operating income, and internal rate of return. This focus, when compounded by a lack of knowledge about building energy performance, has blunted attempts to integrate social and environmental value considerations into real estate (Mills 2015). For ABC and GEBs to grow, real estate professionals will need to translate the system-level benefits these approaches offer, such as increased quality or grid services, into terms recognizable and valued in the field of real estate. Alternatively, skills based on a systemic understanding of buildings, climate, and energy must be introduced into the ABC and GEB real estate workforce and connected with new skills in data analytics and ICT. One possible approach is greater vertical integration, a tack taken by Seattle-based modular developer Blokable. By serving as the developer and builder, Blokable's business model brings real estate into closer contact with architecture, engineering, and construction, reworking both skills and processes. This approach demonstrates the potential for closer collaboration and reconfiguration of business relationships that are now distributed into separate silos in the building industry.

Table 2 summarizes some of the knowledge, skills, and abilities each of the AECORE professions need to address to support ABC and GEBs. Many of the items listed will be useful for supporting both ABC and GEBs. The competencies in Table 2 are a sampling of where upskilling may be needed in each profession generally; note that this list is not exhaustive, and in many cases, some professionals may already have these skills.

Table 2. Areas Ripe for Upskilling in Each AECORE Profession To Support ABC and GEBs

Profession	ABC	GEBs
Architecture	• Designing buildings for manufacturability and disassembly • Understanding aesthetics, structure, and function of low-carbon materials and considering the way they are used in construction and viewed by engineers, operators, and owners • Using BIM tools in a manner that translates to construction and engineering professions • Building energy use benchmarking tools and policies • Modeling energy use and carbon emissions	• Modeling and understanding energy use and carbon emissions • Predicting a building's ability to provide grid services and associated energy and cost savings • Designing low-load buildings for grid interactivity to best serve occupants
Engineering	• Engineering mechanical, electrical, and plumbing systems into prefabricated wall assemblies or manufactured "pods" • Engineering mechanical systems and sizing for low-load and decarbonized homes and buildings • Modeling and understanding energy use and carbon emissions • Understanding the performance and function of low-carbon materials and considering the way they are used in construction and viewed by architects, operators, and owners	• Developing and using building automation software tools • Creating engineering schematics for sensors and controls for building automation • Understanding a building's ability to provide grid services and associated energy and cost savings • Learning how distributed energy resources work within the building system and how to provide engineering

Profession	ABC	GEBs
		schematics for builders, including system integration • Understanding cybersecurity threats and mitigation strategies for interconnected buildings
Construction	• Utilizing 3D printing • Using digital tools to manage construction projects (e.g., BIM) • Gaining experience with low-carbon materials, increasing building science knowledge • Learning to use robotics and drones to assist in the construction process • Learning manufacturing techniques (i.e., industrialized construction) • Learning to install, troubleshoot, and maintain new technologies, materials, and systems	• Understanding a building's ability to provide grid services and associated energy and cost savings • Learning how distributed energy resources work within the building system and what permits are required • Learning to install, troubleshoot, and maintain new technologies and systems
Operations	• Learning to troubleshoot new systems and technologies • Integrating occupant behavior into building operations • Understanding costs and benefits of new technologies and equipment for retrofit and replacement applications • Understanding building energy performance	• Using ICT and data analysis tools • Understanding grid power flows and opportunities for additional revenue from providing grid services • Understanding cybersecurity threats and mitigation strategies for interconnected buildings • Understanding DER O&M
Real Estate	• Understanding building energy performance and financial and environmental impacts of energy use • Understanding functionality, aesthetics, costs, and maintenance needs of low-carbon materials	• Understanding opportunities for additional revenue to buildings from providing grid services • Learning about costs, benefits, and maintenance needs of DER systems

