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An Eye for the Invisible: Exploring the Role of Image-Making in Science

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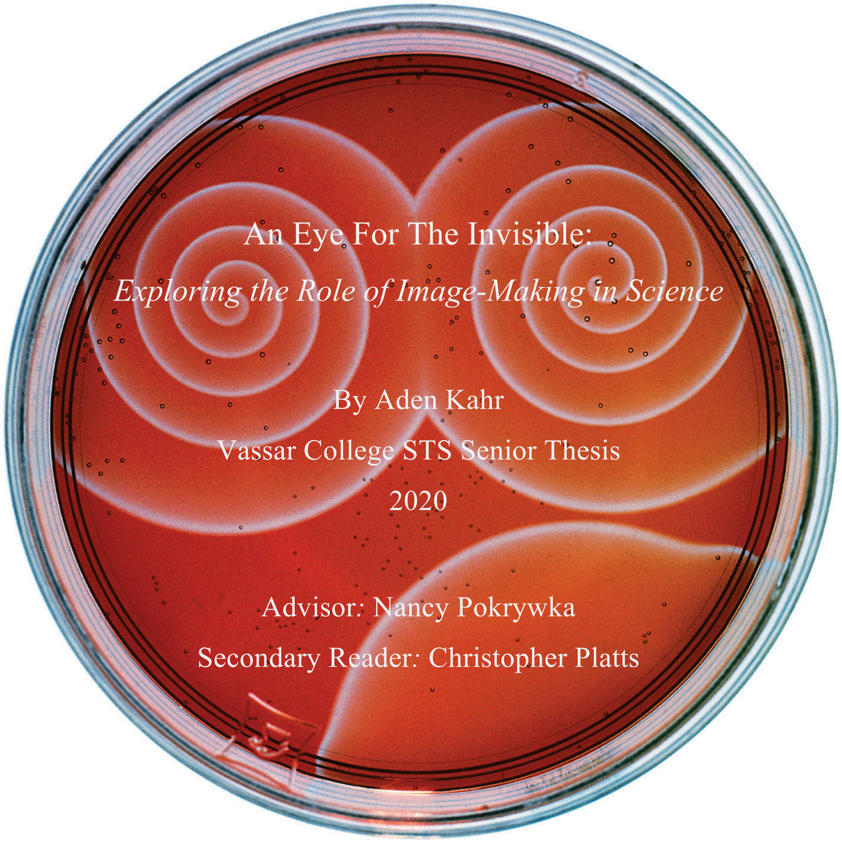

An Eye For The Invisible:

Exploring the Role of Image-Making in Science

By Aden Kahr

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(Top): The patterns of a Belousov-Zhabotinsky chemical reaction in a petri dish (Stephen W. Morris, Flickr)
(Right Side): Another B-Z reaction, notable for its distinctive spirals, progressing over time (Felice Frankel, *Visions of Science*)

-Preface-

I'm a visual thinker. I've always been most comfortable conceptualizing problems, especially scientific ones, when they can be translated into a visible grammar. This would place me, according to some, in the cohort of individuals more reliant on the right side of the brain, the command center for imaginative and emotional expression, than the left, the organ's hub for sequential and logical reasoning. Of course, this dichotomy is a gross oversimplification of the mystery of human cognition, one that probably does not lend itself to such appealingly straightforward models. Its persistence, though, underscores the staying power of the idea it embodies: that these two modes exist on opposite ends of a non-traversable gulf. Either you are a math and science person or an artist, an analyzer or a creative. This partitioning misleadingly suggests that there can't be meaningful overlap between the two. An overarching mission of this thesis is to convincingly prove the falsity of this statement, to show that within good art can be found good science and within good science can be found good art. The following survey of scientific film and photography, what I collectively term "image-making", is a testament to this truth, a collection of works that entertain multiplicities of meanings dependent on the ways in which they are formed, disseminated and handled. Their dual existence as cyphers of research principles and works of art/imagination make them powerful and often neglected tools of scientific inquiry and propagation. It is this capacity to operate on several levels simultaneously and inspire awe on both sides of the brain that, in my opinion, makes them worth 'looking' at.

-Chapter 1-

What Constitutes a Scientific Image?

Photography is not merely an illustration, but a piece of evidence-a kind of document...
-Robert Koch

"If the circumference [of a circle] is composed of a series of points, memory is, like cinema, a series of images. Immobile, it is in a neutral state; in movement, it is life itself."
-Henri Bergson

"...scientific truth should be presented in different forms, and should be regarded as equally scientific, whether it appears in the robust form and the vivid coloring of a physical illustration, or in the tenuity and paleness of a symbolic expression..."
-James Clerk Maxwell

What is the relationship between science and image? Before attempting to answer this question, we must first consider what we mean by 'science' and 'image'. Additionally, we must give definitional shape to a 'science' built around 'image-making' or, more pointedly, the practice of 'scientific image-making'. These tasks are not stray points of theoretical housekeeping. They are necessary primers to get us thinking about a common set of questions and concerns. To use an artist's analogy, we wish to sculpt an argument about the image from a raw material of pictures, historical evaluations and modern case-studies. But if we are to carve well-reasoned points out of this block of unshaped information we must, like any sculptor, have a clear intentionality in our choice of tools. An operative understanding of these semiotic distinctions and boundaries, then, will serve as our hammer and chisel through this process and allow for less discursive and more deliberate engagement with the major themes of the thesis.

For our purposes, the 'scientific image' is any photograph or film made to evidence something unseen, unexplained or otherwise never before presented in such a form. While this narrows the size of our pool by excluding other visual mediums through which science is produced, it remains somewhat vague and raises other semantic and comparative questions. How is showing something as a film different from showing it as a diagram? What does a photographic testimony do that an illustration or abstract model can't? These questions will be tackled by contrasting styles of scientific image-making existing outside the domain of our focus (like illustrations and models) and weighing them against objective and subjective concerns. We'll also explore some examples of photography and film, consider their interrelatedness and examine the ways in which they uniquely encode and transmit ideas and information. In addition, we'll look at the space that the scientific image occupies in the real world. How does it set standards in the laboratory and in journal literature or influence channels of communication and rhetoric between different scientists? What is its relationship to art? In what ways do images stripped of their context assume a larger-than-life status amongst the public and scientists and how is this trade-off between scientific literacy and symbolic power mediated? Most importantly, what does an image say to its observer about what science actually is and does, and how does it do this? A thoughtful consideration of these questions will allow us to reach an agreement about terminology, theory and practice as well as foster a deeper understanding of the scientific image going forward.

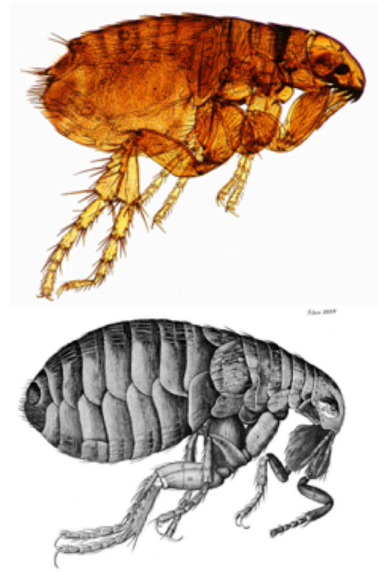
1. *A Picture Worth a Thousand Words*

It is easy to forget, given their outsized presence in our everyday lives, that films and photographs are relatively new forms of visual media. Older techniques for making images such as engraving, wood-cutting, modeling, sculpting, diagramming, printing, painting and illustrating have had centuries, or in some cases millennia, to change, adapt, and align around certain conventions of practice. The camera and cinema entered a world already rich in image materials and traditions. The making of physical models, working instruments, manuscript plates, graphs, lithographs, etchings and ink drawings had long been the joint trade of the scientist and the artist. Working relationships forged between the microscopist and the illustrator or the natural historian and the printmaker led to an intermingling of world-views and a profound cross-pollination of different modes of rhetoric. As the historian Klaus Hentschel notes, this diffusion can be situated within a discipline's "visual culture", or the values, iconography, semiotics and *Gestalten* (practices of pattern recognition and meaning decoding) prevalent at the time of a specific image's inception[1]. The perspectivist drawing techniques and mineralogical cabinet collections of the 17th and 18th centuries, for instance, comprise their own "visual cultures" replete with favored ways of collating knowledge and assembling pictorial meaning. Other examples of deep-rooted visual cultures can be found elsewhere: in the spatial modeling of stereochemists and crystallographers, the mapping of ancient cartographers, the taxonomy of the botanical draughtsman, the frequency readings of the spectroscopist, the blueprinting of the civil engineer, the renderings of the fossil geologist, the abstractions of the theoretical physicist and the pattern recognition of the morphologist[2]. The list goes on and on. This idea of "visual culture" is a powerful tool. It lends us a theoretical framework with which we can integrate diverse image-making approaches, and we will keep it in mind as we explore two precursors to the still and moving image: scientific illustrations and models.

It has been said that scientific illustrations "should be beautiful and the best quality as art, but accuracy comes first. A beautiful but inaccurate drawing is useless to science". In the same breath, it has been stated, "the scientific illustrator interprets what is presented, reconstructs broken or missing parts…no machine can replace the mind of the artist or scientist."[3] In some ways, reconciling these two assertions can be difficult. Their tension speaks to a wider question raised by many a philosopher and sociologist of science: can real objectivity, that is unmediated truth, spring from a science dictated by human judgment? Put another way, can the 'mind of the artist or scientist', a machine with a tendency to reconstruct and imagine, really hope to produce accurate results? This question of objectivity hounds the work of every scientific image-maker but especially that of the illustrator. Unlike (although as we'll see later not completely dissimilar from) the photographer or filmmaker who can rely in part on a mechanical lens, the engraver or sketch artist must constantly filter reality through a lens of their own design. They must make bold decisions about how to present the world by deciding what broken parts to mend, what to translate, what to obscure and what features are worthy of inclusion. In the best of cases, all of these impulses coalesce to form an image that is aesthetically beautiful as well as accurate. Scientific picture-taking and filmmaking, it can also be said, borrows many formal considerations from the illustrating

Photographed and illustrated algae: On the left, a cyanotype from Anna Atkins' *Photographs of British Algae: Cyanotype Impressions* (1843) and on the right, a lithograph from Robert Bentley and Henry Trimen's *Medicinal Plants* (1880) tradition (in fact, as we will see in the following chapter, there is a tangible link between *camera lucida* sketching and early photography).

The most exemplary scientific illustrations, like Robert Hooke's 17th century portrait of a flea, Ernst Haeckel's panoramas of Darwinian diversity, Audubon's watercolors of birds, Vesalius's compendia of the human form and Da Vinci's notebook sketches of anatomy, share a transparent and instantly resonant design. They call out to their viewer like a siren, informing them of both the richness of the natural world and humanity's ability to translate it. This translation rests at the heart of debates surrounding objectivity and, indeed, the merits of different scientific image-making approaches. If the ultimate goal is to reproduce nature as accurately as possible, how does one achieve such a lofty aim in a drawing, especially given that complete agreement over what counts as objective is almost never achieved? Instead, it is constantly being negotiated, not just across different fields (see Hentschel's visual culture argument) but also through illustrating practices that have redefined themselves en masse over the ages. Lorraine Daston and Peter Galison have explored these shifting sands by surveying the evolution of the 'scientific atlas', understood to be "any compendium of images intended to be definitive for a community of practitioners".[4] Such atlases are unbounded in what they can depict, standardize and preserve - organs, stars, planets, neural pathways, fossils, you name it – and yet their true value (for our purposes at least) rests in how the conceptualization of such images betrays a larger



Top: Microscopic view of a flea by Oliver Kim (2010)
Bottom: Robert Hooke's anatomical sketch in *Micrographia* (1665)

dominant epistemology of science. The authority of any atlas rests on the fidelity of its images, but as Daston and Galison point out, what constitutes fidelity is often dependent on context. For enlightenment atlas-makers pre-dating the birth of photography, fidelity was conceived "in terms of the exercise of informed judgment in the selection of "typical", "characteristic", "ideal" or "average" images: all these were varieties of the reasoned image."[5] In other words, the most faithful image was achieved not by direct transcription but through a compositing of observation, abstraction and artistic judgment. Naturalists like Carolus Linnaeus and Johann Wolfgang von Goethe were less concerned with fully accounting for nature's incomprehensible diversity than they were with typifying it. This meant that objects could be reimagined, enhanced or even shown disembodied from their natural habitat in the name of 'truth-to-nature', an approach that to our modern sensibilities might seem subjective but that did not see itself in conflict with objectivity. Standardizing was accomplished through the privileging of archetypes and idealized forms over the unclassifiable irregularities of nature. Linnaeus's leaves were classified around common shapes while Goethe's animal skeleton sketches purported to be instruction manuals for many observable manifestations in nature. While this tendency to characterize the individual through an essential or ideal upon which all variability can be traced back is most blatant in pre-mechanical atlases, it is certainly not unique to them. I'd argue that it


A plate from Ernst Haeckel's *Forms of Nature* (1904) and *American Flamingo* engraved by Robert Havell after John James Audubon (1838) is a fundamental complication, to varying degrees, of *all* scientific image-making, one that arises whenever the scientist, filmmaker, photographer or illustrator has to weigh the verisimilitude and faithfulness of their image with its readability and representative impact. The impulse to pick the best or single prettiest example from a vast population is all too human. Given the choice, the scientific image-maker might take the specimen that demonstrates a clear principle or morphology over that which, while perhaps more 'balanced', obscures what is most hoped to be conveyed.

The danger of this operative mentality, of course, is that by defining what is worthy of inclusion and what isn't, one risks conforming nature to the mind's eye as opposed to treating it on its own terms, no matter how inconvenient. Mechanical objectivity in the nineteenth century presented itself as a panacea to such external judgment and aesthetic predisposition. It advocated an impartial approach, one that treated "snowflakes shown without perfect hexagonal symmetry, color distortion near the edge of a microscope lens, tissue torn around the edges in the process of its preparation" as necessary components of an image's integrity, not blemishes to be eliminated in the name of perfection.[6] This is not to say that this new wave of nineteenth and twentieth century images completely freed scientists from a binding truth-to-nature mindset. Scientists, as mentioned, can always be susceptible to the draw of aesthetic neatness, simplification or even misrepresentation. While the introduction of the photograph and film camera marked a noteworthy inflection point in science's relationship with objectivity, such a relationship had always existed in continuous flux, arbitrated by changes in visual cultures, observational pedagogy, the synergy between scientist and image material and that most unscientific consideration of all: personal predilection and taste.

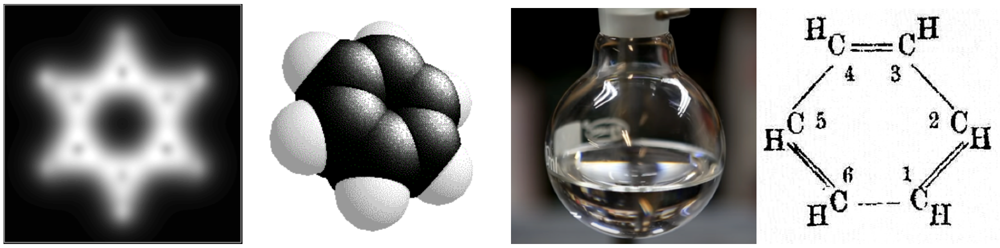
As one moves beyond the early botanist's woodcuts and the anatomist's sketches into the realm of more modern scientific images, objectivity becomes even trickier to nail down. As Galison points out, growth in both type and volume of information leads to inevitable trade-offs. As the image-maker (in this case a surgeon or some other medical professional) develops a stricter affinity for the idea of objectivity for objectivity's sake, they lose "that precise, easily teachable, colored, full depth-of-field, artist's rendition of a dissected corpse. [Instead] You get a blurry, bad depth-of-field, black-and-white photograph that no medical student could use to learn and compare cases".[7] Such unwavering mechanical objectivity also spurs a new type of reliance on human judgment. This 'trained judgment' is constituted by *informed* mental and visual processes, not primitive instances of pattern recognition and symbol-making or a return to old enlightenment idealisms. This judgment-guided objectivity is a bedrock of our modern scientific pedagogy, a highly technical and rigorous ways of processing information. Particle physicists, stellar catalogers and specialized doctors and atlas readers, as we'll soon see, use trained judgment to parse positrons from a bubble chamber, gauge the luminosity of a star, read electroencephalograms and fMRIs and debate the nature of imaged truth itself. Like their

Sketch of a fetus in the womb by Leonardo Da Vinci (1510-1512) and a picture of an 18-week-old fetus taken by Lennart Nilsson that was published in *Life* magazine in 1965.

illustrative predecessors, they do so aware that scientific image-making is anything but a single-mindset endeavor. Never reliant solely on the instrument - the lithographer's limestone or the illustrator's cross-hatching, the biologist's scalpel or the astronomer's spectroscope – it is one that must always be codified in conjunction with something far more unquantifiable: the ability to isolate signal from noise and wade through a never-ending set of possibilities in search of a convincingly judged truth.

2. *Stone's Throw from Reality*

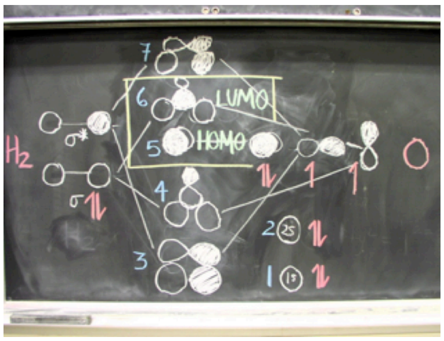
Like illustrations, scientific models have a special place in the practice of science. They can be indelicately divided into two immense categories: physical and mental. As stated by the philosopher Daniela M. Bailer-Jones, the model "can range from being objects, such as a toy airplane, to being theoretical, abstract entities, such as the Standard Model of the structure of matter and its fundamental particles."[8] It can condense complex mathematical relationships into sequences of curves and lines (see Maxwell's transverse electromagnetic wave plot or Schrödinger's electron orbitals), convey position and motion through mechanical apparatuses (consider a Newton's cradle or an orrery), explain and summarize real natural phenomena (everything from the greenhouse effect to protein translation) and act as valuable thought experiments (imagine traveling at the speed of light or using a cat to express quantum uncertainty). Some, like the double helix or the ball-and-stick model of chemical compounds, have ascended to the status of universally recognized symbols. We know intellectually that the base pairs and winding backbone of a plastic DNA model aren't directly 'truthful' in the way that a nucleotide or sugar-phosphate chain at a molecular level would be. The same goes for any proxy used



Different conceptions of benzene. Left to right: An STM (Scanning Tunneling Microscope) density plot of the aromatic compound on a graphite background (C. Ewels of the University of Exeter), a space-filling model (made by Dr. Richard Clarkson), its distilled liquid form in a round-bottom flask (NileRed on YouTube) and August Kekulé's original resonance structure for benzene (printed in 1872).

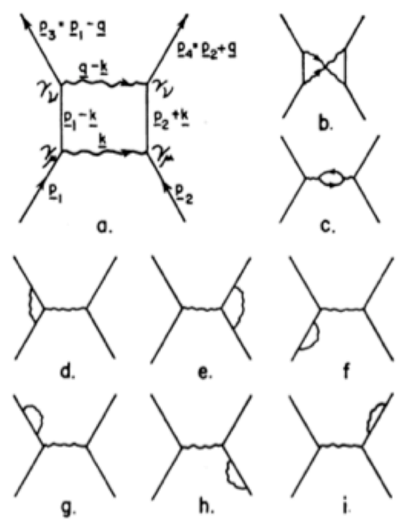
by a scientist like, say, a Pauling model of hemoglobin or a chemist's shorthand for benzene. Still, our mental image of these things is synonymous with the models we have built to see them, a testament to the visual impulse in us all. Like all elements of scientific inquiry, models are made to facilitate an understanding of the universe. They replicate and test theory as well as produce conditions under which ideas and experimental frameworks can be stretched.

Models also prove remarkably elastic. That is, they have an image-like propensity to accommodate different modes of thought into a neat package that lies somewhere between concrete image and abstract symbol. These creations, derived from but often devoid of the tangible materials of research, can provide valuable insights into the scientist's brain. The historian Ursula Klein classifies such external thought processes as 'paper tools'. By this she means the sets of formulas, notations and accounting protocols that arose as the discipline of organic chemistry took shape in the 19th century. While paper tools are not confined to this specific context, they are of special significance to the chemist who speaks a common language of experimental tools of production - valences, formulas, reaction pathways, etc. As Klein explains, "The manipulation of formulas on paper and the visual display of possible recombinations of signs had the suggestive power of introducing *new* significances, which chemists attempted to match up with experimental traces. In doing so, they tacitly modified the existing intellectual framework and introduced new concepts and research objects…”.[9] Herein lies the power of models and especially paper tools. Not only are they useful inventory takers of pre-existing knowledge, scribbles on a blackboard or sheet of paper with meaning to those fluent in them. They are also generative tools that allow scientific thought to be pushed and advanced in new directions. The chemical world has no need for naming conventions, projections or bond lines, but humans do and so we learn about and debate such scientific principles through a language of our own invention. Like any language spoken frequently enough, it acquires the characteristics of a living, breathing entity - one that builds upon itself and acquires new meaning with each exchange.



