Trends in Biotechnology

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Review

Bioart

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Bioart is a creative practice that adapts scientific methods and draws inspiration from the philosophical, societal, and environmental implications of recombinant genetics, molecular biology, and biotechnology. Some bioartists foster interdisciplinary relationships that blur distinctions between art and science. Others emphasize critical responses to emerging trends in the life sciences. Since bioart can be combined with realistic views of scientific developments, it may help inform the public about science. Artistic responses to biotechnology also integrate cultural commentary resembling political activism. Art is not only about 'responses', however. Bioart can also initiate new science and engineering concepts, foster openness to collaboration and increasing scientific literacy, and help to form the basis of artists' future relationships with the communities of biology and the life sciences.

Trends

Bioart is a contemporary art form that adapts scientific methods and biotechnology to explore living systems as artistic subjects.

Interdisciplinary bioart initiatives blur boundaries between art and modern biology with an emphasis on philosophical, societal, and environmental issues.

Bioart plays an important role in critically challenging emerging life science applications, stimulating of scientific thinking, and contributing to new research questions and new technologies.

New concepts emerge for bioart in physical, digital, and computational forms.

Bioart receives ethical criticism for modifying living systems.

Interface of Biotechnology and Art

Bioart utilizes laboratory practice and biotechnology to explore living systems as artistic subjects [1,2]. It is often interdisciplinary, involving researchers and laboratories in creating art. Although subtexts of science are associated with more general cultural forces, few philanthropies commit to fund the joint practice of art and science, including bioart. Accordingly, bioart is constrained by practicalities of access to affordable materials, services, and the commitments expected of laboratories otherwise predisposed to funded research. Nevertheless, an influential community of bioartists has emerged producing work that transcends and evaluates conventional notions about art and science. Art involves conceptual frameworks, fields of association, and avenues of inquiry not investigated by scientists and engineers. Bioart thus presents opportunities for the recognition and synthesis of traditionally separate approaches to critical thinking [3]. Bioartists can introduce research questions, contribute to new technologies, and help to innovate materials for art and science.

Some bioartists adapt biological methods to create expressions of discord and controversy enabling public debates in collaboration with scientists. Biotechnological artifacts used to form disquieting scenarios about perceived risks of genetic engineering are presented as aesthetically appealing cultural commentaries. Regardless of their potential for health benefits and quality of life, genetic technologies have consequences that are not absolutely foreseeable and this has led to public uncertainty about implications for personal privacy and human rights, eugenics, food and drug safety, replacement of natural systems with bioengineered counterparts, involvement of multinational corporations with genetic propriety, worldwide agricultural monopolies, and prospects for the weaponization of biotechnological accessories for the military and law enforcement. Bioartists find these issues to be compelling subjects for their art. Yet, with or without a focus on alarming interpretations of science and technology, all bioart raises questions about social and cultural paradigms [4,5].

At the turn of the 21st century, bioart emerged as a formal subject of academic study. Bioart curricula and dedicated research centers have been established at colleges and universities