4 Closing the Gaps With Social Practice Theory

Market transformation approaches focused on overcoming barriers can undervalue the critical role of social processes (Shove 1999). Historically, frameworks for advancing innovation in energy and buildings tended to focus on overcoming technical gaps, while underestimating the difficulty of addressing social gaps. The coordination and effort required to achieve change is underplayed when gaps are conceptualized as isolated parts of a larger system that runs according to rational economic logic (Guy 2006). Social gaps are often left out of analysis or considered as external factors, because considering actual human behavior in context complicates analyses and undermines the certainty of technical solutions, especially when predictions of future states are in play. Indeed, the inherent uncontrollability and contingency of human behavior stands in stark contrast to the precision of the quantitative approaches that dominate energy- and climate-related research (Galvin 2017). For example, design and construction specifications for making net-zero buildings have existed for decades, but these technical solutions alone have not transformed reality (Lutzenhiser 1994). Shifting expectations for buildings will require changes in systems regulated by complex and interrelated social dynamics. Unfortunately, merely recognizing the interconnection of social dynamics and technical change does not yield actionable insight. To achieve this, the following sections introduce and apply two tools grounded in Social Practice Theory (SPT): the Circuit of Practice and Legitimation Code Theory.

4.1 Introducing the Circuit of Practice

In contrast to what Guy and Shove term the "techno-economic paradigm," the interconnected view of SPT takes a holistic perspective on processes and outcomes (Guy 2000). The word "practice" has specialized meaning in SPT: it does not indicate professional work, as in medical practice, nor individual rehearsal, as in practicing the piano. Instead, "practice" is used to describe large-scale cultural processes that rope together objects, meanings, and doings—the core elements of practice. Importantly, SPT puts practice elements at the center of analysis, rather than focusing on the behavior or choices of a rational economic actor. The three elements of practice are described in Table 3. For example, an SPT-informed analysis of the practice of car driving would take into consideration objects such as cars and roads, meanings such as freedom and self-determination, and doings such as maintaining a car or knowing how to parallel park. In the context of workforce development, the SPT perspective suggests workforce development programs would be most effective by working to symbiotically close as many gaps as possible by coordinating new linkages between practice elements.

Table 3. Elements of Practice

Element of Analysis	Description and Examples
Objects	Material things, such as cars, roads, and buildings
Meanings	Implicit or explicit beliefs shared by some or many members of a culture, such as the sense that individually owned cars are expressions of freedom, *and* explicit sets of rules, such as regulations, codes, and standards
Doings	Skills, such as using a hammer or installing a window, that can be aggregated into larger sets of doings to constitute competencies or routines, such as conducting energy analysis or detecting the sound of a failing compressor

Practice elements are dynamically linked, so that a shift in one element will impact others. This movement between objects, meanings, and doings is referred to as the "Circuit of Practice" (Maguadda 2011).

The next section demonstrates how elements of practice might advance systems-level innovation in the context of high-performance envelope retrofits of existing buildings.