A molecular orbital diagram drawn by the author’s father, an organic chemist and frequent employer of paper tools.

There are countless examples of the evolution of models throughout the history of science, but in quantum physics we find a particularly interesting case study straddling the line between semiotics, image, mathematical theory and utilitarian expediency. To the uninitiated, Feynman diagrams can look like crudely drawn stick-figures. To the nuclear or particle physicist, though, they show a sub-atomic dance orchestrated by the quantum-level attraction and repulsion of electromagnetic forces. The diagrams were dreamt up by the physicist Richard Feynman in 1948 at a conference to help simplify the task of calculating QED, a relativistic description of the interactions of charged particles (such as electrons) and their resulting exchanges of invisible photons of energy. Before their introduction, this task was fraught with difficulty. For one, it seemed impossible to devise mathematical solutions to QED problems with reasonable certainty since invisible photons could in theory shuttle infinite amounts of energy as long as they returned it. Secondly, pairs of electrons could pass along any number of photons between them, leading to unimaginably complex webs of offshoots that had to be summed together.[10] In essence, physicists needed a way to account for each possible transfer of photons and eliminate pesky infinite values in their sums. Feynman diagrams did both of these things by discarding algebraic formalism in favor of simple drawings where electrons became solid lines, photons became squiggly ones and vertices showed points of interaction. From there, one could build a branched network with as many relationships as one liked and, rather than struggle through a thicket of mathematical terms to do so, simply affix an integral value to each diagram and sum them together. This solved one problem. To get rid of the infinite values, Feynman used his doodles as mnemonic devices to keep track of all the integrals in the system. Then, once this work-around had been employed, a physicist could go back and tweak each component retroactively using a series of tricks.



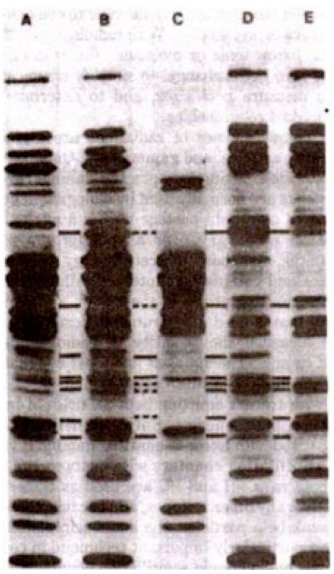
All the ways two electrons can exchange two photons (Feynman, 1949)

At hand was a doozy of a model that operated on several levels – as a veritable shortcut to an intractable problem, as a malleable paper tool for seemingly rigid theory and as a deceptively visual explanation for particle activity. As such, the rules that governed its use were fluid enough to accommodate different types of problems. Instead of using the diagrams for their intended purpose (to solve QED problems) many adopters ended up picking and choosing components of the model and transplanting them into their own fields. Feynman had tailored his diagrams for particles governed by weak interactions but as accelerators began churning out new nuclear particles of the strong interaction variety in the mid-century, "physicists tinkered with the diagrams-adding a new type of line here, dropping an earlier arrow convention there, adopting different labeling schemes-to bring out features they now deemed most relevant".[11] Diagrams previously used to account for electron scattering were now being fashioned to show beta and muon decay. In this context, it became easier to forget that Feynman diagrams were first and foremost mental models. In changing their design, some conflated the diagrams with real physical pictures of particle movement, blurring the line between model and reality even further. The intuitive visual grammar that made the diagrams so appealing had in many cases fooled people into being less critical about what exactly was being conveyed. Just as a plastic model of the double helix eclipses real DNA or an animation of channel gating in a cell membrane stands in for the genuine process, Feynman's figures donned the mantle of *actual* activity without intending to originally. As we look more closely at films and photographs, the lessons to be gleamed from the fate of Feynman's diagrams (namely, that images and symbols are versatile and pliant catalysts for the generation of new thought) are worth keeping in mind. We are never dealing with things set in stone. Rather, scientific image-making relies upon its intrinsic variability and adaptability.

Images, as we've already mentioned, carry with them unique sets of attributes. Some are noticeably shaped by a set in visual culture or worldview while others are re-fashionable and open to interpretation. Some strive to graph reality directly while others summon ideas through analogous models and symbols that can be physically experienced or mentally molded. Scientific films and photographs lie at the crossroad of these image-making approaches and information encoding strategies. Like illustrations and models, they can be clear or elusive, straightforward or circuitous, bendable or appropriable, sometimes all at the same time. While we might be fooled into thinking that these images are somehow more "real" because their means of production appear more technologically and objectively guided, their final products are still firmly shaped by familiar considerations – the what and how of an image-maker's choices to include or exclude, translate, synthesize or mend. We must then look beyond the superficial differences between a film emulsion and a pencil (painting with light vs. drawing with lead) or the act of retouching an image by hand or by computer software (both acts of manipulation, one being far more powerful than the other) and consider the image's intention apart from its material conception.

In some cases, there may be little confusion about what an image is supposed to be telling its viewer. In the case of the flea microphotograph from earlier, its information signaling is pretty direct. While certain choices could throw the structure in a new light and change the feeling of the image (if, for example, its thorax was enlarged by a scanning electron microscope or the specimen was placed against a dark backdrop that effectively inverted its composition), we'd still likely know what it is we'd be seeing. After all, most of have a clear reference point for what a flea looks like and a general understanding of how the optics of a microscope can change an observer's field of view. What if we weren't looking a flea, though, but an image where signal is less straightforward and may even demand interpretation, like an autoradiograph?

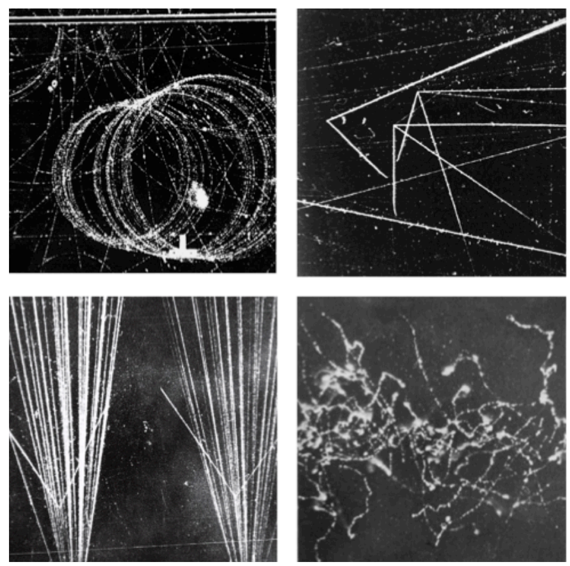
Autoradiographs are exposed film X-ray images of radioactively tagged genetic fragments made by separating DNA or RNA strands in an electrophoresis gel (an extremely common biochemical tool used to break such fragments by size into bands). They are often used to identify the regulatory components of DNA that either “enhance” or “promote” transcriptional activity and, down the road, cell growth. The process of examining such an image is wildly different from that of our flea example. The latter resembles a detailed illustration, its contours unmistakable. An autoradiograph, however, calls to mind the abstract design of a model. Their dissimilarities are multi-fold. Major differences arise not just in the very *nature* of the information encoded in each image but also in the *way* in which such information is encoded and, as we might logically expect, the subsequent process of *decoding* for an observer. In a laboratory setting, this decoding is not instantaneous since, in the case of an autoradiograph (or for that matter an fMRI or particle detector), “the marks on a film or on photographic paper are initially signs without meanings or referents; these signs must first be attached to the objects that they are presumed to represent. This process of assembling a visual trace with a suitable referent proceeds through image dissection. It involves pursuing the threads that lead from bits and pieces of the surface of the display to developments and occurrences underneath.”[12] The individual components of the image have no intrinsic meaning outside of their associations to other laboratory methods, images and established precedents. Bruno



Autoradiograph exhibiting carbon labeled proteins from a T4 phage and virus subfractions. Each column represents a different section of the phage (head, neck, tail, etc.) in which the protein was found. Taken by Drs. D. Coombs and F. A. Eiserling.

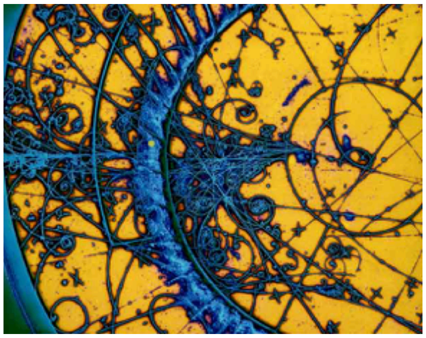
Latour argues something similar when he says, "a scientific image…is a set of instructions to reach another down the line. A table of figures will lead to a grid that will lead to a photograph that will lead to a diagram that will lead to a paragraph that will lead to a statement. The whole series has meaning, but none of its elements has any sense." [13] Like in models, the imaged components are just scaffolding, the beams and cross-braces, from which a building of meaning can be erected. Photons do not travel along squiggly paths, compounds are not paper-thin projections and genetic transcription is not a series of darkening bands and blotches, but thinking about them in such a manner allows for further interrogation and reveals to the scientist "a *window* that opens to a whole new environment of processes and events".[14]

We must then consider two key things when studying any scientific image. First, we need to identify the actual elements of the picture (the things that we can handle and process for ourselves) and the phenomena they're meant to relay (the 'stuff' of the universe that exists in spite of our limited sensory and mental hardware). Then we can bridge them in our minds to form a unity of physical portrait and subject. This melding of the substantial and the ethereal is a magic trick of association that makes what was once invisible suddenly clear. One of the most striking demonstrations of this merging of physical image and hidden reality is found in cloud and bubble chambers. Science tells us many things that we cannot independently verify without proper equipment, testing procedures and adequate knowledge of theory. One of these things, which most must take on faith, is that ionized particles constantly zip around unnoticed, cascading from chain reactions of decay and penetrating through space like barrages of undetectable missiles. Aided by only the eye, this idea might seem fantastic but with a cloud or bubble chamber we can verify the presence of such ghosts and even dissect their spectral flight. The first cloud chamber was invented in 1911 by the physicist C. T. R. Wilson. Hoping to replicate the magic of the clouds he had seen while standing atop a hill in his native Scotland, Wilson devised a controlled experiment in the laboratory to simulate their formation. By applying pressure to and enlarging the volume of a chamber filled with water-saturated air, he was able to form a layer of supersaturated vapor where condensation could occur. When ionizing particles in the form of alpha and beta radiation made contact with the chamber, water vapor condensed around the new ions to create the track of the particle as it flew by.[15] The characteristics of these different "little wisps and threads of clouds", as Wilson called them, came to be recognized as markers of specific particles. Alpha particles appeared as thick, straight tracks while beta particles appeared in the form of wispy, collision-bent tracks. Even better, the density of droplets along the lines carried information about the particles' charges and velocities. When the tracks were placed in a magnetic field, they revealed even more by curving in on themselves and leaving behind a spiral of dissipating momentum.[16]

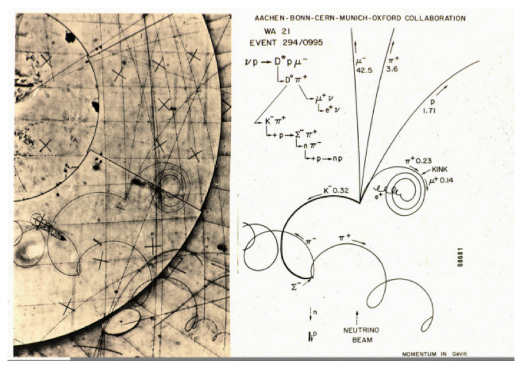


Cloud Chambers Clockwise from top left: A spiraling electron, disintegrating carbon and oxygen nuclei (both made at Lawrence Berkeley National Laboratory), ionization by X-ray beam (C.T.R. Wilson, 1912) and two streams of alpha particles (P. Blacket, 1931-32)

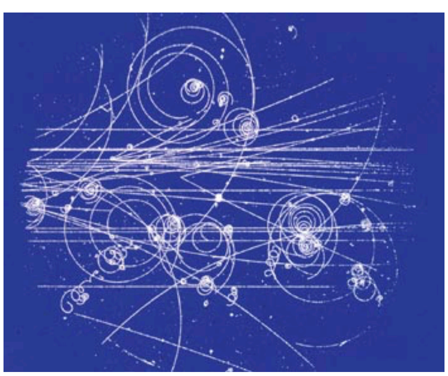
With better chamber designs (some of which replaced air with pure alcohol and dry ice) and more calibrated high-speed photographic apparatuses, physicists were able to use Wilson's invention to peer into a surprising new sub-atomic zoo populated by cosmic oddities such as muons, kaons and positrons. The cloud chamber would be followed in the 1950s with the invention of the bubble chamber, a similar device that swapped out supersaturated vapor for a superheated liquid and condensed tracks for paths of microscopic bubbles. Experimental physics research ballooned thanks to this new riff on an old theme. Photographic shreds of evidence of particle interactions using large bubble chambers were soon captured by the millions, skimmed for strange collisions at organizations like CERN and artfully colored to enhance visibility.[17] As a result, the diversity of cloud and bubble chamber images is truly fantastic. Some, taken through the glass of the chamber itself, look almost avant-garde. Others, such as tracings of particle paths relieved from their background for computational work, appear as detailed paper tools. The most colorful of



Colorfully reinvented bubble shoots made in the Big European Bubble Chamber (BEBC) at CERN.



A neutrino and proton spiral through a magnetic field to make a D meson. The charge of a particle is determined by the direction of its curve. (CERN, 1978)

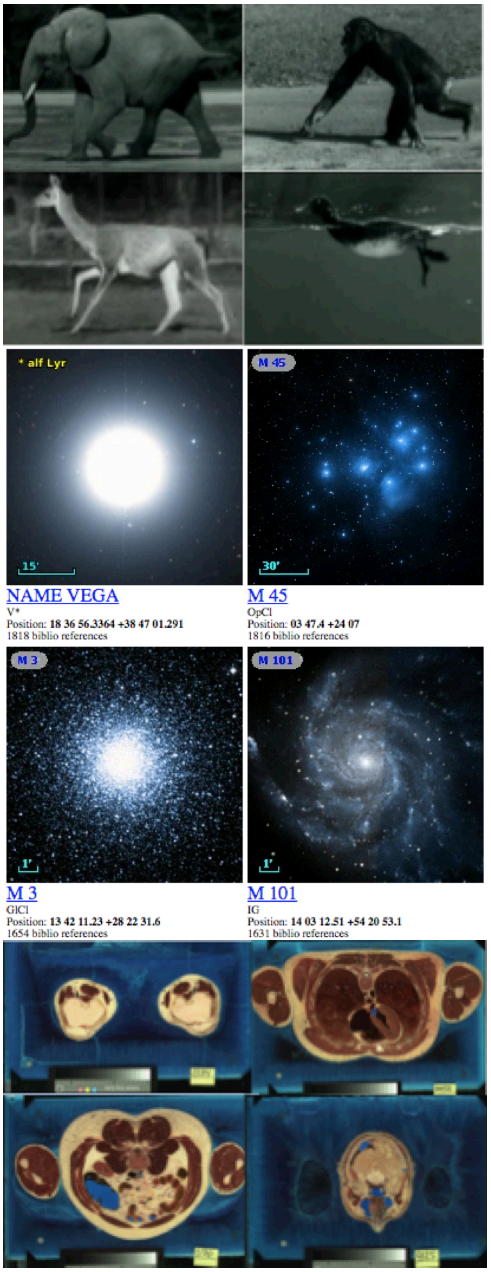


A lambda particle decays in a 32 cm hydrogen bubble chamber. (CERN, 1960) them look more like fine art installations than products of particle physics research. As with autoradiographs, correct "readings" of chamber images come from a trained eye, one that that has amassed experience decoding many atlases, documents and research artifacts. As such the mind is able to assemble a strategy for separating the wheat from the chaff or, in this case, a common ion from a neutrino beam. Still we are not necessarily "seeing" the particles but rather the footprints left in their wake. As stated by one of Wilson's contemporaries, "We can almost see protons and electrons in a Wilson chamber; we can almost see mass being conserved. We do not actually see these things; but what we do see has a very close relation to them."[18] Once again, nature as objective reality remains unattainable but the act of visualizing gets us closer than we could ever hope.

3. *The Art of Science*

Before we move towards a historical account of scientific cinematography and still image science, it is worth pivoting very briefly to discuss the range of rhetorical strategies different types of images can employ. Rich in variety, both in aesthetic presentation and practical use, scientific films and photography can have arcane research value or elicit widespread popular interest, be instructional tools or stimulants for the imagination and adopt a narrative, didactic or experimental tone. Those hoping to be broadcast widely to other scientists must satisfy the conventions of publication dictated by peer-reviewed journals and other formal scientific bodies. On the website of the journal *Nature*, the request that a "final image must correctly represent the original data and conform to community standards" is followed by a host of editorial standards for time-averaged data, time-lapse sequences, data processing, nonlinear adjustments, pseudo-coloring, figure legends and software manipulation.[19] As with raw scientific data, journal figures and images are expected to retain a level of integrity that accurately reflects the methods and outcomes of a given experiment. But given the ease of powerful digital editing tools, many scientists have jumped at the chance to beautify and expedite their results. This has led to concerns about the transparency of image reconstitution and raised questions about how far an image can and should be pushed before it reaches its breaking point.

Research films also play an important role in the formal dissemination of basic experimental results. As opposed to the instructional film in which “only one particular individual [is] incompletely acquainted with the existing body of fact or theory”, the research film is “the application of cinematography to the systematic search for new knowledge in the sciences”. The “techniques of production, analysis and usage of research films in the sciences”, whether exploratory or for formal presentation, are bound by the shared need to impart a clear sense of experimental set-up and results through appropriate camera apparatus, recording format, and editing sequencing.[20] These films can then be passed along to other scientists for interrogation. Some research film and image collections have even attempted the expansiveness of a searchable catalogue. An early example can be found in the *Encyclopaedia Cinematographica*, a grouping of several thousand biological and anthropological 16 mm films that, in a merging of the ‘typifying’ enlightenment atlas and later ‘objective’ documents, attempts a taxonomy of the natural world that “allows both horizontal consultation: the study of all manifestations of a given individual or material, and vertical consultation: by the study of processes and



Top to Bottom: A library of animal motion (from *Encyclopaedia Cinematographica),* an arrangement of stars, galaxies and globular clusters (from *Aladin Sky Atlas*, Centre de Données astronomiques de Strasbourg) and a grouping of full color anatomical images (from *The Visible Human Project*)

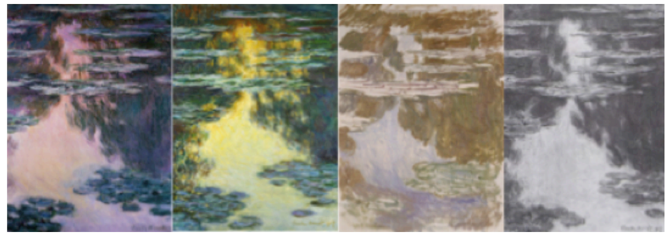
phenomena as they occur in different subjects."[21] Today, this power to search and sort exists at our fingertips like never before. With the ease of a few clicks, anyone with a stable internet connection can sort through a cross-section of a complete human body or scan the sky for entire star systems. The democratization of high-resolution and interactive scientific imaging is a true gift, something that would've awed the illustrators and model-makers of the past.

The image, whether accessed in a computerized database or an old tome, can be a source of revelation as well as new knowledge. Some view this implication as an affront to the sacred temple of scientific impartiality. Others, perhaps, are simply "largely unaware of the value of the visual poetry of their own work".[22] They might go about writing papers and attending conferences oblivious to the inspirational potential of their objects of study, so caught up in the trenches of their research that anything outside it seems immaterial. To them, emotions have no place next to calibrated instruments and data sets. Science is something that is to be tested and understood first, marveled at second.

