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Art on the Nanoscale and Beyond

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Methods of forming and patterning materials at the nano- and microscales are finding increased use as medium of artistic expression, and as a vehicle for communicating scientific advances to a broader audience. While sharing many attributes of other art forms, miniaturized art enables the direct engagement of sensory aspects such as sight and touch for materials and structures that are otherwise invisible. In this article, the development of miniature art is reviewed, from both technological and philosophical viewpoints. First, the historical uses of nano/microscale materials and imaging techniques in arts and sciences are presented. The motivations to create artwork at these scales are discussed, and representations in publications and exhibitions are explored. Examples are presented using semiconductors, microfluidics, and nanomaterials as the artistic medium; these utilized techniques including micromachining, focused ion beam milling, two-photon polymerization, and bottom-up nanostructure growth. Finally, the technological factors that limit the implementation of artwork at miniature scales are identified, and potential future directions are discussed. As research marches toward even smaller length scales, innovative and engaging visualizations and artistic endeavors will have growing implications on education, communication, policy making, media activism, and public perception of science and technology.

1 Historical Significance

1.1 Use of Nanomaterials in Arts

For centuries, artists have made clever use of materials science and technology. The first known artistic expressions by humans, cave paintings, must have required scientific planning and experimentation to produce the pigments used in the paintings. Recently, hand stencils from Sulawesi, Indonesia have been found to date back at least 40,000 BCE which predates art from European caves.[1] **Figure 1a** shows hand stencils from Sulawesi, Indonesia.[1] In 34,000 BCE (Upper Paleolithic), in the Chauvet-Pont-d'Arc Cave, prehistoric humans used pigments to create a hand stencil and drew wild mammals using charcoal and pigments on the cave walls.[2] Without their knowledge, they deposited layers of graphene and nanocomposites on the walls. The cave paintings found throughout the Pleistocene Eurasian world also contained polychrome rock paintings of other animals, wherein yellow ochre, hematite, manganese oxide as well as animal fat were used to control the intensity of the pigments.[3] Figure 1b illustrates the Horse Panel and wild animals in the Chauvet-Pont-d'Arc Cave in France.[4]

The human pursuit of imagination and beauty compelled archaic artisans to search for and modify various nanomaterials with which they could create objects to satisfy curiosity and provide a sense of aesthetics. An early example of nanomaterial use in ancient artwork is the Roman Lycurgus Cup (400 CE).[5] This chalice was doped by naturally occurring silver and gold nanoparticles, forming a dichroic filter that changes color depending on illumination in reflection or transmission. In Middle America, the inhabitants of the Mayan city of Chichen Itza (800 CE) synthesized Maya Blue, which is a corrosion resistant azure pigment (Figure 1c).[6] Maya Blue consists of a mixture of nanoporous clay, and indigo dye which forms a hydrophobic pigment. In the Middle East, Damascus steel swords (300-1700 CE) contained carbon nanotubes, and cementite nanowires, which enhanced their strength and fracture resistance.[7] In North Africa, luster, which is a silver and copper nanoparticle-based glassy mixture, was utilized in decorative arts to produce iridescent metallic glaze. For example, the upper part of the mihrab in the Great Mosque of Kairouan (670 CE) in Tunisia is decorated with mono/polychrome lusterware tiles.[8]

The alchemists of medieval Europe employed water and fire to change the optical, chemical and physical properties of materials.[9] During the Renaissance (1450-1600 CE), ceramicists from Deruta in the Umbria region in Italy produced silver and gold nanoparticles in their glazes.[8, 10] The glass windows of medieval cathedrals (6th-15th centuries) were stained with gold nanoparticles and metal oxides to produce rich colors and tones (Figure 1d).[11] Copper oxide nanoparticles were added to glass to produce a green hue; gold was added for red color, silver was used for yellow tones, and cobalt gave blue coloration. In particular, the manipulation of optical properties of materials, including gloss and visual texture, were important to artists and craftsman, but they were not aware of the underlying nanoscale processes.

1.2 Scientific Photography and Imaging Techniques

Experimentation with camera obscura, a box with a pinhole that projects images by scaling down and rotated images, began in the ancient world. However, it was not until 17th century that the portable camera obscura models were developed.[12] In 1694, the photochemical effect was discovered by Wilhelm Homberg.[12] A transition between trial-and-error materials manipulation and scientifically guided understanding was marked by the invention of wet chemistry-based photography in the early 19th century. Nicéphore Niépce developed the first photolithography technique in the 1820s when he created an image using a camera obscura.[13] Niépce's technique involved photopolymerization (> 8 h) of bitumen over a pewter plate.[13-14] In 1839, Niépce's process was replaced by Louis Daguerre's fast photographic "daguerreotype" process involving the formation of a latent image in a silver-halide containing plate, which was subsequently exposed, developed and fixed.[15] In 1840, William Talbot invented the paper-based calotype, which allowed production of negatives that could be used to make positive copies.[16] In 1842, John Herschel proposed the cyanotype process, which enabled creating images with cyan-blue prints.[17] In 1851, Frederick Archer reported the wet plate collodion process, which combined the desirable qualities of daguerreotype (sharpness and quality) and calotype (printing from a single negative) by allowing the creation of negative images on a transparent glass.[18] Two decades later, in 1871, Richard Maddox reported the gelatin-based silver halide chemistry, which became the standard emulsion for black and white photography.[19] In 1890, the light sensitivity of photographic films was quantified by Ferdinand Hurter and Vero Driffield.[20] The first photographic roll film was commercialized by Kodak in 1885. However, in 1891, color photography was demonstrated by Gabriel Lippmann[21] involving interference of light based on Wilhelm Zenker's theory of standing waves[22] and Otto Wiener's experimental work on standing electromagnetic waves.[23] The invention of photography allowed capturing "the moment" in greater detail than achievable with traditional media including painting and sculpture. Consequently, many artists have embraced photography as a form of fine art created by the vision of the cameraman, who aimed to produce a personal impression rather than merely capturing a realistic representation of the subject. Photography as a fine art was accepted in both Europe and the United States in the late 19th century.[24] Early artists included Alfred Stieglitz and Edward Steichen.[25] Fine-art photography evolved further by movements such as Photo-Secession,[26] the Linked Ring,[27] avant-garde art,[28] and pictorialism.[29]

The use of photography in sciences began after the invention of the daguerreotype process, which was first used by astronomers to capture images of the sun and of a solar eclipse in the 1850s.[30] In the late 19th century, paper-based photographs started appearing in scientific journals and books. In *the Expression of the Emotions in Man and Animals* (1872), Charles Darwin collaborated with photographer Oscar Rejlander to produce one of the first books containing photographs with heliotype plates.[31] An early use of photography in scientific experiments was demonstrated by Eadweard Muybridge in 1878.[32] Muybridge took 24 successive photographs of a galloping horse. He used a zoopraxiscope to project the images in order to understand whether a galloping horse lifted all four feet off the ground during a gait. Muybridge's photography contributed to the development of biomechanics as a scientific field. In the 1930s, Harold Edgerton used a strobe light flash to created high speed still shots of a drop of milk splashing into a glass, a hummingbird flapping its wings, a bullet passing through an apple, and many other captivating scenes.[33] In 1952, Rosalind Franklin, utilized X-ray crystallography and photography to reveal the structure of deoxyribonucleic acid (DNA).[34] Since then, advances in optics, cameras, and light sources have allowed scientists to produce images at increasing resolution and color fidelity.

Further technological advances in scientific imaging included the development of electron microscopy, and atomic force microscopy, which enabled the characterization and engineering of structures at the nano- and microscale. The development of electron microscopy was a significant milestone in the expansion of imaging capabilities.[35] In 1927, Hans Bush formulated the lens formula that showed the focusing effect of a rotationally symmetric magnetic field.[36] In the same year, George P. Thomson and Bell Laboratories demonstrated electron diffraction.[37] Max Knoll and Ernst Ruska built the first two-state electron microscope with a ×16 magnification and verified the lens formula in 1931.[38] The electron microscope was patented by Siemens AG.[39] Later on Ruska improved the magnification up to ×12,000.[40] The first scanning electron and transmission microscopes were constructed by Manfred von Ardenne in 1938.[41] Siemens commercialized the first serially produced transmission electron microscopes with a resolution of 7 nm operated at 70 kV in 1939.[42] The spatial variation from these electron microscopes was recorded by exposing a silver halide photographic film to the electron beam, or projecting the electron image onto a fluorescent screen coated with phosphor or zinc sulfide.[43] In 1981, the discovery of scanning tunneling microscopy by Gerd Binning and Heinrich Rohrer at IBM enabled the imaging of surfaces with 0.1 and 0.01 nm lateral and depth resolution, respectively.[44] In 1986, the development of atomic force microscopy by Binning allowed imaging with sub-nm resolution.[45]

The advent of computers also changed the way we think of art and data storage. Alan Turing, the first computer programmer in history, became also the first known scientist to use computers for artistic purposes.[46] In 1950, while working at the Manchester Computer Machine Laboratory, Turing decided to program musical tunes as user-friendly warning systems. His colleague Christopher Strachey picked up on this idea to program the first conventional piece of music ("God Save the King") in 1951, which was broadcast by the British Broadcasting Corporation (BBC). Strachey also wrote the first computer game (a game of checkers), creating what became the first screen representation of a real object – many years before the first digital cameras were invented.[46]