4.2 Applying SPT To Close Gaps: ABC Envelope Retrofits

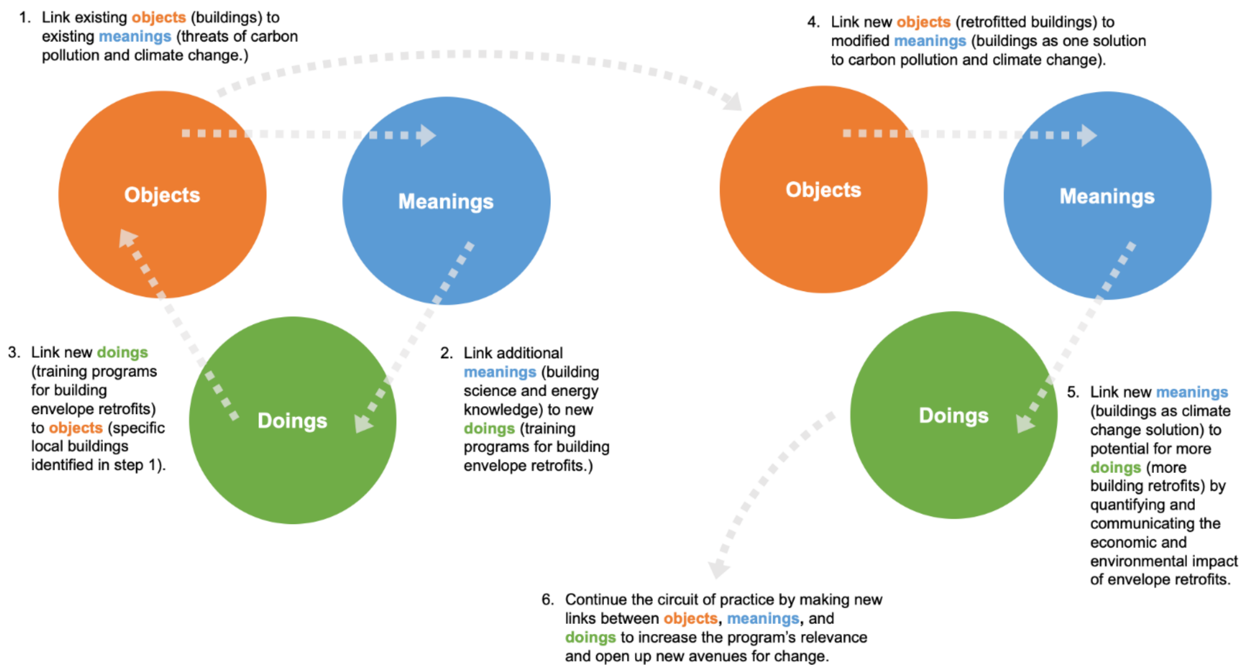


Figure 3. Using the Circuit of Practice to inform workforce development efforts on ABC retrofits

A program focused on ABC envelope retrofits could remap connections between the elements of practice, as shown in Figure 3. This example involves six sequential, coordinated moves between the practice elements of objects, meanings, and doings. The first move would connect objects to meanings: in this case, making the case that existing buildings can address the threats of carbon pollution and climate change. Once people start to think of buildings as part of the problem and a potential solution, the second step would be to link these new meanings to ABC envelope retrofit skills. The third step is to develop and deploy effective training programs and curricula in basic building science and energy knowledge, linking these new doings to specific existing buildings. At this point, we have completed one loop around the circuit: starting with objects, moving to meanings, then doings, and finally back to objects. The circuit continues in step four, where new objects are developed to document projects and launch new meanings into circulation. In step five, new meanings are created through quantification, comparison, and communication, supporting further growth in doings. Finally, in step six, we move from doings back to objects.

Considering the Circuit of Practice is helpful because it highlights the importance of addressing objects, meanings, and doings in parallel. For example, a 2016 report states that "The skilled trades are currently seen as 'dirty,' low-status, physically difficult, boring, low-paying, and unskilled. While some acknowledge that HVACR technicians are critical to addressing important issues facing our society, they are generally not highly valued, and new workers are not attracted to the career" (Heinemeier et al. 2016). An approach that focuses only on the development of skills would miss the critical need to reshape the meanings that deter people from entering the field. The Circuit of Practice approach also suggests that efforts to reshape practice are more effective when interventions simultaneously target multiple practice elements.

Photo from iStock 674133526

The Cool Biz initiative, sponsored by Japan's Ministry of Environment in 2005 and continuing today, has been effective at decreasing energy use. After only two years, it claimed a 1.14 million ton decrease in carbon emissions, achieved by setting air conditioners in office buildings to no lower than 28°C (82.4°F) in the summer months. CoolBiz coordinated changes in **doings** (thermostat settings, AC operation, and energy generation) and **objects** (warmer office temperatures). To increase adoption, a coordinated fashion campaign was introduced, targeting a shift in **meanings**. CoolBiz encouraged men to switch the traditional jacket and tie for Hawaiian-style shirts through an advertising campaign and special CoolBiz sections in department stores. This tied a shift in both **meanings** (making different clothing socially acceptable) to the increased availability of different **objects** (cooler clothing). Those on the edge about making the switch could pick up stickers that read "Excuse my clothing, I'm doing Cool Biz." A later Cool Biz campaign pointed out that women were often cold in office settings, tying the same set of objects to a newly resonant set of meanings: an emergent cultural discussion about gender inequality (Lim 2011, Chou 2019, Southerton, McMeekin, and Evans 2011).

