IMAGES SCATTER INTO DATA, DATA GATHER INTO IMAGES

Peter Galison

1. Forbidding the Required Image

Stepping back from the specific sciences, a powerful theme running through them comes into view, one central to the arguments and evidence they produce. In brutally short form, it is this:

"We must have images; we cannot have images."

We *must* have scientific images because only images can teach us. Only pictures can develop within us the intuition needed to proceed further towards abstraction. We are human, and as such, we depend on specificity and materiality to learn and understand. Pictures, sometimes alone, often in sequences, are stepping stones along the path towards the real knowledge that intuition supports. First, Plato says, we grasp the triangle in the sand, then the triangle drawn more finely, then triangles in general, then the idea of triangles behind all particularities of individual triangles. But the virtue of pictorial representation goes beyond pedagogy and abstraction – it extends to discovery. For we can ask: What are we humans good at? We are good at recognizing and seizing upon visual patterns. We grasp family relationships among tactile-visual forms, we extend, modify, innovate on the basis of intuition *(Anschaulichkeit)*. Perhaps this is because the long process of evolution has left us with a pattern-recognition capability well matched to the world. Perhaps it is a psychological or socialized virtue inculcated by experience. But whatever its source, the power of pattern recognition is a crucial feature of scientific discovery; one we cannot and should not forego. Finally, beyond pedagogy or even epistemology, images get at the peculiar – the unique – features of nature in a way that a calculation or verbal description can never do. By mimicking nature, an image, even if not in *every* respect, captures a richness of relations in a way that a logical train of propositions never can. Pictures are not just scaffolding, they are the gleaming edifices of truth itself that we hope to reveal. So goes the brief for the scientific image: pictures are pedagogically, epistemically, and metaphysically inalienable from the goal of science itself.

And yet: we *cannot* have images because images deceive. Pictures create artifactual expectations, they incline us to reason on false premises. We are human, and as such are easily led astray by the siren call of material specificity. Logic, not imagery, is the acid test of truth that strips away the shoddy inferences that accompany the mis-seeing eye. Abstraction, rigorous abstraction, is exactly that which does not depend on pictures. Abstraction properly conducted proceeds through the formal, the logical, and the systematic. Rigorous, logical *non*-intuitive reasoning is the royal road to knowledge. For that, knowledge is not and should not be restricted to the paltry part of nature that our visual imaginations can conjure out of daily experience. So when we ask what we are capable of knowing, we must put aside the childish playthings of the pictorial. Pedagogy and epistemology ought to be set right to prepare the mind for right reasoning. After all, we are capable of a cognitive austerity that refuses to stare at the seductive image and instead demands hard-edged, uncompromising understanding. If pictures cannot be drawn of the very large, the very small, or the very complex, so be it. Training, discovery, and truth are all dependent *only* on unambiguous propositions and their logical arrangement. So the scientific iconoclast announces: In the end, the truths of the world will be given to us by the relentless application of logic tied strategically to experiment; truth is something wider and deeper than the pictorial imagination can ever hope to encompass.

For the last hundred and fifty years, and perhaps even longer, the sciences have been caught in this endless struggle. In my field of science studies, before the 1970s, there was a tendency to dismiss the pictorial, to de-emphasize the role of the pictorial in the development and present conduct of science. Then came a reversal: widespread acclimation to the idea that science was overwhelmingly about the visual.

Pictures, taken to be both more local and more contingent than propositions, entered as exhibit A in the case against science-as-algorithm. Trying to settle this battle between the picture-local and the proposition-universal strikes me as a losing bet.

My goal instead is neither to bury the scientific image nor to sanctify it, but rather to explore the ways in which the sciences find themselves locked in a whirling embrace of iconoclasm and iconophilia. That sudden, powerful opposition-attraction between wanting to know with eyes-open and wanting to know with eyes-closed has produced some of the most turbulent and generative times in the history of science. These are the moments of the iconoclash.

Back in the 1880s, Henri Poincaré, one of the era's best known mathematicians, philosophers, and physicists, reflected on the role of qualitative, visually-oriented work in mathematics. Looking over older mathematical books, he said; contemporary mathematicians saw work punctuated with lapses in rigor. In light of these lacunae, many of the older concepts – point, line, surface, space – now seemed absurdly vague. The proofs of "our fathers" (as Poincaré put it) looked like frail structures unable to support their own weight, desperately in need of repair. Wielding the sharp axe of logic, a new generation had hacked the old knowledge to ribbons by finding logical counter-examples to received mathematical wisdom.

