HIGH-TECH

FROM CLASSROOM TO CLEANROOM

Virtual twin experiences are poised to exponentially scale the next generation of students and workers in the semiconductor industry.

Over the last century, great success was achieved in the aerospace industry by leveraging simulations to quickly train large workforces for complicated tasks. Today, the semiconductor industry faces its own workforce challenge as it seeks to digitally transform while rebalancing its global manufacturing footprint amidst a challenging demographic environment.

Modern spatial computing devices enabling virtual twin experiences present a new opportunity for semiconductor stakeholders to efficiently and effectively enhance their educational programs, attract and retain talents and scale the next generation of highly skilled workers.

DASSAULT SYSTEMES

THE PROMISE OF IMMERSIVE TRAINING EXPERIENCES

In 1910, a small aircraft company based in Puteaux, France, just outside Paris' city center, built the first aircraft ground training device called the 'Tonneau Antoinette,' introducing a new era in flight simulation. This invention and others to follow were born from an increasing demand for trained pilots and a nagging deficit in flight instructors and available aircraft to facilitate the learning process. Simulation training addressed this issue by segmenting skills that could be learned through simulation from those that require real-world experiences. This approach proved so valuable to onboarding large workforces that by World War II, nearly all U.S. Air Force pilots were trained using flight simulators – accelerating a military pilot's time-to-service. Today, flight simulation training – including virtual, augmented and mixed reality platforms – is an integral step to becoming a pilot and an essential resource in closing the industry's demand-supply gap.

In 2023, airlines in North America were short 17,000 pilots, mainly due to pandemic-led early retirement. That gap is projected to grow to 24,000 by 2026.[1] In response to this recurring workforce issue, stakeholders across the aviation ecosystem are doubling down on more advanced virtual reality (VR) training applications. For example, United Airlines is building a $100 million training center in Denver, Colorado, including twelve full-flight simulators. Embry-Riddle Aeronautical University recently expanded its enrollment capacity by offering a four-week introductory VR course that allows students to learn before they ever sit in an actual cockpit – reducing the time to their first solo flight by 22% on average.[2] The U.S. Air Force Academy has also turned to VR courseware to scale its instructor-to-student ratio.

The aerospace industry is now extending VR beyond pilot training to improve situational awareness, particularly in low-visibility situations. It plans to include a recently Federal Aviation Administration (FAA) approved mixed-reality headset called SKYLENS, as part of a comprehensive enhanced flight vision system.[3] These aerospace examples and many more across other labor-intensive industries highlight the promise of immersive training experiences to accelerate student learning and scale workforce development.

STATE OF GLOBAL SEMICONDUCTOR WORKFORCE

The semiconductor industry currently faces its own workforce gap that is now amplified by geopolitically-driven demands for 'semiconductor sovereignty.' Once-in-a-generation government funding designed to rapidly expand semiconductor manufacturing capacity outside of Asian countries will further exacerbate the demand-supply workforce gap, creating an opportunity for workers in declining industries to transition to high-tech.

> "A skilled and diverse pipeline of workers is critical to building a sustainable domestic semiconductor industry and achieving the CHIPS Act's economic and national security goals."
>
> – Gina Raimondo,
> U.S. Secretary of Commerce

In the U.S., demographic realities, including fewer Science, Technology, Engineering and Mathematics (STEM) trained workers entering the job market (with only 6% of college graduates majoring in engineering[4]) and a retiring industry-trained baby boomer generation, contribute to a shrinking semiconductor workforce. According to the U.S. National Institute of Standards and Technology (NIST), a skilled and diverse pipeline of workers is critical to building a sustainable domestic semiconductor industry and achieving the CHIPS Act's economic and national security goals – making workforce development a top priority. To achieve these goals, the U.S. seeks to double its semiconductor workforce, triple its graduates in semiconductor-related fields and train 100,000 new technicians.[5] A recent Deloitte study estimates that by 2030, more than one million additional skilled workers will be needed to meet demand in the semiconductor industry.[6]

On top of an increasingly complex technology stack, these factors point to a second 'perfect storm' on the horizon – where future semiconductor manufacturing output falls below available capacity – causing the pace of innovation to slow, inflating prices across multiple industries, stagnating global economies and diminishing military security. This is a dire future outcome, but one that can be averted if government, academia and industry work together and embrace a new classroom-to-cleanroom approach to training and workforce development.