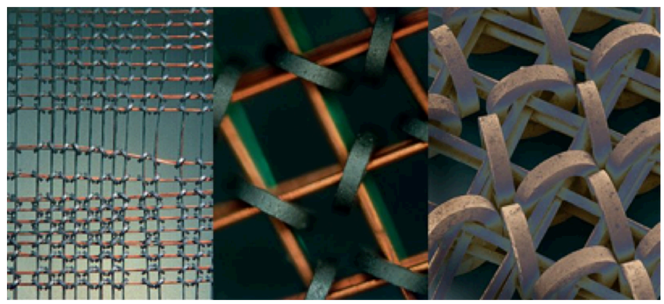
But who is to say that acknowledging one part of something's essence negates all its others? It would be foolish to equate art with science outright, but why can't we look at an image of an electric current or a solar spectrum as an artful impression, a shimmering broadcast emanating, like a painting, from something far greater than the parts that received it? What is an image but a chance glimpse at a truth, a delicately impressed fingerprint of reality?

The soft colors, wistful figures, textured brushstrokes, and quiet perspectives of a painting are appreciated as extensions of the artist's 'creative process', that sequence of factors and decision that makes the final picture what it is. They are subject to the whim of incalculable variables like the time of day, quality of light, choice of paint and emotional state at the time of composition. We understand that if any of these things were to change (if the oils were mixed differently or the canvas were positioned at a higher vantage point or the sun filtered in through a tree before hitting the subject) so too would the resulting picture. We also recognize that the context and setting in which we view such a work of art affects our relationship with it. Why shouldn't we try to define an analogous process/context of viewing for the scientific image-maker?

Scientific images are not paintings or loose impressions. They have a theoretical obligation to the disinterested pursuit of truth and knowledge, not an allegiance to feeling and expression. But it is the misconstruing of this pursuit as infallibly accurate and self-contained that wrongly places them in a class of their own, hermetically sealed from any type of 'process'. In reality, scientific images, whether they be hand-drawn renderings through the microscopic, pixelated broadcasts from space, movies of moving particles or models of genetic code transcription, arise from a process that, if not as imperfect and subjective as that of the painter, at least hues more closely to it than we'd like to believe. Additionally, the perceived 'truthfulness' of a scientific image is not an innate feature of its existence but something that is constantly being negotiated along multiple developmental stages and molded by internal and external drivers.



Impressionist art is relative: Four studies of the same water lily pond by Claude Monet



So are science images: Three studies of the same computer memory core taken by Felice Frankel using (left to right) a scanning, compound and electron microscope (false color).

All images, we often fail to appreciate, are unmistakably colored by the techniques, motivations and contexts behind their creation and reception. We must consider, then, how and for what reason they are prepared, where and to whom they're presented and how they engage in the act of interpreting and being interpreted. Deciding what any given image says about itself and what we in turn say back about it is not an uncomplicated task. It is easy to look at images passively as things that *are*, but we must always look at them critically as things that *become.* The art historian Svetlana Alpers explains this distinction when she writes, "I employ the word 'picturing' instead of the usual 'picture' to refer to my object of study. I have elected to use the verbal form of the noun for essentially three reasons: it calls attention to the *making* of images rather than to the finished product; it emphasizes the inseparability of maker, picture, and what is pictured; and it allows us to broaden the scope of what we study…”.[23] Perhaps appropriately, the sentiment applies as equally to her actual object of study, 17th century Dutch painting, as it does to scientific images. Pictures are not born into the world devoid of considerations outside of themselves. They are multi-layered, not flat, and to treat them as such would be to deny what makes them so rich in the first place.

To quote another art world figure, “We only see what we look at. To look is an act of choice.”[24] So too is the act of looking at our looking. In the following pages, we’ll do as much, interrogating our own gaze as well as the one that looks back at us. Within our museum of the scientific image, we’ll see nature’s recurring form and pattern reflected in humanity’s determined pursuit to tame it. By the end, we might hope to reach the same conclusion that the soviet filmmaker Vsevolod Pudovkin did while making a research film on the psychological conditioning experiments of his fellow countryman Ivan Pavlov[25]:

“*My meeting with science strengthened my belief in art.”*

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[1] Hentschel, Klaus, *Visual Cultures in Science and Technology: A Comparative Study,* Oxford University Press, 2014. “Introduction” (pgs. 9-80).

[2] Ibid, Hentschel covers many of these sub-categories of visual culture in depth throughout his book

[3] Elaine R. S. Hodges. “Scientific Illustration: A Working Relationship between the Scientist and Artist.” *BioScience*, vol. 39, no. 2, 1989, pp. 104–111.

[4] Daston, Lorraine, and Peter Galison. *Objectivity*. New York, Zone Books, 2007. p. 63.

[5] Ibid, p. 66.

[6] Galison, Peter. "Algorists Dream of Objectivity." pp. 3.

[7] Ibid.

[8] Bailer-Jones, Daniela M. *Scientific Models in Philosophy of Science*. University of Pitts burg Press, 2009. p. 2

[9] Ursula Klein: Experiments, Models, Paper Tools. Cultures of Organic Chemistry in the Nineteenth Century. Stanford, Calif.: Stanford University Press 2003. pgs 2-3.

[10] Kaiser, David. "Physics and Feynman's Diagrams: In the hands of a postwar generation , a tool intended to lead quantum electrodynamics out of a decades-long morass helped tr ansform physics." *American Scientist*, vol. 93, no. 2, Mar. 2005, pp. 156-65.

[11] Ibid. p. 164

[12] Knorr-Cetina, Karin, and Klaus Amann. "Image Dissection in Natural Scientific Inquiry." *Science, Technology and Human Values 15*, vol. 3, 1990, p. 263.

[13] Latour, Bruno. "What is Iconclash? Or Is There A World Beyond The Image Wars?", p. 34.

[14] Refer to xii, pg. 262

[15] Wilson, C. T. R. "On an Expansion Apparatus for Making Visible the Tracks of Ionising Particles in Gases and Some Results Obtained by Its Use." *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, vol. 87, no. 595, 1912, pp. 277–292.

[16] Brandt, Siegmund. *Tracks of Single Particles in Wilson's Cloud Chamber (1911)*. Oxford University Press, 2009.

[17] O'Luanaigh, Cian. "Seeing the invisible: Event displays in particle physics." *CERN*, 4 June 2015.

[18] Eddington, A. S., *The Philosophy of Physical Science.* Cambridge: Cambridge University Press, 1939, pg. 134.

[19] "Image integrity and standards." *Nature Research*, Nature, 2020.

[20] Michaelis, Anthony R. *Research Films in Biology, Anthropology, Psychology and Medicine*. New York
City, Academic Press Inc., 1955. Pg. 3.

[21] Tosi, Virgilio. "Cinematography and Scientific Research". UNESCO. *International Scientific Film Association*, p. 25.

[22] Frankel, Felice. "Envisioning Science-A Personal Perspective." *Science*, vol. 280, no. 5370, 12 June 1998.

[23] Alpers, Svetlana. *The Art of Describing: Dutch Art in the Seventeenth Century*. University of Chicago Press, 1983. p. 26.

[24] Berger, John. *Ways of Seeing*. Penguin, 1972. p. 8

[25] Vöhringer, Margarete. "Pudovkin's 'Mechanics of the brain' Film as physiological Experiment."

-Chapter 2-

The Birth of the Scientific Image

"…Now light, where it exists, can exert an action…"

-W. H. Fox Talbot

"Shortly before it flew, and now, a prisoner, it reveals itself the rules that govern it. It can be understood."

-Étienne-Jules Marey

Today's scientific filmmaking and photography give tangible form to the imperceptible in a way that seems effortless. Its practitioners are able to condense time, space and movement into sequences of images with such frequency and ease that we're in danger of becoming desensitized to their wonder. We take for granted, for example, our ability to see an embryo form, watch a string oscillate harmonically or follow a time-lapse of the night sky. These technical and aesthetic marvels, broadcast through our screens and into the fabric of our collective imagination, are so familiar to us that we often fail to appreciate their ability to stretch and compress chronology, scale fields of vision and reveal the invisible mechanics of the universe.

Without the camera, this power to overcome the limitations of our senses and perceive the levels of reality that exist beyond them wasn't always assured. In order to better evaluate our modern-day capabilities and understand the implications of image-making in science, we must construct a history of scientific image-making. The following pages will attempt to do so by chronicling the work of a continuum of artists, scientists and innovators and by contextualizing their contributions along the more general histories of film artistry and empirical inquiry in which they run concurrent. This chapter is not meant to provide an exhaustive or overly comprehensive overview, nor is it meant to read as history in a vacuum. Rather than simply trace out the contours of the narrative (the who, what, where and when of events), it will attempt to assess the why and how as well. This critical assessment will be foundational to the rest of the paper, as it will allow us to assemble a fuller picture of the role of cinematography in science over time.

The sections of this chapter make up three parts. The first briefly summarizes some of the photographic processes that served as antecedents to the cinema while the second and third look at the birth and development of scientific cinematographic practices in a period during which their methodology and function began to take shape. The following chapter will pick up this historical trail and look in depth at the proliferation and widespread adoption of scientific images in the 20th century: as artifacts of science in the form of research films, as tools for translation and education and as works of popular art and entertainment to be distributed and viewed. It is important to note that while this structure is useful for the purposes of writing, it is not meant to imply a neat or linear progression of moments the way a strip of celluloid does. The story of science and film, like the story of everything else, is as much a product of its tendency to circle back in on itself, invert its path, and obey the randomness of discovery as it is of some straight and narrow march forward.

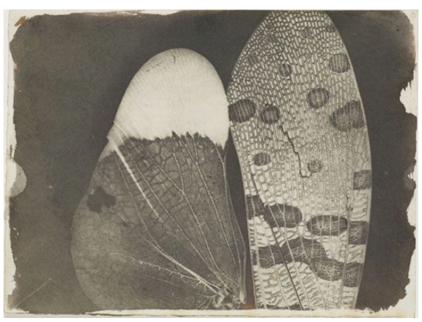
1. *Beauty is in the Eye of the Camera*

It is logical to begin a history of scientific cinematography with an account of some of the earliest photographic efforts. These formative decades would see the practical and theoretical groundwork laid for later moving image pioneers. Methods to successfully expose, develop, fix and project images would grow out of experiments in photography and find direct relevance in the formation of the tools of the cinema.

The invention of photography, if measured by the production of the first permanent image, is attributed to Joseph Nicéphore Niépce, a lithographer interested in the faithful reproduction of engravings. Using a *camera obscura*, a pinhole device that projects inverted images onto the walls of its chamber, and a photosensitive method involving the application of a flow of bitumen onto a pewter plate, Niépce was able to make picture impressions as metal engravings. He called this process heliography and used it to take the oldest known photograph, a crude approximation of the view from outside his country estate window.[1] The shortcomings of the heliographic technique were many, principle among them that exposure times lasted for hours or even days. This fact, along with the insensitivity of his plates to light, were major flaws that limited the types of subjects that could be captured. These difficulties–lengthy exposure times and insensitive plates–would prove to be recurring barriers in future photographic endeavors, obstacles to overcome.

Niépce's work would find continued life, however, in the research of a fellow Frenchman, Louis Daguerre. Already familiar with the communicative powers of light and image through his invention of the diorama, a screen painting that changed based on its stage lighting, Daguerre set his sight on freezing the images of the *camera obscura* in time, first with phosphorescent substances and then through a working partnership with Niépce to develop heliography.[2] In 1831, while studying the effectiveness of different chemical agents, he suggested that silver iodide could be made to act as an effective light-sensitive layer on a photographic plate.[3] The obsessive pursuit of this hunch would lead to the invention of the self-named Daguerreotype process. Made by the contact of a polished iodized plate with mercury vapors, the Daguerreotype process produced a positive, ghost-like image using a considerably shorter exposure time and a chemical process by which the latent image (the invisible mark left upon introduction to light) could be brought out. More importantly, it suggested the viability of a practical photography and offered a commercially and scientifically sound way to achieve it.

It is through the Englishman William Henry Fox Talbot, however, that we can draw an even more direct line to modern photography. Like Daguerre and Niépce, Talbot found inspiration in the projections of earlier optical instruments used to aid artists, specifically the *Camera Lucida,* a prism which he took to Italy to sketch with. He found, though, much to his dismay, that his drawings never reached the sublimity of the "fairy pictures, creations of a moment" visible through the glass of the *Lucida* that were



Talbot, *Microphotograph of moth wings* (1840)

"destined as rapidly to fade away". [4] This twin frustration over the image's inherent ephemerality and the obvious shortcomings of his drawing hand got Talbot to wonder if "it were possible to cause these natural images to imprint themselves durably, and remain fixed upon the paper!". This thought, remarkably simple in construction but profound in its implications, would lead him down a road of discovery culminating in the invention of the calotype. Using sheets of paper coated in light-sensitive silver iodide, Talbot would find a way to develop and fix images with a chemical wash to produce negatives where light and dark reversed themselves compositionally. These, he realized, could be handled in broad daylight and, unlike Daguerreotypes, be used to easily reproduce positive images of themselves.[5] Talbot's multi-step chemical image-making process would prove so reliable that it would hold sway until the advent of digital photography. Step into any darkroom, and one will inevitably see a permutation of these developing, fixing and printing methods being observed as standard practice.

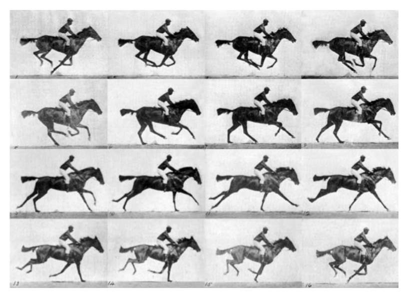
Talbot, Calotype of *An Oak Tree in Winter* (1842-43) showing the negative and positive image.

There are, of course, many other important nurturers of the photographic art, and as many equally important movements within it, all outside the scope of this chapter. Photographs would, in the years following the work of Niépce, Daguerre and Talbot, be appropriated by a great many botanists, meteorologists, zoologists, geologists, physicists and other scientists as tools with which to experiment, document and explain their work. Built into these snapshots of the natural world was an implication of motion and transformation, making the advent of scientific photography the first step in a natural evolution towards the cinema, a new scientific art as powerful as photography in its ability to inform, persuade and provide spectacle.

2. *Galloping Horses, Falling Cats and Racing Humans*

Histories of cinematography often begin around the turn of the 19th century with the birth of a commercial or mass cinema. This casting of film history, while at home in a historiography that places value on the idea of film as a form of viewable commerce, wrongly attributes its true technological inception. Sandwiched in between early work on photography and the spread of movies to theaters around the globe is a stretch of decades that saw the study of motion handled in experimentally rigorous terms. It is through the application of film in deciphering confounding scientific questions during this time that the first mechanical, cinematographic world-view begins to emerge. Existing at the crossroad of art and science and employing a unique alchemy of spectacle and testimony, fact and illusion, its creation story will help us better appraise science movies as material objects with multiplicities of form and interpretation.

The beginning of movies is commonly mythologized around a dispute over whether or not a horse picks all four of its hooves off the ground at any point during its gallop. A question hotly debated in the papers of a rapidly industrializing California by the public, intellectuals and horse-breeders alike in the early 1870s, it became one of great personal interest to the railroad baron Leland Stanford. In an effort to validate his opinion that equestrian motion does involve complete lift off from the ground, he commissioned the photographer and artist Eadweard Muybridge to investigate the issue. An ideal fit for the job having had experience with new photographic techniques through his travels to Yosemite documenting cliffs and waterfalls using large-format cameras with glass slides and long exposures, Muybridge set about the problem of horse locomotion by designing a controlled working space in Palo Alto complete with a race-track and a shed for photographic equipment. It is here that, after several years, he perfected a way to capture the strides of a horse mounted by a rider.[6] Using 12 stereoscopic cameras with shutters released through an electrical trip-wire mechanism that engaged when in contact with a hoof, he was able to prove that horses do for a split-second suspend their body in mid-air,

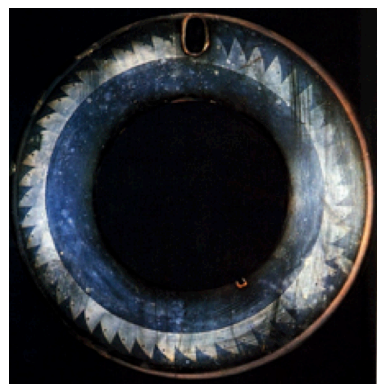


A reproduction of Muybridge's horses (1878) a curious truth of nature that had been previously invisible to the naked eye. This was an ingenious feat, and no easy one either. The cameras had to be perfectly synchronized and the intervals between each fraction-of-a-second exposure carefully plotted.[7] This 'instantaneous photography' was akin to a delicately choreographed dance, and its results were both aesthetically beautiful and scientifically valuable. Muybridge recognized this much and embarked on a lecture circuit to exhibit his findings with the use of artist renditions and lantern slides. He would also end up adding 12 more cameras to his arsenal of instruments, a decision that, whether by coincidence or causality, mirrors the standardization of frame rate to 24 frames per second observed today.

It was not simply enough to view these series of images as parts of a whole, however. The magic arose when these discrete units were projected together with enough speed to invite the illusion of continuous motion. To do this, Muybridge invented the Zoöpraxiscope, a variation on earlier devices such as the Phénakisticope, Zoetrope and Stroboscope. These predecessors, circular discs with images positioned radially around a point, induced in their viewer the appearance of movement when spun through a series of slits and mirrors.[8] These spinning visual pinwheels played a crucial role in pre-cinema, and helped inspire Muybridge's embryonic film projector. The Zoöpraxiscope's importance rested on the fact that it could reassemble for a viewer in New York or Paris what Muybridge's eyes would've seen in Palo Alto. Ink drawings of his famous photographs (the originals suffered from vertical distortion when used in the machine) were copied onto a glass circle and placed

Muybridge, *Jumping; Handspring; Somersault; Springing over a Man's Back:* Plate 522 from *Animal Locomotion* (1887) behind a plate of slits. These were then positioned between a magic lantern light source and a set of lenses.[9] When used, the Zoöpraxiscope treated the viewer to a complete vision of a horse trotting through space, allowing them to independently validate Muybridge's counter-intuitive findings.

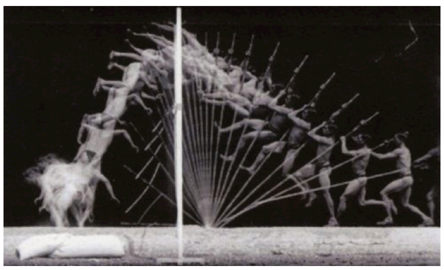
Muybridge's motion studies, though, did not exist independent of others. Many artists and scientists before and after would help outline the expressive and communicative potential of the cinema. One of them was the astronomer Pierre-Jules-César Janssen, remembered for his declaration that "photography is the retina of the scientist" and for his implementation of this ethos in studying the heavens.[10] In 1874, the transit of Venus across the sun drew hoards of scientists in an attempt to measure its parallax and the existence of its corona. Janssen understood that images could verify the existence of science that normally eluded the eye, and using a 'photographic revolver' of his own making proved this value to astronomers. The first cinematographic camera of its time, the revolver had a cannon-shaped body that housed a barrel lens, two shutter disks and a round plate sensitized by the Daguerreotype process. An automatic cog rotated the plate, and as it moved, its edges were exposed to sections of the transit.[11] The resulting images were literal embodiments of partitioned motion, an inverted Zoöpraxiscope. Whereas Muybridge took static snapshots and transformed them into movement, Janssen took movements and transformed them into a series of moments. This



Janssen's circular plate showing the transit of Venus (the planet can be seen as a small dot along its fin-like edges).

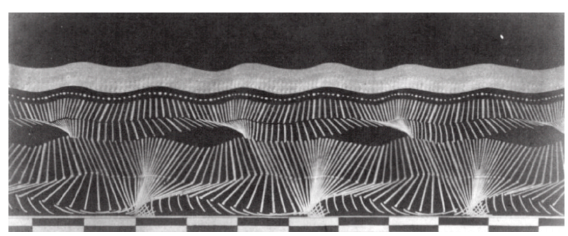
breakdown of the celestial body's trek into individual photographic plates offered fellow scientists a new way of interrogating time and space through mechanical means.

But the central figure of this proto-cinema period, or at least its most prolific case study, is found in Étienne-Jules Marey. A master of chronophotography, the superimposition of multiple frames of movements to make a single picture, Marey spent much of his energy cataloguing and indexing motion. He began his locomotion studies in a laboratory where, using pneumatic devices no doubt familiar to him from his studies on the circulation of blood through the human body, he calculated with reasonable exactitude the rate at which a pigeon flaps its wings and, in the vein of Muybridge, the speed at which a horse strides.[12] Marey used a drum attached to a pen and cylinder of paper (similar in principle to the way in which a seismograph or lie detector visualizes data) to measure changes in air pressure that result from movement. These numerical and spatial graphs isolated dynamic phenomena like the flight of a bird or the jogging of a human subject and transposed them onto a piece of paper where they could be understood.



