Picturing science: using art and imagination to explore new worlds

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Artistic methods have been used throughout the history of science as a tool for research, dissemination, education and outreach. Traditional artistic approaches provide the flexibility to explore and integrate ideas, promoting hypothesis generation and inspiring creative thinking. We describe two artistic approaches that we have applied in our own research: the use of intuitive metaphors to make new connections and present scientific subjects in an interpretable manner, and an integrative approach that synthesizes diverse sources of data into a self-consistent image. The process of creating artistic renderings inspires us to examine scientific data from new angles and capture the current state of knowledge within a broader context. Artistic hands-on activities and non-traditional media like fashion and video games have the power to engage new communities, sparking curiosity for science and increasing public understanding. Overall, translating scientific concepts into art is a powerful tool for exploring scientific data as part of research, as well as bridging the gap between the scientific community and the general public.

Art and science: greater than the sum of the parts

It may seem like imagination is antithetical to the objective nature of science, but this is far from the truth. The entire process of hypothesis generation is an act of imagination in disguise, building a mental picture of a particular way that existing knowledge fits together into a fuller view, which then may be tested by experiment. Science art is a powerful tool in our methodological toolbox for unleashing and harnessing the possibilities of scientific imagination, helping us develop new hypotheses and helping others understand them.

This idea is nothing new – scientists have relied on artistic practice since the beginning of the scientific method. Indeed, historical scientists needed to be artists, and before the days of photography, sketchbooks were an essential part of the observational sciences. These drawings continue to be an inspiration – we all have our favourites, such as Walther Flemming's drawings of dividing cells, Darwin's illustrations of finch beaks and Ernst Haeckel's celebration of biological form. The act of drawing was itself an integral part of the scientific process: the necessary perception and attention to detail helped these pioneers discover patterns and sparked new ideas that led to paradigm shifts in our scientific understanding. Today, however, traditional forms of artwork have become increasingly optional with the widespread availability of highly automated computer graphics visualization, digital plotting programs and photography, and scientists are gradually losing touch with the power of hand-drawn art as a tool for science.

Throughout our careers, we have incorporated artistic practice into our scientific work, to the benefit of both. We are both formally trained and do research in biological science, and have fit an informal training in art into our spare moments. Having been introduced to drawing by her mother, an artist, Mierzwa rediscovered the arts during her PhD while communicating her thesis work, and has been exploring creative approaches to visual science communication in the forms of drawing, fashion and interactive media. Goodsell started painting in early life under the guidance of his grandfather, and began producing scientific art as part of his graduate work in x-ray crystallography, developing new methods to use the nascent field of computer graphics to display molecular structures.

Today, we both routinely use visualization tools to display, analyse and disseminate our experimental data and results. We have also explored the use of artistic techniques to enhance and communicate our research in two overarching ways (Figure 1): creating intuitive metaphors that inspire creative thinking and facilitate understanding, and building integrative views with data from different sources, giving us the freedom to fill in grey areas with our intuition based on what is already known. The tools of art, both traditional and interactive,

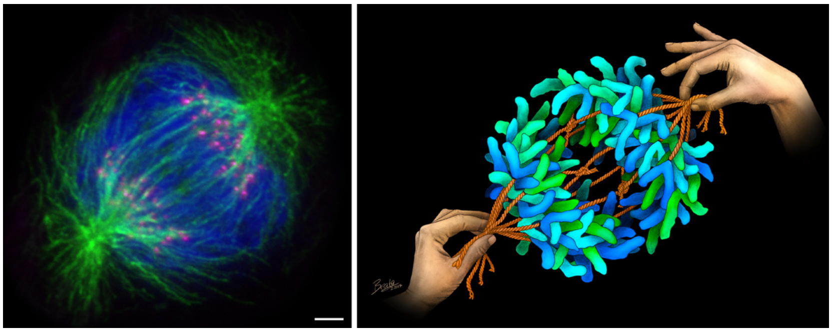

Figure 1. Art can deepen our understanding of scientific concepts. This figure exemplifies two of the themes discussed in this article – using metaphor and integrating scientific data. Left: Microscopy image of a dividing human cell in anaphase, showing DNA (blue, stained with DAPI) and the mitotic spindle (green, labeled with α-tubulin antibodies) that attaches to the chromosomes through centromeres (magenta, CREST antibodies). Scale bar, 2 µm. Right: The illustration integrates information from the immunostaining with traditional artistic techniques and incorporates metaphorical elements to guide viewers through the process of how chromosomes are segregated during cell division (image by Mierzwa).