NEW SKILLS NEEDED FOR SEMICONDUCTOR WORKFORCE OF THE FUTURE

To succeed, future training programs must account for a rapidly changing industry and address the skills that will be required across several key dimensions. A highly functional domestic semiconductor industry will need more than engineers and technicians to be successful. New understanding and competencies across multiple job functions, including finance, legal and operations, will be necessary for the ecosystem to thrive. There are several industry perspectives to be addressed:

POLITICAL

U.S. and EU government CHIPS Acts are creating a more balanced competitive landscape by reducing the historical cost advantages many Asian semiconductor companies enjoyed through government subsidies. New domestic supply chains must be established to support this shift, creating a need for workers trained in supply chain management and other operations-focused fields. With the realization that semiconductors are now as central to modern economies as oil, the U.S., in particular, is laser-focused on increasing its domestic chip manufacturing footprint, which had fallen to 12% in 2020.[7] Safeguarding its supply of chips not only bolsters the economy but protects national security. A significant shift to military defense-related application-specific integrated circuits (ASIC) design by companies like Lockheed Martin's subsidiary ForwardEdge will place greater importance on the foundry manufacturing model. A new workforce must be trained in high-volume manufacturing methods and process integration. Development programs focused on model-based systems engineering (MBSE) and electronic design automation (EDA) training will help reduce learning cycles and accelerate time-to-yield, which are important objectives of U.S. and EU strategy.

ECONOMIC

Managing the cost of construction and operations will be paramount to integrated device manufacturers (IDMs) and foundries as they build additional domestic capacity. The ability to create new fabs efficiently and ramp technologies quickly will establish their payback periods, determine profitability timelines and drive overall market share. Supply chain ecosystems must also ramp up their operations in parallel with fab construction projects. Success will depend on workers trained in fab design, equipment layout and the management of highly complex projects. For example, fab virtual twins can help accelerate the process by providing a digital representation that contractors can use to optimize building design and suppliers can use to develop their products in parallel for seamless ramps. Operations engineers can also leverage fab virtual twins to simulate production scenarios and improve manufacturing throughput. Training in these areas will help drive profitability and encourage further expansion.

SOCIAL

Historically, entry to the semiconductor industry required a bachelor's degree in engineering for basic jobs and a Ph.D. for more advanced positions in research and development. This model worked well when most manufacturing was offshored to lower-cost countries. A new domestic-based industry will need to segment jobs with more granularity. Similar to what aerospace and automotive companies have implemented for decades, semiconductor companies will need to reduce barriers to entry. This is achievable by working with educational institutions to establish apprenticeships and associate-level technical degrees across various disciplines – including materials science, chemical and electrical engineering, firmware development and fab operations management. Local governments must implement semiconductor vocational programs for students seeking an alternative to a college education. These opportunities create a larger pool of eligible workers and help reduce overall operating expenses. With students' limited access to semiconductor cleanrooms, advanced equipment and seasoned educators, VR training stands out as a proven technology that can help enable workforce development at scale.

TECHNOLOGICAL

As process technology nodes continue to push the boundaries beyond nanoscale to angstroms, Moore's Law is quickly reaching its physical limit. The complexity and costs associated with continuing to focus on semiconductor scaling are nearing a point of diminishing returns. Greater emphasis is now placed on new chip architectures, quantum computing, artificial intelligence (AI) and machine learning to continue advancing performance. Semiconductor manufacturers have shifted their focus to three-dimensional heterogeneous integrated packaging (3DHI) and chiplets as alternatives to scaling. Unlike monolithic system-on-chip (SoC) systems, chiplets offer a modular approach that leverages both advanced and legacy nodes to reduce costs and complexity. A rise in outsourced semiconductor assembly and test (OSAT) service providers will join in-house ASIC design departments and domestic foundries to create more specialized chips at lower volumes with reduced costs. This triad will rely heavily on simulation analysis to co-design and develop new semiconductor package technologies as efficiently as possible. The next-generation workforce will require simulation analysis training to build representative models and interpret their results as a primary part of their job scope. This shift from front-end engineering to back-end manufacturing creates new opportunities to leverage virtual twin experiences for chip configurations and thermal management.