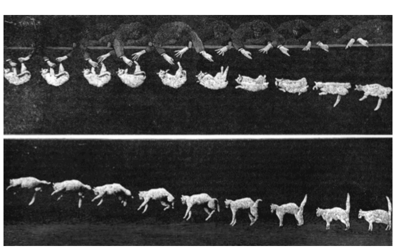
Marey, Chronophotographic study a pole vaulter leaping (1890)

Marey next looked to the work of Janssen to craft an improved photographic gun, one that could serve his high-speed needs. His take on the mechanical, barrel-shaped template was even closer to that of an actual gun than the astronomer's. Once



Marey, Chronophotographic study of a man walking (1884) constructed, it was able to take an image twelve times each second with exposure times clocking in at 1/720th of a second each.[13] Marey used his high-speed gun to great effect by adding portraits of insects, birds, donkeys and dogs in motion to his visual encyclopedia of physiology. The gun was portable and quick, opening up a whole new world of possibilities for motion capture artists. Still, in order to discern patterns from the juxtaposition of different parts of an image, Marey needed a way to condense all stages of motion into a single print. This is what his chronophotographs, quite literally 'time pictures', were able to do. Looking at them, one is struck by their fluidity and completeness of action. Like Muybridge's pictures, they impart a logical continuity, but their effect is somehow amplified by the way in which bodies overlap and life spills out into lines of action. For Marey, the objective was to abstract motion, to sculpt it from its essential parts. Therefore, a chronophotograph of a man running need not feature his face or body so long as his limbs, the anatomical structures actually moving, were delineated with strips of metal.[14] This reduction of form to its elemental parts allowed him to view action sequences geometrically. Human motion, once a blur, was now something that could be modeled mathematically.

In later years, Marey would gravitate towards even more abstract subjects, like the movement of blood through capillary tubes, the hydrodynamic properties of waves produced by aquatic creatures and the aerodynamics of flight.[15] These pursuits anticipated the trajectory moving image-making would take in the twentieth century, away from existing for its own sake to becoming a methodology useful in the fields of physics and



Marey, *Falling Cat* (1894)

medicine. In 1894, Marey produced a cinematographic depiction of a cat being dropped and reorienting itself upright before hitting the ground.[16] The resulting film, like all of Marey's work, exists as a work of serious inquiry, a deconstruction of the axioms of nature no less legitimate than any other. It is also, however, undeniably amusing, and it is these two forces, the image as subjective entertainment and the image as objective testimony that end up coexisting in novel ways around the turn of the nineteenth century. Marey balked at the idea of his work being misconstrued as anything other than pure science, but there is no denying that his films and chronophotographs exist on a visceral plane that lends them lives of their own. This duality, defined mainly by ideological clashes but also by occasional symbiosis, marks the dawn of 'cinema' proper, which we will investigate briefly before pivoting to a discussion of a few final milestones in the appropriation of scientific film and photography.

Air streams as seen through a triangular prism and 57 different channels, 1901 (Marey, Cinémathèque française)

3. From Purity to Production

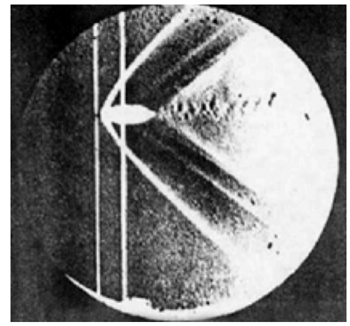
When we conjure up the early days of the movies, we imagine a train inching ever closer to center frame à la the Lumière brothers or an outlaw breaking the fourth wall and shooting at us by way of Edison.[17] These early pictures are shining first examples of a new art form destined to take the world by storm. They signal a growing popular demand for moving images that not only fascinate with their novelty but also transport the imagination of the viewer through fictionalized stories and candid depictions of the everyday. Their existence and mass proliferation, however, would not have been possible without the introduction of celluloid. Many early photographic endeavors were constrained by the limitations of glass and other solid materials upon which images had to be fixed, and while the transition from wet to dry plates marked an important step forward, it did nothing to phase out the rigid materials with which they had to be cast. Celluloid, on the other hand, allowed pictures to be produced on thin and flexible strips of laboratory synthesized plastic. George Eastman of the Eastman Kodak Company helmed this revolution in medium by bringing to market transparent roll film that could be spooled through inexpensive camera bodies to take multiple exposures.[18] His introduction of this new stock to the consumer, along with the necessary infrastructure to support it, democratized photography and would do the same for film. Not long after the christening of Eastman's new film stocks, William K. L. Dickson, a photographer working under Thomas Edison, used them in his work on the Kinetoscope, a peep-hole device through which continuous loops of film ran through a light source and shutter to produce short vignettes of movement. As Edison wrote in his patent application, the Kinetoscope aimed to be an "instrument which does for the Eye what the phonograph does for the Ear" and while the device fell short of successful sound synchronization, it proved to be a scalable motion picture machine and a useful template for inventors abroad. Most relevant to later efforts to manufacture and project celluloid was Dickson's introduction of the 35 mm wide film format and his decision to perforate both sides of the film so that a sprocket could take up reels with ease.[19]

On the other side of the Atlantic in Lyon, the Lumière brothers Auguste and Louis worked on making their own movie apparatus. In 1895 they released their

Cinématographe to great acclaim.[20] A hand-cranked wooden box, it also used 35 mm perforated film but what set it apart from Edison's invention was its ability to project images onto a large screen viewable to a crowd of people. Film, therefore, was no longer constrained by the individual viewing experience of the Phénakistiscope or Kinetoscope. The act of watching a Lumière film in which workers exit a factory or a man pours a drink from a bottle were universally shared experiences, not solitary acts.[21] Movies could now be broadcast to the collective rather than the individual, a fact that would necessitate the building of an industry spanning production, distribution and exhibition around moving images. This commercial view of the cinema differed from that of Marey and his contemporaries who only saw film as a way to shore up human comprehension by recording the truth. This debate over the true nature of cinema would be propelled, especially in France, by arguments over which camp held the most legitimate claim to discovery, a question that would never receive a satisfactory answer and whose importance is perhaps negated by the fact that the each side benefitted in some way from the other. Early film industrialists like Edison, Dickson and Lumière certainly built off of each other, but their most profound debt was to figures like Muybridge, Marey and Janssen upon whose shoulders they stood. Likewise, the offspring of those proto-cinema scientists benefited greatly from the new technologies of their industrial contemporaries. Projection tools created for entertainment and commerce would end up aiding in the dissemination of scientific information as more researchers adopted them. In this way, scientific cinematography provided the impetus for a technological evolution whose benefits it would later partake in itself.

Societal institutions also began reaping the benefits of scientific cinematography and photography, namely the healthcare system and the military. Albert Londe, a Frenchman who worked in the Salpêtrière hospital in Paris, was one of the early figures to forecast the integration of the fruits of the capitalist machine into the environment of the research laboratory. Outshined by the Lumières in the realm of original technical inventions but a rigorous experimenter nonetheless, Londe developed a way to capture chronophotographic plates of patients undergoing epileptic fits, instances of hysteria and other physiological and psychological abnormalities. These images were made with the use of electromagnetic triggers and a metronome and they proved incredibly useful to doctors and specialists in the field by allowing them to study the kineticism and deficiencies of the human body in a clinical setting.[22] This fascination with medical photography would find staggering levels of payoff in the following century, with X-ray photography and other imaging techniques serendipitously coinciding with the building of a modern-day healthcare infrastructure, but figures like Londe were crucial adopters. Another figure who recognized the value of medical photography early on is the Romanian doctor Gheorghe Marinescu who took images and short films of his neurologic patients before and after treatment. His aim was to assess the effect of treatments on subjects with natural gait disorders resulting from hemiplegia and locomotive ataxia.[23] In both Marinescu and Londe's work, there are the obvious formal and technical marks of Marey (a single figure walking in successive stages against a monochrome background) but they exist in a unique medical framework. This specificity of utility, as diagnostic tools readable to experts in the fields of neurology and physiology, set them apart in form and function from Marey's locomotive studies.

The military complex seized on the illustrative power of scientific images early on as well by working with the German photographer Ottomar Anschütz. Known for a series of albumen prints showing storks nesting and taking flight (these were collected in a book which would later influence Otto Lilienthal, the first human to successfully fly with a glider), Anschütz's first foray into military work came in 1886 when the Kaiser's ministry of war commissioned him to take over one hundred photos at the Equestrian Military Institute at Hanover.[24] The result of this trip was a series of images of cavalry soldiers and horses to be used as training tools in the field. He also was given the opportunity to explore ballistic weaponry and managed, with limited success, to photograph a shell flying out of a cannon. The study of ballistics in motion would prove pivotal in the development of high-speed photography. Contemporaries of Anschütz, rather than attempt to photograph airborne entities straight-on as he did, used what was known as a Schlieren apparatus and shadowgrams to image the supersonic flow of a bullet through space. This was done by employing known principle of optics. Rays of light undergo a change in mediums with different refractive indices. When a bullet exits the barrel of a gun, it produces a density gradient in the air. This change in density affects the light source passing through it, resulting in a fingerprint of the disturbance around the projectile.[25] This flow visualization technique and variations on it can be used to see the atmospheric collateral of any number of high-speed mechanical or chemical reactions (a lit match, a wind tunnel, a cruising aircraft). This is all to say that high-speed photography would ultimately rise to the challenge of suspending time in



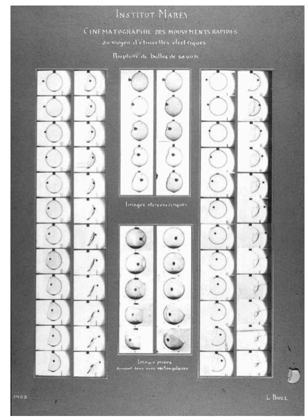
A shadowgram showing a shockwave around a bullet (Ernst Mach, 1888) incomprehensible fractions of seconds, even if it still existed in an early stage when Anschütz was working with cannons.

Anschütz's most important non-militaristic venture was the refinement of Muybridge's Zoöpraxiscope through the invention of the Tachyscope and Electroachyscope.[26] Iterations of the same instrument, both revolved transparencies viewable by intermittent sparks from a Geissler tube, a glass filled with excited inert gas. Their primary edge over earlier models like the Zoöpraxiscope was that they dispensed with drawing reproductions in favor of high quality photographs that made for a better viewing experience. In fact, the quality of the Electroachyscope would not be surpassed until the introduction of the Lumière's Cinématographe.

In the twilight of his life, Marey passed the baton of research off to a new crop of scientists through the creation of the Institut Marey, a laboratory space where experimenters could continue his investigations into physiology and movement. The institution would become a launching pad for all sorts of notable filmmakers. Two of its members, George Demenÿ and Lucien Bull, exemplified the ethos of the institution and heralded a Renaissance period of sorts for scientific research filmmaking. Before their falling out, Demenÿ was a close assistant of Marey's and helped to establish common research practices at the institute where his interest in gymnastics melded well with his flying and swaying chronophotographic subjects. Never content with just doing research for research's sake, Demenÿ continually looked towards applying his findings in the real world. In 1891, he photographed 18 frames of himself

"I Love You" as performed by George Demenÿ (1891) mouthing phrases like “Je Vous Aime” in an attempt to recreate language production through close-ups. This, he believed, could be used to help the hearing and speech impaired learn to read lips, but the motion of the faces when run was too choppy to be a truly effective teaching tool.[27]

Lucien Bull also worked at the Institut. There, he made hundreds of films, many of them completed with a specially-made high-speed camera. One shows a bubble being penetrated by a bullet, reminiscent of many later artful depictions of the uncommon behavior of common objects when in slow-motion. Another shows the flight of a dragonfly in stereoscopic view, an early experiment in three-dimensional recording and playback. Bull took over as the head of the Institut after the death of Marey and would work for nearly half a century perfecting high-speed motion capture, starting at 500 frames per second and eventually reaching a staggering 1,000,000 fps some two decades before his death.[28]



Lucien Bull, *Soap Bubble Bursting,* 1904

The birth of the scientific image, much like the birth of photography and the birth of the modern cinema, cannot be attributed to any one figure or isolated period of time. A wide cross-section of people and ideas were needed to create the necessary theoretical, technological and aesthetic considerations for imaged science to flourish. The invention of photography, helped along by Niépce, Daguerre and Talbot, allowed moments in nature to be reliably reproduced and viewed long after they had faded, frozen in time like insects in amber. Imaging these same moments *over* time, then, became the next frontier to be conquered. Janssen, Muybridge and Marey pursued this task with different methodologies united by a shared desire to overcome practical challenges and produce artifacts of great beauty and utility. The coexistence of pure research and commercial exploitation would peak with the introduction of superior movie-making instruments from Edison, the Lumières and Eastman. This, in turn, opened the doors for future tinkerers, inventors and salespeople. Around the same time, Albert Londe used pictures in a diagnostic context and Ottomar Anschütz investigated the role of film in the military and other sectors of public interest. Finally, at the Institut Marey, luminaries like George Demenÿ and Lucien Bull forged a path forward for future documentarians by synthesizing their curiosity for a wide range of subjects with testable experimental procedures. All of these breakthroughs accumulated to form a foundational blueprint for the scientific image as a tangible object in the new century.

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-Chapter 3-

Seeing Science in the New Century

"It took the modern period, based on science, to develop an art from scientific sources."
-Berenice Abbott

"It would never have occurred to the pioneers of cinema to dissociate research on film from research by means of film."
-Jean Painlevé

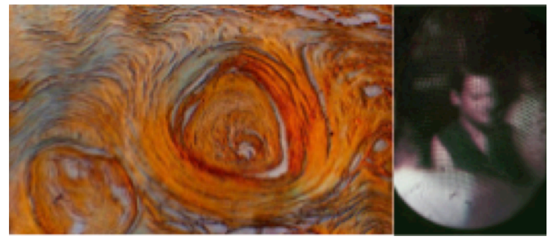
If the nineteenth century witnessed the birth of the scientific image, then the twentieth century saw its maturation into an expansive field of inquiry. Spurred by a wave of technological progress driven by the forward inertia of a new era, science realigned along promising and previously unexplored avenues. The artificial eye of the camera allowed what was once the domain of the laboratory to be transmitted and multiplied to virtually anyone. Not only other scientists but any layperson with an interest could adopt the gaze of a microbiologist studying a bacterial colony, an oceanographer probing deep-sea marine ecosystems or a physicist mapping the collision of atoms. In relaying these events, the scientific image successfully synthesized the functionality of the instruments that came before it. Its frames could express the magnifying powers of a microscope, the enormity of a telescope or the secrets of an electromagnetic sensor, all while sculpting the dimensions of scale and time in ways previously unthinkable.

The sheer number of films and photographic documents produced is overwhelming. Their variety of subject matters and technical approaches reflect the exponential growth and specialization of the sciences during the 20th century. This makes their complete cataloging an impossible order and might explain why, with the exception of a few mid-century efforts, centered scholarly attention has been scattered. As a result, there is no established historical roadmap to follow, no agreed upon way of writing about the material. With too much ground to cover, this chapter cannot attempt an encyclopedic approach in the name of covering as much material as possible. Instead of striving for a continuous narrative, it will consist of profiles (of individuals, of research techniques and most importantly of the films and photographs themselves) loosely grouped around shared aesthetic concerns and research preoccupations. The resulting appraisals, deemed interesting in their own right while being representative of wider trends, will suggest to the reader that the definitional boundaries we've erected for evidenced 'science' are sometimes too narrow, that empiricism and inventiveness are not mutually exclusive but actually go hand-in-hand and that the act of 'seeing' can be as valuable and revolutionary as any other form of engagement.

1. *Imagining Space, Time and Spectacle*

In describing the illustrative power of the microscope, the photographer Roman Vishniac wrote, "in nature, every bit of life is lovely. And the more magnification we use, the more details are brought out, perfectly like endless sets of boxes within boxes".[1] His statement was meant as an analogy for the wonders of photomicroscopy with which he produced awe-inducing color images of the infinitesimal, but it also serves as a neat encapsulation of the broader ethos of the twentieth century scientific image-maker. In their quest to reproduce time and space on a roll of film and distill the essence of nature's form into the perfect photograph, these new cinematographers and photo scientists flung themselves into a never-ending chase for beauty and the unexpected. Each new discovery teased something next to uncover, some unknown dimension of reality to be documented. Image-making in the new century was like peering into the limitless world of the microscope, where nothing ever ended and each box, each image that presented a problem or epiphany, contained within it an infinite set of others.

Vishniac also unintentionally crafted a perfect visual metaphor for 'seeing' science. In addition to his stunning series of colorized microscope transparencies, of everything from enzymes to mitotic activity to close-up views of blood vessels and skin cells, he conducted research on the optical systems of insects.[2] It is from this work that he came to dissect the compound eye of a firefly, mount it to a lens and take an image through it. The resulting snapshot, as though from the perspective of the bug, induces the odd sensation of looking at something familiar made unfamiliar through a new set of eyes. And what better way to describe the effect that scientific images have on their viewer? The best of them offer the ability to look at something old with a profound sense of the new. This is a sentiment that will become especially relevant in the following chapters as the very act of looking at and understanding common objects (through X-ray, infrared, UV, time-lapse, macro and high-speed photography, fluorescence, electron microscopy, stroboscopy and spectroscopy, among other techniques) is turned on its head.



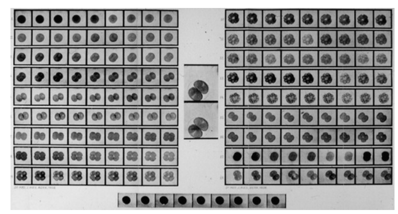
Roman Vishniac. Left, *Skin from my left hand* (1965). Right, *My daughter as seen through a firefly's eye* (1952)

This reinvention was already taking place at the very beginning of the century in the arena of popular entertainment. The Charles Urban Trading Company, one of the early film production units to take advantage of the commercial opportunities presented by the new medium of cinema, set its sights on making scientific films for popular consumption. In order to create a catalogue of shorts that would appeal to his clientele, the company's head Charles Urban hired the naturalists F. Martin Duncan and Percy Smith to train their eye on the world of the small. The result was a set of pioneering works in microcinematography notable as much for their tonal approach to their subject matter as for their attention to detail and pioneering use of time-lapse photography. Shown in theaters, movies like Duncan's *Cheese Mites* (which magnified in great detail the critters that lurk inside pieces of cheese) and Smith's *The Acrobatic Fly* (in which a fly is haplessly pinned to a microscope stand and made to "juggle" items) provoked curiosity, amusement and disgust in equal measure in their viewers.[3] Percy Smith's *The Birth of a Flower* best exemplifies the draw of these early works by showing color-tinted flowers magically spring to life from tight buds into offerings of petals. Natural cycles of transformation such as the metamorphic life-span of a butterfly or the flowering of a rose take several days or weeks to be observed, but with the manipulation of frame rate during capture and projection, they became events that could be experienced in single sittings. Early scientific film, then, presented the opportunity to not only see what flew under the radar of human vision but also to experience time spans that lay beyond human perception. The Urban films presented their subjects, features of the biological world, without a didactic or overtly

Clockwise from right: Two flies performing circus tricks on a ball in F. Percy Smith's *The Acrobatic Fly*//Select stills from Roberto Omegna's *The Life of a Butterfly* (1911) and Percy Smith's *The Birth of a Flower* (1910) paired with digital time-lapses of a monarch butterfly and a pink lily shot by Neil Bromhall and David de los Santos, respectively (from YouTube).

informative agenda. Instead, they appealed to the general public's desire to see something new and, above all, exciting.