also have the tremendous potential to engage new communities and spur the imagination of others, making meaningful connections that will resonate with people of all backgrounds – researchers in different fields, students, educators, the general public – and help them to explore new scientific hypotheses and discoveries.

Making connections: metaphor in science art

The explosion of new structure determination, bioinformatics, as well as biochemical and microscopic methods has greatly increased the abundance of available biological data, and with it our understanding of the molecular world. Many mechanisms work differently on the molecular level than they do in the world humans interact with. This often makes scientific concepts difficult to imagine, fuelling misunderstanding and mistrust of the scientific community as a whole.

Luckily, a picture is worth a thousand words, and intuitive visuals have the incredible power to help us understand complex and abstract ideas at a glance. For example, Figure 1 depicts a pair of hands pulling on rope to convey the concept of the mitotic spindle exerting force to segregate chromosomes during cell division. The illustration in Figure 2 complements the model figure of a research paper and uses metaphor to highlight the dynamic nature of a membrane fission machinery. The structure is composed of multiple small subunits, represented by building blocks, that rapidly exchange while they assemble and constrict, with Lego figures portraying the protein exchanging the subunits. These dynamics allow the structure to narrow and split cellular membranes during

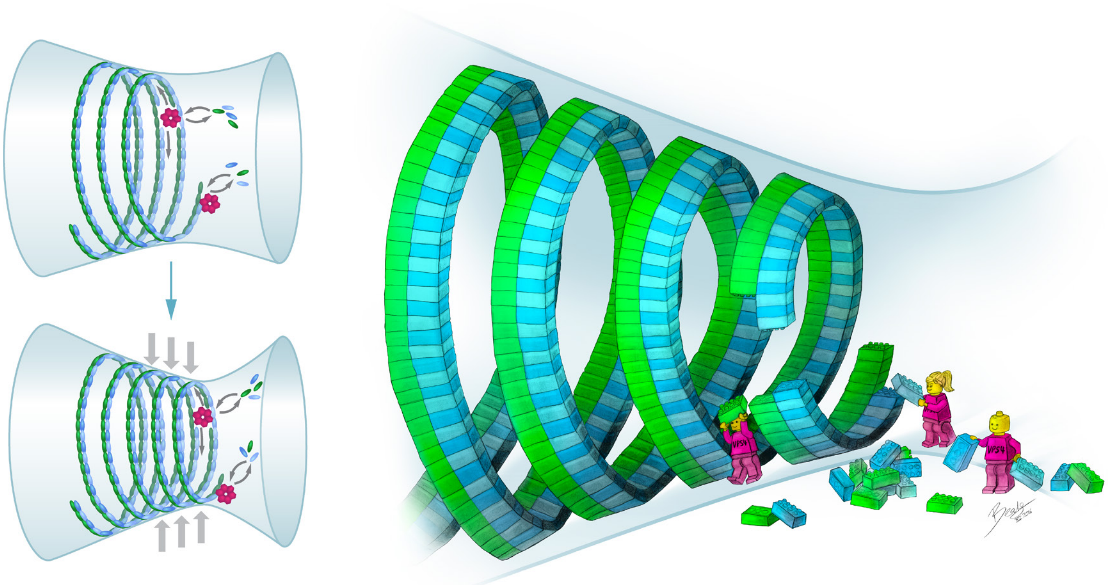

Figure 2. Using intuitive metaphors to communicate the dynamic nature of the membrane fission machinery ESCRT-III. Left: Model schematic (adapted from doi:10.1038/ncb3559), showing assembly and constriction of ESCRT-III polymers. Dynamic turnover of ESCRT-III subunits CHMP4/Snf7 (green), CHMP3/Vps24 (cyan), and CHMP2/Vps2 (blue) is mediated by the AAA-ATPase Vps4 (magenta). Right: Illustration using the metaphor of building blocks for single ESCRT-III subunits and Lego figures to represent Vps4 (same color code as model schematic). This artistic interpretation aims to highlight how subunits are exchanged within large assemblies and how this might facilitate shape adaptations to different membrane geometries (images by Mierzwa).