While silver halide photography was based on nanomaterials, bottom up approaches to pattern nanomaterials had not been developed at that time. However, advances in the integrated circuits and decreasing costs in semiconductors in the 1970s represented a new platform to create rewritable photographic images that could be modified with computers. The development of digital cameras has revolutionized photography. The origins of digital photography date back to 1970 when charge-coupled devices (CCD) were first developed at Bell Labs.[47] George Smith and Willard Boyle invented a solid-state video camera that allowed the capture of images of high enough quality to allow for broadcasting on television. However, it was not until 1981 that the first digital-magnetic video camera (Mavica, Sony Corporation) entered the consumer markets. Mavica captured images using a charged-coupled device (CCD) sensor, and recorded images (720,000 pixels) as magnetic pulses on 2.0" diskettes.[48] In 1986, Kodak reported the first megapixel sensor, which was capable of recording 1.4 M pixels. Several years later, Kodak released the first digital camera system (DCS 100) that incorporated a Nikon F-3 camera and a 1.3 M pixel sensor for use in photojournalism.[49] However, the first fully-digital consumer camera (Dycam Model 1) was introduced to the markets in 1990 by Logitech.[50] Dycam Model 1 captured images with a fixed-focus lens (8 mm) and a 376×240 pixel CCD camera at 256 shades of gray, recording them on a 1MB random-access memory (RAM) in tagged image file format (tiff). In 1994, low-cost cameras such as QuickTake 100 (Apple) with 640×480 pixels were introduced to the consumer markets.[51] In subsequent years, the miniaturization of digital components allowed Kodak, Nikon, Toshiba and Olympus to produce smaller cameras for incorporation in scientific instruments. Digital photography has created a medium to capture and post-process images, which opened up opportunities for science communication and other applications. For instance, the incorporation of cameras into microscopes, permitting the visualization of nano/microscale material morphologies and processes, provided the capability to capture images at low light levels, and allowed for intracellular imaging.[52] The advances from photography to the electron and atomic force microscopy have set the stage for producing and imaging structures at nano/microscale for the visualization of science, creating a new medium for artistic expression.

1.3 Convergence of Art and Science

The domains of art and science have traditionally been separate, both by the creators of content and by their educators. Although Renaissance humanists, with Leonardo being their most famous example, took exception of this view, scientific and artistic methodologies are typically still taught separately from our early childhood as disparate disciplines. In 1959, Charles Snow stated that the intellectual composition in the western society was split into two cultures: literary intellectuals and the natural scientists.[53] He expressed that the great divide between these cultures was a major hindrance to improve humanity. Indeed, the two cultures have distorted images of themselves and there exist a lack of understanding and little common ground. However, the arts offer the sciences an essential store of images, ideas, metaphors and language. The Copy Principle of David Hume states that the scientific understanding cannot always be arrived by experimental approaches but sometimes must originate in the mind.[54] For example, atomic physicist Niels Bohr imagined the invisible nucleus of an atom as an oscillating drop of liquid. Similarly, the standing waves in the early days of wave theory of light were conceived as vibrating strings. These metaphors originate from sensual experience and from the vocabulary derived from arts and humanities. Hence, the combination of social and physical sciences is necessary for the recognition and synthesis of different thinking approaches.[55]

Creative interactions between scientists and artists, or the engagement in art by scientists, have been infrequent and are still gaining recognition. In response to this situation, many organizations have initiated programs to bring together artists and scientists to spark collaboration, and to encourage science visualization as a means of public engagement (**Table 1**). An early example is the Leonardo journal (MIT press) which was established by Frank Malina in 1968 to feature articles on the application of science and technology to arts and music. In 1982, the International Society for the Arts Sciences and Technology was established to expand the operations of the journal to conferences, symposiums, and workshops. Many prominent academic initiatives promote the intersection of art and science. In 2000, the University of Western Australia established SymbioticA, which is an art program that engages the public with the uses of biology to encourage critical thinking and raise awareness about ethical concerns in biotechnology research, in particular through tactical media. The Art|Sci Center at the University of California (Los Angeles) is an initiative affiliated with both School of the Arts and the California NanoSystems Institute (CNSI). It promotes the collaboration in between media arts and bio/nanosciences, organizes events and exhibitions, and offers artists in residency program. Since 1975, Nikon has featured "Small World" art program, which is a forum for showcasing complexity at nano/microscale through its photomicrography and movie competitions. The imaging techniques in these competitions include light microscopy with fluorescence, phase and interference contrast, polarization, darkfield, confocal, deconvolution, and combination of these techniques. Furthermore, Cris Orfescu has coordinated annual International NanoArt Festivals since 2004.

Via the self-organization of artists and scientists, and creation of numerous interdisciplinary initiatives emerged as a new discipline, which is referred to herein as "art on a nano- and microscale". Creation of nano/microscale art involves (i) intentional fabrication of a structure by controlling the organization of the materials using chemical reactions or physical processes, or by the discovery of natural nano/microstructures, (ii) visualization of the nano/microstructures using microscopy, (iii) artistic interpretation and manipulation of the created images and/or structures to tell a story, convey a feeling, or communicate a message, often involving digital modifications such as coloring, collage, or assembly of multiple images, and (iv) showcasing the artwork via the Internet, in exhibitions or installations. The motivation to create nano/microscale artwork may include spurring creativity, conveying a message or feeling, demonstrating a capability in technology, demonstrating a physical principle, enhancing understanding of a technology, or creating attractive images.

In this Review, nano/microscale art created on semiconductors, polymers, microfluidic devices, other carbon-based materials, and biological interfaces are discussed. Artwork fabrication techniques such as focused ion beam milling, laser-directed two-photon polymerization, soft lithography, nanopatterning, and protein/cell micropatterning are summarized. Microphotography in life sciences is also described as an emerging art field. Furthermore, the implications of such artworks in physical and natural sciences in creativity, imagination, communication, language and the promotion of science and technology from a broader perspective are explained. The discussion is concluded by addressing the benefits of this growing area of artistic activity for the public, and outlining potential future directions.

2 Microscale Art

Contrasting the unintentional use of materials in historical artifacts, we now have the scientific knowledge and technical capabilities microengineer art. The creation of microscale art began due to the advances in photolithography and integrated circuits. Recently, the microscale artwork has expanded to soft lithography, where fluids are controlled at microscale to draw the images of iconic structures or create abstract art. These artworks represent social trends, cultural values, storytelling, self-expression, and beauty and emotion.

2.1 Semiconductor Artwork (Chip Graffiti)

An earlier example of intentional incorporation of art in microfabricated devices date back to the emergence of semiconductor industry in the 1970s. “Chip graffiti” was conceived and implemented so that designers of semiconductor chips could place a creative touch on their work, and discourage the plagiarism of their designs.[56] These markings included chip designer’s names, renderings of favorite pets, cartoon characters, and were particularly found in chips made in the US and Europe (in particular Germany), yet were less prevalent in

Japanese-made chips. At that time, artwork on the chip served a useful purpose since it was used as evidence to reveal counterfeiting.

Chip graffiti were found on chips manufactured by semiconductor companies such as HP, IBM, Motorola, Texas Instruments, Advanced Micro Devices, Western Digital, Phillips, Cypress Semiconductor, Intel, STMicroelectronics, and Siemens. One of the early chip graffiti was designed by the former HP chip designer Willy McAllister and his team, and fabricated using the late Silicon-on-Sapphire technology in the 1970/80s.[56] This graffito consisted of a visual pun on the adder logic circuits on the HP 1000 Tosdata 64-bit floating multiplier (**Figure 2**a). The graffito had adders (summer in a digital circuit), and engorged snakes with swollen stomach, where the "adder" was also the name for a venomous snake (*Vipera berus*). The team also created an early chip graffito that illustrated a "running cheetah" on the early HP-PA microprocessor in the HP-900/750/755 series computers (Figure 2b). The design was inspired from the image on the cover of the September 1986 IEEE Computer magazine.[57]

Chip graffiti were influenced by lifestyle trends, cartoon characters, television, nature, and rivalry. Mr. T from the action-adventure television series the A-Team (1983-1987) was featured on a single-chip "T1" transceiver integrated circuit (DS2 151Q single chip, Dallas Semiconductor) (Figure 2c). The 50 µm-wide wireframe version of Daffy Duck was found on a reduced instruction set computing (RISC) microprocessor (Figure 2d). Chip design engineers at Siemens designed an integrated circuit (M879-A3) containing a wagon-pulling 60 µm-tall Smurf, which was originally created by Belgian cartoonist Pierre Culliford (Peyo) (Figure 2e). In the early 1970s, Mickey Mouse (Walt Disney Company) was featured on Chip Graffiti in Mostek 5017 alarm clock integrated circuit, where he points to 12 and 7 creating a clock (Figure 2f). Milhouse Van Houten, a character featured in the television series the Simpsons (1989 - present) was found on a Silicon Image Sil154CT64 digital transmitter integrated circuit (Figure 2g). Another cartoon character in the Road Runner Show (Warner

Bros.) premiered on television in 1966 was etched on a HP 64-bit combinatorial multiplier integrated circuit (Figure 2h). A HP design team headed by Howard Hilton in Lake Stevens, Washington designed an osprey (*Pandion haliaetus*) on a decimation filter integrated circuit utilized in signal analyzer instruments, which was produced by John Guilford (Figure 2i). Chip design engineers (Charlie Spillman) at HP also paid tribute to Lassie, a rough collie dog character featured in television from 1940-90s. Her miniaturized version was found on a HP support chip removed from a motherboard containing PA-7100LC chipset (1994) (Figure 2j). The codename for this project was LASI derived from a Local Area Network (LAn) interface and a Small Computer System Interface (scSI) port. Additionally, Marvin the Martian character, designed by Mark Wadsworth and Tom Elliot, was illustrated on a CCD image sensor used by the Spirit and the Opportunity rovers sent to explore Mars in 2003 (Figure 2k).