4.3 Introducing Legitimation Code Theory

To address the gaps outlined in Section 3, we employ a core concept underpinning SPT, the concept of the social field. As defined by the sociologist Pierre Bourdieu, fields are arenas specific to particular groups of people, governed by rules that are both implicit and explicit. Most social fields operate with a set of written and unwritten rules. People in a field must play by both sets of rules to get ahead. Just as there is competition within fields, there is competition between fields. In the context of the AECORE industry, architecture, engineering, construction, operations, and real estate each constitute a social field operating with its own rules.

Because these fields are related to but distinct from one another, what Bourdieu called the "rules of the game" cannot easily be aligned. This is a fundamental challenge for ABC and GEBs, which aim to coordinate and streamline stakeholders across the building industry. Indeed, one strategy for maintaining the boundary around a field is to make it fundamentally incompatible with other fields.

Enforcing field boundaries is a fundamental strategy for maintaining autonomy of individuals within a field and of the field itself. It allows those in a field to make a claim of expertise, exert control over the rules that govern the field, and garner status and financial reward. The way that these fields intersect—and the rules that underpin them—makes aligning outcomes in AECORE difficult. Architecture follows a set of rules patterned after the art world. In contrast, engineering is inscribed as applied science. Both of these fields operate with large degrees of autonomy. In the terms of field theory, architects and engineers—especially those who occupy positions of power in the field—write the rules that govern the fields in which they operate. Construction and operations, broadly speaking, have less autonomy; they are bound to work within sets of rules set by others. Having more professional autonomy is strongly associated with social status in the United States (Stevens 1998). Many explicit and implicit "rules of the game" in the context of construction and operations, such as following instructions and obeying authority, are strongly associated with field logic that does not align with the logics in creative fields, such as architecture. To create change in AECORE, the ABC and GEB workforce must be equipped to bridge these divides, both within and between fields.

Legitimation Code Theory (LCT) is an educational theory grounded in Pierre Bourdieu's field theory. The overarching goal of LCT is to overcome the fragmentation of knowledge that characterizes many fields of education and society. LCT is especially relevant to efforts such as ABC, GEB, and others that require synthesis of previously separate areas of knowledge (Creutzig et al. 2018). According to Karl Maton, who has done much of the theoretical work underpinning the LCT approach, a fundamental focus is to "reveal different dimensions of the 'rules of the game': the bases of achievement underlying social fields of practice. Such bases are often unwritten and unspoken," meaning that "they 'go without saying' in ways that, when accessible only to actors from specific backgrounds, generate social inequality" (Maton 2015). For example, the underrepresentation of women and minorities across the building industry indicates the presence of spoken and unspoken rules that have effectively limited entry and continued participation in the social fields that constitute the broader building industry.

LCT aims to make these rules legible to those in the field, both through analysis and approaches to pedagogy and professional development. Once rules are understood, those in the field can follow the rules—or work to change them. For example, one interviewee pointed to the need to identify alternatives to problematic management styles that perpetuate the overrepresentation of men across the building industry. Because LCT provides a systematic way to account for the patterning of interactions in relation to their outcome, it can help those in the field see more clearly the cost of the status quo and the opportunity afforded by inclusion. Notably, interviewees driven by the urgency of the climate crisis saw the need to increase equity and inclusion within the AECORE workforce as an imperative, not only because they believed it to be the right thing to do, but because they saw it as a matter of practical necessity. Rocky Mountain Institute's Adam Parker put it this way: "this is an all-hands-on-deck situation." Effective tools are needed to remove barriers to participation across the AECORE workforce.

LCT is useful in moments of change because it offers a set of tools for identifying and overcoming barriers to knowledge transfer. In the parlance of LCT, these tools are called "legitimation devices." Of the five devices LCT offers, we focus on Specialization, which is represented by the diagram in Figure 4.