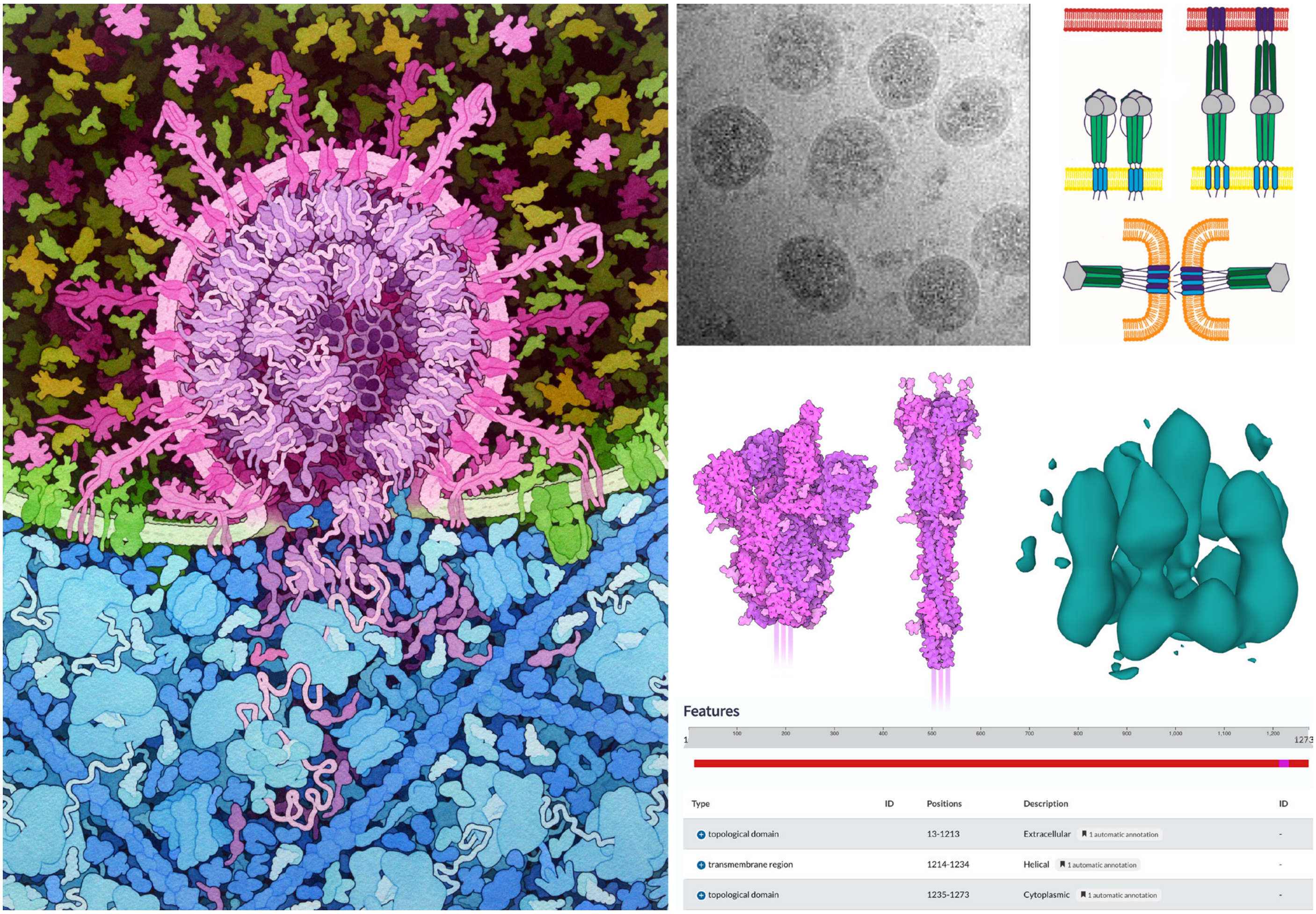

Figure 3. Integrative illustration of SARS-CoV-2 fusion. Left: The painting shows the virion (magenta and purple) fusing with an endosomal membrane (green) and releasing the viral RNA into the cytoplasm (blue) (image by Goodsell). Right: Sources of information include cryoelectron micrographs of whole virions (EMPIAR-10492), schematic illustrations of viral fusion (doi:10.3390/v12070693), crystallographic structures of spike proteins in pre-fusion and post-fusion states (PDB ID 6crz, 6xra), cryoelectron structures of the ribonucleoprotein (EMD-30429) and entries from UniProt to estimate the sizes of missing portions, such as the intracellular portion of the spikes (UniProt P0DTC2).

processes like cell division or intracellular sorting. In this case, Lego pieces provide a familiar metaphor for assembly of complex structures from subunits to communicate insights from the study.

Combining scientific representations with metaphor and analogy allows us to place abstract concepts into a familiar context, understand the material more deeply and convey even the most complex scientific themes in intuitive ways. Metaphors can make data engaging on multiple levels, making the main concept meaningful to viewers who are not familiar with the material, while still including subtle details and references to more complex biological concepts for experts to appreciate. These types of metaphors are widely used in textbook materials for teaching and in editorial images for public outreach, often with elaborate story-telling elements. Metaphors also help in the essential task of facilitating communication between scientists, particularly to promote collaboration between increasingly specialized fields, inspire creative scientists to join research groups and encourage interdisciplinary research.