ENVIRONMENTAL

The semiconductor industry has a long way to go to reach net zero carbon emissions. The U.S. and EU are currently targeting 2050 to achieve this milestone. Semiconductor manufacturing contributes to 31% of global greenhouse gas emissions and is expected to grow as chip demand increases.[8] Water and energy consumption are also environmental issues. Some large fabs use up to 10 million gallons of water daily and as much as 100 megawatts of power each hour. Water recycling efforts help offset some of the impacts, but it is clear that semiconductor manufacturing takes its toll on

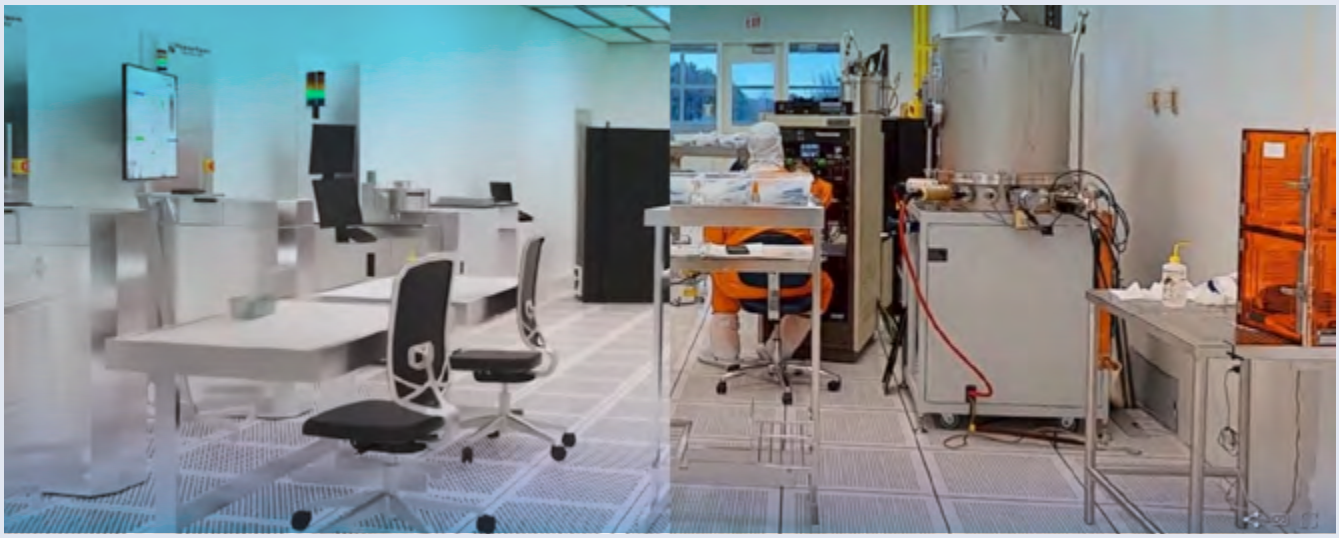
the environment. Over time, these issues can be addressed with more efficient manufacturing processes and a greater reliance on clean energy. One area that is receiving more near-term scrutiny is the use of hazardous chemicals. The semiconductor industry phased out perfluoro octane sulfonic acid (PFOS) in 2019 and has committed to phasing out perfluoro octane acid (PFOA) by 2025. However, it continues to use many hazardous short-chained PFAS.[9] Several working groups and consortiums seek to address this issue, but as of now, semiconductors cannot be manufactured without them. This reality highlights the need for greater 'green chemistry' education in the semiconductor industry. Applying AI and molecular-level virtual twin simulations can accelerate the development of safer chemicals and materials. A focus on 'green chemistry' should become a standard component in future materials science degree programs.

LEGAL

Many new policies tied to CHIPS Act funding affect the transfer of semiconductor technology to countries which are deemed to pose national security concerns. Leading-edge manufacturing expansion is restricted, as is the sale of specific advanced manufacturing equipment and engagement in joint research or technology licensing efforts. Export control of semiconductor technology used in military defense applications has also tightened. The global semiconductor supply chain struggles to navigate these new and expanded restrictions while keeping current operations profitable in parallel with building new domestic manufacturing hubs and supply chains. The legal complexity of producing chips is at an all-time high, indicating the need for more profound educational programs on semiconductor patent law and international technology transfer policies. The pendulum is undoubtedly swinging toward semiconductor sovereignty today, but it will eventually turn back to a more global-centric ecosystem where semiconductor legal expertise will become even more critical.

The implications of these semiconductor industry perspectives combine to help characterize the magnitude of change underway and some of the challenges a new workforce will encounter. Immersive virtual twin learning experiences can address this by transferring knowledge via next-level collaboration across multiple domains. For example, patent attorneys, design engineers and operations managers can discuss the merits of innovations within immersive environments where real-time improvements can be made earlier in the development cycle. Through these shared virtual experiences, existing silos can be eliminated and deeper cross-functional understanding can flourish.