The motivation to create chip graffiti decreased after the US congress passed the Semiconductor Chip Protection Act (1984), which made copying the identical working parts of the chip a copyright violation.[58] This act made the purpose of having a graffito on a chip redundant. The incorporation of chip art in current semiconductors is also discouraged by the automation of the circuit design process, and the risk that complex patterns can cause data processing errors, which can delay a product cycle.[59] As a result of risk factors, HP banned logos in its fabrication plants in 1994.[60] However, chip designers in other companies continued to create artwork. Chip graffiti is still found on 1 in 10 chips currently produced.[56] Hence, the introduction of copyright laws, the automation of chip manufacturing, and the technical changes around chip design have significantly decreased the number of chip graffiti. Nevertheless, the chip graffiti featuring the copy of popular characters or original designs represent an appreciation for the artistic expression at microscale.

2.2 Microfluidic Artwork

Microfluidic devices consist of channels that allow the movement of fluids for the investigation of transport phenomena and applications such as high-throughput analyses.[61] The visualizations of microfluidics can be created by wetting channels with colored fluids to show the principles of laminar or turbulent flows. Some of the earliest visually appealing images in microfluidics were created by Felice Frankel and George Whitesides, including the cover of a September 1992 issue of Science, to illustrate scientific principles.[62] **Figure 3**a shows drops of water (blue and green) organized into square regions (4×4 mm) that are separated by hydrophobic boundaries. The same journal's 1999 July issue illustrated a graphical abstract that consisted of multiple channels flowing different dyed solutions.[63] As the channels merged, their fluids maintained parallel laminar flows (Figure 3b). Additionally, Frankel and Whitesides have authored books that presented examples of visualization at the nano/microscale and described how images could be designed to engage audience and enhance communication.[64]

Albert Folch and his colleagues also created visually appealing microfluidic devices that were colored with different dye solutions, and digitally modified to obtain a vibrant collection of images (Figure 3c, d). Folch team also created dynamic microfluidics videos, in which the flow rate and the dyed solutions in the channels were mediated by the rhythm of the music played. Another creator of visually-appealing microfluidic devices, Tanner Neville, conceived the idea while he was developing a technique to pattern proteins on substrates.[65] Figure 3e shows a microfluidic device resembling the Golden Gate Bridge, created by Neville and Albert Mach. Preparing poly(dimethylsiloxane) microfluidic devices with a strong vacuum prior to filling the channels allowed for easy filling of long dead-end channels. Organic dyes were added to a UV curable epoxy resulting in permanent colors. The Campanile (University of California, Berkeley) as a microfluidic device was also depicted by Neville and Austin Day (Figure 3f). The Campanile was fabricated by soft lithography and consisted of 6 fluid channels with dead-ends filled with different colors of dyes. Another contributor to microfluidic art was Ran Drori, who formed ice crystals in microfluidic devices. Figure 3g shows a microfluidic chip for studying ice-binding proteins using a cold stage on an inverted microscope. When the temperature was reduced suddenly, dendritic ice growth in the microfluidic channels was observed.[66] Figure 3h illustrates a microfluidic device entitled "The Sphere" by David Castro and David Conchouso at KAUST (Saudi Arabia), providing an impression of a celestial body as seen through the window of a futuristic spacecraft.[67] The image was created from a droplet (40 μL) hanging between two fluids in a cuvette. This droplet was formed between a layer of perfluorohexane and mineral oil, and it consisted of agglutinated latex beads mixed with human C-reactive proteins.

Visually-appealing images were also created to demonstrate the complexity and self-assembly, or show capabilities to control chemical and physical processes. Research on microfluidic fabrication of complex microparticles and their assembly has offered appealing visualizations that suggest an artistic approach and provide while demonstrating key underlying concepts. For example, particles created from a mixture of superparamagnetic colloidal nanocrystal clusters and photocurable monomer solution resembled microscopic dice with colored spot patterns.[68] The microparticles reflected light of patterned colors that resulted from the control of the spacing between the colloidal superparamagnetic nanocrystals achieved by adjusting the magnetic field (Figure 3i). When the magnetic field was varied, the color of the ink changed, and by using lithography and UV-initiated polymerization, the colors (5-200 µm) could be fixed over the particle surface. The particles could be spun and functioned as stirring bars for chemical reactions. Another fabrication technique involved particle assembly of microscale components using railed microfluidics to create visually-appealing images.[69] In this method, structures were guided in the microfluidic channels that consisted of groves as rails on the top surface. Some of the microfluidic grooves were designed to specifically fit to polymeric microstructures. Hence, this mechanism allowed for the construction of 2/3D microsystems by fluid-controlled self-assembly. Using railed microfluidic channels, an image of a Greek temple was created (Figure 3j).

3 Nanoart

The capability to control color, shape, and structure by the physics of material formation, interaction, and assembly represents an new medium of artistic expression.[3] Capturing images of nanomaterial structures also has provided many engaging scientific visualizations with similarities to macroscale life forms and man-made structures. The aim of nanoart has primarily been demonstrating new nanofabrication methods to create engaging visualizations that show the intricate capabilities of the fabrication technology. However, the themes of promotion of science and technology to the public, media activism, and cultural attributes have also emerged. The installed exhibitions included interactive experiences that allowed the viewers to touch, hear, and see responsive artwork.

3.1 Lithographic Writing of Artwork

An early example of artwork at the nanoscale was created by Alessandro Scali and Robin Goode in collaboration with Fabrizio Pirri from the Polytechnic University of Turin. The team created an artwork showing a map of Africa, entitled Actual Size in 2007 (**Figure 4**a). The pattern was etched through oxidative lithography on a silicon wafer using a 10 nm wide tip of an atomic force microscope.[70] In Actual Size, the team wanted to draw attention to the current status of Africa, which is anthropologically significant and has vast lands, but poor, exploited, and neglected. Hence, the notion of being unrecognized, unexplored, and invisible was represented at nanoscale. Figure 4b illustrates a field effect scanning electron microscope image of another artwork called Probation, which was fabricated using silicon-on-insulator technology.[71] The geometry of the artwork was defined using a positive photoresist on a layered silicon-insulator substrate using optical lithography, and subsequent removal of the bulk silicon through anisotropic etching. The geometry of the statue on the remaining layer was created by reactive ion etching of silicon. Finally, the buried oxide solution was eliminated using hydrofluoric acid. The Statue of Liberty is an icon of freedom; however, the artist wanted to express the idea that liberty was limited by constructing the statue at microscale.[72] Exhibited at BergamoScienza festival in Italy, these artworks utilized nanotechnology as a functional and enabling means of expression to enhance the message of the artwork.

Focused ion beam milling (FIBM) is a lithographic fabrication technique that was used for creating artwork. As an established technique in the semiconductor industry, FIBM involves selective ablation of materials with nanoscale accuracy using liquid-metal ion beams at high primary currents.[73] An early use of FIBM for art can be identified in Rafael Lozano-Hemmers's work entitled "Pinches Pelos". The artist's gold-coated hair was engraved with words using FIB milling. This microfabricated artwork was displayed at Bitforms gallery (New York City) in 2013. Artists Marcelo Coelho and Vik Muniz also utilized FIBM to draw images on sand grains. The motivation of this work was to question perspectives about the physical world.[74] Sandcastles were drawn by Muniz using camera lucida, an optical device that allowed superpositioning of the object being viewed upon the surface of the drawing.[75] The sandcastle images were drawn on a sand grain by FIBM (Figure 4c). This allowed the object being represented on the material that the object was made out of. The use of camera lucida and microfabrication represented the developments before and after photography, highlighting the role of photography in simulating the reality. The artists' project was displayed at Tel Aviv Museum of Art in 2014, as part of a comprehensive retrospective on the work of Muniz.

3.2 Two-Photon Polymerization of Artwork

Two-photon polymerization (TPP) involves spatial-resolution controlled 3D photopolymerization of a UV-absorbing resin within the focus depth of a near-infrared laser beam.[76] The speed of the polymerization stimulated by the two-photon absorption is proportional to the square of the photon density at each position in the resin. Microfabrication through TPP can be used for creating artwork at subdiffraction-limited resolution (150 nm).[77] **Figure 5**a illustrates a 'bull' sculpture (10×7 µm) produced by laser light-directed photopolymerization of a light-sensitive precursor mixture, which may consists of urethane acrylate monomers, oligomers, and photoinitiators.[78] For example, to polymerize the monomer mixture, a Ti:Sapphire (Ti:Al_2O_3) laser beam at 76 MHz and 780 nm with a 150 fs pulse width can be used.[78] The creators of 'bull' sculpture were inspired from Fantastic Voyage, a 1966 science fiction film that plotted a medical team that shrank to microscopic size and travelled into a scientist's body to repair a brain damage using laser light.[79] The creators envisioned that the bull could pull a drug carrier through the blood vessels, create microscopic sensors, templates for cell cultures and 3D computer memories.[80] To show complex structures that can be created by TPP, Nanoscribe GmbH (Germany) has fabricated 3D microlandmarks from photosensitive materials (Figure 5b,c). The photosensitive material might consist of pentaerythritol tetraacrylate containing 4,4'-bis(diethylamino)benzophenone photoinitiator (1.5 wt%). The Ti:Al_2O_3 fs laser beam (33 mW) could be scanned at 44 mm s^{-1} over the photosensitive material while moving the x-y axis by 0.5 µm to construct the structures layer by layer.[81]

Multiphoton lithography was utilized to microfabricate sculptures by artist Jonty Hurwitz in collaboration with Stefan Hengsbach at the Karlsruhe Institute of Technology and Yehiam Prior at the Weitzmann Institute of Science. Hurwitz took an image of a model (Yifat Davidoff) using photogrammetry, and used this image to microfabricate a human sculpture named "Trust" with nanoscale features (Figure 5d). He was also inspired from Antonia Canova's work entitled "Psyche revived by Cupid's Kiss" (1787-1793, Louvre Museum), which led to another microsculpture, entitled “Cupid and Psyche” (a self-portrait of himself and Davidoff) (Figure 5e). This work represented the artist’s emotions toward Davidoff as his first love. The sculpture was digitally assembled on an ant head to put the size in perspective. According to Hurwitz, these microscale artworks represented the moment in history that we were able to create a human form at the same scale as the sperm. The blend of art and science in these works was featured in a range of art journals, newspapers, and television channels.