As scientists, the process of translating complex scientific findings inspires us to examine the material from new angles, impacting the way we think about and present our own research. In this way, the act of considering how to artistically communicate a finding is tremendously helpful in making connections between familiar concepts and asking the right scientific questions to design creative experiments. Creating illustrations and considering the metaphors within them also inspires us to take a step back and break down the essence of exciting findings, allowing us to highlight the impact without diluting the core message.

Figure 4. Art is a powerful way to engage new communities. Top left: Science fashion incorporates themes from cellular processes, such as the constriction of the microtubule-filled intercellular bridge (purple) by ESCRT-III polymers (green) during the final step in cell division (photo credit: Ruben Gutzat). Top right: A science-themed video game, Microscopya, invites players to experience the beauty and complexity of the molecular world inside the cell (www.microscopya.com) (images by Mierzwa). Bottom: A coloring activity at the RCSB Protein Data Bank empowered people of all ages to explore viral structure in the early days of the coronavirus pandemic (https://pdb101.rcsb.org/learn/coloring-books/coloring-coronavirus).

Filling gaps: art and integrative science

Science is an on-going journey: every discovery poses many new questions that need to be answered. Science is also a distributed, multinational effort involving competition and collegial rivalry, so some threads of knowledge may be tightly woven, and others barely started. This effort can be highly siloed: scientific concepts are often studied and presented as isolated pathways in individual laboratories, detracting from the importance of the interplay between biological processes and layers of complexity. Scientific artists are often tasked with creating imagery that integrates the current state of knowledge to capture the context of scientific results. Traditional artistic techniques are the perfect tools to combine data from different sources and put everything into a broader context to fully appreciate the intricacy of biological systems. Artistic conceptions make it easy to draw less-understood elements in lower detail, rather than being forced to fill the gaps and possibly limit exploration.