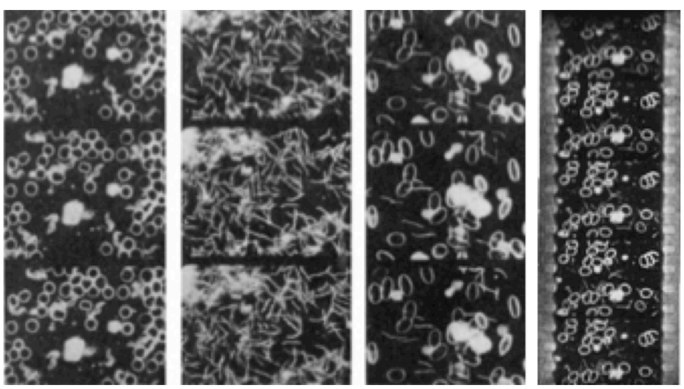
These Urban Bioscope pictures, as they were called, were the tip of the iceberg for time-lapse and micro-cinematography. They were joined by other efforts designed to maximize scientific utility. Nearly a decade earlier the botanist Wilhelm Pfeffer of Leipzig used stop-motion and chronophotography to produce temporal illustrations of the stages of plant growth driven by heliotropism. In 1907, Julius Ries, a Swiss who had worked with the Marey institute to film the stages of cell division, managed to divide the fertilization of sea urchin eggs into discrete images. These images could then be run together to convey in full the embryonic process of mitotic replication. This achievement was matched contemporaneously by Lucienne Chevroton and Fred Vlès in France with a study of sea urchin zygote cleaving.[4]



Julius Ries, the stages of division in a sea urchin egg (1907)

These types of films, made in controlled experimental environments for scientists to share and discuss, visualized principles of the biological sciences (the stages cell division, botanical growth) traditionally represented through drawings and diagrams but never before seen outside of these formats. Their verisimilitude demonstrated another value of the scientific film: to supplement the weaknesses of indirect renderings of items of study which were useful but could never hope to convey the special texture and motion of a moving image sequence.

The indefinable qualities that made film such a wonderful tool for instruction were not lost on Jean Comandon, a microbiologist and filmmaker who would become an important figure in the emerging field of micro-cinematography. Interested in bacterial afflictions and reliable ways to diagnose them, Comandon looked to syphilis, a disease widely known as being hard to identify due to its long latency period and ability to disguise itself. He did so through the ultramicroscope, a new invention capable of viewing colloidal particles smaller than a wavelength of light.[5] Unlike conventional optical microscopes, which lit from below and relied on the reflection or absorption of light, the ultramicroscope acquired images through the scattering of light emitted perpendicular to its optical axis.[6] By using this technique, Comandon was able to spot syphilis' microscopic bacterial component, the spirochete, as a bright form against a black background. This dark-field illumination, unique to the microscope's optical properties, resulted in striking images of the spirochete that when compressed through time-lapse delineated its worm-like movement across the frame. The ultramicroscope, in other words, revealed a footprint characteristic to syphilis that could be observed in samples of blood and other bodily fluids. Comandon projected short sequences of these findings for others with the aid of the Cinematograph. Affixed to these projections was a clock pendulum and scale of distance so that the viewer could experience what was being seen through the prescribed quantitative language of the researcher.

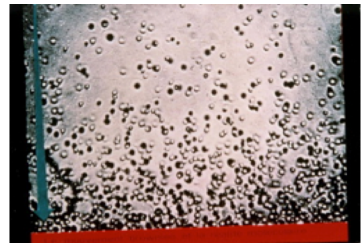


Left to right: Trypanosomes in the blood of a mouse, spirochetes in infected blood, spirochetes in the blood of a chicken and an original strip of the syphilis film taken by Comandon from 1909

The future of science filmmaking would find homes in France's largest distributors – Pathé (with whom Comandon would team up for studio space and resources), Gaumont and Éclair. Other countries, scientists and entertainers would also find good fortune in the arena of popular science filmmaking. Drawing on the innovative ‘tricks’ of Duncan, Smith and Urban and the research methods of Pfeffer, Ries and Comandon, they would find new ways to probe the depths of the zoological, bacterial and botanical world. But at the same time that film emulsions were capturing flora, fauna and the microscopic, an entirely new way of seeing, informed by invisible particles and bewildering emissions, was emerging.

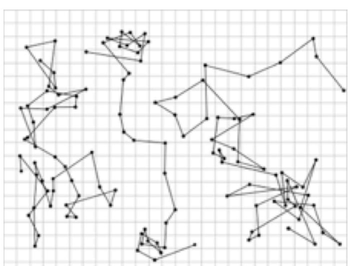
2. *X-rays, Atoms and All That Cannot Be Seen*

The ultramicroscope, aside from illuminating the agent of syphilis, played a vital role in visualizing atomic theory at the beginning of the century. Scientists had long known that small, granular particles adhered to irregular and continuous motion when suspended in liquids and gases. These erratic and seemingly unpredictable collisions were labeled as Brownian motion. The potential to document this motion was the crown jewel of proponents of atomism, a doctrine stating that systems of molecules are governed by the kinetics of heat energy and average, probabilistic behaviors. Not only would direct observation of Brownian motion give atomists a sorely needed empirical lifeline to fend off a barrage of criticism from classical thermodynamics but it would also act as incontrovertible proof of their theory.[7] These were the stakes when Albert Einstein published his paper on the matter in 1905. In it, he suggested that rather than trying to record the instantaneous velocity and direction of Brownian particles, a near impossibility, one could instead ignore their untraceable transit from point A to B by characterizing their behavior as mean *displacement.*[8] While Einstein’s formulation is sound, it is difficult to grasp, as many theoretical advancements are, due to its reliance on original and complicated mathematical vernacular. This is where the scientific image proves invaluable, as it can communicate theory, only more intuitively. This is what the ultramicroscopy of the physicist Jean Perrin did in the case of Brownian motion. Perrin's images, while not designed at the outset to test Einstein's results, nonetheless validate them in a way that suggested a poetic synergy between the abstraction of thought and the concreteness of the image.



A microphotograph taken by Jean Perrin of gamboge, a gum resin used in his experiments, suspended at different heights in water (Palais de la Découverte, Paris)

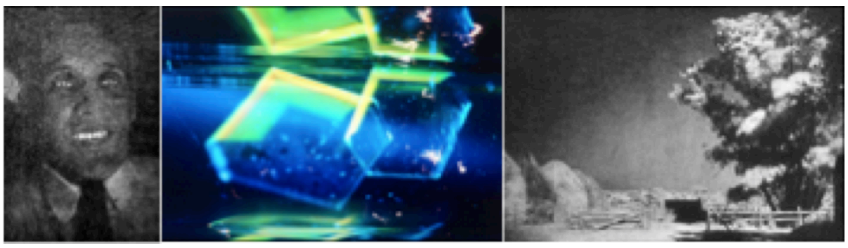
Before Perrin, others like Max Seddig and Victor Henri had used cinematography and the ultramicroscope to take snapshots of Brownian systems. Their efforts, however, were less convincing than those of Perrin who succeeded in part by accurately measuring the density and size of his particles and by using the microscope to take a detailed account of their distribution. Seddig's methods, it has been argued, were in fact comparable and took Einstein's conception of time and distance through displacement at face value by expressing them through the analogous language of film (each frame, after all, is a discontinuous segment of the observed particle's actual journey).[9] But it is Perrin's exposures that showed without a shred of doubt that colloid solutions obeyed the same laws as gases and that grains, while much larger, could accurately convey the essential stochasticity of the individual atoms and molecules present in the solution. Said another way, the ability to see Brownian motion elevated conjecture to observable fact



A diagram of particle displacement redrawn from Perrin's original 1909 publication and meant that the atom, while still un-seeable in its naked form, could now at least be explained through its visual proxies: plotted curves and frenzied specks in the ultramicroscope.

Like the chance movement of atoms, the existence of radioactive phenomena and emissions that lie beyond the visible electromagnetic spectrum nowadays are accepted as gospel in the scientific canon. They are explained thoroughly in our textbooks, exploited as sources of energy and inextricably linked to our modern security and healthcare infrastructures. Their ubiquity of application in instruments either too specialized or too mundane for the average person to take a consummate interest in has normalized features of science inherently strange. They exemplify the notion that, in spite of their widespread integration into our everyday lives, much of what is tangible exists far outside our immediate field of perception. That is until science, in conjunction with the image, peels back the layers of reality to reveal surprising and complicated truths.

One of these truths, that the spectrum of light is in fact wider than the range registered by the human eye, had been known since 1801. This in when Frederick William Herschel discovered infrared light by measuring the temperature gradient of visible prismatic light with thermometers.[10] It would take nearly a century after this discovery, however, for non-visible forms of light to be introduced into the realm of photography by Robert W. Wood. An inventive experimenter known for his competence in debunking scientific falsehoods (he disproved the existence of N-rays, a new craze sweeping science in the early 1900s, by establishing the confirmation bias of its discoverer), Wood spent much of his time conducting research on energetic forms of light. In 1903, he made a filter that transmitted only UV radiation.[11] He used this blacklight, later termed a Wood's lamp, to photograph his teeth, hands, and craters of the moon that were indifferent to visible light and had therefore gone unnoticed.[12] He also made landscapes bathed in the infrared, an achievement pre-dating IR film emulsions and later developments in thermal imaging. These images differed drastically in color absorption, opacity and shadow and showed the variety of ways in which one could peer at the natural world.



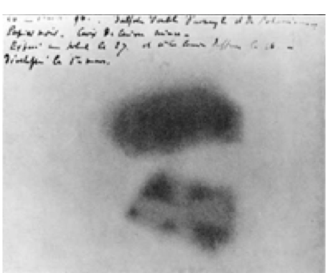
Left to right: An ultraviolet self-portrait of Robert Wood (notice the unnatural whites of his eyes and teeth), crystals taken under a blacklight by the author (UV light has been absorbed and re-emitted as visible greens and yellows along edges) and an infrared landscape picture taken by Wood (1910).

They fit nicely with Vishniac's transplanted eye by envisioning things in, quite literally, a new light; to see a tree through the infrared gaze of a bullfrog or a flower through the ultraviolet receptors of an insect is the ultimate perspective shift. His pictures demonstrate that vision is relative and show that "the appearance of the world at large is merely the result of circumstances that the human eye perceives…". Wood's sentiment was no doubt informed by his own work as well as the direction he saw science taking towards a brave new world, one launched nearly a decade earlier by the detection of new emissions that threatened to rock the boat of physical reality.

The discovery of the X-ray in 1895 by Wilhelm Röntgen was a shock with fantastic implications. The story of its detection, which goes to show the serendipitous circumstances under which leaps in research (and image-making) are often made, goes as follows. One night, while investigating the particles escaping from the enclosure of a modified Crookes tube (a glass vacuum made to propagate streams of cathode rays), Röngten observed a strange glow emanating from a cardboard sheet coated in fluorescent barium platinocyanide. After experimentally ruling out the cathode rays as the source of the observed excitation (they had been blocked with light-sealing paper and would've been unable to reach such a distance), he set about characterizing this new type of radiation, which he termed X-rays to denote their unplaceable nature. It quickly became clear that X-rays could be blocked by lead or the bones of the hand but could otherwise penetrate most opaque objects. Even more remarkable was the fact that the rays, upon contact with a photographic plate, produced a *shadow* of the object pictured.[13] This is shown clearly in the first radiograph ever taken, a plate of the wedding-band hand of Röntgen's wife that aroused curiosity and amateur interest in X-rays around the world.

Frau Röntgen's hand (1895)

The following year, as the new scientific oddity of X-rays was just beginning to be understood, radioactivity was uncovered through photographic means by Henri Becquerel. Inspired by Röntgen's breakthroughs, Becquerel set about studying the relationship between luminescent bodies and X-rays. To do so, he exposed a few crystals of uranium salts (known for their quick absorption and reemission of light) to the sun as they rested atop a photographic plate wrapped in a metal screen. During one experimental run, the weather complicated matters by proving intermittently overcast. This turn of events forced him to develop his images without proper daylight exposure. Thinking that the absence of sunrays would hinder the excitation of the crystal's phosphorescence, Becquerel expected to find faint images.



Ghostly exposures of Becquerel's spontaneously emitting uranium salts (1896)

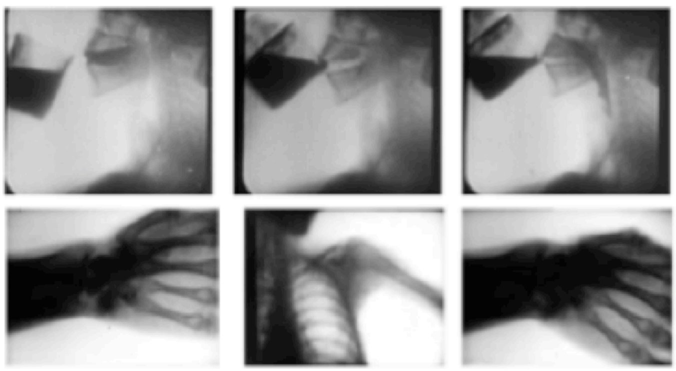
Instead, however, he found fully formed dark splotches on the plate.[14] These imprints had been formed in darkness by self-emanating rays that, like Röntgen's, traversed opaque materials but were characteristically different from X-rays. He termed them 'uranic rays' and eventually lost interest. It would take the labor-intensive efforts of Marie Curie and her husband Pierre (who would isolate tiny quantities of radium and polonium, new elements prone to instability and decay, from massive heaps of the ore pitchblende) to truly enumerate the importance of the new radioactivity.[15] Still, its beguiling presence is there in Becquerel's image, just as the power of the X-ray is demonstrated photographically in Röntgen's portrait of a hand.

These kernels of new knowledge were signs of the future, omens of great scientific, societal and technological upheaval destined to shape a gallery of twentieth century horrors and wonders. The volatility of the atom would find destructive outlets in warfare (the blast shadows of Hiroshima form indirect but sobering parallels to the images above) or be exploited for nuclear energy production while the refinement of X-ray technology would cement it as a cornerstone of physical science research and a versatile, life-saving imaging tool. In describing these new thresholds on which science now teetered, the biologist D'Arcy Thompson said in 1917, "we have come to the edge of a world of which we have no experience".[16] Once again, the image would rise to the challenge of navigating and understanding the headier implications of this new world in which X-rays allowed people to see *through* matter and radioactivity showed that matter *itself* was unstable.

An autoradiograph of contaminated shoes left by residents of towns affected by the Fukushima meltdown in Japan. 24 hour exposure taken by Masamichi Kagaya.

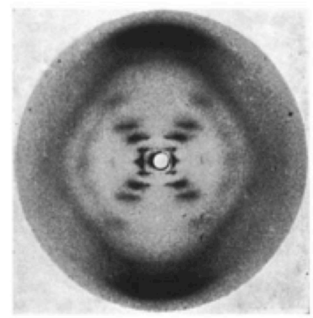
Suddenly, the living and inanimate became linked to their underlying structure as never before. This is where their secrets lay and where the image needed to probe.

While radiation came to be understood as the emission of alpha, beta and gamma particles from atomic nuclei, X-ray technologies reached new heights.[17] Still pictures taken in the years after Röntgen's discovery were soon eclipsed by moving film radiograms that showed organ respiration and digestion. Other problems plaguing early roentgenograms and X-ray cinematography would be solved over time with better emulsions, stronger tubes and a series of clinical advancements. This happened at such a fast and sustained rate that by the mid-century, direct and indirect (through the use of a fluoroscopic instrument) X-ray films and photographs could be guaranteed to be reliably accurate in virtually any clinical setting.[18]



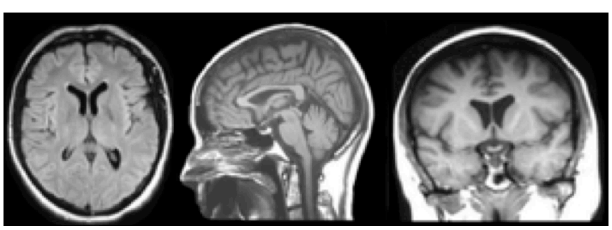
Above: Roentgenfilm I: An X-ray demonstration of fluid traveling down a patient's throat. (1936). Stills from video.
Below: "Cineradiographic studies" of joint movements of the human body. (1948). Stills from video.

While X-rays were revealing secrets of the body, they were also undressing the structural features of crystalline solids. In 1912, Max von Laue and two of his colleagues discovered that X-rays diffract from atomic gratings – crystals. These diffraction patterns, it would be realized, were the Fourier transforms of the ordered arrangements of atoms in space and could be used to make composite images of crystal lattices that included their electron density, atomic bonds and symmetry/disorder.[19] X-ray crystallography and its various forms would over the years unravel the secrets of viruses, enzymes, proteins and other biochemical molecules, leading to important advancements in chemistry, biology and the pharmaceutical industry. Its most widely recognized application, however, is found in Rosalind Franklin's picture of the diffraction pattern of DNA which, albeit without proper credit, Watson and Crick used to formulate perhaps the most popular image in all of science–the double helix.[20] The Franklin picture is exhibit A in the case that scientific photographs can act as repositories of complicated information while also being admired for their elegant simplicity.



Rosalind Franklin and R. C. Gosling's *X-ray diffraction pattern of the B form of sodium salt of DNA* (1952)

The legacy of x-rays, namely the idea that seeing an object's interior is necessary to understanding it as a whole, is attested to by other miraculous advancements in body imaging. The CT scan, developed in the early 1970s, used computing power to scan "slices" of the body detected by a series of angled X-rays beams[21]. As it advanced, computerized tomography allowed for non-invasive scans of the living brain whose folds and cross-sections had only been seen on the dissecting table or during surgery. But while CT excelled at imaging bones and cartilage, it had difficulty detecting soft tissue surrounding those areas.[22] The MRI, an unlikely outgrowth of research in nuclear physics, solved this problem. Theoretically underpinned by the measurable magnetic spin moment, or nuclear magnetic resonance, of atoms, MRI machines re-align the protons of hydrogen atoms found in localized areas of the body with an alternating magnetic field. They then irradiate these protons with pulsing radio frequencies that excite their spin and produce a



Axial, sagittal and coronal MRI views of the brain taken by David C Preston, MD (2006) signal that is sent back, collected and turned into a three-dimensional projection of an anatomical feature.[23] Unlike tomographic scans, MRIs do not use X-rays. Its images are inverted X-ray scans, where positive and negative space (bones and soft tissue) reverse themselves.

Apart from these technical aspects, medical imaging technology stands out because of its visceral connotations. MRIs are seen as alive and fleshy compared to the coldness and sterility of an X-ray. The ultrasound of a fetus spells life, while a body scan of a malignant tumor portends death. These preconceptions about what pictures represent can greatly shape their reception among patients and the general public. On the other hand, a radiologist, pathologist or sonographer might have a very different interpretation of the same image, one informed by training and experience. This is all to say that medical scans are effective scientific images because they carry a subjective power of persuasion (as expressive portraits of illness and health) as well as a literal usefulness (as pieces of bodily evidence). And like all effective scientific pictures they are tied up in competing and overlapping expectations and readings.

Ultrasound of a fetus taken by Dr. Wolfgang Moroder (2012)

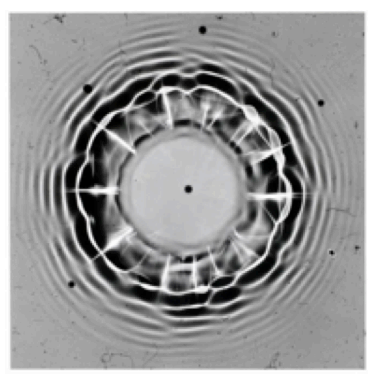
3. *Strobes, Seahorses, Soap Bubbles and Snowflakes*

Scientific images are often perceived as too impersonal, top-heavy on information or reliant on a viewer's prior knowledge to resonate on a purely emotional level. They are framed as being constituted solely from their subject matter and technical considerations, cases of form explicitly following function instead of works of pure art. This, of course,

Compositional similarities between Antelope Canyon in Arizona and a citric acid reaction. (taken from Viator.com and ICP's Roman Vishniac collection)

is nonsense. The great science films and photographs have as much expressive potential and beauty of form as their non-scientific counterparts. The differences between a spectrogram and a cityscape or a portrait of a bacterium and a portrait of a person are inconsequential if both have the visual unity and coherence of design that make for a startling image. The pictures of the scientist are subject to the same concerns and guiding principles of any picture: When and where should I put the camera? Am I effectively conveying texture, saturation and shape? How should this be framed? Does the depth-of-field, contrast or shutter speed need adjusting? Most importantly, am I striking a balance between these things that will make for the best possible composition?

For Harold Edgerton, Jean Painlevé, Berenice Abbott and Wilson Bentley, this last question could be answered in the affirmative. Their photographs and films, often surprising but never boring, exemplify the notion that within nature there exists startling works of art and that if science wishes to reveal nature's character then it must embrace a tactful artistry to match.



Edgerton, *Water drop splash* (1986) taken at the exact moment a fluid makes contact with a film emulsion.