The quadrants of the Specialization plane map the relationship between knowers and knowledge. Each quadrant represents a distinct form of this relationship, titled the knowledge code, elite code, relativist code and knower code. The x-axis represents a continuum between weaker and stronger social relations, or connections between knowers, and the y-axis represents a continuum between weaker and stronger epistemic relations, which indicate how context-dependent knowledge is. The code in the field of construction and building is a *knower* code. This code is context-specific; to be useful, knowledge must be specific to the knower and the context. A legitimate builder is one who is recognized by peers as having the embodied knowledge of how to skillfully swing a hammer. In contrast, the dominant code in the field of engineering is a *knowledge* code. Here, what counts is abstract knowledge: knowing how to swing a hammer does not matter much, but being able to perform a calculation does. Social relations are also less important than knowledge: get the right answer to the calculation and you are a legitimate engineer. Architecture occupies the position of an *élite* code, named not for reasons of status, but instead because legitimacy is granted by being both the right kind of knower and having the right kind of knowledge—one that balances the role of the artistic, creative, and embodied experience (a knower code) with a practical, problem-solving, and technical role (a knowledge code) (Carvalho, Dong, and Maton 2008). Operations spans the dimensions of the knowledge and knower codes, depending on the specific task being performed. Real estate development occupies the relativist quadrant, where being seen as legitimate has little to do with specialist knowledge or the specific attributes of the knower. Mapping the current arrangement of AECORE onto the Specialization plane looks something like this:

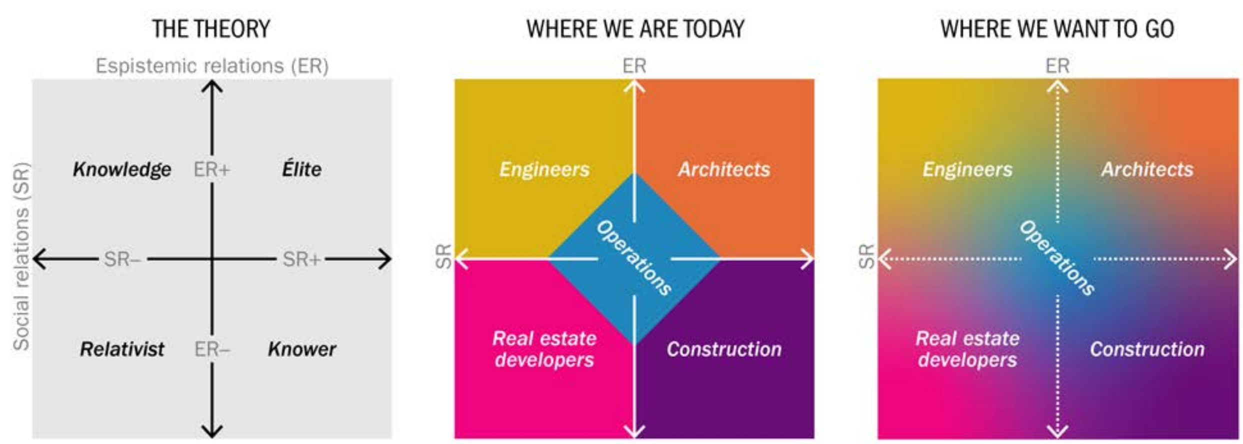


Figure 4. An expansion of the Specialization plane as it relates to AECORE

Source: Maton (2014) and NREL

This mapping sheds light on some familiar conflicts. Take, for example, the architect who is perceived as impractical by the engineer because he or she is interested in preserving the aesthetic quality of a design. Thinking about this in terms of the Specialization plane, we can see that the architect is speaking in terms that make sense within the élite code, whereas the engineer sees value through the lens of the knowledge code. In turn, the builder may be frustrated by the demands of the engineer who specifies a new material because the builder lacks experience working with that material. Section 3.2 contains an example from our interview with Stacy Smedley that can be understood more deeply using the tools of LCT. The dimension of Specialization underscores Smedley's point that tradespeople have outsized influence in scuttling new materials, such as low-carbon concrete, especially if they have not worked with the material before. Is it sticky? Can it be finished just like conventional concrete? From the standpoint of LCT, the knower code highlights the role of direct, embodied knowledge. But the architect and engineer who are trying to convince the tradesperson to use the new material are each emmeshed in their own code. They have likely settled on the low-carbon concrete for reasons that have little to do with the context-dependent quality of usability and more to do with abstract knowledge related to the desired aesthetic of the building or the requirements of a code or green building standard. While the architect and engineer occupy fields where different codes are valued, they both value knowledge-code-based explanations. It is likely they will try to convince the tradesperson to use the new low-carbon material using abstract information in the form of promotional materials, measurements, or specifications—a form of knowledge with little value to those operating with a knower code. The tradesperson wants to know what it *feels* like to use the material. LCT describes this as a code clash, and experiences of it are likely familiar to anyone who has tried to effect change in the building industry.