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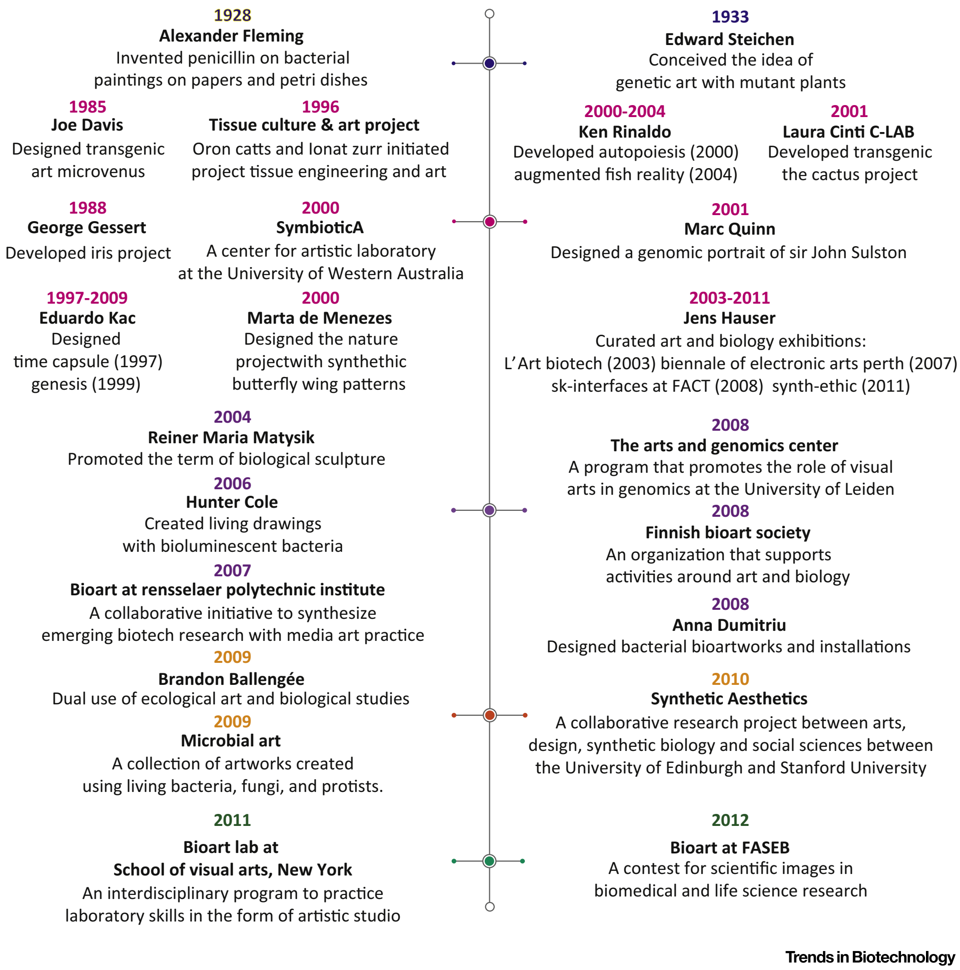

Figure 1. Pioneers, Programs, and Initiatives at the Intersection of Biology and Art

worldwide (see 'Academic Bioart Programs' in the supplementary material online). Figure 1 shows the pioneers, programs, and initiatives at the interface of biology and art.

Historical Contexts

Aesthetically inspired manipulations of the biological world reach deep into history. Art and literature representing the 'quickening' of nonliving materials or transformation of one living substance into some other form coincided with the appearance of cultures dependent on the cultivation of species derived from wild-type progenitors. Classical Greeks noticed homologies in the geometries of human physiology and other forms in nature. The art, architecture, and mathematics of the Greek 'Golden Age' reflected biologically derived principles and these in turn formed the groundwork for the arts and sciences of the European Renaissance.

The history of scientific illustration reflects the influence of biologists on artists in the 19th and 20th centuries. Examples include the collaborations of Charles Darwin and Oscar Rejlander (1872) and the work of German biologist Ernst Haeckel (1899) notably influencing Paul Klee [6,7]. D'Arcy Wentworth Thompson's book *On Growth and Form* (1917) is thought to have been one of the factors promoting abstract expressionism in the arts.

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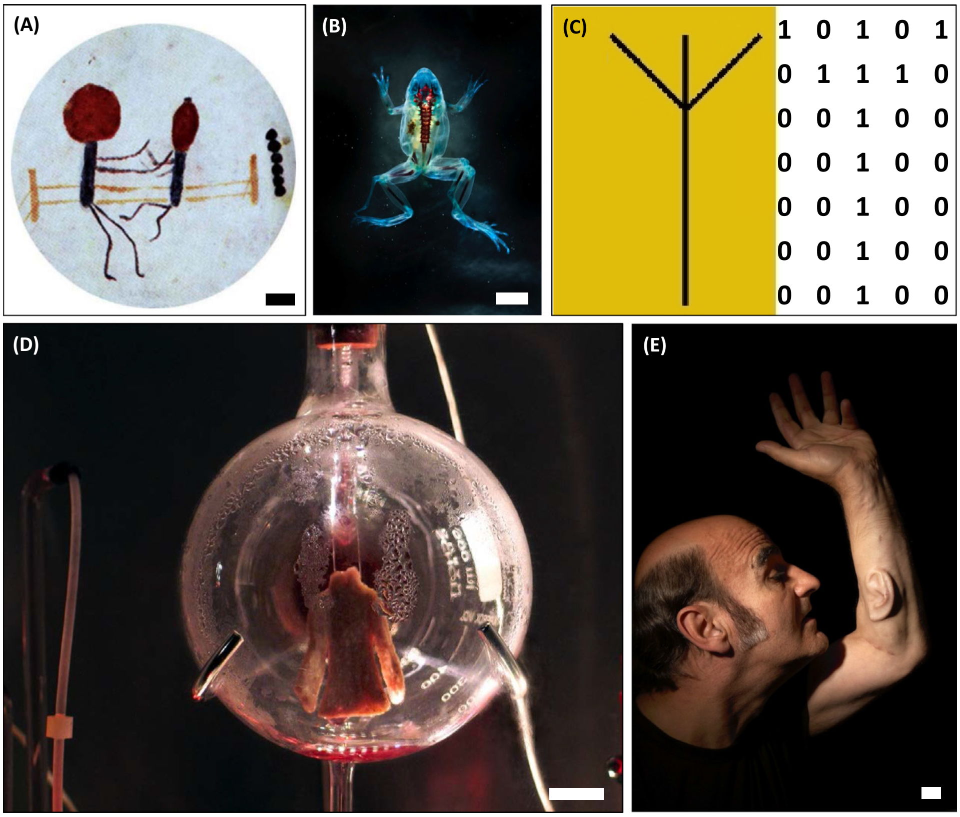