Poincaré: we know, as "our fathers" did not, that there are crowds of bizarre functions that "seem to struggle to resemble as little as possible the honest functions that have some useful purpose." (One thinks: honnêtes fonctions for honnêtes hommes.) These newfangled functions might be continuous and yet be constructed in such a peculiar way that it was impossible to define their slopes. Worse yet, Poincaré lamented, such strange logical constructs seem to be in the majority. Simple laws seem to be nothing but particular cases, islands of order in a vast sea of bizarre and complex ones. There was a time when new functions were invented to serve practical goals; now mathematicians invent new functions purely to show how these assemblages escaped from and refuted the faulty proofs of the great mathematical predecessors. If we were to follow a strictly logical road, Poincaré added, we would familiarize beginners, from their very start in mathematics, with this "teratological museum" of monstrous proof-destroying functions.

But such a teratological museum was not one Poincaré counseled his reader to visit – neither students nor pure mathematicians. In mathematical education, he argued, intuition ought not be counted least among the faculties of mind to be cultivated. For however important logic was, it was by way of intuition "that the mathematical world remains in contact with the real world; and even though pure mathematics could do without it, it is always necessary to come back to intuition to bridge the abyss which separates symbol from reality." Practitioners *always* needed intuition and for every pure geometer there were a hundred practitioners. But Poincaré's case against rampaging logic applied equally to experts; even pure mathematicians need intuition. Logic surely was important for demonstration and criticism, but intuition was the key to creating new theorems and inventing new mathematics. As far as Poincaré was concerned, without intuition the mathematician was like a writer shackled forever in a cell with nothing but grammar. Addressing his fellow teachers, Poincaré urged them to emphasize the intuitive and to abandon their cultivation of those monstrous functions that now roamed the earth with the sole purpose of haunting the legacy of our mathematical ancestors.[1]

Poincaré followed, or tried to follow, his own advice. For much of his career he relied exclusively on the "honest functions" in whose company a practical man would want to be seen. He drew and suggested pictures incessantly, taking on problems that were at one and the same time physically real, visualizable, and mathematically engaging. One such problem was the stability of the solar system.

[1] _ Henri Poincaré, La Logique et l'intuition dans la science mathématique et dans l'enseignement, in *Oeuvres*, 11, pp. 129-133, citation on p. 132. The discussion of Poincaré is drawn from Peter Galison, *Einstein's Clocks, Poincaré's Maps*, W.W. Norton, New York, forthcoming.

In a contest set in the 1880s, Poincaré submitted a set of remarkable demonstrations of the stability of the solar system. Amid much fanfare he won. Then one of the examiners spotted an ambiguous move deep in the prize paper and wrote Poincaré for clarification. A moment of stunned silence. Poincaré confessed that as he had pulled on the problematic thread that the proofreader had spotted, the whole of the argument had begun to unravel. What he had hoped was an insignificant exceptional case proved to be anything but, and in the effort to patch the tear he had had to re-weave the whole cloth – and created the physics of chaos.

Poincaré had aimed to show that, within a small range of error, the planetary system would continue to cycle as it had always done. Instead, he found that a solar system with even three objects (say a Jupiter-like planet, an earth-sized planet, and an asteroid) would, under a wide variety of conditions, spiral far from the tranquil orbits with which it began. By the time he wrote up his famous trilogy of books, *New Methods in Celestial Mechanics,* it was abundantly clear that his pictorial imagination had met its match. Honest functions had run amok:

> When we try to represent the figure formed by these two curves and their infinitely many intersections, each corresponding to a doubly asymptotic solution, these intersections form a type of trellis, tissue, or grid with infinitely fine mesh. Neither of the two curves must ever cut across itself again, but it must bend back upon itself in a very complex manner in order to cut across all of the meshes in the grid an infinite number of times.

"I shall not even try to draw it," Poincaré added, yet "nothing is more suitable for providing us with an idea of the complex nature of the problem."[2] Beginning with a pedagogical, philosophical, and practical bent for the geometrically-visualizable, Poincaré faced a blank page that would not fill.