The integrative illustration in Figure 3 is a case in point. It was created as part of a series of illustrations that captured coronavirus biology during the pandemic, incorporating information that was available at the particular time. At the time this one was created, some aspects of the virus were well characterized: the sequence was determined and used to define the viral proteome, atomic structures were available for pre-fusion and post-fusion forms of the spike ectodomain and cryoelectron micrographs revealed the overall size of the virions and arrangement of spike

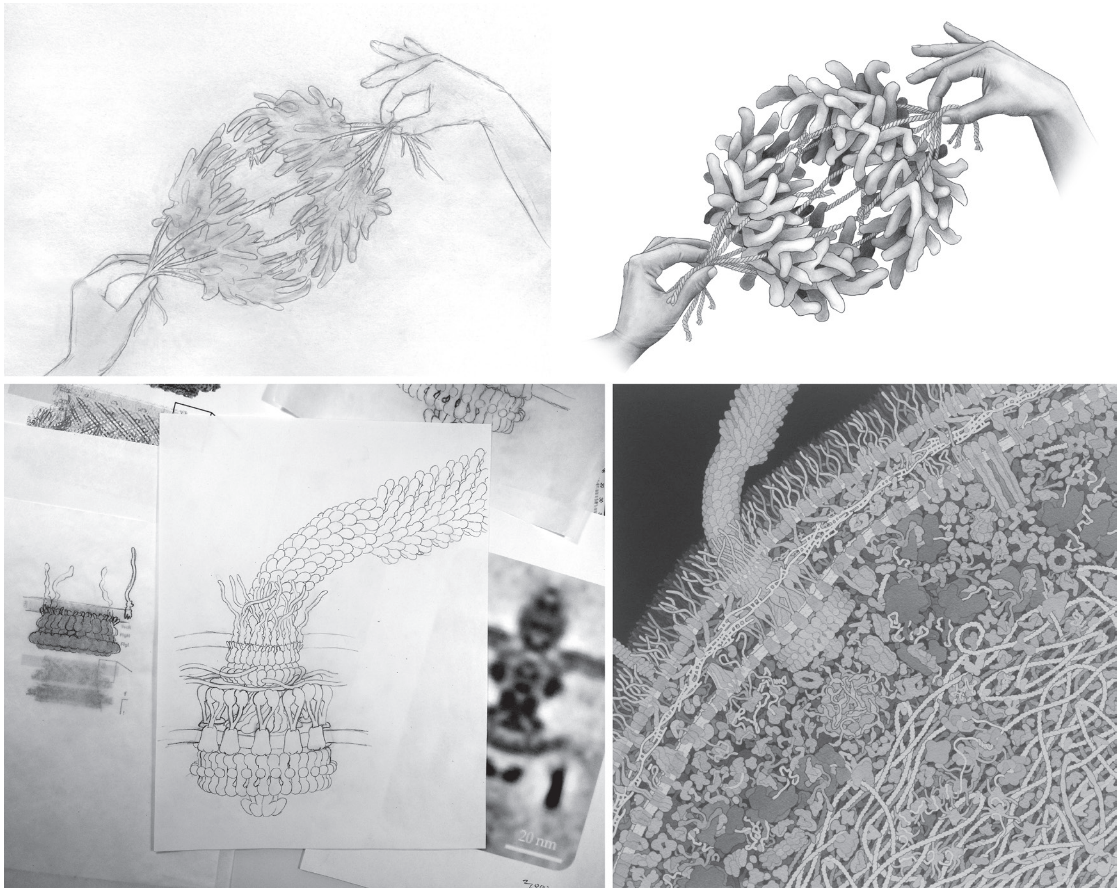

Figure 5. Examples of working sketches and final artwork. Top: Sketch and drawing for the illustration in Figure 1 (by Mierzwa). Bottom: Sketches and final artwork of a flagellar motor for a cross-section of an *Escherichia coli* cell (doi:10.2210/rcsb_pdb/goodsell-gallery-028) (by Goodsell).

and ribonucleoprotein complexes. Many other aspects remained opaque: the best views of the ribonucleoprotein were tantalizing cryoelectron reconstructions, the M (membrane) protein was based largely on homology modeling, and many of the intermediate structures of the spike along the fusion pathway were largely the realm of conjecture. We have used a similar traditional approach to help scientists integrate their own information, for example, in an on-going effort to capture the state of knowledge about autophagy with Daniel Klionsky (see Further Reading).