Trends in Biotechnology

Figure 2. Historical and Contemporary Bioart. (A) Germ paintings on paper by Alexander Fleming. Bar, 1 cm. Courtesy of Kevin Brown of the Alexander Fleming Laboratory Museum. (B) Cleared and stained Pacific tree frog gathered from Aptos, CA, USA by Brandon Ballengée (2012) in scientific collaboration with Stanley K. Sessions. *DFA 186: Hades*, unique digital c-print on watercolor paper. Bar, 9 cm. Courtesy of Ronald Feldman Fine Arts, New York and reproduced with permission. (C) Conceptual drawing of *Microvenus*. Courtesy of Joe Davis, 1988. (D) *Victimless Leather* project showing a miniaturized leather jacket using skin cells by SymbioticA. Bar, 2 cm. Courtesy of Oron Catts and Ionat Zurr and reproduced with permission. (E) *Ear on Arm* project. Bar, 3 cm. Courtesy of Nina Sellars and reproduced with permission.

Juxtapositions of art and biology have serendipitously stimulated scientific discovery. In the 1920s, Alexander Fleming, discoverer of penicillin, created ‘germ paintings’ on paper, illustrating stick figures, soldiers, and houses (Figure 2A) [8]. Fleming's bacterial paintings became noteworthy for the discovery of penicillin on his art. Fleming found that fungi killed bacteria in paper artwork, contributing to the discovery of antibiotics. A more recent example of bioart influencing scientific discovery is found in the work of the artist Brandon Ballengée. Collaborating with biologist Stanley K. Sessions in 2009, Ballengée provided explanations for missing limbs in amphibians [9]. Ballengée intended to raise awareness about endangered species. Analyses of Ballengée's images also showed patterns of deformation useful to environmental and developmental biology, subsequently leading to scientific field studies (Figure 2B).

Ornamental horticulture is also counted among precedents for bioart. Over millennia, plant and animal breeding selected for aesthetically pleasing qualities and altered phenotypes in many species. Despite these aesthetic choices, advances in horticulture and animal husbandry were not traditionally recognized as art. Photographer Edward Steichen's (1879–1973) 1-week exhibition of flowering delphiniums organized at the Museum of Modern Art in New York in 1936 is cited as one of the hallmarks of bioart [10]. It is often reported that Steichen's exhibition included delphiniums genetically altered with colchicine, a chemical later used by horticulturalists to produce desirable mutations in crops and ornamental plants. Steichen used colchicine to produce varieties of delphiniums ('Carl Sandberg' 1938 and 'Connecticut Yankee' 1960), but not in 1936. The first publication of the effects of colchicine on plant materials did not appear until the following year [11]. Edward Steichen was not the first or only artist to deal with the hybridization and selection of plants. Claude Monet, Cedric Morris, and William Caparne are among many who were renowned for accomplishments in horticulture as well as art.

Contemporary artist and horticulturalist George Gessert specializes in the selection and hybridization of irises [12,13]. Gessert is distinguished from other hybrid-plant producers because he embraces formal exhibition and publication venues. Like Steichen, Gessert is included in the roster of bioartists. The examples of Steichen and Gessert demonstrate that artists' applications of Mendelian genetics (1866) also fall into broad categorizations of bioart.