In what at first may seem an equally peculiar turn of fate, late in life Poincaré found himself in precisely the opposite situation. Having struggled desperately for years to prove a theorem about the three-body problem, to find a universal rule, Poincaré bowed to his age and health. To the editor of the journal he had published in for years, he confided: "What embarrasses me is that I will be obliged to put in a lot of figures, precisely because I could not arrive at a general rule, but I only accumulated particular solutions."[3] I said that Poincaré's embrace of provisional pictures only at first seems peculiar because there is a strong sense in which I think it is not at all out of the ordinary. In the sciences of the last century and a half, the pictorial and the logical have stood unstably perched, each forever suspended over the abyss of the other.

Through geometry – through his hunt for a stable, pictorially-oriented geometry, Poincaré had come to a point where complexity had overwhelmed the pictorial. Conversely, through the search for a general rule he had been driven to pictures.

Quite aside from the intrinsic importance of Poincaré's work – the launch of many decades of work on chaotic phenomena – this twin reversal brings us to a more general state of affairs. At the heart of the scientific image is the search for rules; at the heart of the logical-algorithmic has been a hunt for the recognition that is the eternal promise of representation. Said another way: the impulse to draw the world in its particularity never seems to be able to shed itself of the impulse to abstract, and that search for abstraction is forever pulling back into the material-particular.

The strain of the abstract-concrete winds throughout the history of mathematics; Poincaré's concerns were by no means unique. Dutch mathematician Luitzen Brouwer, for example, devoted much of his life to defending the view that mathematics was about truth, and that the true existence of mathematical objects could only be established by constructing them. That is, if you wanted to show that there was a

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[2] _ Henri Poincaré, *New Methods of Celestial Mechanics*, trans. Daniel Goroff, American Institute of Physics, New York, 1993, vol. 3, section 397, p. 1059.

[3] _ Gaston Darboux, Eloge, p. LXVII. Memoire published Rendiconti del Circolo Matematico di Palermo, t. XXXIII, session of 10 March 1912, reprinted in Poincaré, op. cit.

Geometry Room / 1893 / model exhibition at the Technische Hochschule, Munich, in celebration of the third annual meeting of the German Mathematical Union / © photo: Archive Deutsches Museum, Munich

Mathematical models were designed to inculcate a visual-intuitive understanding of mathematical concepts that were otherwise hard or even impossible to picture: shadows of four-dimensional objects, newly contrived mathematical functions, topological relations, or non-Euclidan geometries.

function that oscillated a certain way below x = 1 and then rose exponentially above x = 1, you had to actually exhibit it. Logic, by contrast, was at best a helpmate in the foundations of mathematics; the notion that logic was absolutely valid was anathema to him (as he made clear in 1908 with "On the Untrustworthiness of Logical Principles").

David Hilbert violently disagreed. As far as Hilbert was concerned, the goal of mathematics was not so much to construct particular mathematical entities (functions, geometries, spaces), but to demonstrate that the starting assumptions did not lead to a contradiction. So for Hilbert (as indeed for most mathematicians) existence was not at all a matter of having to construct the object in question: If the assumption that a certain function did *not* exist led to a contradiction, then the function existed. Period. The *reference* of mathematical symbols was nothing. Hilbert's mathematics was syntactic, not semantic or in Herbert Mehrten's terms "modern" rather than "counter-modern."[4] Even geometry did not *say* anything. As Hilbert was supposed to have quipped, the propositions of geometry would be just as true if one took every occurrence of "line," "point," "plane" and replaced them with "table," "chair," and "mug." In the end, mathematics was a combination of abstract rules and meaningless signs, for which the fascination with construction, intuition, and models was irrelevant.

In the end, neither side could win this war. Brouwer, whose maximalist position held that all mathematics should be founded on his intuitionist foundations, and who rejected

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[4] _ Herbert Mehrtens, *Moderne Sprache Mathematik*, Suhrkamp, Frankfurt/M., 1990.