5 Enabling the Future

This section includes activities that apply to both the traditional building industry workforce and the emergent ABC/GEB workforce. The following actions address the interconnected potential of efforts that would support the adoption of ABC and GEBs and increase the existing workforce's systemic knowledge of buildings, energy, climate, and occupants.

1. **Reposition building industry careers by developing a new set of meanings to link building industry careers to a better future.**

   Several interviewees related a sense of dismay related to the current state of the U.S. building industry. They expressed frustration that the hard work that does happen on building sites is not recognized, that the industry seems to be in a race to the bottom with respect to costs and quality, and that attempts to improve the industry through regulation are most often received with skepticism, if not outright antagonism.

   Although it may be difficult to reset expectations of the existing building industry, the bifurcation of the market offers the possibility to define a new category of meanings aligned with ABC and GEBs. This category would recognize the value of the existing workforce that is committed to high quality work, while also allowing for new entrants. Efforts to align culturally valuable meanings with the new fields of ABC and GEBs can directly translate to workforce development by attracting a robust, diverse, and dedicated workforce, and by creating a broader cultural recognition of the value of ABC and GEBs. Assigning new meanings to ABC and GEBs could have a spillover effect for the overall building industry, allowing the industry to connect their work with a better future.

   The Circuit of Practice can be used to attach new meanings to building industry careers. A coordinated effort to reposition the building industry as a central venue for fighting climate change, increasing economic value, and addressing social equity will help attract more people to the field who are interested in a high-tech, climate-positive career.

2. **Differentiate ABC and GEBs from traditional building careers and support two distinct but overlapping workforce pipelines.**

   A two-pronged approach will equip the current and future workforce to service two divergent markets: the traditional/existing building pipeline, and the ABC and GEB pipeline.

   Differentiating between the traditional building industry and the emergent ABC/GEB industry can offer several opportunities. First, differentiation isolates some of the resistance the traditional workforce may have toward major disruptions to the way they currently conduct business. Multiple interviewees suggest that trying to change the internal culture of many players in the existing building industry may be an uphill battle. Therefore, articulating a new pipeline for ABC and GEBs offers an opportunity to leave these entanglements behind and connect ABC and GEBs to a new set of meanings linked to climate change. This also presents an opportunity to rebrand these careers as high-tech and meaningful for combating climate change, increasing resilience, and providing healthy spaces to live and work.

Second, the existing workforce will evolve, and many will be interested in learning new skills and approaches as more robotics and automation are introduced to job sites. Differentiation allows for a focus on upskilling and retraining in areas where innovative tools and techniques are being implemented now—such as designing/installing HVAC systems for low-load homes—to raise the bar for the existing workforce. Partnering with existing education and training providers and labor organizations will reach those who design, build, sell, and operate homes and buildings, today and in the future.

LCT tools can be used to help people in existing fields interface with their counterparts in adjacent fields and can help them restructure the industry to account for the emergent needs of ABC and GEBs.