Environmental artists of the 1960s and 1970s, including Robert Smithson, Hans Haacke, Walter De Moria, Robert Morris, Christo, and James Turrell, are known for reshaping landscapes. Like today's bioartists, environmental artists challenged conventions for the exhibition and sale of artwork. Where bioart can be too infinitesimally small, environmental art was too large and site specific to be acquired by collectors. Environmental artists paved hillsides with asphalt (Smithson), resurfaced barrier islands with plastic (Christo), and reshaped volcanic craters (Turrell). However, artists learned that these works of art could have unexpected consequences. The era of environmental art was one of awakening consciousness about ecology and the vulnerability of species and natural environments. Some environmental artists incorporated these issues into their work (Box 1) [14,15].

Not all environmental art was environmentally destructive, but by the mid-1970s artists became much more cautious and circumspect about their interactions with nature. With the rise of environmentalism, environmental art retained its fascination with the large scale, but artists turned from manipulations of natural landscapes to art having remedial effects at sites damaged by human activities. Environmental art became 'reclamation art', a surviving relationship of art and environmental biology that overlaps with the interests of many bioartists. Coupled with advances in the life sciences in the late 20th century, environmental art helped set the stage for the appearance of bioart in the 1980s.

Contemporary Bioart

Emerging life sciences provided only part of the inspiration for bioart. Astronomy, astrobiology, and the search for extraterrestrial intelligence (SETI) also influenced bioart. In the 1980s, artist Joe Davis collaborated with Harvard geneticist Dana Boyd and others to organize projects involving interstellar radar transmissions for extraterrestrial intelligence. The limitations of radar technology prompted Davis and Boyd to consider alternative biological carriers for such messages (Box 2) [16]. In 1986, Davis and Boyd transformed *Escherichia coli* with a plasmid

Box 1. Ten Turtles Set Free

Artist Hans Haacke purchased ten endangered Hermann's tortoises (*Testudo hermanni*) and subsequently released them at St. Paul-de-Vence, France, a region where one of two subspecies of the endangered tortoise is endemic. The work, Ten Turtles Set Free (1970), was intended to draw public attention to excesses of the pet trade and the destructive effects that humanity has on the delicate balance of nature. However, Haacke released the wrong tortoise subspecies. The two subspecies are *T. hermanni boettgeri/hermanni* and only the latter traditionally occupied a range in France. Photographs of Haacke's emancipated tortoises reveal that at least six of ten animals were *T. hermanni boettgeri*. Haacke's *T. h. boettgeri* are likely to have hybridized with local *T. hermanni hermanni*. Later studies of captive *hermanni/boettgeri* hybrids have shown decreased reproductivity. Despite honorable intentions, Haacke's introduction of non-native *T. h. boettgeri* was likely to have compromised genetically distinct lineages of both tortoises and threatened the biodiversity of Hermann's tortoises.

Box 2. Biological Carriers

Davis and Boyd recognized that contamination of extraterrestrial environments with terrestrial life forms could have tragic consequences both in terms of future scientific investigation of possible extraterrestrial organisms as well as for any extraterrestrial life forms actually encountered [16]. Responsible implementation of such 'biological spacecraft' would have to take these issues into account. *Microvenus* nevertheless toyed with the idea of sending trillions of engineered bacteria into space as an alternative sign of human intelligence. As an information carrier, Davis *et al*. wrote that "*Microvenus* bacteria, perhaps as *Bacillus subtilis* spores, would be superior to other media that have been used or proposed for extraterrestrial communication because they could endure the extreme conditions of vacuum, cold and radiation in outer space and would be more economical carriers of messages than either spacecraft or radar transmissions."

coded with a graphic icon. Using techniques previously employed to code SETI radar messages, the pre-Germanic character 'ᛉ' (*algiz*) representing life and femininity was encoded into a binary image and introduced into bacteria as a 28-mer synthetic DNA molecule (Figure 2C). DNA synthesis, purification, and cloning with *E. coli* were performed at Jon Beckwith's laboratory at Harvard and Hatch Echols' laboratory at the University of California, Berkeley. This was *Microvenus*, the first art created with the tools and techniques of molecular biology.

Microvenus was 'proof of concept' that information could be inserted into and retrieved from bacterial DNA [17]. Ironically, Davis' model interstellar carriers never left the laboratory. Because *Microvenus* bacteria are recombinant, biosafety guidelines restrict it to laboratory containment. *Microvenus* was the first of many experiments in which generic information was inserted into living organisms in the form of synthetic DNA. Notably, most of these experiments were conducted for scientific purposes, and Davis has been cited for his contribution.