EVOLVING FROM PHYSICAL TO VIRTUAL WORLDS



Virtual twins embody fundamental values for excellence in training, acceleration of experimentation and sustainable innovation. Made available on a secure cloud-based digital platform, semiconductor stakeholders empowered by virtual twins can experience a new dimension of collaboration. Virtual twins are comprehensive high-fidelity physics-based representations of the real world encompassing three primary aspects:

1. ENGINEERING: This aspect covers the why, what and how – including requirements, function, logic and the virtual 3D model. It provides the basis for component and system design and simulation within their intended application.

2. MANUFACTURING: Including product, process and resources, this aspect covers the bill of materials and processes. It describes the necessary steps, operations and materials required to create a product in the real world.

3. BUSINESS: Driven by performance, this aspect is used to model and optimize partnerships, plan for customer demand and manage IP throughout the value chain. Engineering, manufacturing and business aspects reinforce each other along the innovation continuum where real and virtual worlds become fully integrated.

Each industry has unique challenges and use cases where virtual twins can be applied. In the semiconductor industry, five main twins have been defined from micro to macro-level experiences:

1. REACTOR TWIN
Capturing the dynamic molecular-level interactions of chemistries and gases under pressure and heat; reactor twins are integral to materials science research and development. They can help inform process twins during recipe development and generate data repositories to facilitate the discovery of new materials. Primarily used by scientists for foundational research, they can help visualize the behaviors of atoms and identify patterns.

2. PROCESS TWIN: Emulating process recipes, these twins are the primary enablers for front-end research and development. For example, they can simulate etch, deposition and lithography steps during node development and optimize recipe parameters to achieve desired results. Process twins are the primary vehicle for reducing experimentation costs and time tenfold. By maintaining a catalog of standard process twin emulations for each tool, engineers can quickly identify new requirements and focus areas for future research.

3. EQUIPMENT TWIN: These twins provide a digital footprint of the physical tool and can be used for fab layouts, material handling and supporting sub-system designs. New equipment in the design phase can be placed virtually in its intended environment to facilitate planning, installation and commissioning. They are ideal for training new operators and implementing predictive maintenance.

4. FAB TWIN: These twins are used for the design, planning and construction of a facility – including the sub-fab systems, cleanroom layout, air handling and water and power distribution networks. Fab twins capture as-planned and as-built configurations and are also used for capacity expansion projects. Operations engineers can use them to optimize for cost and throughput as well as measure the environmental impact of future operations. Fab twins are ideal for IDMs and foundries building multiple fabs requiring copy-exact technology transfers.

5. ECOSYSTEM TWIN: These twins are used for immersive collaboration across a network of stakeholders focused on solving a shared problem. The twin's perspective will vary based on the depth of collaboration and analysis required. The primary stakeholder groups that will participate include chip companies, foundries, wafer fab equipment suppliers, OSATs, academic research labs, industry consortiums, government-led technology agencies and chip customers. Ecosystem twins are managed on a secure cloud-based platform that enables IP protection, digital continuity, change management, simulation data curation and access control. One critical use case is the ability to co-design, develop and simulate a chip package within the operating environment of an end-use product, taking into account form factor, thermal footprint, vibration and signal integrity.

REALIZING THE POWER OF VIRTUAL TWIN EXPERIENCES

A recent PwC survey discovered that 34% of companies agree that VR provides a more effective way to develop and train their employees. The consulting firm found that VR learners were four times faster to train than in the classroom, 275% more confident to apply skills learned after training, 3.75 times more emotionally connected to content than classroom learners and four times more focused than their e-learning peers.[10] These statistics help set the stage for a modern approach to addressing the semiconductor workforce demand-supply gap. VR training and education are now underpinned by multi-physics-based virtual twins representing real-world entities and processes. What can be experienced in the real world can be experienced virtually – from the molecular to the system level – and to the environment the system operates within. These experiences enable rapid learning in context and the ability to perform scenario analysis to drive innovative thinking and higher levels of collaboration.

Universities worldwide that operate semiconductor research facilities, such as Purdue's Birck Nanotechnology Center, are leading the application of virtual twins in expanding and accelerating their semiconductor degree programs and enhancing the capabilities of their cleanrooms. In addition to supporting student education, these universities typically host external researchers and scientists with limited access to costly equipment. Management and operations of the cleanrooms are also aspects for universities to staff and optimize. To address these responsibilities, three initial immersive virtual twin experience domains and six personas are currently in development for virtualization:

EDUCATION

1. **Students:** Initial use cases include an introduction to cleanroom environments, such as gowning procedures, chemical safety protocols and equipment overviews. VR learning modules help to scale cleanroom onboarding and improve overall semiconductor degree program efficiency.
2. **Researchers:** Introduction to advanced equipment operations – including an overview of user interfaces, their mechanical operations and the expected outcomes – for this target persona. VR learning modules provide deep working knowledge of tool capabilities to accelerate time-to-experiments.