3. **Support efforts that value the full range of skills necessary to realize the potential of ABC and GEBs equally, rather than defining a set of skills siloed in specific AECORE professions.**

   As LCT and other research shows, skills inventories do not fully capture the role of social context and meaning in job performance, inadvertently limiting the number of entrants to a field. Furthermore, approaches that place different AECORE jobs as collections of skills and tasks on a hierarchical ladder might make them less attractive to the broad swath of Americans that identify as middle class, where professional identity is a key marker of social worth. In addition, explicitly or implicitly describing jobs that require high levels of manual ability, strength, or other specialized, embodied competence as "low skilled" sends a signal to people in those positions that their labor is not valued. This threatens to deepen the divide between managerial positions held by degreed professionals and those doing jobs that largely involve manual labor. Therefore, ABC and GEB workforce development efforts should take care to equally value the full range of skills required to advance the building industry. Efforts should enable trust, respect, and knowledge to flow across existing boundaries between and within AECORE professions. Articulating a vision for what type of person the student is becoming, and what type of work needs to be done to achieve meaningful outcomes, will help to express the equal value of skills across professions.

   Workforce development is often categorized into education and training programs. Training teaches someone to do something specific (installing a water heater), and education prepares students for a range of opportunities because students are taught to understand how systems connect and how to approach and solve problems. Both approaches are needed to support ABC and GEBs, but it is important to be mindful of how a lopsided focus on skills can inadvertently limit the potential of those who are well-trained but are not able to advance without a broader education. LCT approaches have been used to understand and overcome unintentional outcomes of vocational education programs that can limit students' future potential (Wheelahan 2015).

LCT can develop a specific type of learner by including a consideration of disposition and professional identity (Giloi and Quinn 2019). This would allow LCT-informed workforce development programs to better answer the industry's need for workers with desirable attitudinal and personality characteristics, in addition to skills (Holmes 2001).

4. **Organize ABC and GEB institutes to build regional industries with dedicated job pipelines.**

   This action points to the opportunity to develop regionally specific ABC and GEB workforce training programs that are attuned to the resources, organizations, and needs of different areas. Organizing these programs as applied research institutes would allow for the emergence of a network of ABC and GEB initiatives tailored to the needs of a specific place. These institutes could draw from several existing models and recommendations, such as the National Science Foundation's guidelines for advancing the STEM[4] education pipeline. They should bring in a wide range of stakeholders beyond architects, engineers, and industry representatives, including tradespeople, community college and high school educators, and career counselors. Tuning these institutes to meet the needs of a specific region would mean working with organizations that provide certifications and credentials. In turn, these efforts would create more certainty that a given ABC or GEB institute's efforts would create pathways to future jobs.

   The TallWood Institute, a university-industry partnership that has successfully advanced the market for mass wood construction, offers a model for ABC and GEB consortia. TallWood is a joint project of Oregon State University's engineering program and University of Oregon's architecture program. It is funded through state appropriations, grants from the Forestry Service, and a network of industry partners that form an advisory board. TallWood conducts applied research, such as structural testing, in a dedicated facility, and is launching a master's degree program that is attuned to the needs of the industry.

   LCT tools can help us evaluate successful efforts objectively to understand what has worked in which regions and to better understand how to scale and translate to other regional, educational, and professional contexts.

5. **Break down silos among AECORE professions and educational institutions.**

   Education and training programs focused on the existing and emergent ABC/GEB workforces should include an emphasis on a harmonized understanding of building science across AECORE disciplines. Convening representatives from across the worlds of AECORE education and training, accreditation, and the trades could help to identify a core curriculum and set up new alliances to drive innovation. Equally

[4] Science, technology, engineering, and math subjects are collectively referred to as STEM.

important is the ability to effectively use data and software tools that facilitate efficient communication among disciplines.

LCT offers specific tools and interpretive frameworks that explain how complex knowledge can be communicated in ways that make sense to those in a specific field (Maton 2019). These specialized approaches could be used to close building science knowledge gaps in fields such as engineering (King 2010) and architecture (Brainard and Correa 2019), or to support approaches to interdisciplinary architecture and engineering education (Laboy and Onnis-Hayden 2019). LCT tools also inform how foundational knowledge of building science, climate, and energy can be adapted and taught to overcome, rather than perpetuate, segmentation between AECORE fields. For example, these tools could be used to ensure that programs embed foundational knowledge of building physics, rather than a superficial knowledge of code, in their curricula (Gertis 1984). This would amplify the impact of interdisciplinary teaching efforts conducted in collaboration with industry partners (Vander Poel and Griffin 2017). LCT tools can also be used to inform new programs of education that aim to identify and overcome problematic professional and disciplinary divides.