A 1995 Harvard exhibition, The Riddle of Life, focused on another of Davis' artworks [18]. Davis' *Riddle of Life* realized one of several 1958 'thought experiments' in which Max Delbrück, George Beadle, Salvador Luria, and others created textual and physical models of DNA molecules holding English-language messages. DNA could not be easily synthesized *de novo* in 1958 and was not conveniently synthesized until the mid-1980s. Thus, Delbrück and Beadle never created actual language-holding molecules. To celebrate this episode in science history, Davis collaborated with biologist Stefan Wölfl at Burghardt Wittig's laboratory at the Free University in Berlin to synthesize a 174-mer DNA molecule first conceived by Max Delbrück. This molecule was encoded with the words 'I am the Riddle of Life. Know me and you will know yourself.' In 1994, Davis and Wölfl transformed *E. coli* with *Riddle of Life* DNA and retrieved the language information it contained using Sanger DNA sequencing [18].

Davis' May 1998 presentation about genetic art at the 17th International Sculpture Conference in Chicago was voted the most popular conference lecture [19]. In the same week, Davis delivered four lectures at the School of the Art Institute of Chicago hosted by Professor of Art and Technology Studies Eduardo Kac.

In 2000, Davis exhibited *Microvenus*, *Riddle of Life*, and another recombinant artwork, *Milky Way DNA*, at Ars Electronica, an international arts exhibition held annually in Linz, Austria. *Milky Way DNA* contained a high-resolution digital image of the Milky Way galaxy initially obtained by NASA's Cosmic Background Explorer (COBE) in 1990 [20]. The digital COBE image is a number that can be directly converted into DNA where C = 00, T = 01, A = 10, and G = 11. However, not all randomly generated DNA sequences can be successfully inserted into living cells owing to the biochemical and biological details of how DNA is conserved and replicated. Davis also wanted to prevent translation of information-holding DNA into unwanted protein. To overcome these problems while compressing input data, Davis invented *DNA Supercode*, the first of several 'DNA programming languages'. Davis eventually used his DNA programming languages to encode other data into DNA while minimizing the functional effects on host cells.

The 2000 Ars Electronica exhibition also confronted problems implicit in the public exhibition of recombinant organisms. By this time, Davis was affiliated with Alexander Rich's laboratory at MIT Biology, whereas in all other American laboratories disposition of recombinant organisms is regulated by guidelines initially established by the US National Institutes of Health (NIH). Moreover, international transfer of recombinant organisms is subject to policies in both the country of origin and that of destination. In 2000, Davis opted not to remove modified organisms from the MIT laboratory. Instead, Davis recreated them at European laboratories (Clondiag GMBH, Jena, Germany and Reinhart Gessner's laboratory at the Humboldt University of Berlin) before the exhibition. Furthermore, a laboratory-equivalent enclosure was constructed at Linz with supervision and periodic inspections by Austrian biosafety authorities. This enclosure allowed visual exhibition but not physical access to recombinant organisms. All bacteria featured in the exhibition were autoclaved when the exhibition closed. Davis continues to produce work in the landscape between art and science (see 'Davis' Projects' in the supplementary material online).

Davis has been criticized by some for facilitating the 'aestheticization' of biotechnology and playing down perceived risks of long-term impacts on society and the environment. There are assertions that this aestheticization is not adequately concerned with 'critical reflection' and 'discussion' of these impacts [21].

Bioart proliferated in the decades following Davis' *Microvenus*. Artistic interpretations of biotechnology, molecular biology, genomics, and other life sciences have also been expressed in nonbiological media including dance, performance art, sound, computer graphics, and architectural design (see 'Emerging Bioart Concepts' in the supplementary material online). Recently, nano/microscale technologies have emerged as a platform for the production of art in many forms, including bioart, semiconductors, polymers, microfluidic devices, and carbon-based materials [22]. While many artists sought to raise ethical questions about biotechnology applications, moral and ethical concerns were also raised about bioart itself (Box 3) [23–25].

In December 1998, Eduardo Kac published his treatise on transgenic art [26]. In 1999, Kac commissioned Charles Strom (then at the Illinois Masonic Medical Center, Chicago) to create *E. coli* transformed with a biblical quote (Genesis 1:28) encoded in plasmid DNA [27]. In *Genesis* (1999), Kac used UV light to intentionally mutate DNA in his transformed bacteria [28]. Kac's intention was to recover and decode mutated plasmids that would contain altered biblical quotes [29].