3D microscale protein-based objects with complex geometries were also created using multiphoton lithography. Jason B. Shear and his team at the University of Texas at Austin have developed a high-viscosity protein-based reagent that allowed fabricating 3D microstructures such as Möbius strips.[82] Figure 5f shows a partially-constrained structure fabricated from a BSA protogel, containing four chain links and an 18-point spiked star. The protein gel contained BSA in DMSO, and rose Bengal in HEPES-buffered saline solution. The structure was fabricated using a dynamic mask-based process, where objects were represented as a range of images sequentially displayed on a digital micromirror device (DMD).[83] A focused ($Ti{:}Al_2O_3$) laser beam was raster-scanned across the DMD in planes to incrementally form the 3D structure along the optical axis. Hence, these demonstrations represent the potential of using protein-based materials in creating artwork.

3.4 Nanoparticle-based Artwork

Nanoparticles as inks could be printed to create visually-appealing images. The sun is the alchemical symbol for gold, proposed by the 17th century alchemist Robert Fludd.[84] An image of the sun was printed by gold nanoparticles (**Figure 6**a).[85] Discrete nanoparticles were organized deterministically on grooved surfaces using directed assembly. The nanoparticles were arranged in predefined positions defined by the geometry of the template. To create the image, silicon templates were molded in the order of 1 cm^2 from hardmasters containing grooves (40 nm - 10 µm). The mold was inked with a colloidal suspension, and the wetting properties and the geometry allowed filling the grooves. Finally, the particle assembly was contact printed on plain substrates through tailored adhesion. The image contained 20,000 gold nanoparticles (Ø= 60 nm) and printed in 12 min.[85] This work represented an example of using nanotechnology in the context of history to create a story to captivate the reader's attention.

Optical properties of materials could be used to demonstrate scientific principles, or attract readers. For example, attention-catching images were created from quantum dots that exhibited size-dependent emissions properties.[86] Monodisperse CdSe quantum dots were produced by the pyrolysis of the organometallic precursors including dimethylcadmium and trioctylphosphine selenide in a coordinating solvent containing trioctylphosphine oxide (TOPO).[87] The dots were filtered out as powders using size-selective precipitation, followed by growing a shell using diethylzinc ($ZnEt_2$) and hexamethyldisilathiane ($(TMS)_2S$) as the zinc and sulfur precursors. Photographed by Felice Frankel, Figure 6b shows a series of vials with luminescent CdSe/ZnS nanocrystals (Ø= 2.3-5.5 nm) emitting light at 470, 480, 520, 560, 594, and 620 nm (left to right). Frankel's work with quantum dots contributes to thinking by producing explanatory images, developing creative ways to visually communicate scientific findings, and leveraging visual communication.

Another nanomaterial that was used to create visually-appealing artwork is ferrofluid. This magnetizable liquid consists of surfactant-coated iron oxide nanoparticles (Ø= <10 nm) suspended by Brownian motion. Carrier liquids contain mineral and silicone oils, polyesters, polyethers, synthetic hydrocarbons, and water.[88] Sachiko Kodama began creating ferrofluidic sculptures in 2000. In "Protrude Flow", she created an interactive ferrofluidic artwork, in which the surface morphology and color was changed dynamically.[89] The ferrofluid formed spikes along magnetic field lines as the magnetic surface force exceeded the fluid weight and surface tension. The shape of the sculpture was transformed by the changes in lighting, music, and human voice.[90] Her work in kinetic and interactive art was inspired from the geometry and the symmetry in nature. For example, Morpho Towers (2006) featured ferrofluidic standing spirals, which were depicted as ocean and tornadoes.[91] This idea was based on Japanese concept of *mitate* (juxtaposition), which refers to mimicking natural phenomena, and it provides freshness and an element of surprise, producing an intriguing experience.[92] Her ferrofluidic artworks were exhibited in many media art exhibitions around the world, including Museum of Contemporary Art, Tokyo in 2010. Another artist, Fabian Oefner, created millefiori-like patterns using ferrofluid and water colors (Figure 6c). When watercolors were added to ferrofluid, they were confined within the barriers of ferrofluid. This solution formed black channels and ponds that did not comingle due to the hydrophobicity of the ferrofluid.

3.5 Nanoart for Broader Audiences

Many recent uses of nanotechnology in art also show the potential of visualizations to connect science with cultural and political issues. The ‘Nanomandala’ (2003) was an installation created by media artist Victoria Vesna in collaboration with nanotechnologist James Gimzewski and sound artist Anne Niemetz.[93] The installation involved a disk of sand, where various images were projected in evolving scale from the molecular structure of a sand grain to an image of a complete mandala. The sand mandala, an image of the symbol that represented the universe in Buddhism, was created by Tibetan Buddhist monks, in collaboration with the Los Angeles County Museum of Art. The installation was complemented with a meditative soundscape that was derived from the process of mandala making. Vesna was inspired from the work of nanotechnologists, who purposefully arranged atoms at the nanoscale, and its analogy to the work of monks, who laboriously created mandalas grain by grain. Hence, these two processes practiced in traditional cultures and modern scientific communities represented a common ground centered around patience.[94]

In 2008, A. John Hart and his colleagues created “Nanobama”, patterned structures of vertically aligned carbon nanotubes (CNTs) resembling Barack Obama. The work was based on the artist Shepard Fairey’s “Hope” poster, which became popular during the 2008 presidential election (Figure 7a). On election day, Hart posted a series of images on the website nanobama.com as well as the Flickr photo gallery, and accompanied the images with a description of CNT fabrication. This description, and the slogan “Vote for science” were intended to convey Nanobama as an example of nanotechnology, using a popular image and newsmaking theme as the visual channel. The number of CNTs in each of the microscopic Nanobama structures was ~150 million, which was chosen to represent the number of Americans who voted in 2008 presidential election. The widespread worldwide media attention of Nanobama, including newspapers, magazines, and academic journals indicated how such a combination of emerging technology, popular interest, and engaging visualizations could help advance public discussion of science. Media coverage used Nanobama in several different ways: including as an introduction to stories about the recent election, as a companion to perspectives on science policy in the Obama administration, and as a lead-in to the discussion of miniature artwork.

Nanoscale structures can capture the imagination of readers when the images are presented in a context that general public understands. Wim Noorduin and colleagues utilized a dynamic reaction-diffusion system to rationally grow elementary structures by controlling the diffusion of CO_2 in a solution of barium chloride and sodium metasilicate.[95] By varying the CO_2 concentration, pH, and temperature, a bouquet of hierarchically assembled multiscale structures with different levels of complexity was created. The SEM images of these structures were digitally colored and enhanced to resemble flowers (Figure 7b). This work was featured in numerous magazines and newspapers read by the general public. Hence, visually-appealing nanotechnology images in an easily understood context represent a medium for creating a common ground, initiating media activism, intriguing imagination, and educating the general public.

Nanoart has been utilized to stimulate critical thinking and question responsible technology development. Todd Siler‘s metaphorical artworks interpret what nature makes and what humans make of nature.[96] Inspired by the empirical work of Geoffrey A. Ozin, this art searches the creative process involved in designing and building nanomaterials such as crystals, wires, sheets, and tubes.[97] The team created several installations, abstract paintings and sculptures to capture the distinctive feature of nanomaterials, self-assembly and their behavior changes with size.[98] Siler‘s art serves as propositional schematics and creative catalysts for sparking innovative thinking. The theme of Siler and Ozin’s work involves metaphorical art that correlates the humanbrain’s handiwork and nature’s innovations in nanotechnology, and its responsible application to pressing world problems. These artworks also critique the effect of developments in nanotechnology on the environment and humanity. Siler’s installation, Metaphorming Nature, featured artworks visualizing nano- and micro-scale bottom-up to top-down processes and physical interactions between atoms and nanomaterials such as nanoscale crystals, wires, sheets, and tubes (Figure 7c). Furthermore, these artworks questioned the perceived fear about the unknown implications of nanotechnology among the public. Siler’s works were exhibited at CU Art Museum, University of Colorado, Boulder and the Armory Show, New York City in 2014.

The Materials Research Society has an annual Science as Art competition, which encourages the creation of visualization methods that allows the analysis and presentation of scientific work.[99] This initiative aims to highlight micrographs that transcend the role as a medium for transmitting information, and transform into objects of beauty and art. The structures for the competition have been created from copper, gold, nickel, zinc, indium, their oxides and alloys, as well as compounds such as silicon, graphite, Ti_3AlC_2, SiC, CoFeB, SnS, GeTe, KOH, and epoxy, block copolymers, and polystyrene. Chemical and physical vapor deposition, focused helium beam writing, chemical and electrochemical etching, annealing, electrodeposition, deep reactive-ion etching, and self-assembly were utilized to create nanostructures. These micrographs featured nanowalls, foams, composites, nanowires, magnetic structures, nanocrystals, nanopillars, pyramids, porous patterns, films, and lamellae. The micrograph images were digitally colored and presented within a theme. While most of the images were uncontrolled structures that resembled macroscale objects, some images were rationally designed to create artistic expressions.