Spreading the word: artistic avenues to engage new communities

Creative approaches to scientific communication have the tremendous power to spark interest and curiosity about science. Scientific concepts can be daunting to people not trained in science: the imagery and writing used in journals is often dense and technical, posing a large barrier to understanding. Artistic approaches provide many different avenues for reaching audiences who may have never been engaged by science. This gives non-scientists the chance to appreciate the beauty of biology, increasing public understanding and trust in the scientific method, and perhaps even inspiring a future generation of scientists.

Science is traditionally viewed as a standalone interest, and students with multiple passions are often encouraged to focus on a degree, and ultimately a career, in the sciences *or* in the humanities. And yet, we have found that presenting science with artistic approaches that go beyond the classroom and textbook facts sparks genuine fascination in these audiences, inspiring curiosity and wonder for the molecular world (Figure 4). For example, fashion explaining cell biological processes or fabrics printed with microscopy images can highlight the visually stunning intricacy of cellular structures, igniting conversations with those who would not have glimpsed these images otherwise. Interactive media, such as science-themed video games like Microscopya (www.microscopya.com) or public-participation efforts like FoldIt (https://fold.it/), allow players to experience biological mechanisms while exploring the molecular world. Science-themed drawing, painting and crafting activities can engage creative students to learn about cellular structures, bringing the beauty of science to their attention. For example, many hands-on activities are available at the RCSB PDB (pdb101.rcsb.org) for download to explore biomolecular concepts, including paper folding activities to explore DNA and protein structure and coloring activities related to coronavirus and structural biology. This helps teach experiential learners who have a harder time grasping scientific concepts through memorizing facts.

Finally, and perhaps most importantly, we often notice that when we discuss our artwork with young students or non-scientists, they come up with excellent scientific questions without even realizing it. Making science more accessible and meaningful via alternative visual and interactive means can inspire a future generation of scientists and bring creative minds into the field, laying a foundation for innovative research and changing the way we as a society approach scientific research, education and communication.

Sketching science: traditional tools for exploring ideas

Every time we give a talk, someone in the audience asks us why we still use pencils and paper, instead of simply using the many excellent visualization tools that are available. It's very true, digital visualization is far faster, and with its direct pipeline from data to image, more accurate – but traditional media provide a freedom that is difficult to achieve with visualization tools. The act of sketching allows us to combine different sources of information into a coherent whole, expands our options to highlight the aspects that we want to communicate and enables us to draw elements that we don't yet fully understand using less detail without limiting imagination.

When we illustrate scientific findings, the process of sketching helps us connect with the science more organically as the artwork develops. We start by researching the background, sifting through manuscripts from multiple scientific disciplines, going through each piece of data to identify which concept is the most important to highlight, and then finding metaphors or integrations to communicate the essence. We invariably create multiple sketches at the initial stage, and even when we know what we want to depict, it is only during the sketching phase that the idea fully develops (Figure 5). These sketches also allow us to experiment with balancing accurate scientific information and abstract imagery. We have also experienced this process in collaboration with other scientists, helping them explore their ideas using the tools of art. This often involves multiple rounds of sketching and revision, and it's always a pleasure to see our collaborators progressively jump into the process, marking up drafts and providing sketches of their own.

Invariably, the process of designing metaphors and integrating data from different sources prompts us to ask questions we might have not thought to ask otherwise. These questions are often difficult to answer, and require out-of-the-box thinking and exploration of multiple disciplines to address. This is a perfect example of how art sparks imagination and creative thinking, inspiring us to broaden our horizons and transform how we conduct and communicate our science. ■

Further Reading

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David S. Goodsell divides his time between computational biology research and science outreach. His research includes development of the computational-docking program AutoDock, and CellPack, a method for three-dimensional modeling of large portions of cells. David's artistic work includes three decades of work on depiction of the cellular mesoscale and non-photorealistic rendering methods for molecules and cells. He authors the "Molecule of the Month" at the RCSB Protein Data Bank, an illustrated series that explores biomolecular structures from the PDB archive and their relationship to human health and welfare, and has written four general-interest books on molecular biology and bionanotechnology. Email ID: goodsell@scripps.edu. Twitter: @dsgoodsell