In 2000, Kac visited Louis-Marie Houdebine's laboratory at the National Institute of Agricultural Research (INRA), Jouy-en-Josas, France and was introduced to laboratory rabbits modified with GFP several years before Kac's visit [30]. Kac asked to have one of Houdebine's GFP rabbits for use in an art exhibition. Kac later variously claimed to have created the rabbit himself and to have had a GFP rabbit created for him at INRA [31,32]. When INRA declined to release a GFP-cloned rabbit for public exhibition, Kac mounted an international publicity campaign accusing INRA of

Box 3. Rising Concerns at the Interface of Biology and Art

Bioart has received criticism because modification of living systems for artistic purposes is perceived to be frivolous interference with nature. Bioartists have encountered opposition from advocates of humane treatment of animals, who object to transgenic modifications of animals. Together with molecular biology, bioart cannot be undertaken in some countries, where religious proscriptions against genetic modification are enforced. Bioart encounters criticism stemming from public hysteria about bioterrorism and the potential for a resurgence of eugenics. By contrast, tissue cultured artworks such as TC&A's *Victimless Leather* manipulate cellular populations rather than donor-organisms and as of yet, there seem to be no outspoken advocates for natural rights of viruses and plasmids and microorganisms such as bacteria, yeast, and protozoans.

censorship and widely distributed digital images of a glowing green rabbit [33]. Kac entitled this project *GFP Bunny* and named the rabbit 'Alba' [34]. Houdebine later maintained that no rabbits at his laboratory were created for Kac [35]. Furthermore, the GFP rabbits in his laboratory did not fluoresce bright green because the gene for green fluorescence was not expressed in rabbit fur [16].

The ethical contexts of bioart also came into question when artist Steve Kurtz was detained by police for suspected bioterrorist activity in the atmosphere of fear and paranoia that followed the 9/11 attacks. *Bacillus atrophaeus*, *Serratia marcescens*, and a laboratory strain of *E. coli* were found in Kurtz' residence [36]. Kurtz did not ultimately face bioterrorism charges, but in 2004 a grand jury indicted him on federal criminal mail fraud and wire fraud charges [37]. Kurtz, current chair of the Department of Art at the State University of New York at Buffalo was a founding member of the Critical Art Ensemble (CAE), an acclaimed art and performance collective that has mounted international exhibitions and performances dedicated to civil disobedience and political action focusing on social issues, including genetically modified organism (GMO) agriculture, the Human Genome Project, reproductive technologies, genetic screening, and biological warfare [38]. The CAE has labeled its art 'tactical' and created work focusing on government agencies and large corporations perceived to misuse biotechnology [39]. Kurtz and collaborators challenged biosafety protocols while preparing a CAE work in 2004 [40,41]. This project was intended to demonstrate the ineffectiveness of biological warfare as a weapon of mass destruction by the intentional dispersal of simulated biological agents in public spaces (Box 4).

While the CAE mocked threats of biological warfare, other artists advocated covert use of biological agents to oppose genetically modified foods. British artist-activists Heath Bunting and Rachel Baker founded the Cultural Terrorist Agency as a funding organization to support actions against large corporations. In 1999, Bunting and Baker announced the release of SuperWeed Kit 1.0, allegedly containing natural and genetically modified weeds resistant to Monsanto's 'Roundup' (glyphosate) herbicides [42]. They made roundup-resistant SuperWeeds available at no cost to interested parties. One obvious use of SuperWeeds was for activism in the form of agricultural sabotage. In 2005, Bunting partnered with Danish activists to use small N55 rockets

Box 4. Marching Plague: Germ Warfare and Global Public Health

In May 2004, Steve Kurtz was detained by police for suspected bioterrorism activity at his home in Buffalo, NY. Professor Robert Ferrell, chair of the University of Pittsburgh's Human Genetics Department, had illegally transferred several bacterial strains (for which Ferrell was eventually prosecuted) to Kurtz who was growing them at his home. The bacterial strains found at Kurtz' residence were identified as *Bacillus atrophaeus*, *Serratia marcescens*, and a laboratory strain *Escherichia coli*. In the Cold War era, these organisms were considered "harmless" and were used as simulants to substitute for known dangerous pathogens in biological warfare studies. Typical laboratory organisms such as yeast, *E. coli* and *Bacillus subtilis* are not ordinarily pathogenic. Laboratory strains developed for research have wild-type counterparts known to safely coexist with humans and other organisms in nature. Yet, many laboratory bacterial strains have been genetically modified with genes from viruses and other bacteria to enhance usefulness in cloning and gene expression. They may also contain artificially-inserted genes for antibiotic resistance. In keeping with ethical protocols and NIH guidelines, material transfer agreements from companies supplying laboratory strains generally prohibit disposition outside controlled environments or redistribution of microbiological samples.