4 Picoart

At an even smaller scale, picoart involves atomic manipulation to create static and dynamic structures having visual appeal. In 1989, Don Eigler at IBM became the first person to manipulate individual atoms to draw patterns (**Figure 8**a).[100] A scanning tunneling microscope (STM) was used to arrange 35 xenon atoms to write the company acronym, which represented the first controlled atomic assembly. The tungsten tip of the microscope was used to pick atoms by applying a short voltage pulse, and the atoms were positioned by applying a voltage pulse of opposite polarity. Figure 8b shows IBM “Blue Nickel”, which represents the adaptation of multiple cultural positions: single color obsession like Picasso; overwrought sense of melancholy; and exposure of the nonlabor of the ‘work’ of art by using the scientific instrument.[101]

A Boy and His Atom was the first atomic scale stop-motion animation created by Nico Casavecchia, Andreas Heinrich, and Christopher Lutz at IBM Almaden Research Center in 2013 (Figure 8c).[102] The video-game resembling animation depicts a boy playing with an atom that transforms into various patterns. At the beginning of the animation, the atom separates from a bulk material, which represents a twelve-atom magnetic memory. The patterns were created by 65 carbon monoxide molecules on a copper substrate in a device that operated at -268 °C. 242 still images were captured by a scanning tunnel microscope, where the oxygen component of each molecule appeared as a white dot in each frame (45×25 nm). The motivation of this animation was to create an abstract artwork to question science and technology. The animation implies that advances in atomic manipulation aims to create extreme computation and data storage at infinitesimal proportions.

5 Microphotography in Life Sciences

Imaging cellular and tissue architectures involves microscopic contrast methods such as bright field, polarization, and fluorescence. Recent advances in digital processing, labeling, and high-performance optical imaging devices (e.g., CCD/CMOS cameras with low noise and high-quantum efficiency) have improved the resolution, sensitivity, and specificity of molecular detection capabilities of microscopic analyses.[103] These visualization technologies have benefitted to neuroscience[104], oncology,[105] immunology,[106] and developmental biology.[107] Despite rapid progress, emerging bioimaging and detection techniques are not well recognized by the general public. To promote activities in biological research, there is an emerging trend to create nano/microscale photography that shows artistic views of cellular life. Nikon’s Small World contest, Art gallery of Lab on a Chip journal, and Olympus BioSpaces digital imaging competition cover these micrographs.[108] Differential interference constant (DIC) microscopy has been used to image subcellular physical structures of cells without labelling.[109] For instance, Rogelio Moreno used DIC microscopy to photograph aquatic animal Rotifer, revealing its mouth interior and heart shaped corona (**Figure 9**a). Sub-diffraction limited microscopic images based on super-resolution microscopy were also created in conjunction with computational biochemistry that improved the resolution.[110] Muthugapatti K. Kandasamy photographed super-resolved subcellular structures in bovine pulmonary artery endothelial cells, which were stained for actin (pink), mitochondria (green) and DNA (yellow) (Figure 9b). Confocal microscopy was also utilized to image deblurred features of multicellular organisms.[111] For example, Dominik Paquet photographed an aesthetic Alzheimer Zebrafish by fluorescently labeling tau gene (red) pathological tau (blue) and neurons (green) across its body (Figure 9c).

Micropatterning coupled with advanced imaging was also used to construct artistic scenes in life sciences. Particularly, proteins and cells were spatially controlled to create various biological designs at nano/microscale.[112] Albert Folch and colleagues created such artistic images including 'microfabricated apples', 'the partying cells in the island', and 'neurons looking at you'.[113] In microscopic apples, albumin (red) and fibronectin (green) proteins were coated onto micropatterned substrates using elastomeric templates (Figure 9d). For cellular-level photography, live cells exhibited directed growth on substrates containing protein masks to form cellular micropatterns as illustrated in 'partying cells' (Figure 9e) and 'watching neurons' (Figure 9f).

Polymers were also used to create micropatterned structures based on lithography and microfabrication.[114] For example, stamp microstructures were created from agarose gel (Figure 9g). This work comprised seven rectangular notches (0.5 × 1.0 mm) that were used to print food dyes. The microstamp was colored due to the diffusion of these dyes into the gel matrix during patterning. Micropatterned polymers were integrated with cellular samples and digitally modified to create hybrid structures. For instance, Nicholas Gunn created microscale polymer pedestals on a glass substrate. 3T3 cells cultured on these micropallets were digitally colored (Figure 9h). Furthermore, micropatterned polymers were combined with cell cultures to create visually appealing images. Christopher Guérin created such an image with cells growing on biopolymer scaffolds (Fig. 9i). Additionally, the use of transgenic biotechnologies created a field called "bioart" that tackles social practices such as the risks of genetically modified animals.[115] Since bioart and life sciences utilize common approaches including imaging methods, the microphotographic expressions in life sciences will gain new meanings, annotations, and roles in a social context. Furthermore, advances in life sciences and synthetic biology will lead to new opportunities for visualization and the use of biotechnology as a means of creating artwork in addition to communicating scientific information through visualizations.

6 Discussion

Raising awareness of current scientific developments and their benefits for society is crucial to political support and research funding. The adoption of new technologies relies on the investment of the general public, who are often more likely to support technological changes if the benefits and potential risks are clearly understood.[116] Hence, the large-scale distribution and the implementation of nano/microscale technologies require the ability to effectively convey its benefits and limitations to the public. Academic norms and habits must continue to change in order to encourage direct engagement with the public. Federal agencies and private donors have introduced initiatives to increase the transition of scientific knowledge from academia directly to the public over the last decade. Such initiatives are necessary because the scientific knowledge does not always flow from experts to the public, but is a shared and multidirectional interactive experience.[117] However, scientists and technology developers are not optimally trained to communicate their research to the general public.[118] The creation of further synergies between art and science can augment scientific outreach effort and enable broader public awareness about nano/microscale technologies.

Arts have a long-standing reputation to challenge dominant paradigms and reduce widely-spread misperceptions.[119] For example, arts through installations and exhibitions can challenge established but outdated norms, express concerns about social injustice, create an atmosphere that encourages public debate, and thereby influence individuals of all ages.[120] Arts also promote new perspectives for looking at marginalized or silenced issues and give a voice to topics considered taboo. Therefore, arts liberate ideas by playing an emancipative social role challenging the status quo.[119, 121] Arts also allow synthesizing, simplifying and conveying complex scientific ideas while also rendering the information memorable.

Consequently, the utilization of critical art in communicating emerging technologies can distill scientific knowledge to a socially fundamental level and encourage new ways to look at problems, which can play a significant role in public campaigns.[122] For example, installations and exhibitions can encourage technology developers to communicate in alternative ways, and to convey complex scientific concepts to the public more effectively at a socially acceptable level.[122] The visual and performing arts also create memorable moments and a celebratory atmosphere by appealing to emotions, which are physiological changes to sensory experiences. When the emotions are targeted, individuals pay more attention to a particular event and commit to the cause storing information in their long term memory.[123] According to the Triandis' Theory of Interpersonal Behavior, emotions significantly influence the behavior, which is moderated by moral beliefs, and cognitive limitations.[124] Such an experience can create three main forms of stimulation: neutral ground, liminality, and communitas.[125] The neutral ground enables the discussion of controversial issues around the technology development and safety concerns about their diffusion into our daily lives. Liminality represents a psychological ambiguity, in which the basic ideas and norms are broken down or weakened, and this disorientation allows the individuals to reposition their points of view. Lastly, communitas is the unstructured community, where all the members are treated equally and experience liminality as a group. Hence, the incorporation of arts into technology communication can promote new ways of considering issues, appeal to emotions, and form a celebratory atmosphere.

Nano/microscale art render indistinct the formerly distinguishable concepts of artifact and nature.[126] Art at nano/microscale also represents a historical shift from the older epistemic values of mechanical objectivity. This concept allows transending our perception of reality from a solely visual culture to connectivity and sensing. The combination of nano/microfabrication and arts emphasizes building from the bottom-up rather than top-down. In contrast to the traditional means of producing macroscale art through abstract distance or symbolic extraction, nano/microscale art directly appeals to the feelings associated with local contact that combines poiesis (making), techne (craft), and episteme (true belief). Nano/microart negotiates and reworks cultural boundaries between science and art while creating a critical disruption and parody that challenge *de facto* thinking, cultural logic and values in a meaningful and positive way. For example, the artistic expressions of the preparation processes and applications of nanotechnology to biotechnology facilitate discussion about the health and environmental implications, which are critical factors in encouraging pro-technology behavior. Hence, art at the nano/microscale is a platform to familiarize the public with the omnipresence of emerging technologies, facilitate spreading scientific knowledge, promote responsible technology development, influence opinion, and educate the public.