the principle of the excluded third ("A or not A"), failed to persuade his contemporaries who were unwilling to abandon the enormously powerful proof by contradiction. And Hilbert, in spite of his vast accomplishments in mathematics, after Kurt Goedel had to concede that his program of providing a unified foundation for all mathematics was also doomed to failure. But the representation of a pure Hilbert, a Hilbert utterly disdainful of the intuitional-pictorial, is problematic in other ways. Hilbert's friend and ally Hermann Minkowski made essential use of the *Anschaulich* when he took that most unvisualizable domain of mathematics – pure number theory – and showed that it could be radically reconceptualized in *visual* terms. Minkowski's treatise, *The Geometry of Numbers,* became one of the classic works in modern number theory and Hilbert supported him unstintingly. Minkowski then performed the same trick a second time when he showed that Einstein's relativity theory itself could better be understood in geometric-pictorial terms. Push on the logical-numeric and out comes the pictorial-geometric. Even in his own later writings, Hilbert left behind the polemical moments that are often seized upon to show the purity of his logicism. He found himself pulled towards the intuitive-visualizable in his work on geometry:

> "In mathematics, as in any scientific research, we find two tendencies present. On the one hand, the tendency toward *abstraction* seeks to crystallize the *logical* relations inherent in the maze of material that is being studied, and to correlate the material in a systematic and orderly manner. On the other hand, the tendency toward *intuitive understanding* fosters a more immediate grasp of the objects one studies, a live *rapport* with them, so to speak, which stresses the concrete meaning of their relations.
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> As to geometry, in particular, the abstract tendency has here led to the magnificent systematic theories of Algebraic Geometry, of Riemannian Geometry, and of Topology; these theories make extensive use of abstract reasoning and symbolic calculation in the sense of algebra. Notwithstanding this, it is still as true today as it ever was that intuitive understanding plays a major role in geometry. And such concrete intuition is of great value not only for the research worker, but also for anyone who wishes to study and appreciate the results of research in geometry."[5]

These remarks introduced a book where Hilbert celebrated the diagrammatic and intuitive on practically every page. But the power of the pictorial was not just registered in Hilbert's writing. No, the trace of these late nineteenth century debates is left in many German, or for that matter French, American, or British, mathematics departments. Dig around the attics and closets of any older department in the United States, for example and, more likely than not, you will find stunning three-dimensional models of different mathematical functions.

Mathematical models seem to have originated with Gaspard Monge in the Ecole Polytechnique of the early nineteenth century. Carried on by his disciples, the tradition prospered for some years before dying out during the last third of the 1800s. By contrast, in Germany the tactile-visual approach to mathematics flourished in just those late nineteenth century years – strongly pushed by mathematicians Felix Klein and Alexander Brill. Designed originally for three specifically mathematical purposes, models fit perfectly into a widening German enthusiasm for joining practical and abstract concerns throughout the sciences.

Models offered Klein, Brill, and their allies a direct method of teaching; they promised to give students a tactile, sensory-based intuition of the objects of their research; and they served as concrete symbols of the many newly-created mathematical institutes. Painstakingly assembled from wood and plaster, wire and paper, glass and brass, publishing companies began to sell these incarnated abstractions, converting, as it were, textbooks into textobjects. Here one