With appropriate biosafety precautions in place, some recombinant bacteria are routinely and safely handled in high school classrooms, but this was not the case for Kurtz' home in Buffalo, NY. Kurtz was not charged under bioterrorism laws, but was indicted on counts of mail and wire fraud for the two bacterial cultures found in his home. These cultures had been obtained illegally from the American Type Culture Collection (ATCC). Geneticist Robert Ferrell was indicted along with Kurtz for providing him with the samples from ATCC. Kurtz had submitted an application to become a registered ATCC customer, but the application was denied due to his improvised facilities and lack of established biosafety protocols. Ferrell was charged with ordering materials with intent to transfer them to Kurtz in violation of the contract he signed with ATCC. In February 2008, the New York Times reported that Ferrell plead guilty to these charges and was sentenced to a year of unsupervised release and fined $500. Both *B. atrophaeus* and *S. marcescens* are now known to be opportunistic pathogens and CAE's subsequent release of both organisms into publicly accessible environments can still be called into question (see also "Opportunistic Pathogens" in the supplementary material online).

with SuperWeed payloads that could dispense seeds more effectively and over broader areas than mere hand dispersal [43].

Australian artists Ionat Zurr and Oron Catts founded Tissue Culture and Art (TC&A) in 1996. Following the TC&A model, the University of Western Australia created SymbioticA, a research center that enables artists to experimentally practice life science research, in 2000 [44]. Zurr and Catts specialize in projects involving techniques of regenerative medicine and tissue engineering wherein selected cell types can be grown on biodegradable scaffolding for uses in research and medicine. Catts and Zurr have employed the term ‘semi-living’ to describe their work with these materials [45]. At Ars Electronica 2000, Zurr, Catts, and Guy Ben-Ary presented *Semi-Living Worry Dolls*, in which mouse fibroblast tissue was grown onto substrates resembling Guatemalan ‘worry dolls’ – traditional dolls used by Guatemalan children to absorb their worries at bedtime [46].

Zurr and Catts also consider their art inherently political. A TC&A manifesto proclaims interest in ‘new discourses and new ethics/epistemologies that surround issues of partial life and the contestable future scenarios they are offering us’ [47]. In 2003, their *Disembodied Cuisine* installation for the L’Art Biotech exhibition in Nantes, France comprised tiny ‘deathless’ steaks grown from tissue collected from a live *Xenopus laevis* [48]. Thus, Zurr and Catts turned attention to the slaughter of animals for food. Likewise, their 2004 *Victimless Leather* project used tissue culture techniques to grow a miniature leather jacket from immortalized cell lines without killing animals and promoting awareness about the moral implications of leather products and ethical concerns surrounding the sacrifice of animals for aesthetic reasons (Figure 2D) [49,50].

Another tissue engineered project, *Extra Ear – ¼ Scale* (2003) was conducted by Stelarc, an Australian performance artist and professor at the School of Design and Art (SODA), Curtin University, Perth [51,52]. In collaboration with TC&A at SymbioticA, a quarter-scale replica of Stelarc's ear was cultured in a rotating bioreactor using cells seeded over a polymer scaffold. *Ear on Arm*, a subsequent Stelarc project, involved surgical implantation of an ear-shaped Medpor (a porous, biocompatible material) scaffold into the artist's own left forearm in 2006 (Figure 2E) [53]. This project aimed to raise awareness about ‘what it means to be human’.

Paul Vanouse, professor of Visual Studies at State University of New York (SUNY), Buffalo, is another artist who describes his work as questioning the social implications of genomics, DNA profiling, and scientific culture [54]. *Deep Woods PCR* (2011), conducted at Banff National Park (Canada), was art and ‘do-it-yourself’ (DIY) biology intended to reexamine the scientific process of discovery. Vanouse used water buckets arranged around a campfire to perform polymerase chain reaction (PCR), a laboratory technique used to create large numbers of DNA molecules identical to a few initial samples [54].