Edgerton, it should be said, might have been offended by the suggestion that he was an artist. After all, he is quoted as saying, "Don't make me out to be an artist. I am an engineer. I am after the facts, only the facts."[24] It is a direct yet vexing statement from a man who shaped the high-speed world in his own delicate image. Edgerton's career as an electrical engineer at MIT spanned the majority of the twentieth century. It is his photographic output that he is most remembered for. Using a deft hand, trained eye and unappeasable curiosity, he set about documenting the world in as many new and inventive ways as possible. Many of his accomplishments were achieved by harnessing the power of strobe lights synchronized to a single-flash mechanism. This method is akin to taking a photograph with a flash bulb in the complete dark, only the high-speed photographer deals with windows of opportunity lasting unimaginably small fractions of a second.[25] Edgerton's single-flash apparatus, a set-up of high intensity lamps, triggers and a camera, allowed him to stop moments of acceleration like the flight of a bullet or the trajectory of a tennis ball with piercing exactitude. He also pioneered the use of the stroboscope, an instrument he first used to identify damaged rotary blades at the research facilities of General Electric and later adapted for his own purposes at MIT.[26] The effect of the stroboscope can be observed by synchronizing a pulsating light with a running faucet. In uninterrupted light, the naked eye sees an indistinguishable stream of water, but with the aid of the strobe, a cascade of discrete, pearly drops emerges. Strobe technology divides motion into its component parts, a property valuable for practical motor repair, but Edgerton's genius lay in recognizing its potential to transcend traditional use.

Edgerton, *Cutting the card quickly!* (1964)

Bullet through apple (1964). Not without a sense of humor, Edgerton used this image in a lecture entitled "How to Make Applesauce at MIT.

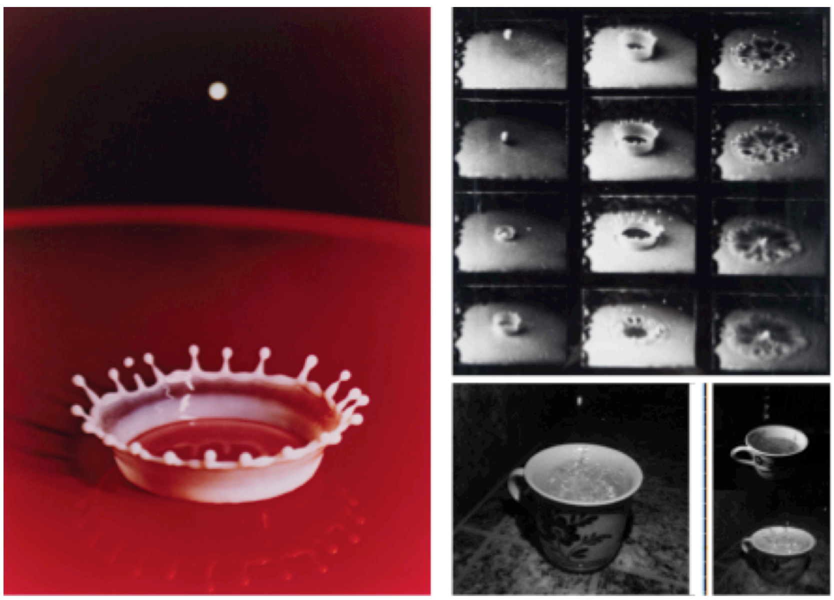
The stroboscope and flash, while elevated in purpose by Edgerton, were not entirely new technologies. Their roots stretched back to figures like Muybridge and Anschütz who cheated the limits of human vision. Instruments from the previous chapter like the Zoöpraxiscope and Tachyscope were essentially stroboscopic prototypes, albeit ones with Geissler tubes instead of instantaneous flashes of light and metal slits instead of 1/100,000 of a second exposures. Edgerton's coupling of these age-old experiments in vision persistence with electronic equipment and circuits allowed him to tame time and space with remarkable aptitude. His photographs follow in the tradition earlier high-speed recording and the chronophotography of Marey but they all have a competence, sharpness and sheen that sets them in a class of their own. These qualities are also found in his films, some of which show the results of staged sonar demonstrations (the MIT alumni pool and marine biologist Jacques Cousteau were

Left to right: Edgerton using a motorized fan to create vortexes of smoke and a picture I took after observing a similar formation rise from my pancakes.

Edgerton's multiflash photographs of Gus Solomons Jr. (1960) and a baseball batter (1965) along with re-creations featuring my grandfather made using an iPhone.

integral collaborators during Edgerton's foray into underwater photography). Others, like the popular short *Quicker'n a Wink,* walk the audience through his laboratory process.[27]

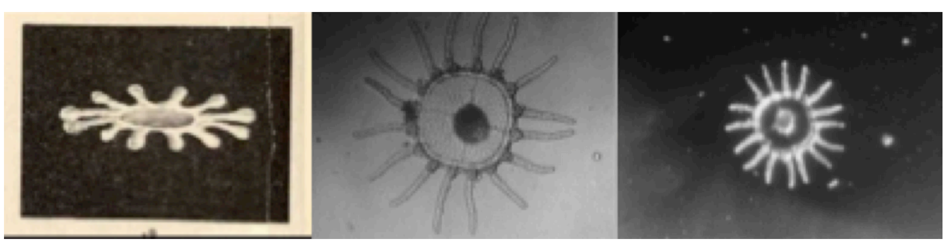
It is this process, which straddled the line between the perfectionism of the artist and the inquisitiveness of the engineer, that sheds the most light on his legacy. Take, for instance, the creation story behind the poster-child for popular science photography, Edgerton's famous portrait of a milk splash. A perfect image of careful folds, pleasing symmetry, and painterly contrast of light, shadow and color, it instills a wonder for nature's perfect and simple geometry, a picture fully-formed on arrival. In reality, the success of *Milk Drop Coronet* was the beneficiary of decades worth of trial and error that resulted in thousands of early and late exposures of broken crowns and half-formed splashes. While adamant about being an investigator first and composer second, Edgerton's perseverance in chasing a particular 'look' speaks to his instinct for the ideal image, one which would, in the words of his colleague James Killian, be "eloquent as well as lucid….the best possible correlation between meaning and expression".[28]



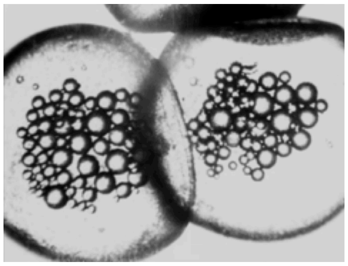
One of the most strikingly composed photographs of all time, Edgerton's often-published *Milk Drop Coronet* (1957), next to earlier, discarded film tests and a few unsuccessful experiments in fluid stroboscopy by the author.

It is worth mentioning that Edgerton's experiments in fluid dynamics were preceded by the physicist Arthur Worthington who, in 1895, published his own pictures to middling success[29]. Worthington's splashes and Edgerton's selection process speak to a parallel between research and image-making. Both rely on the accumulation of better results achieved through the implementation of vision with material, and hypothesis with experiment. This process of honing finds its natural end when the right result or snapshot, that is the one that correlates the most with its maker's original vision, is realized. It is this quest for perfection that unites the artist with the scientist and makes Edgerton's pictures both objective documents and personal expressions of the world around him.

Unlike Edgerton, Jean Painlevé had no qualms about being called an artist. To him, the imagination was something to be championed, not discredited. A true original, Painlevé worked during his career as a biologist, educator, animator, underwater filmmaker and photographer of sea-life. His film output, marked by a singular collection of playful and tonally surprising experimental shorts, is as varied as his professional resumé. They run the gamut of the documentable, from the love rituals of the octopus and the feeding of the vampire bat to the life of the urban pigeon and the universe of the sea urchin. Some meditate on population and crystal growth while others look at extraterrestrial surfaces and the fourth dimension.[30] Painlevé also made several research films meant to run with only title cards and no music. One



Sharing shape: An engraving from Arthur Worthington's *The Splash of a Drop* (1895) and two stills from Jean Painlevé's *How Some Jellyfish are Born* (1960)



A shot of cytoplasms from *The Stickleback's Egg* (1925)

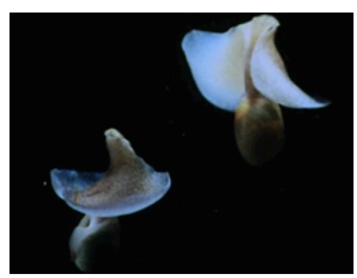
shows surgery being performed on a hemorrhaging dog while another reveals in great detail the structure and fertilization of the stickleback fish egg. He is most remembered, though, as an auteur of colorful science films that use voice-over narration and musical cues to guide their audience through their immersive images. His unique films, poetic and surreal depictions of worlds only accessible by the camera, showcase a sense of fun and wondrous creativity too often lacking in explanations of science.

Painlevé used a number of filmic techniques in an exploratory capacity. These include use of magnification and time-lapse cinematography as well as optical effects and inserted diagrams. In the short *Diatoms*, we see microscopic algae zip around the frame like 'ships at sea', their frenzied activity revealed by accelerating time. Elsewhere, the ultramicroscope reveals their fan-like colonies and morphologies in strange and glowing gradients of color, the result of chromatic aberration. Every insert and tracking shot shows Painlevé's miniscule actors engaged in a grand drama. In one instance, we see a jittery arthropod oscillate back and forth in agitation. As its shaking becomes furious, the music swells to a high-pitched breaking point and the narrator suggests that it is having a nervous breakdown. These elements of humor and anthropomorphizing are found in many of Painlevé's films. In *Sea Urchins*, close-ups of suction cups, jaws and gnashing teeth take

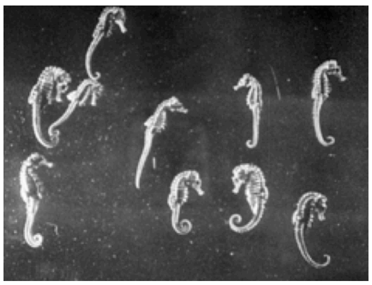
Nature's sculpture in *Sea Urchins* (1954) on a vivid and ghastly form. Bright red feelers assume the look of imposing columns and wild-looking stems float in the ether like flowers in a wind-sculpted field. Sequences like these are derived from a desire to document but also a want on the part of the filmmaker to engage the viewer's symbolic imagination. Painlevé was undoubtedly concerned with showing these exotic and inaccessible worlds as they were, but he was also very much interested in tethering them to the familiar. Inserts of vampire bat wings and octopus tendrils become visual metaphors for appendages of the human body. Even when the world being charted is non-aquatic, as is the case in *Liquid Crystals* (a kaleidoscopic view through a polarizing microscope of isotropic crystallization) there is an animating force and anthropomorphism at work on the audience's interpretive experience.

Painlevé's desire to connect human and zoological form is often expressed in poetic montages of dance and music. In *Hyas and Stenorhynchus*, crustaceans are seen waltzing to Chopin and in *Acera, or The Witches' Dance*, the treading of mollusks through muddy terrain is set nicely to classical music. Propelled by curved flaps, they bob around to a buoyant melody, parachuting in and out of frame like trained dancers. We learn that these choreographed sea snails can act as either male or female in the fertilization process, an ability they share with the subjects of Painlevé's most popular movie, *L'Hippocampe* (*The Seahorse*). Made in a confined aquarium space with a mobile camera unit (this tended to be the norm, although some films were shot with scuba gear

A spirograph worm extends its awesome plumage in *Hyas and Stenorhynchus* (1927)



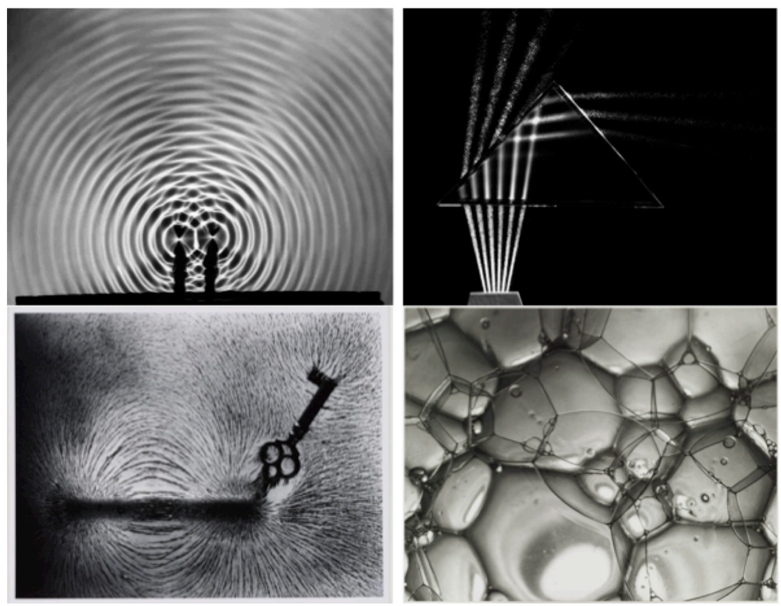
Two mollusks dance in *Acera, or The Witches' Dance* (1972) and a water-proof camera rig of Painlevé's own making), the short focuses on the enigmatic seahorse, a favorite animal of the surrealists.[31] Replete with serene imagery and tongue-in-cheek asides (footage of an actual horse race can be seen behind the tank at one point), it is a memorable aquatic menagerie not least for its melding of scientific fact and artistic fiction. This characterization can be applied to Painlevé's entire body of 'magic realist' films.[32] Nearly all of them champion a synergy between fact and fiction and suggest a greater potential for the science film achievable through an expansion of its aesthetic and operational boundaries. The filmmaker himself summed up the rationale behind his unorthodox approach by stating, "Science is a fiction. To make science-fiction is downright useless".[33] And he was right. The reality of science is as unbelievable as any fabrication. After all, how could someone look at the curled form of the seahorse or the tentacles of the color-shifting octopus or the branches of the developing jellyfish and be in need of an even greater fiction? As Painlevé showed us, nature's most fantastic secrets rest beneath our water-treading feet.



A gathering of seahorses in *L'Hippocampe* (1933)

Polymer spherulites growing in *Liquid Crystals* (1978)

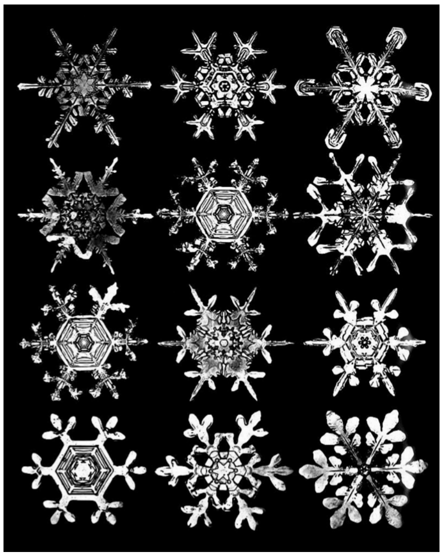
Berenice Abbott was not interested in fiction of any kind. A strong believer in the impartiality of the camera, she lent her formal artistic experience to the scientific community in order to creatively interpret its problems and foster a mutually beneficial linking of the two. By the time Abbott transitioned into scientific image-making, she had already earned photographic frame for her portraiture and depression-era New York cityscapes.[34] Her early science work focused on relaying objects like soap bubbles and penicillin molds with her invention of the Super Sight camera, essentially a flipped *camera obscura.* Whereas that photographic forerunner took a wide expanse and filtered it through a pinhole, Abbott's invention took a small object in a light box and projected it onto a large sheet of photosensitive paper to enhance its contrast and sharpness.[35] This need for razor-sharp picture clarity also permeated her work as an editor for *Science Illustrated.* Not afraid to tell scientists when and where they lacked visual panache, Abbott advocated for her photography to become a utilitarian tool in the laboratory and classroom. Her pictures command attention not just for their high contrast and deliberate lighting but also for their educational functionality. The series of images she produced in the late fifties for the national initiative known as the Physical Sciences Study Committee 'teach' the key principles of science, not through laws and equations but by plainly showing them in action. Her rendering of a light beam passing through a prism shows in one concise sweep three pillars of optics known for centuries: reflection, transmission and refraction. Another picture, of an inference pattern resulting from two wave ripples, is not only a pleasing picture but also a replication of the double-



Bernice Abbott, clockwise from right: *Multiple Beams of Lights* (1958-60), *Soap Bubbles* (1946), *Magnetism with Key, no. 7* (1958-61) and *Wave Interference Pattern* (1958).

slit experiment that shows the dual wave-particle nature of light.[36] A similar integration of theory and image can be found in her strobe snapshots of falling balls and swinging pendulums that neatly encapsulate the fundamental concepts of Newtonian physics (just as her iron filling photos shows the orderly contours of a magnetic field). Abbott's images, especially her stroboscopic studies, live on in high school textbooks. They are seen and appreciated by generations of students assigned to read blocks of text doing in so many words what her pictures were able to do with none.

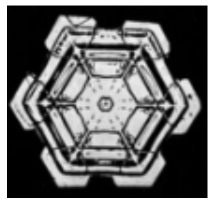
We end our journey with the quiet but profound work of Wilson Bentley, a farmer boy from Jericho, Vermont with no formal scientific training who nonetheless left his mark on the fields of meteorology and crystallography. Bentley grew up under the spell of the winters that blanketed his rural landscape in snow and ice. While others milked dairy cows and tended to crops, he marveled at the ephemerality of the snowflake through the microscope.[37] This childhood interest led him to a life's work of capturing and recording of dew, window frost and snow crystals. Still celebrated today for their lucidity, Bentley's photomicrographs are all the more impressive for being entirely self-made in his modest farm shed with a bellows camera and his knowledge of the land. Each ice crystal, a glistening and unique variant on a shared hexagonal design, beckoned to him to be preserved before evaporating into thin air. To take their picture, Bentley devised a procedure that demanded great patience and quick thinking. First, he collected the day's snowfall on a black board and speedily transported it indoors to fend off the threat of wind. He then identified the best crystals with a magnifying glass, moved them onto a microscope slide with a wooden splint and pressed them to its glass surface with the careful caress of a feather. Once this was done, he fit the plate holder onto the attached camera apparatus, pointed it towards the sky for ample ambient light, set the lens to a high f-stop and, using a homespun wooden pulley mechanism, focused for a proper exposure.[38]



A page from Bentley's *Snow Crystals*

Bentley's thousands of pictures, fantastically eye-popping visions of colorless minutiae, are found as duplicate negatives in the book *Snow Crystals*. Flipping through its pages, one can admire the patterns, symmetries, grooves, ridges, arms, planes and air cavities of the crystal up close, marvels of nature's architecture that silently evaporate on our winter coats and melt in our hands. The constitution of the snowflake was, of course, an old mystery by the time Bentley's photos made their way into the world. Even the astronomer Johannes Kepler, in his 1611 treatise *The Six-Cornered Snowflake,* wondered aloud about their origin and ultimate purpose. Hoping to find an answer, he looked at the geometric ornamentation of materials like the honeycomb and pomegranate before throwing up his hands and attributing their creation to what he called *facultas formatrix* or the formative faculty of God.[39] Thanks to advancements in X-ray crystallography, we can now take God out of the equation and answer Kepler's question by enumerating the structural and molecular properties of ice. And yet Bentley's images, like those of Abbott, Painlevé, Edgerton, are still spiritual. They persist in spite of new knowledge, timeless for testifying to the obsessiveness of the artist and the exactitude of the scientist and for never failing to spark an appreciation for the *facultas formatrix* present in all things.

Sculpted with care and a desire that comes from wanting to *know* more deeply by *seeing* more deeply, the most astounding scientific images are the ones that, like an untouched snowflake, open the mind and enrich the soul with possibility.

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-Chapter 4-

Modern Landscapes in Scientific Image-Making

"In a magnified view, a yeast cell - or some other tiny, everyday material - can…rival the monumentality of something much larger. Similarly, a poorly composed picture of a galaxy may fail to convey any sense of great size and scale…the means of representing the object are not fixed and given…"

–Elizabeth A. Kessler

"Now the photograph is as malleable as a paragraph, able to illustrate whatever one wants it to."