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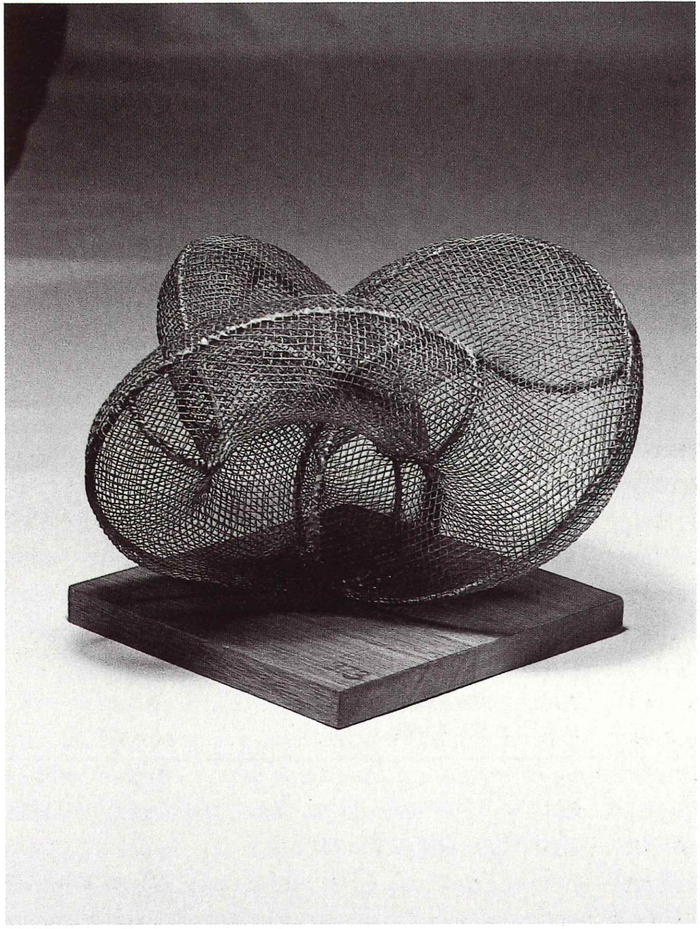
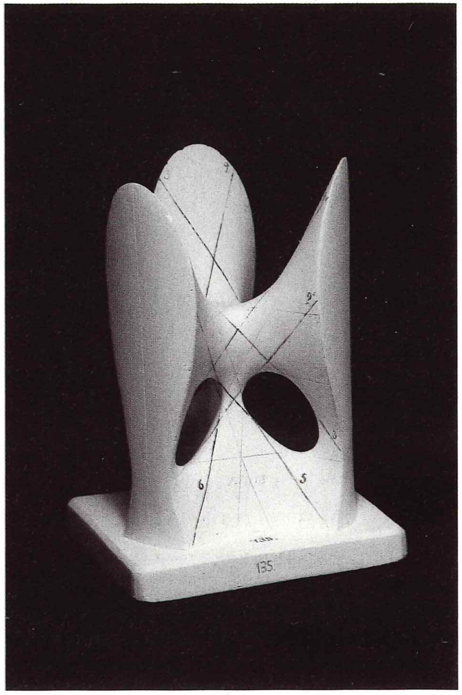
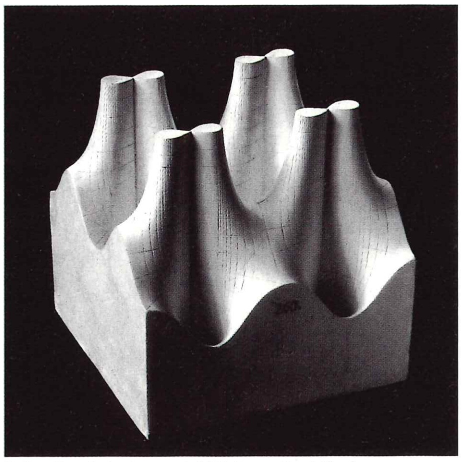
[5] _ David Hilbert and Stefan Cohn-Vossen, from the Preface to *Geometry and the Imagination*, AMS Chelsea Publications, New York, 1952, p. III.

Boy's surface / wire model / collection of the mathematics institute of the University of Göttingen

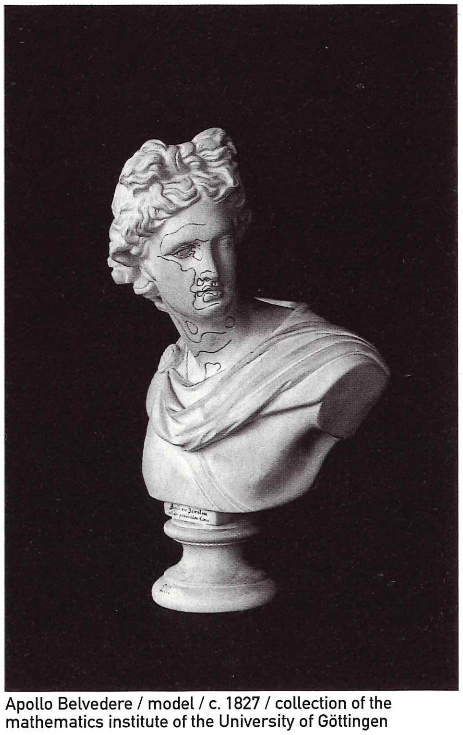


Clebsch diagolnal surface / model / c. 1870 / collection of the mathematics institute of the University of Göttingen