Not all bioart is dedicated to critical discussion of biotechnology. Some artists employ biotechnology for traditional practices such as painting. In 2001, Al Wunderlich, then professor of Painting and Mixed Media at the Rhode Island School of Design in Providence, collaborated with Joe Davis to produce *Living Paintings* [16]. Wunderlich used artists’ brushes to paint nitrocellulose substrates with a palette of *E. coli* transformed with fluorescent proteins in a range of four colors [55]. David Kremers, an artist at the California Institute of Technology, began producing ‘bacterial paintings’ in the 1990s. Kremers exhibited his 1992 painting *Trophoblast* (bacteria grown on an acrylic plate and sealed in synthetic resin) at Paradise Now, a landmark exhibition ‘picturing the genetic revolution’ at Exit Art in New York in 2000 [56]. Scientists have also contributed paintings created with bacteria and other work to important artistic venues (see ‘Biopaintings’ in the supplementary material online).

Concluding Remarks and Future Prospects

The life sciences can be expected to have increasing impacts on art along with those they are likely to have on society at large. Collaborative relationships and ethical issues unfamiliar to artists a few decades ago can be expected to gain new priorities as artists' expand their interactions with the scientific community. While some scientific laboratories have demonstrated willingness to collaborate with bioartists, prerequisites for biosafety and the creation and containment of recombinant organisms have also found place in schools of art and art/science research centers. Likewise, galleries and museums can be expected to provide corresponding formal contexts for the public display of bioart.

Bioartists without institutional affiliations are finding resources and mentoring within the growing 'do-it-yourself' (DIY) biology community, where individuals without formal training study life sciences in community-access laboratories furnished with low-cost reproductions of common laboratory equipment or with instruments and machines recycled from institutional and corporate sources.

Technologies addressing fundamental biology questions continue to become available to artists. DNA sequencing technology has advanced at an extraordinary pace, as has computing. High-throughput sequencing of whole genomes is becoming faster and less expensive. These advances have changed the face of biology and have already found artistic applications (see Davis' project with *Malus sieversii* and *Malus ecclesia* in the supplementary material online).

The work of bioartists to contain text, images, and books in biological archives suggests a world in which the terrestrial biome becomes a message board. As techniques mature to improve the data-handling characteristics of DNA, biological databases and information handling systems may come into existence with the potential to replace the internet. It is not difficult to imagine that, one day, standard 'smartphone' apps/accessories will become available that can rapidly sequence DNA [57–61].

Clustered regularly interspaced short palindromic repeat (CRISPR) technology and iPS cell technology are two late-breaking technologies currently transforming the field of biology [62–67]. Today's bioartists are capable of adapting these technologies to create art, but these abilities come hand-in-hand with unprecedented responsibility (see 'Emerging Technologies in Genetics' in the supplementary material online). In 2003, Davis *et al.* predicted that artists would find themselves creating functional genomes, organisms made from whole cloth or from scratch, or organisms based on new principles of life. There are still many open questions regarding the relationships of art and biology (see Outstanding Questions), yet these predictions seem closer to reality than ever before [16].

With the rise of Romanticism several centuries ago, artists seemed to shed longstanding commitments to scientific and technical literacy while, at the same time, science started its long march toward secularization [68]. In this century, art and science are in the process of disengaging from this legacy of separation. The interdisciplinary landscape of life sciences has come to include chemists, physicists, engineers, mathematicians, and computer scientists. Partnerships with bioartists can contribute cultural and aesthetic contexts essential to translating basic research into useful applications. While the role of bioart in both the criticism and application of science will undoubtedly continue, perhaps a more profoundly important and yet less recognized contribution may be the ability of bioart to help science understand itself.

Author Contributions

A.K.Y., J.D., and A.F.C. wrote the manuscript. S.H.Y. and G.M.C. made intellectual contributions and edited the manuscript. A.K.Y. and J.D. contributed equally.

Outstanding Questions

Can bioart accelerate the reunification of art and science?

Can artists who have little knowledge of the short-term operations of biotechnology issue credible warnings about its perceived 'long-term effects'?

How do contemporary biotechnology and emerging life sciences alter the traditional relationships of art and nature?

Can bioart introduce new modalities to the practice of scientific research as well as art?

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Supplementary Information

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