6 Conclusion

Approaching workforce development with social contexts in mind will be as important to the success of ABC and GEB adoption as addressing technical and knowledge gaps. Opportunities for increasing the knowledge and skills of the existing and future workforce will present themselves differently in each discipline across the AECORE professions.

Social science offers tools, such as the Circuit of Practice and LCT, to overcome the most difficult obstacles that hinder the flow of knowledge among the AECORE professions. Further work is needed to apply LCT tools to close the gaps between AECORE fields by designing approaches that overcome barriers to the knowledge exchange between fields.

Additional analyses to help facilitate the suggested actions in Section 5 include: (1) analyzing regional opportunities for industry-education institutes, (2) clearly articulating what common base of knowledge is needed by each of the AECORE professions, (3) taking a global inventory of successful ABC and GEB efforts to adapt learnings to fit the U.S. context, and (4) developing LCT pathways for creating a new pedagogy for AECORE training and education programs.

The interconnected nature of ABC and GEBs suggests that a coordinated effort across AECORE professions will yield the best outcomes for increasing the pace and scale of adoption. If we only focus on improving skills, we will miss the opportunity to rebrand the building industry and associated careers as meaningful, high-tech, and climate-positive. We must seize the opportunity to reposition these careers to appeal to younger generations and attract a diverse workforce.

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Appendix. List of Interviewees

- Aaron Holm, Co-CEO of Blokable
- Anne Pfleger, Kari Schutte, Tamae Partain, Members of the National Association of Women in Construction
- Aparna Brown, holds a Ph.D. in Developmental Neuroscience and is Director of Operations for BirdBrain Technologies
- Art Morales, Site Supervisor at Shaw Construction
- Diana Fisler, Building Materials Consultant from ADL Ventures; Martha Campbell, Principal of Rocky Mountain Institute's (RMI) Carbon-Free Buildings Team; Lucas Toffoli, Manager of RMI's Carbon-Free Buildings Practice and Project Lead for the Advanced Building Construction (ABC) Collaborative; and Adam Parker, REALIZE Market Consultant at RMI
- Iain Macdonald, Director of the TallWood Institute, and Judith Sheine, Professor of Architecture at the University of Oregon and Director of Design at the TallWood Institute
- Ivan Rupnik, Co-Founder of ModX and Associate Professor at Northeastern University's School of Architecture
- Jaya Mukhopadhyay, Associate Professor of Building Energy Performance at Montana State University
- Julia Day, Director of the Integrated Design and Construction Lab at Washington State University
- Kate Simonen, Executive Director of the Carbon Leadership Forum and Associate Professor of Architecture at the University of Washington
- Kimberly Llewellyn, Senior Product Manager of Emerging Markets, Mitsubishi Electric Trane US
- Laura Heon, North American Channel Sales Manager, Centrica Business Solutions
- Les Goldberg, Executive Account Manager, Dassault Systèmes, and Marty Doscher, Construction, Cities, Territories, and Industry Business Consultant Senior Director, formerly VP AEC Industry, Dassault Systèmes
- Lindsay Baker, CEO of International Living Future Institute and Board Member for Measurable, formerly VP of The Global We Company, President of Comfy, and former Member of the Google Green Team, Sustainable Operations
- Mani Golparvar-Fard, Co-Founder of National Institute of AI in Construction and Associate Professor of Civil Engineering, Computer Science, and Technology Entrepreneurship at University of Illinois-Urbana, and Pingbo Tang, associate professor of civil and environmental operations at Carnegie Mellon
- Martin Fischer, Professor of Civil and Environmental Engineering at Stanford, and Andrew Peterman, Executive Director of Stanford Engineering's Center for Integrated Facility Engineering
- Peter Schneider, Senior Consultant at VEIC
- Salla Eckhardt, Director of Innovation & Digital for Microsoft Global Real Estate and Security – Center of Innovation
- Stacy Smedley, Executive Director of Building Transparency, Director of Sustainability at Skanska USA.