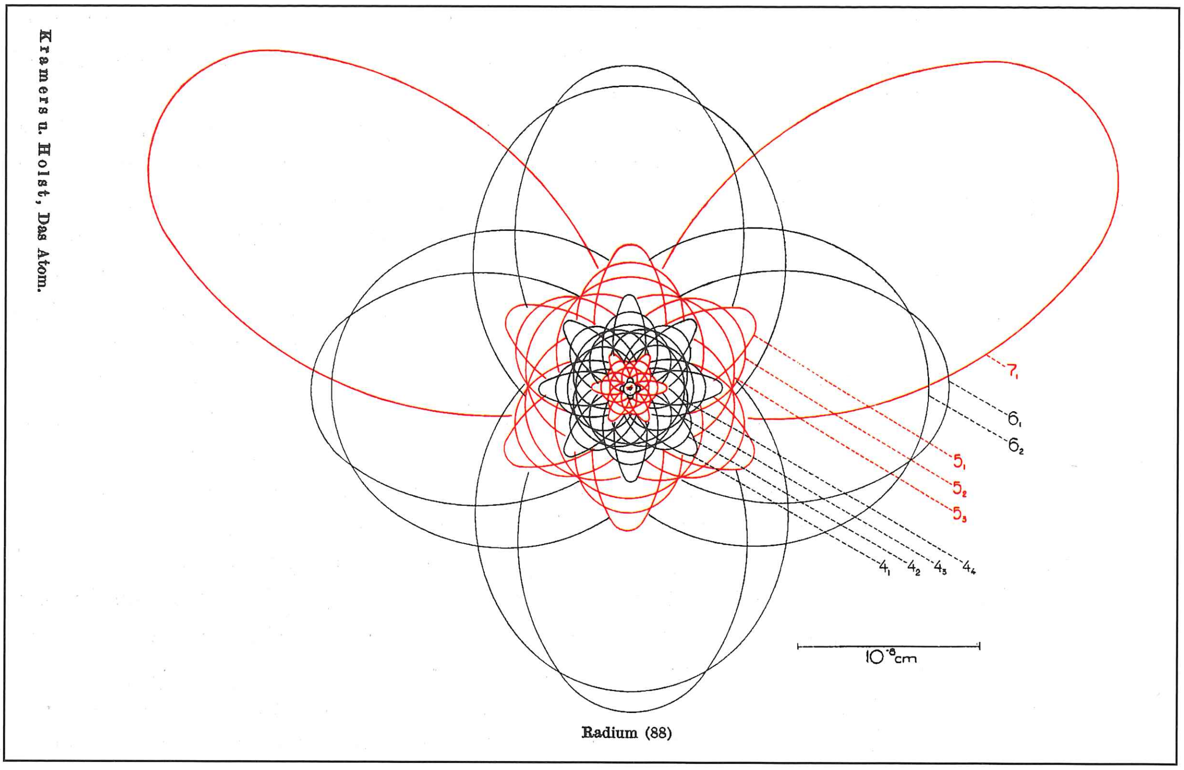




P-function / plaster model / © from: Gerd Fischer, Mathematische Modelle, Vieweg & Sohn, Braunschweig/Wiesbaden, 1986, p. 126, fig. 129
The model is one of mathematician Karl Weierstrass' new and highly »unintuitable« mathematical creations



Apollo Belvedere / model / c. 1827 / collection of the mathematics institute of the University of Göttingen



Picturing Bohr Orbits / © from: H. A. Kramers, Helge Holst, Das Atom und die Bohrsche Theorie seines Baues, Julius von Springer, Berlin, 1925, p. 193

Following Bohr's early work physicists began drawing the new allowed orbits for electrons. Even here certain features were excluded from those that could be drawn – transitions between orbits had no continuous representation. When Heisenberg extended the Bohr theory, he at first argued strenuously that visual intuition was impossible. In the canonical formulation of quantum mechanics in the »Copenhagen interpretation« a new form of visualization was sanctioned, but one much more limited than the pictures of the old quantum theory.

finds gears within gears driving spiro-graphic displays of ellipses, cycloids, and other functions. There are perfect polyhedra, space-filling shapes, close-packed spheres. More abstractly there were also models of four-dimensional shapes projected into three dimensions – a kind of materialized shadow of forms beyond our normal sensory grasp. There are models too that were cast to reveal the behavior of special functions, some only just recently concocted by mathematicians like Karl Weierstrass. Eventually, even the German mathematicians sidelined these plaster, paper, wood, and wire sculptures as more formal conceptions of the discipline gained ascendancy. But for decades, supported by the indefatigable Klein, they served not only to teach "spatial intuition" to generations of students, but to advance fundamental research into descriptive geometry, differential geometry, and topology.[6]