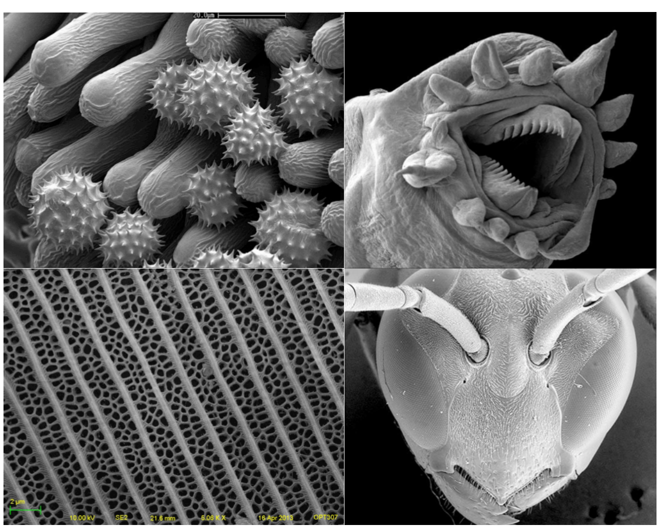
–Fred Ritchin

We live in an unprecedented time for image production. In an age where data are common currency and information is trafficked at unheard of volumes and speeds, visualized science keeps pushing further against its bounds. With each new conceptual leap and technological breakthrough we seem to inch closer to the precipice of what is possible, limited only by the pace of progress and the height of our imagination. The shift from analog to digital image acquisition has been a profound one. It has lead to unforeseen capabilities in access, scale, storage and replication but has also wrapped image-making in a veil of unseen processes. Some complicate the task of evaluating the image on its own terms while others, perhaps, call for a restating of the term 'image' altogether.

While the scientist's picture has always been adjustable, it is now more fluid than ever, governed by a host of interfaces and modes of capture. These range from electronic sensors and powerful microscopes to computer editing software, delicate bits of circuitry and bulky information processors. Raw data is retouched, cleaned, segmented, composited, compressed, focus stacked, falsely colored and otherwise massaged to reach a desired look. While these procedures are directly responsible for the integrity of the image, their presence is not always immediately obvious. Where do these computerized visions and pixelated artifacts, radically different in their behind-the-scenes engineering but familiar in their pursuit of new sights, fit into our story of the image?

To tease out some of the directions in which scientific image-making has and will continue to be pulled, we will mention a few relatively recent developments and try to deconstruct them into their component parts. The first section will look at the applications of electron and fluorescence microscopy in untangling the secrets of the incredibly small. The second will consider exciting developments in the field of astronomy and its attempt to untangle the secrets of the incredibly large and distant. We'll round out our discussion by mentioning some recent still and moving scientific image feats that just maybe hint at the future.

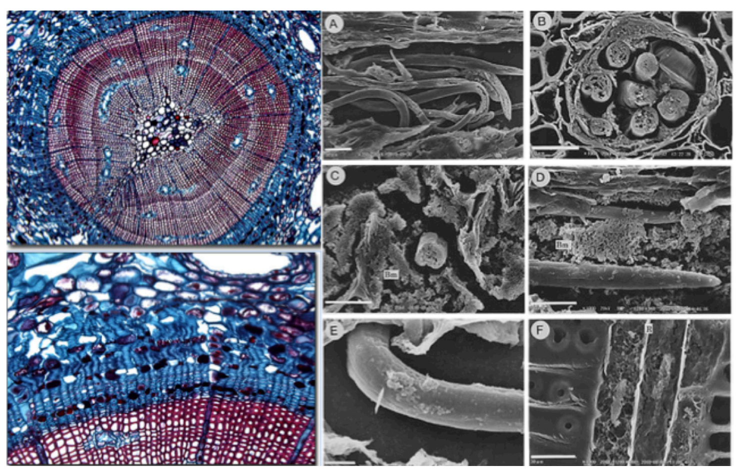
1. *Peering Down and Looking Through*



Left to right: Scanning electron microscope images of daisy pollen (Roger Heady), a hydrothermal worm (FEI and Philippe Crassous), the interior structure of a butterfly wing (Amanda Amori, University of Rochester) and the head of a bee (Hitachi High-Technologies)

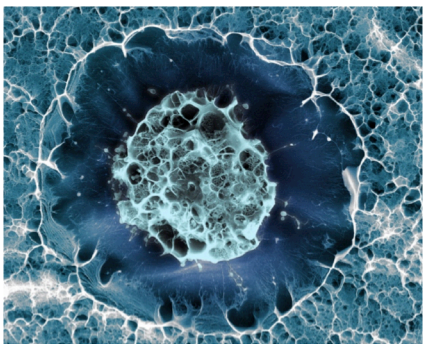
Today's microscopes are responsible for some of the most visually entrancing representations of science. Their images, whether made with beams of electrons or strategically placed fluorescing materials, illuminate some of the most bizarre pockets of biology and the material sciences: clusters of blinking neurons, landscapes of fractured metals, inert anthropomorphic forms, nightmare-inducing visages of the living. Like pictures of far-flung corners of space or the deepest of underwater depths, they grant us access to the inaccessible, showing us the world in all its otherworldliness. Modern improvements in computing power and technology have only enhanced this power and enabled startling improvements in color, magnifying power, resolution and depth of field. Scientists, in scanning the nanoscale with such power, have been given exceptional leeway to fabricate images how they see fit. As a result, the topography of the microscopic world is more dependent than ever on the tools being used to mine it.

The challenge of modern image-making, be it through a satellite or a CCD telescope or a digital camera attached to an electron microscope, lies in resolving so that as little detail and information is lost in the process. The scanning electron microscope (SEM) is a testament to image clarity. The electromagnetic equivalent of a stereo light microscope, SEMs are made up of an electron column, specimen chamber, vacuum pump, set of detectors, computer monitor and control panel.

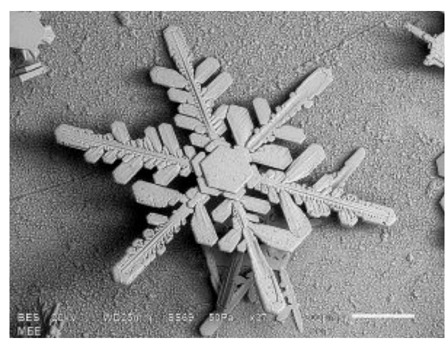


(*Left to Right*) Levels of magnification: The resin canals and tissue of pine wood stained and taken with a CCD camera at 10x and 20x magnification (Michael W. Davidson). Electron microscope images of pine on a scale of 10-30 μm (Yasuhara Mamiya).

Once a sample is placed in the chamber for observation, a stream of primary electrons is accelerated through the vacuum column by an electric field formed between a thermiotic cathode (a tungsten filament) and anode. These electrons are then focused, much like light in a conventional microscope, but with a current-induced electromagnetic lens instead of a piece of glass. This beam proceeds to hit the specimen in a raster pattern, a back-and-forth scanning motion used to generate an image one line at a time (this same technique is used to make interlaced pictures in old cathode ray television sets). As this happens, the primary electrons either dislodge the sample's secondary electrons or hit their nuclei and backscatter. Depending on the imaging mode, the resulting secondary and backscattered electrons are detected, sent to a monitor and converted into dots on a grayscale that aggregate to form a detailed black-and-white image. The elemental composition of a sample can also be determined by detecting the characteristic X-rays that are released from primary electrons colliding with the atom.[1] The transmission electron microscope (TEM) is another useful application of the short wavelengths of electrons. Instead of raster scanning, TEMs send electrons straight through the object. This method results in less dimension and texture than provided by a SEM but proves invaluable for imaging thin materials like tissue sections, cell membranes, crystal lattice dislocations and viral molecules.

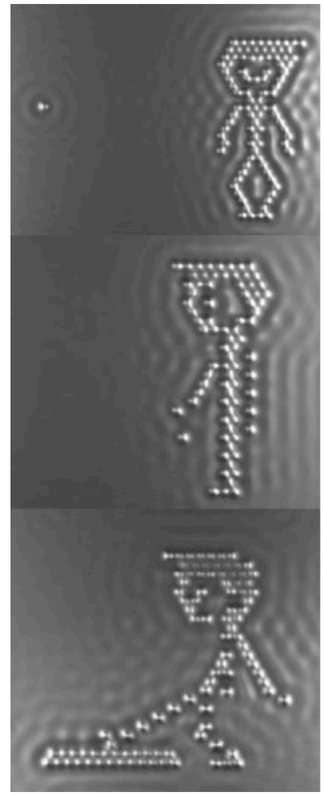


A false-colored stem cell taken through a cryogenic scanning electron microscope (S. A. Ferreira et. al.)



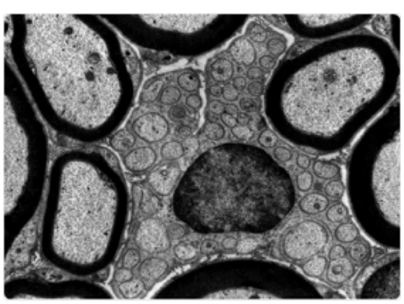
A modern take on Bentley: An SEM image of a snowflake (Kurt Schenk)

The fundamental technologies underpinning electron microscopy are not particularly new (the basic design for the SEM dates back to the mid-1930s). The instrument's longevity, however, lies in its capacity to work in conjunction with other operations and features that improve efficiency, sensitivity and targeting precision: negative staining, sputter coating (in which samples are dehydrated and metal plated), cryogenic preparation (cryo-EM), spectrometry, aberration-correcting electromagnets and direct-electron detectors to name a few.[2] Developments in nanotechnology and biological research have come from these additions as well as devices like the scanning transmission electron microscope (STEM), a combination of the raster components of SEM and the penetrating functions of TEM, and the scanning tunneling microscope (STM), an application of quantum tunneling that uses voltage and a fine metal point to probe the surfaces of nanotubes and move *single* atoms like building blocks.[3]

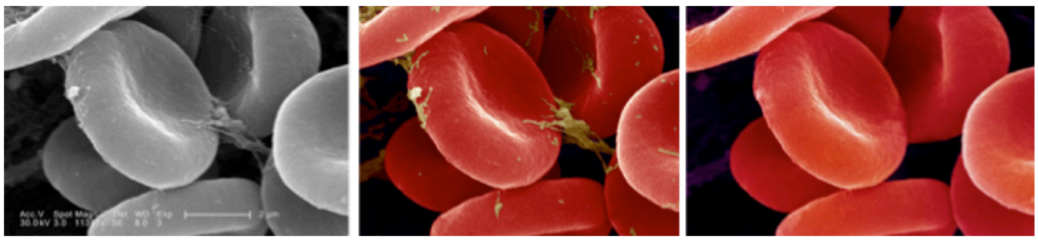


Stills from *A Boy and His Atom,* a stop-motion movie made with a scanning tunneling microscope about the atomic bond of friendship (IBM, 2013). Each frame required moving single atoms

Electron microscopy is made all the more creative an endeavor with programs like Photoshop that 'colorize' otherwise grayscale images. The options available to the microscopist for post-manipulation are quite wide and include using a lookup table to artificially ascribe hue to shade, editing manually or



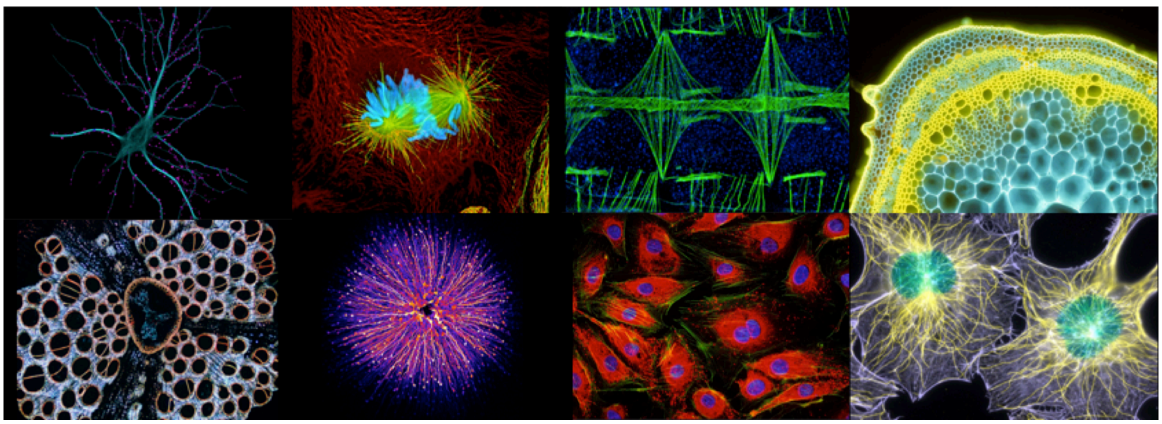
A TEM micrograph of a cell and myelinated fibers (Jose Luis Calvo) with an automated photo-analysis software and superimposing images to increase compositional contrast and shadowing. One can also render flat results three-dimensional by measuring two or more SEM images taken at different angles (in a process known as stereophotogrammetry).[4] The most widely published EM pictures are presented with



Two edits (middle and far right) of an EM image of red blood cells (left). Neither of their captions made mention of artificial coloring, smoothing of background or erasure of details (taken from *Getty Images* and *Science Photo Library*).

pseudo-color and fake depth so as to be more intuitive. These types of interventions, if recklessly made, can obscure raw data and create misleading features. When done thoughtfully, they can make the unfamiliar more palatable and guide the viewer past extraneous information. They are not just facelifts but adjustments with real implications for image data and interpretation and their prevalence speaks to the disconnect between what we see and what we want to (or expect) to see and our new-found ease, provided to us by computers, in bridging this gap irrevocably. These are familiar considerations, one which we've seen in longstanding debates over objective representation, the role of personal taste and the obligations of the impartial image.

The visual aesthetic of the microscopic image has also been expanded with advancements in fluorescent microscopy. Techniques existed before the introduction of fluorescence to make the planar view of the microscope more 'interesting' and reveal structural and chemical secrets otherwise elusive in conventional bright-field microscopy. These included phase-contrast microscopy in which background and specimen-scattered light is treated separately, and differential interference contrast or Nomarski microscopy in which polarized light is divided by a prism into two beams, sent through a specimen and then rejoined.[5] These techniques imbued images with colors, brightness and relief not normally seen in a transparent view. Fluorescence microscopy, however, uniquely takes advantage of the phenomena of fluorescence and phosphorescence (both of which involve the absorption and re-radiation of a wavelength of light), adding a beautiful glowing aura to the microscope's field of view that is both scientifically valuable and

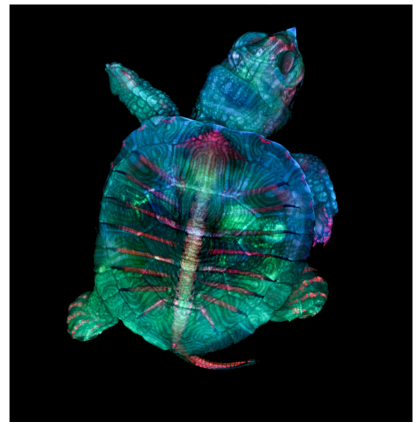


Top: Fluorescent images of hippocampal neuron (62x mag, Kieran Boyle), newt lung undergoing mitosis (240x mag, Alexey Khodjakov), mosquito heart (100x mag, Jonas King), soybean stem with two fluorochromes (50x mag, Phil Gates).

Bottom: Stem of a morning glory vine (4x, Dr. Edgar Javier Rincón), central region of the retina (40x mag, Hanen Khabou), endothelial cells (100x mag, Jakob Zbaeren), fibroblasts of a mouse (100x, Dr. Torsten Wittmann) [All images were featured in Nikon's Small World Contest}

lovely to look at. Fluorescent indicators tailored to specific targets (such as lipids, anti-bodies, individual organelles and ions) are used to excite regions that in turn give off lower energy wavelengths that the microscope captures. This labeling is, amazingly, achieved simultaneously at different points on the sample using individualized fluorescing tags like fluorochromes and fluorophores. Additionally, the biologist can use bandwidth filters, dyes, stains and photobleaching to track molecular movement and isolate areas of cell activity more assuredly.[6] Optical sectioning, in which the microscope divides the focal planes of the fluorescent image, along with digital manipulation techniques like focus stacking (which creates a fuller depth-of-field) and compositing (sometimes of several hundred images) assist in making truly stunning demonstrations of probed objects. But as with astronomical objects or anything that involves counting photons, resolution is diffraction-limited (super-resolution microscopy not withstanding).[7] This is especially true in the case of fluorescent microscopy done to localized proteins and other structural components that can only be seen with EM.[8]

Still, fluorescent images have become something of a craze, and for good reason. They are versatile tools capable of illuminating everything from gene expression to neural pathways. They're also that rare class of scientific image (think radiograms, X-rays) that captivate with their alien glow. It is this strange glow of nature (green fluorescent proteins, after all, come from jellyfish) gifted to the image-maker that has, in a very meta-twist, become a way to investigate its very source. Who knows what other gifts lie waiting to be discovered or what other kinds of radiant, twinkling pictures will come from them.



An autofluorescing turtle embryo excited with three different wavelengths. The final image was compiled from hundreds. (Teresa Zgoda and Teresa Kugler)

2. *Gazing Up and Searching Beyond*

One of the major throughlines of this thesis has been the multiplex nature of the scientific image, the fact that its most characterizable aspect is its unwillingness to be uniformly characterized. Its identity and value are rooted not in the prevalence of any single gestalt or framework but in the coexistence of several operating together. The image's success in eschewing categorical confinement is evidenced in the competing terms we use to describe it: subjective and objective, artful and scientific, inspiring and impartial, existing and made, truthful and misleading. These dualisms are nowhere more prevalent and intertwined than in a field utterly transformed by the digital revolution: astronomical imaging.

In the basement of the Sanders Physics building, tucked away in a block of rarely visited file cabinets, there is a stack of plates enclosed in browning manila envelopes.

Records of old-school spectrometry at Vassar

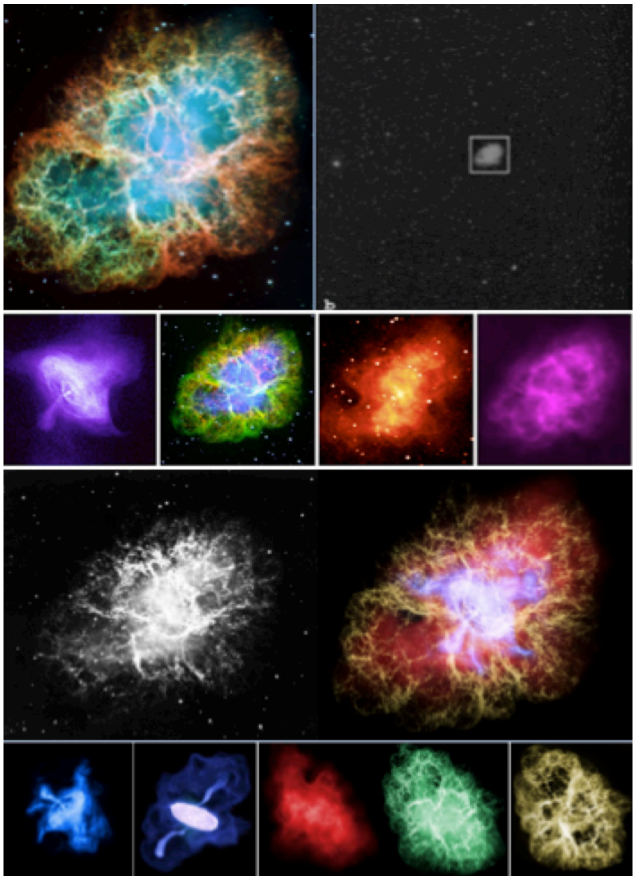
Labeled with the names of several observatories and marked with small dashes denoting the spectral composition of starlight, they're reminders of a time not so long ago when astronomers at the mercy of analog photography recorded the heavens on sheets of brittle glass. This mode of image-making, once the norm, has since been completely phased-out, made obsolete by numbers and CCD pixels. The astronomy of today is digital, its information detected by ground-based telescopes and space satellites on light-sensitive arrays, sent to computers and processed accordingly. Rich in aesthetic designations and image methodologies, its processes holds the awesome power to shape, with far greater effect than any single photographic plate, our understanding of the universe and place within it.

Images of the cosmos are often misconstrued as objective pictures, sights that if one had access to a powerful stellar camera could be framed through the viewfinder. In this reading, astronomical images are unmediated arrangements of photons. Quasars really do shine like flares in the night, ionized gas does glow in radiant color and spiral galaxies are as wispy and ephemeral as they appear in their "photographs". These notions are reinforced (or at the very least left unquestioned) by news articles with titles like

"Observatory Snaps Cosmic Soap Bubble"[9] and "Hubble Opens New Eyes on the Universe"[10] that grant the act of recording the universe the familiarity of a family portrait or human vision. The specifics of making famous images like the Pillars of Creation or the Cat's Eye, Butterfly or Crab nebula are left unspoken. Their symbolic weight and emotional appeal outweighs the intermediary steps of astronomical imagining (masking, sharpening, noise reduction, multi-wavelength coloring and saturating) that make them possible. This is not to say that space images are invariably doctored or sensationalized. Observational astronomy is predicated on gathering light to make images from raw data and in many instances making these images more legible through color and definition allows scientists do to their work.[11] Nor does it imply that every visual signal from above transmitted down to us is free from the temptations of a fraudulent romanticism. Touched up astronomical images are neither whole truths nor flat-out lies. To question whether the visible light of Hubble or the infrared images of the Spitzer Space Telescope exist as dream-like panoramas of fabricated frontiers or as scientific explications of real space features and events is to miss the point. Both designations carry an element of truth.