INFRASTRUCTURE

3. **Facility Managers:** Fab layout and equipment installation simulations – including airflow, ultra-pure water and electrical systems analysis – help improve this persona's job performance. Simulations are used to optimize fab flow and reduce air particle contamination.
4. **Operations Managers:** Power, water and chemical consumption simulations – including GHG emissions by tool and process recipe – help this persona operate cleanrooms in more environmentally friendly ways. Simulations are used to measure and optimize sustainability metrics.

RESEARCH & DEVELOPMENT

5. **Process Engineers:** Virtual process integration, materials design and discovery – including simulated and physical data curation – provide this persona with improved what-if analysis capabilities. Simulations are designed to accelerate module-level development and time-to-yield.
6. **Scientists:** This persona can more rapidly synthesize data for AI-enabled design of experiments, including rapid hypothesis testing and analysis. Simulations help deliver a tenfold reduction in experimentation costs and time.

These personae use cases are not merely theoretical. Leaders across the semiconductor industry are now working together collaboratively in partnerships and consortiums to put in place the necessary elements that lay a solid foundation for virtual twin experiences. Current modes of educating students, training workers, and conducting research will quickly become outdated as a new semiconductor virtual twin experiential paradigm emerges.

PREPARING THE SEMICONDUCTOR INDUSTRY FOR 2030 AND BEYOND

Although semiconductor sovereignty is a critical objective for most CHIPS Acts, no single government can control an entire semiconductor supply chain. For example, certain raw materials, such as cobalt and key manufacturing equipment, including EUV, are only available in specific locations in the world.

To achieve sovereignty, countries must create ecosystems with trusted partners, like those now forming between the U.S., EU and Japan. This approach also applies to highly skilled workers. The extreme complexity of semiconductor engineering and manufacturing requires experts worldwide to collaborate and share knowledge and know-how. Again, no single government can produce the highly skilled workers required to meet the needs of a rapidly expanding industry. This is where the power of virtual twin experiences hosted on a secure cloud-based platform is paramount. As regional semiconductor hubs mature, they will naturally connect globally to accelerate innovation, eventually connecting as a cohesive ecosystem with other industry ecosystems, such as transportation, aerospace and life sciences.

After six decades of steady growth, the semiconductor industry has reached a decisive point. Global sales of approximately $520 billion in 2023 are expected to grow to $1 trillion by 2030.[11] Much of this expected growth is attributed to an insatiable appetite for more computing and data storage, faster wireless communications and the growth of autonomous transportation. Underpinned by a future 6G network, we can expect to move freely in the cyber-physical continuum between the connected physical world of senses, actions, experiences and its programmable digital representation by the end of this decade.[12] As these new capabilities come online over the next six years, we will see the proliferation of AI-enabled electronics, humanoid robotics and advanced computing – bringing new efficiencies to our daily lives.

Supplemented by spatial computing devices, such as Apple's Vision Pro headset, virtual twin experiences will not only transform how students learn and workers are trained, as they are today, but will eventually serve as a sixth sense or proprioception for the next-generation semiconductor workforce. The future of technology is certainly bright and will open up entirely new ways of living and working for many of us. Virtual worlds not only extend and improve the real world – they enable passionate people to imagine sustainable innovations capable of harmonizing product, nature and life.

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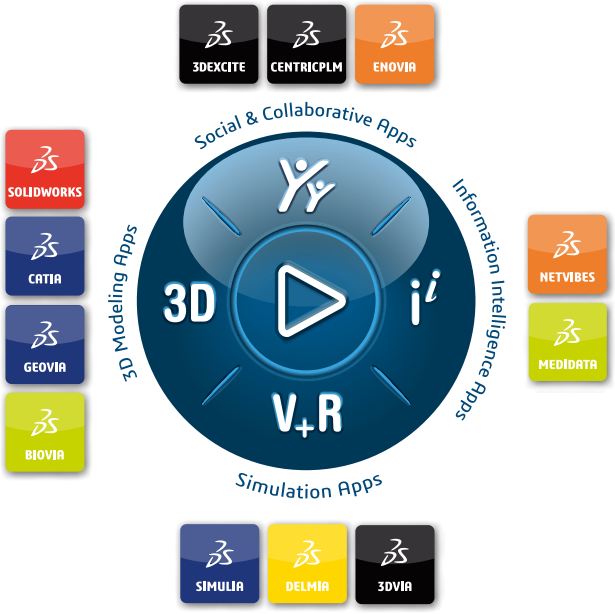

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