Nano/microart has a role to play in critical thinking and creativity. Learning of scientific concepts is a contextual process mediated by cognitive,[127] affective,[128] motivational,[129] and sociological[130] factors. Because messages delivered through nano/micro art has the potential to appeal to different senses, it can stimulate episodic,[131] tangential,[132] incidental learning,[133] and create long-term memory. This requires creating installations that go beyond sight to appeal a multitude of senses including taste, smell, chemoreceptors, hearing, touch, and other sensory modalities such as vibration, balance, and kinesthetic sense. For example, Midas (2007), an immersive biomedia nanoart installation created by Paul Thomas, involved a visual and sonic interaction with a 3D skin cell model.[134] The interplay of vision, touch and hearing challenged the human perception by extending aurality, and reworking geographies within the ontologies of touch. Potential interactive installations may include themes such as biotechnology, social controversies, digital world, information technologies, robotics, and human-machine interaction. Such nanotechnology exhibitions are well positioned to combine with other disciplines such as responsive sensing materials, mobile applications, and optical art involving Pepper’s ghost, photonic crystals, holography, and laser light installations.[135]

Other unexplored frontiers include performing nano/microarts: acting, music, dance, theatre, performance poetry, ballet, illusion, opera, standup comedies, and puppetry. Such promotional initiatives will not only allow imagination for new technologies, but also enable recruiting students into the fields of nano/microtechnology and innovation.

The nano/microart installations can be presented in interactive learning modules of visual elements to simulate chemical and physical phenomena and quantum effects. For example, visuals that can zoom in and out of material geometry, or move them around can enhance the interaction experience. For example, using motion detection (PlayStation, Sony; Xbox, Microsoft; Wii, Nintendo), the audience can control the atoms or nanomaterials to explore states of matter. These systems can provide intuitive 3D animations integrated with visual and haptic feedback. These interactive platforms can include exponential notation to understand and compare the size of nano/microscale materials to macroscale objects. A practical approach is creating virtual electron microscopes that allow adjusting the focus, contrast, and magnification of nano/microscale artwork and other forms of life. Other approaches may include installations exploring the fundamentals of nano/microtechnology using interactive videos and performances. Such installations may also include themes such as explanations about how transistors and integrated circuits work and their manufacturing, inner workings of electron microscopes, quantum mechanics/behavior, DNA self-assembly, protein synthesis, manipulation of electrons and nanomaterials, and creation of nanodevices. Game-based learning is another approach that can be incorported in interactive installations.[136] For example, NanoMission (Playgen, London) has created video games, in which the players explore the applications, role, and importance of nanoscience including nanoparticle-based drug delivery.[137] In these missions, players learn about the operation of nanoelectronics, building and functionalizing molecules, nanoscale imaging, bottom-up self assembly, and nanomedicine. Hence, nano/microtechnology integrated into interactive media and arts holds potential as a communication tool to introduce new concepts to the public. The future of nano/microart lies at interactive platforms for spurring creativity, and promotion of science and technology, and creating public discussions about the implications and opportunities of nanotechnology.

7 Conclusion

Nano/microscale materials have been utilized in creating tools and artistic work since prehistoric times. However, only recently, we have gained the ability to directly manipulate and image matter from the macroscale down to atomic resolution. This leap in imaging and controlling matter represents a breakthrough in the human endeavor to understand the invisible small-scale phenomena in our macroscopic world and to engineer versatile technologies. Nano/microscale materials and device engineering require awareness of the safety of human health and protection of finite environmental resources. As the public embraces emerging technologies and products at nano/microscale, the scientists and technology developers should be prepared to disseminate their findings concisely and timely to the public and policy makers.

The effective communication of ideas outside the scientific domain requires understanding of human psychology and the way the brain processes and maintains information in a social context. Arts have been a predominant stimulator and catalyzer for simplifying and effectively communicating complex concepts. The advent of controlling and imaging matter at nano/microscale has created new art forms, which have been utilized to spur creativity and new ideas, educate the public, and influence policy making. At the center of these emerging artistic domains is the collaboration between scientists and artists who are learning to collaborate in order to achieve common goals. Artists and scientists approach creativity and exploration in different perspectives, and working together enables new ways of questioning, discovering and interpreting the matter. Whether through governmental, academic, or industry initiatives, scientists and artists are self-organizing to create nano/microart. This collaboration stimulates discussions with the aim of finding solutions for the most pressing needs of society, and advancing our understanding of human existence.

We are in the midst of a development phase, where concepts in data-driven sciences and emotion-driven arts are intersecting more frequently.[126a] Aided by the growth of interdisciplinary research and emerging digital platforms, collaboration between arts and sciences is evolving to educate the public about novel materials and engineering concepts integrated with new aesthetic perspectives. These emerging nano/microtechnology platforms represent new media of expression and communication for both artists and scientists. However, value of nano/microart can only be exploited by putting the technology in a context to deliver a specific message, where the meaning is enhanced by the small size and the sense of mystery presented by the real objects. Such approaches require going beyond visually appealing images, and emphasizing messages that combine intellectual engagement with clarity of presentation to the intended audience. This spectrum between art as a pure expression using nano/microscale media and art designed to cultivate public understanding of technology is an essential element of the growing era of nanotechnology.

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Figure 1. Art in the ancient world and medieval ages. (a) Hand stencil from Maros on the island of Sulawesi in Indonesia (40,000 BCE). Scale bar = 10 cm. Reproduced with permission.[1] Copyright 2014, Macmillan Publishers Ltd. (b) The Horse Panel and wild animals in the Chauvet-Pont-d'Arc Cave in France (36,000 BCE). Courtesy of Jean Clottes. Scale bar = 1 m. (c) Maya Blue on a mural showing warrior from Bonampak, Mexico (580 - 800 CE). Reproduced with permission.[6a] Copyright 2004, The Royal Society of Chemistry (RSC) on behalf of the Centre National de la Recherche Scientifique (CNRS) and the RSC. (d) Panel 8e from the Great East Window (1405–1408) at York Minster, showing the Army of the Horsemen, described in Revelations ix: 16–19. Scale bar = 10 cm. Reproduced with permission.[11b] Copyright 2014, Elsevier.

Figure 2. Chip artwork. (a) A “full adder”pun on a Hewlett-Packard logic circuit in 1980, (b) A cheetah drawing in a 1988 memory chip in the HP-9000 series controllers, (c) Mr T, (d) Daffy Duck, (e) Smurf, (f) Mickey Mouse, (g) Milhouse Van Houten from the Simpsons, (h) Road Runner, (i) A flying osprey, (j) Lassie the dog, and (k) Marvin the Martian. Scale bars (d,e)= 10 µm. The images were captured with a high-powered optical microscope (Nikon FX/L) under differential interference contrast at 50-600× magnification. Courtesy of the Florida State University.