The Andromeda, or M31, galaxy taken on a plate by Edwin Hubble in 1924 and depicted, in false-color, by the space telescope named in his honor (Carnegie Observatory Archives and University of Utah/Hubble Space Telescope

Referring back to our sets of dualities, we might say that astronomical imaging itself is similarly bifurcated. One side is populated by the images of the actual observer, technician and processor. These pictures (not in any traditional sense it should be noted) are the ones most likely to be published and traded within the astronomical community. They are often colorless and blurry, what one non-astronomer describes as having "the feel of low-res graphics, or pictures still being rendered".[12] Their value lies not in an appeal to grandeur but in the amount of scientific information that can be extracted from them. The other side is the stuff of the exalted. It is found in coffee-table spreads of colorful galaxies and nebulae, the amateur's magazine centerfolds of the most radiant outer-reaches of space and promotional images of columns of sparkling gas and pixie dust. These "pretty pictures" as astronomers call them are willfully manipulated and propped up with graphic illusions to appear more striking.[13] Imperceptible infrared, X-ray and radio wave



Different Depictions of the Crab Nebula

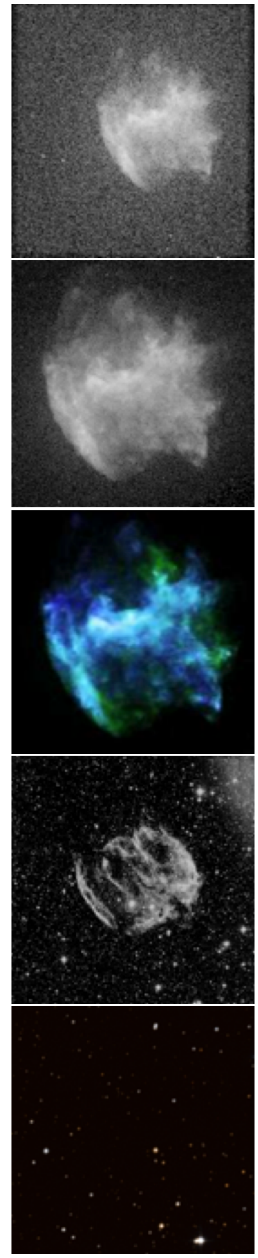
Line 1: A false-color composite (Hubble Space Telescope) and ground-based optical image (Digital Sky Survey)

Line 2: X-ray (NASA/CXC?SAO), optical (Palomar Observatory), infrared (Keck Obs/2MASS/IPAC-Caltech/NASA/NSF) and radio (NRAO/AI/NSF) wavelengths

Line 3: The nebula on red-sensitive film (Walter Baade, Hale Telescope, 1950) and a second Hubble multi-wavelength structural rendition (still from NASA Universe of Learning video)

Line 4: Components of line 3 color image: high-energy heart of the nebula (Chandra X-ray Observatory), pulsar jets, infrared light (Spitzer Space Telescope), visible sulfur and oxygen emissions (HST) radiation are fitted with false colors, suggesting (by praying on the perceived trustworthiness of the photograph) that if we were to come face-to-face with a supernova or orbiting star system we'd see its boundaries demarcated in fiery reds and calming purples. And because of our yearning for what we cannot reach and our desire to dream outside of ourselves, we're "generally only too willing to acquiesce" to these suppositions.[14]

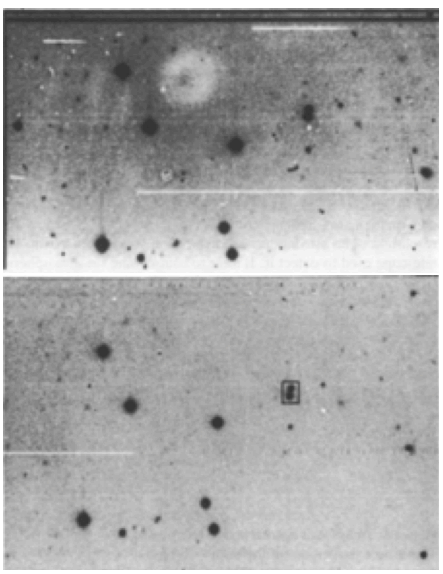
But the divide between utilitarian and beautiful is not inflexible. It is the bleeding over of aesthetics into science and science into aesthetics that makes images of space such surprising objects of study. In 1987, only three years before the inaugural deployment of Hubble's wide field camera, Michael Lynch and Samuel Y. Edgerton embarked on an ethnographic study of two different observatory communities in an attempt to get at the heart of how astrophysicists conduct and view their own work. By watching them operate in their natural environment and by forcing them to explain what they were doing to the uninitiated, the duo concluded that astronomers tend to make use of color and other elements of composition in pursuit of representational realism and that while this "composing of visible coherences, discriminating differences, consolidating entities and establishing evident relationships" falls short of a formal aesthetic, it still comprises an exercise of judgment or an "*art* situated within the



Top to Bottom: A raw, merged and colorized view of the W49B nebula (Joe DePasquale, Chandra X-ray Obs.). The same nebula in the infrared (Palomar Obs.) and optical, where it is undetectable (Digitized Sky Survey).

performance of scientific practice".[15] It is misleading, they suggested, "to suppose that, (1) the sense of what is nice or beautiful about popularized, colorful renderings has nothing to do with substantive astronomical properties, and (2) doing 'real' science excludes any notion of art or aesthetics." It is the following sentence that, while culled from Lynch and Edgerton's field notes and isolated conversations, can be seen as a general aphorism for astronomical and scientific image-making: "*Hidden within the dichotomy between 'aesthetics' and 'science' is a specification of each member of the pair contained within the explication of the other.*"[16]

What a gem of an observation. Just as there is science informed by aesthetics there is an aesthetics informed by science. The later encompasses the 'daily' research tasks performed mechanically and with limited critical examination: gauging best sampling procedure, troubleshooting software, eliminating image bias and dark response (both unwanted side-effects of pixel and environment), making flats, cleaning noise bands, dust and other physical and electronic obstructions, deploying smoothing and sharpening functions, flagging objects and creating masks.[17] These are the necessary conventions needed to turn a detected source into a digitally reconstituted map of encoded values (a.k.a. a 'usable' image). While highly procedural and mathematically governed, these actions are still human-driven deletions, additions and reconstitutions. They



Above: CCD detector with 'cosmetic defects' like bias, burnt out pixels, epoxy from manufacturing and cosmic rays.

Below: The cleaned-up frame (pair outlined in box is a result of 'gravitational lensing' in which the bending of a single object's light multiplies its image to the observer)

Lynch and Edgerton paper, Rudolph Schild, Harvard-Smithsonian Astrophysical; Observatory comprise a scientifically sanctioned aesthetic whereby the "materials through which a craft is embodied lend form and substance to the object revealed".[18]

At the same time, science is informed by a more traditional kind of aesthetics. It is the materiality of the pretty picture: composing deliberate color and monochromatic gradients, making use of a color palette and false color designations, increasing contrast, cropping and figuring, deciding which astronomical features to highlight and which to relegate to the background. These are sets of materials as much at home with the aesthetic of landscape portraiture as with digital image processing. As there were artistic implications in an aesthetics informed by science, there is scientific value in these converging colors, shapes and artificial boundaries.

Secrets of the sky: *Above,* an Einstein ring made from light bent by a massive object through gravitational lensing as postulated by general relativity (taken by the Wide Field Camera 3 of HST).

Below: This "Bullet Cluster" image shows hot X-ray gas, or normal matter, in pink and a denser matter (calculated by gravitational lensing) in blue. The clear separation between the two is often cited as direct evidence of dark matter.

Astronomical imaging is by necessity an incongruous but co-dependent marriage of art, science, guesswork and intuition. Its subjects are not the kind that can be photographed on a lab bench or filmed intimately. They are cosmic entities separated from us by millions of light years, manifested as shifting temporal illusions and complicated by atmospheric, interstellar, optical distortion and digital detection. Their life cycles play out on scales so unimaginable they induce painful headaches. And yet we can still 'see' the grooves and swirls of their invisible structures, reduce their enormity down to the size of a postcard and imagine ourselves through them. If that doesn't validate the magic of the image then nothing can.

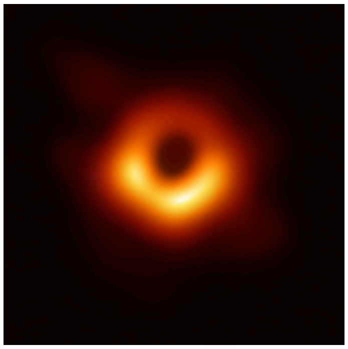

Spectacular Hubble Space Telescope Images of the Monkey Head Nebula (NGC 2174) and the Butterfly Nebula (NGC 6302)

3. *Taking Stock and Moving Onward*

On April 10th of 2019, scientists representing the Event Horizon Telescope (EHT) held six simultaneous press conferences on four different continents.[19] The synchronized pageantry, spread across the globe to reflect the collaborative planning, observations and data processing of an international network of researchers, telescopes and information servers, culminated in the unveiling of a single image of a blurry red ring. That picture, today recognizable as the shadow of the black hole in the heart of the Messier 87 galaxy, is a miracle, at first glance aesthetically underwhelming but in every other sense overwhelming. Both a resounding validation of the predictions of relativity and a likely heralding of the future of the image, it's as appropriate a place as any to pause and consider where seen science has gone and where it is likely to end up.

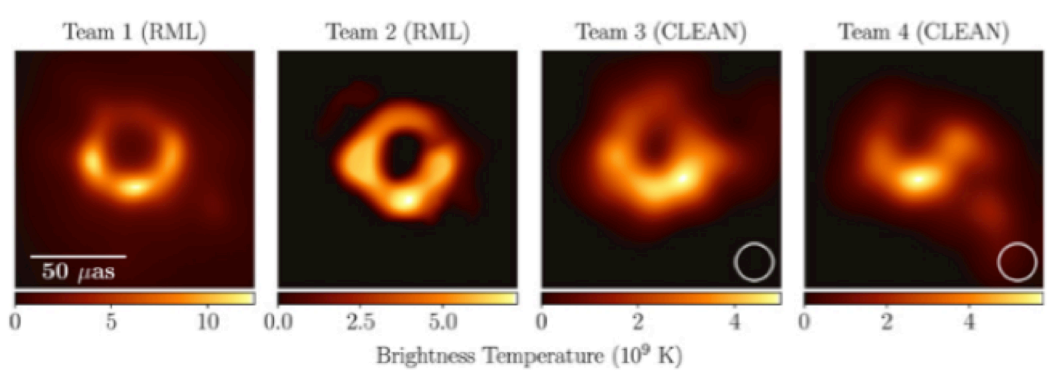
When the EHT announcement was picked up in the following days by websites, blogs and newspapers, everyone rushed to explain the plausibility of the image.[20] How was it that scientists could capture the light of an object from which light itself was unable to escape? It seemed like the perfect magic trick, the latest entry in a list of breakthroughs that had to be taken on faith. A suspension of the need to understand fully is asked of by many modern scientific images, but it becomes especially necessary when viewing something, especially a theoretical construct like a black hole previously only viewable through simulations and artist's renditions, for the very first time. It is a sensation, as we've seen, at some stage familiar to all who have stood at the gates of a new vista and stepped through them: the 19th century photographers who came to compartmentalize the motion of hooves and the flight of birds into discrete frames, the turn of the century microscopists who tracked the motion of energetic particles and living particulates with precision, the medical imaging and X-ray vision pioneers who mapped the body, the biologists, material scientists and astronomers who, with the aid of technology, find clever ways to throw their nets farther and sink their probes deeper.

The impossibility of the Event Horizon image is an encouraging sign that such vistas are still out there, waiting to be found. Their uncovering will undoubtedly require an evolvement of the image, both as a material construct and as an increasingly complicated form of digital reconstitution. The way we tend to describe the black hole image and similar-looking assemblages of information rarely reflects this evolution. We characterize processes that we do not understand with familiar but ill-fitting language. By failing to meaningfully dissociate the act of data interpretation from the final form it ends up taking, we group things that don't belong together. Unconsciously or not, we draw a line between the accretion disk of the M87 black hole and a photographic portrait because both share in superficial qualities like delineated boundary and focus on a single subject. By doing so, we ignore the unique constructs that make each image different from the next and grant ourselves permission to think cursorily about how their meaning is assembled.



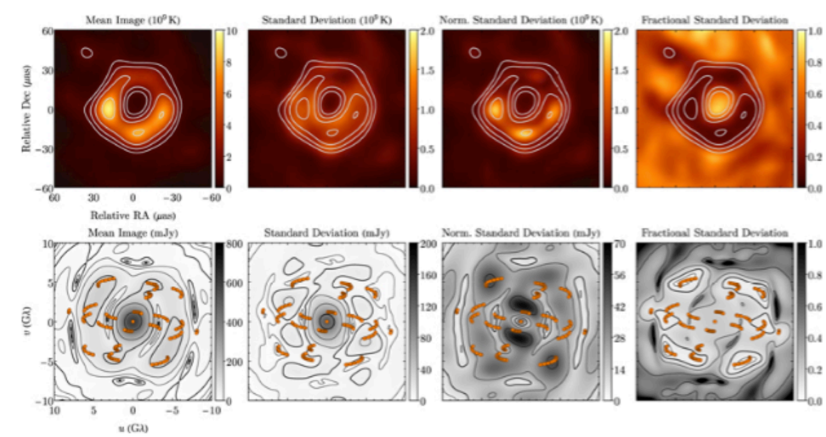
Gravitational Doughnut?
The first visible black hole (Event Horizon Telescope, 2019).

So what exactly are we seeing when we look at the Event Horizon Telescope's red smudge? We'd like to think that images are true reflections of reality, but which reality are we referring to? The first step in the EHT process was the collection, in 2017, of radio signals by a collection of interconnected telescopes known as a very long baseline interferometry (VLBI) array.[21] Based on the laws of diffraction, one needs a telescope rivaling the size of the Earth to resolve a distant black hole like the one in M87. Interferometry skirts this infeasibility by training multiple, spread-out telescopes on a



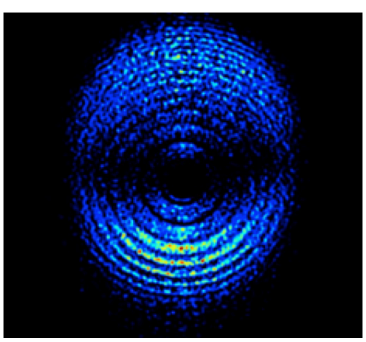
The first images of the M87 black hole's outline made by four separate teams (Fig. 4 in "The First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole", April 10, 2019, *Astrophysical Journal*).

source at different angles, in effect approximating an impossibly massive instrument with improved resolving power. This information was then physically transported to a central location. As massive as it was (much was made of the fact that the data retrieved from the eight telescopes made up the largest set for any one scientific experiment ever done) it had crucial gaps that needed to be filled.[22] This was like having the outline of a jigsaw puzzle and being made to complete it correctly by picking the right pieces from a bottomless bin of stray pieces from other puzzles. The EHT team needed an effective way to sort through the many possible permutations available to them and narrow down their potential avenues of reconstruction. Using data calibration techniques, Fourier transforms and other involved algorithms, they set out to make accurate and informed associations, applying underlying assumptions as infrequently as possible. To eliminate bias, they split themselves into four groups, each of which used its own data pre-processing and imaging procedures to produce, independent of the other teams, a likely shape for the black hole.[23] When the sections reassembled to communicate their findings, they found that each of their completed puzzles shared a common component: a bright, asymmetric ring, the last visible cry of matter before being lulled into the black hole's gravitational pull and sucked into oblivion. Differences, however, arose in the treatment



Calculating the statistical uncertainties of assumptions applied by an imaging parameter on a single day's results (Fig. 17 from same paper) of brightness distribution and other features, attributable to the ways in which each team defined their parameters.[24] Image processing, then, can lead to consensus and alignment with models and expected results, but it is not a simple mapping of one value onto another. The visualization of the M87 black hole can be thought of as a highly educated and informed guess at a reconstruction, its final 'look' mediated by a number of variable factors. What we end up seeing in the famous image is the result of VLBI radio observations but also (and of equal importance) the output of scientists who spent great amounts of time mulling over, as the sternest of puzzle-makers might, a series of best fits, logical connections and plausible approximations.

So maybe the future of the scientific image lies in large, interworking projects, where observing instruments are constructed virtually and the amount of data used to process final pictures fills rooms of hard drives. Or maybe it will play out in the refinement of the old. Harold Edgerton, master of the strobe, would never have been able to imagine that short intervals of pulsating light could be cut down to the speed of attoseconds, a unit of time so brief that its analog in seconds is comparable to twice the age of the universe. Nor would he have been able to predict that researchers would be able to study the dynamics of sub-atomic particles using ionizing fields and quantum stroboscopes.[25] Eadweard Muybridge and Étienne-Jules Marey, who strung together frames taken in hundredths of a second, would be stupefied to find out that researchers can slow down short films of electron scattering nearly a billion billion times (and then play them back for our viewing pleasure). Painlevé, Abbott and Bentley,



The ionization event and scattering of an electron in a strong infrared laser field (J. Maurittsson, 2008) too, would no doubt have something to say about scanning the undersea with lasers, making computerized models and using an external video monitor to snap pictures.

The story of scientific image-making has been one of unknowable twists and turns, starting with the imprinting of familiar natural objects and ending with the resolving of black holes, single atoms, molecule sized structures and distant galaxies. It is not presumptuous to assume that its future, whatever shape it takes, will shock, surprise, frustrate and amaze in ways we simply cannot foretell.

The ultramicroscopist and astronomer, engraver and model maker, crystallographer and physicist, painter and photographer, diagram tinkerer and radiographer, naturalist and filmmaker: all cajole the truth out of its hiding place in a way that can only be described as beautiful. It is an adjective that if not treated as anathema tends to be spoken in measured breaths. But embracing the beautiful is necessary. To be stirred and to understand is not to engage in a contradiction but to amplify the truth twice over. As Ralph Waldo Emerson once wrote, “Science was false by being unpoetic…..[it] does not know its debt to imagination.”[26]

How could anyone disagree?

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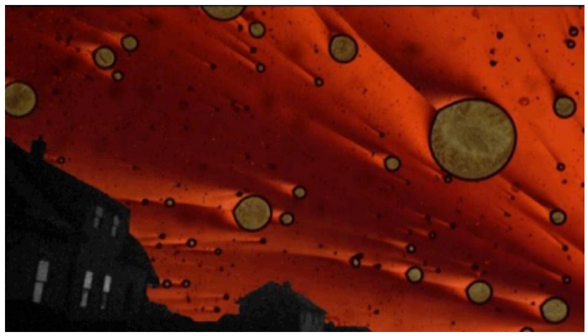
-Concluding Remarks-

In reflecting back on a few of my own science classes, I realize that images rarely took precedence over formulas and equations. I was usually told that the road to a concept was already well trodden and that, in order to reach its end myself, all I had to do was follow a tested roadmap of theories and operations. Sometimes this journey was short and painless. I'd scan the ground for footprints, look at my notes or textbook and something would click. I'd be there. Other times, I'd get lost in a jungle of confused thoughts, led astray by pathways and variables with no markers, unable to cut my way out. I'd be told, in the midst of my frustration, that something truly great awaited me on the other side. And so I'd keep searching, for a missed turn or overlooked shortcut, until a familiar thought took up space in my head: maybe I'm just not a good enough explorer to get there on my own.

But despite such moments of waning confidence, I've always believed in the existence of the 'other side' even when I couldn't fully see it. I am reminded of science's ability to recast perception and upend expectation whenever I look at a photograph of something unseeable or marvel at a film I didn't think could ever be made. I hope others feel similarly and leave this reading with a head spinning with ideas and a greater appreciation for imaged science as a whole. Writing this thesis helped me realize that while I may not have the most 'scientific' brain, I do have one that can feel wonder, and maybe that's enough. Like art, science rewards free-form exploration, not, as we are sometimes taught, a rote stroll down a pre-paved path. I get comfort knowing that if I ever get lost in that jungle again, as I'm sure I will, I can look at an exposure of a star or a micrograph or a movie of suspended motion and remember that wherever there is a dead end there is also a path waiting to be forged around it.



A photograph superimposed onto a meteor shower-like sheet of microscopic crystals taken by the author