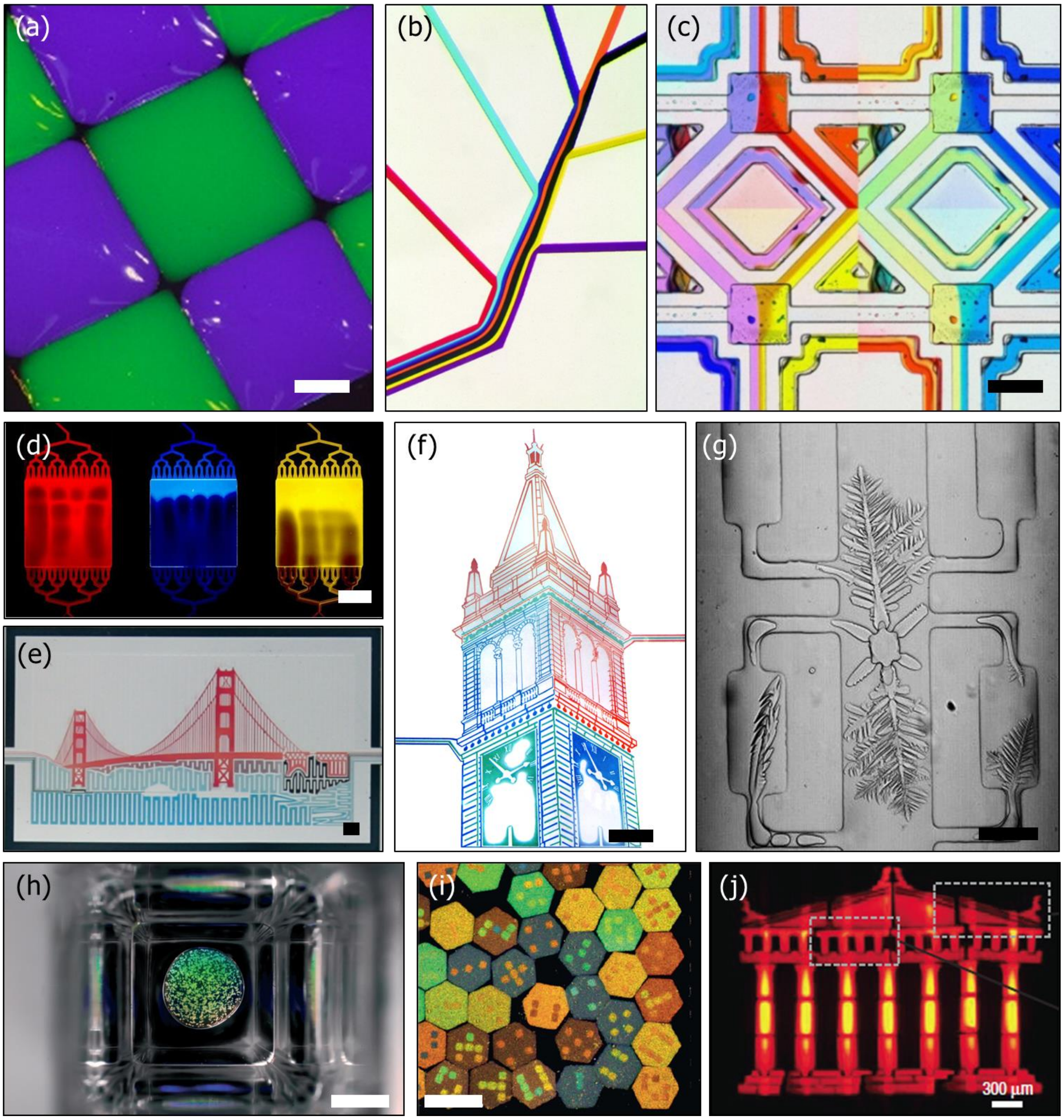

Figure 3. Microfluidic artwork. (a) Dyed water droplets separated by hydrophobic boundaries. Courtesy of Felice Frankel. Scale bar = 1 mm. (b) Science 1999 July issue featuring a microfluidic device from the Whitesides group. Seven channels colored with different dye solutions converge in a single channel and move in parallel laminar flow. Courtesy of Felice Frankel. (c) The “Chromatic Labyrinth” collage was created from a culture chamber that allowed growing cells under controlled conditions. The collage was formed by changing the hue of the original image. Courtesy of David Cate and Albert Folch. Scale bar = 200 µm. (d) “The Color of Viscosity” was created by flowing aqueous dextran at different flow rates in the microchannels, and the colors were digitally added to the photographs. Courtesy of Chris Sip and Albert Folch. Scale bar = 500 µm. (e) The Golden Gate Bridge. Courtesy of Albert Mach and Tanner Nevill. Scale bar = 500 µm. (f) The Campanile (University of California, Berkeley). Courtesy of Austin Day and Tanner Nevill. Scale bar = 1 mm. (g) Ice Crystal Growth in Microfluidics. Courtesy of Ran Drori at Ido Braslavsky's lab at the Hebrew University of Jerusalem (2014). Scale bar = 100 µm. (h) The Sphere. Courtesy of David Castro and David Conchouso. Reproduced with permission.[67b] Copyright 2015, the Royal Society of Chemistry. Scale bar = 1 mm. (i) Superparamagnetic colloidal nanocrystal dices

assembled in a microfluidic device. Scale bar = 500 µm. Reproduced with permission.[68] Copyright, 2010 Macmillan Publishers Ltd. (j) Complex self-assembly in railed microfluidics. The channel and groove depths are 37 and 41 µm, respectively. Reproduced with permission.[69] Copyright, 2008 Macmillan Publishers Ltd.

Figure 4. Microfabricated artwork by focused ion beam milling (FIBM). (a) Actual Size. Scale bar = 100 nm. Reproduced with permission.[70b] Copyright, 2007 Macmillan Publishers Ltd. (b) Probation. Courtesy of Alessandro Scali and Robin Goode, 2007. Scale bar = 100 µm (c) Sandcastle draft of Eltz Castle (Germany) on a sandgrain. Single pixel resolution = 50 nm, single line = 0.4-1.0 µm, scale bar = 50 µm. Courtesy of Marcelo Coelho and Vik Muniz.

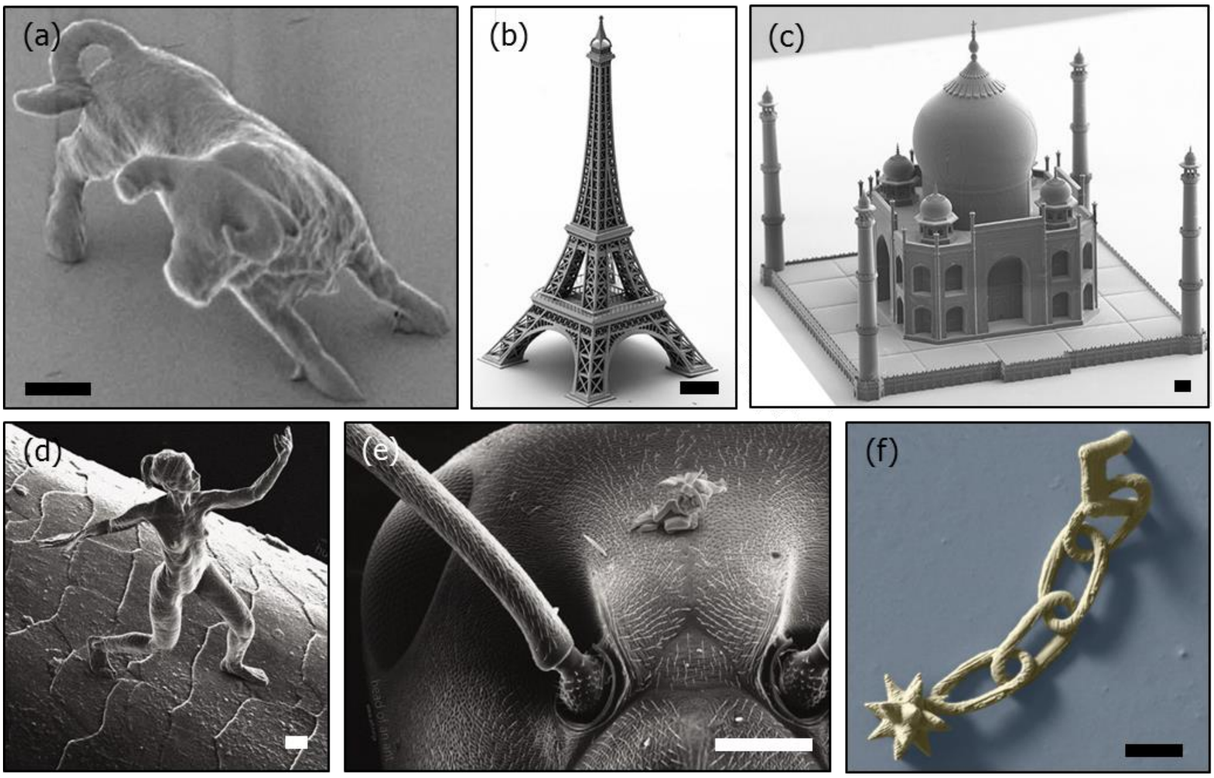

Figure 5. Nano/microfabricated artwork by two-photon polymerization. (a) Bull sculpture. Scale bar = 2 µm. Reproduced with permission.[138] Copyright, 2001 Macmillan Publishers Ltd. (b) Eiffel Tower, Scale bar = 100 µm, Courtesy of Nanoscribe GmbH. (c) Taj Mahal, Scale bar = 100 µm, Courtesy of Nanoscribe GmbH. (d) Human sculpture on a hair named "Trust". Scale bar = 10 µm. Courtesy of Jonty Hurwitz. (e) "Cupid and Psyche" on an ant head (assembled later) from novel Metamorphoses by Apuleius. Scale bar = 100 µm. Courtesy of Jonty Hurwitz. (f) A morningstar with a chain. Scale bar = 10 µm. Reproduced with permission.[82] Copyright, 2013 Wiley-VCH Verlag GmbH&Co. KGaA, Weinheim.

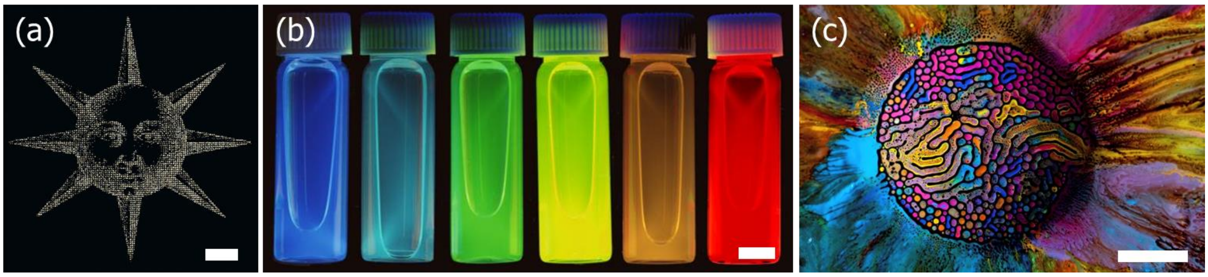

Figure 6. Nanoparticle-based artwork. (a) Micrograph of a sun composed of gold nanoparticles. Reproduced with permission.[85] Copyright 2010 Macmillan Publishers Ltd. Scale bar = 10 µm. (b) Quantum dots. Courtesy of Felice Frankel. Scale bar = 1 cm. (c) Millefiori created from ferrofluid. Courtesy of Fabian Oefner. Scale bar = 5 cm.

Figure 7. Nanoart for broader audiences. (a) Nanobama, Scale bar = 100 µm. Image courtesy of A. John Hart. (b) Biomimetic complex structures formed with self-assembly. Reproduced with permission.[95] Copyright, 2013 American Association for the Advancement of Science. Scale bar = 25 µm. (c) “Envisioning a Cornucopia of Nano-Neuro Innovations (1 to 100 nm) on the Horizon: From Bottom Up to Top Down” (2011-12) mixed media on synthetic canvas (porous inorganic material) (Courtesy of Ronald Feldman Fine Arts, New York, NY). Photographed by Lael Siler. Scale bar = 10 cm.

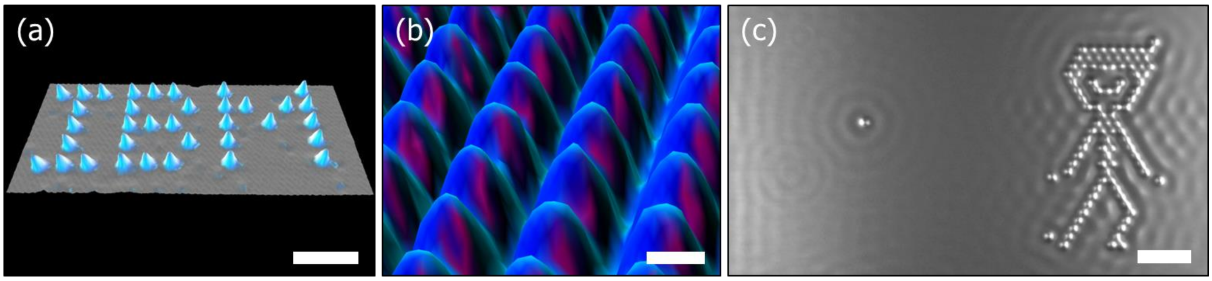

Figure 8. Picoart. (a) The first example of patterning atoms at nanoscale. Scale bar = 1 nm. (b) “Blue Nickel” consisting of uninterrupted periodicities was inspired by the tessellations created by the Moors or those of Maurits Escher. To render the unreconstructed FCC (110) surface appealing to the public, the artist created the "blue period". Scale bar = 0.1 nm. (c) A Boy and His Atom. Scale bar = 5 nm. All images are courtesy of IBM Corporation.

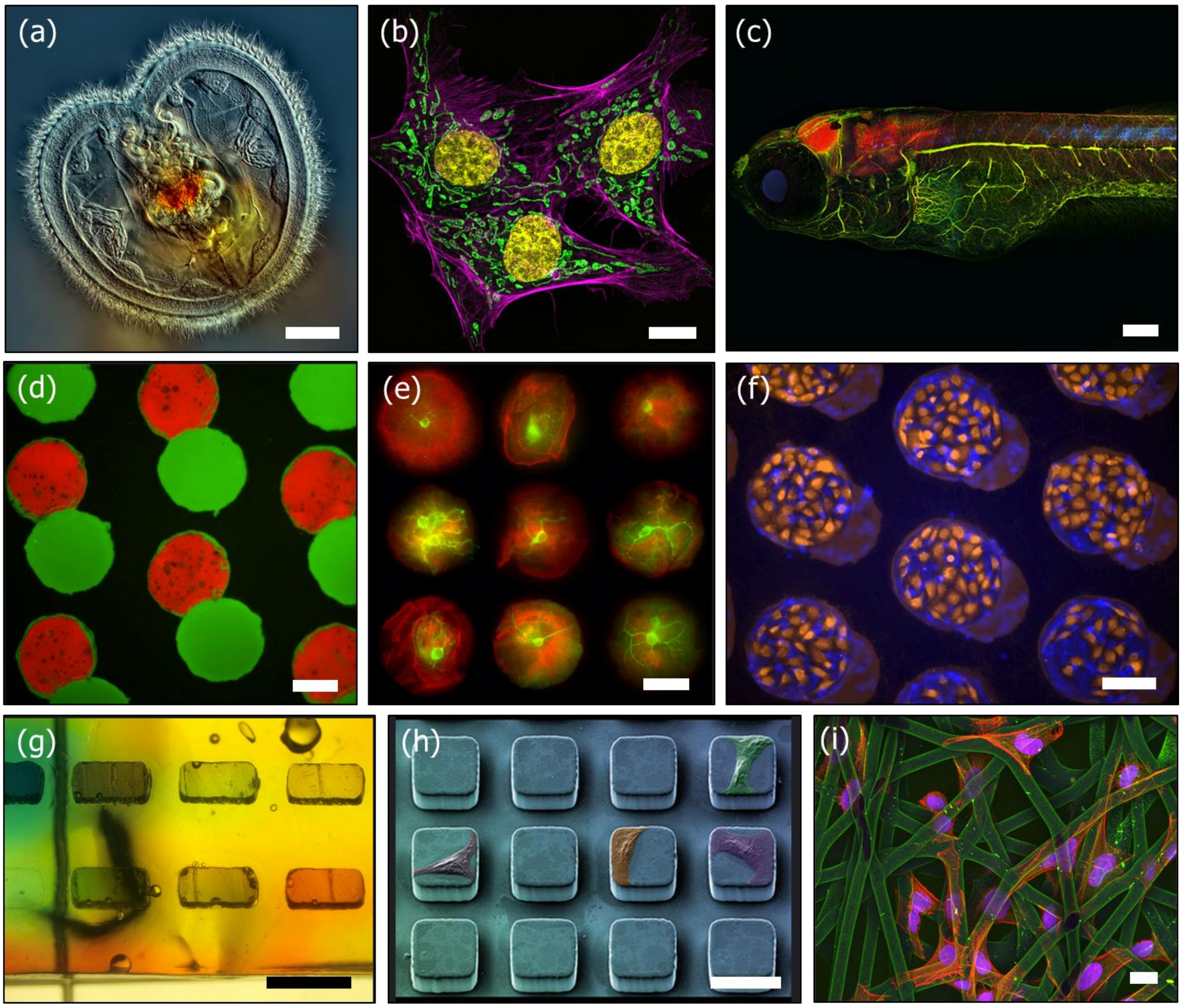

Figure 9. Microphotography in life sciences. (a) Aquatic animal Rotifer imaged by differential interference contrast microscopy. Scale bar = 50 µm. Courtesy of Rogelio Moreno. (b) Intracellular structures of bovine pulmonary artery endothelial cells visualized by super-resolution microscopy. Scale bar = 10 µm. Courtesy of Muthugapatti K. Kandasamy. (c) Neurons in an Alzheimer zebrafish were imaged by confocal imaging. Scale bar = 100 µm. Courtesy of Dominik Paquet. (d) ‘Microscopic apples’ based on micropatterning of albumin and fibronectin proteins. Scale bar = 100 µm. Courtesy of Anna Tourovskaia and Albert Folch. (e) Partying cells in the island at night. Scale bar = 100 µm. Courtesy of Anna Tourovskaia and Albert Folch. (f) ‘Neurons looking at you’ cellular micropatterns. Courtesy of Xavier

Figueroa and Albert Folch. Scale bar = 100 µm. (g) Microscale stamp with rectangle notches made of agarose gel. Dyes diffused into this stamp give its colorful patterns. Scale bar = 1 mm. Courtesy of Albert Folch. (h) Cells on micropatterned polymer pedestals. Scale bar = 40 µm. Courtesy of Nicholas Gunn. (i) Cells cultured on a biopolymer scaffold. Scale bar = 10 µm. Courtesy Christopher Guérin. Small World photomicrography contest. Reproduced with permission from Nikon, and the Royal Society of Chemistry.

Table 1. Sciart initiatives and programs

Initiative Program	Description	Founded
Leonardo Society	An international society for the arts, sciences, and technology	1968
Nikon's Small World	A competition for photomicrography	1975
SymbioticA	A program for bioart at the University of Western Australia	2000
NanoArt 21	Founded by Cris Orfescu, an organization for nanoart competitions, festivals, and exhibitions	2004
UCLA Art|Sci Center+LAB	A center to promote the integration of arts and bio/nano sciences	2005
Bringing Art into Technology (BAIT)	Folch lab outreach program to make scientific disciplines accessible through artistic manipulations of micrographs.	2007
Roche Continents	A summer program that brings together art and science students across Europe to learn about arts and creativity	2007
Le Laboratoire Paris/Cambridge	An organization dedicated to the development of radical ideas, and provide educational programs.	2007
ArtScienceLabs at Harvard	Founded by David Edwards, an international network of labs focusing on educations programs for art and science.	2008
µTAS Art in Science Contest	A contest for art-on-a-chip images	2008
Art of Science at Caltech	A contest for images at nano/micro/macroscale	2008
ArtSciLabs at UT Dallas	Directed by Roger Malina, a program that promotes collaboration between artists and scientists for creating artworks, scientific data analysis tools, a technology testbed. It also develops activities involving the integration of the arts, design and humanities in science, technology, education and mathematics (STEAM).	2013
xREZ Art + Science lab at UNT	Directed by Ruth West, a creative studio and research program to forge productive paths from the intersection of the arts, sciences and humanities to open new portals of imagination, knowledge and communication.	2013

Biographies

Ali K. Yetisen received his Ph.D. degree from the University of Cambridge in 2014. He researches nanotechnology, photonics, commercialization, government policy & regulations, and arts. He has taught biotechnology and entrepreneurship courses at Harvard University and University of Cambridge. He authored 30 journal articles, and a book on photonic devices. He has served as a policy advisor in the British Cabinet Office. He has been the recipient of Cambridge Infectious Diseases Fellowship, the Ann & Norman Hilberry Scholarship, and Roche Continents Award.

Seok-Hyun (Andy) Yun received his Ph.D. degree in Physics. His thesis research led to a startup company in Silicon Valley, where he managed engineering to productize fiber-optic devices for telecom. Currently, he is an Associate Professor and Director of Bio-Optic Lab at Harvard Medical School and Massachusetts General Hospital, an affiliated faculty of the Harvard-MIT Health Sciences and Technology, and the Director of the Harvard-MIT Summer Institute for Biomedical Optics. His research areas include optical imaging, photomedicine, biomaterials photonics, and biological laser. He holds over 50 patents, many of which have been licensed to the industry.

Nano/microscale art is a discipline that practices creative activity at small dimensions. It brings together the expertise in arts and sciences to spur creativity, promote scientific advances, and challenge dominant paradigms. This Review covers miniaturized art in semiconductors, microfluidics, and nanostructures. It also discusses the perceived limitations of nano/microscale artistic practice and points out potential future directions.

Keywords: communication, photography, visualization, microfabrication, nanofabrication

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Art on the Nanoscale and Beyond

ToC figure