2. Picturing the »Unanschaulich«

This instability between image and logic, number and diagram, syntax and semantics appears again and again, not just in mathematics. From the earliest days of quantum mechanics in the 1910s, visualization was on trial. Back then, physicists wanted to draw pictures of the atom with electrons sailing around the nucleus, and yet Niels Bohr refused to picture how an electron could ever jump from one orbit to another. You could ask about the energy of the electron's stable starting orbit. You could discuss the electron's orbit after it jumped.

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[6] _ Ulf Hashagen, *Der Mathematiker Walther von Dyck als Ausstellungsorganisator und Museumsgründer*, Arbeitspapier, Münchner Zentrum für Wissenschafts- und Technikgeschichte, 1999; Ulf Hashagen, Walther von Dyck (1856-1934). Mathematik, Technik und Wissenschaftsorganisation an der Technischen Hochschule München, Steiner, Stuttgart, forthcoming. I would like to thank Ulf Hashagen for many helpful comments.

That was enough to calculate how much energy must be released – and the colors of light that must be emitted. But neither Bohr nor his theory had anything to say about the inner workings of the transition – about *how* the electron got from its starting orbit to its ending one. Or rather they did have something to say: Here was a case of *ignorabimus*; we cannot know, it is beyond what it is given to us to know. We must neither speak nor draw of the transitions.[7]

Bohr's quantum non-visualization was more than simply a matter of not knowing the transitional path of the electron; it was not, for example, like the practical ignorance that we have about the detailed positions of all the air molecules in the room. No, it was more than that, more a matter of the way things are than of our state of knowledge. Bohr's injunction against visualization was a metaphysical rather than an epistemological iconoclasm.

Werner Heisenberg seized on Bohr's idea and developed it much further by systematizing methods of calculation so that Bohr's techniques could extend to much more complicated problems. For example, if an atom had four possible orbits, A, B, C, and D, Heisenberg wanted a new mechanics that would take into account all the ways for an electron to get from A to D. For example it could proceed by A->B->C->D; or it could leap A->C->B->D. Or it could follow any of the other permissible paths. The results of Heisenberg's methodical summary of these transitions was an array of numbers along with a set of rules for how to manipulate these arrays. Known as matrix mechanics, the new methods provided physicists with a dramatic new way of approaching the microworld. Calculate things that could be observed, said Heisenberg, calculate spectral lines, or calculate scattering patterns: but abandon the doomed attempt to visualize the inner recesses of the atom. Heisenberg's was a stunningly successful program, as his calculation tools cracked open a myriad of problems in the physics of the very small. But the price was clear and pushed Bohr's injunction against visualization even further. For Heisenberg too it was forbidden to ask about what causes an electron to take a leap, or how the electron effects the transition between orbits. But while Bohr worried about limits to spatial-visual intuition, Heisenberg celebrated it.[8]

The cultured, sometimes mystical Austrian physicist Erwin Schrödinger clashed furiously with Heisenberg over the role of pictorial intuition in physics. "I knew of [Heisenberg's] theory, of course," Schrödinger acidly remarked, "but felt discouraged, not to say repelled, by the methods of transcendental algebra, which appeared very difficult to me and by the lack of visualizability." Vision was what Schrödinger wanted – vision, and an understanding of the detailed processes that underlay what we could see with our eyes or our instruments. His "wave mechanics" explained important pieces of the experimental puzzle by treating particles as waves and examining the ways in which they scattered. Heisenberg's reaction was as visceral as Schrödinger's: Schrödinger's visual wave theory was "disgusting" Heisenberg confided to colleague, Wolfgang Pauli.[9]

Canonizing both viewpoints in the "Copenhagen interpretation," Niels Bohr forced a tense cease-fire: under some circumstances the Heisenberg view would prevail and one would have only numbers and the laws that spoke of conserved quantities (conservation of energy and momentum, for example). In these cases any talk of a particle's trajectory was strictly forbidden on pain of deriving nonsensical predictions. But under other experimental set-ups it would be perfectly possible to speak of a particle's trajectory through space and time – and in those circumstances all hope of applying the conservation laws would be lost.

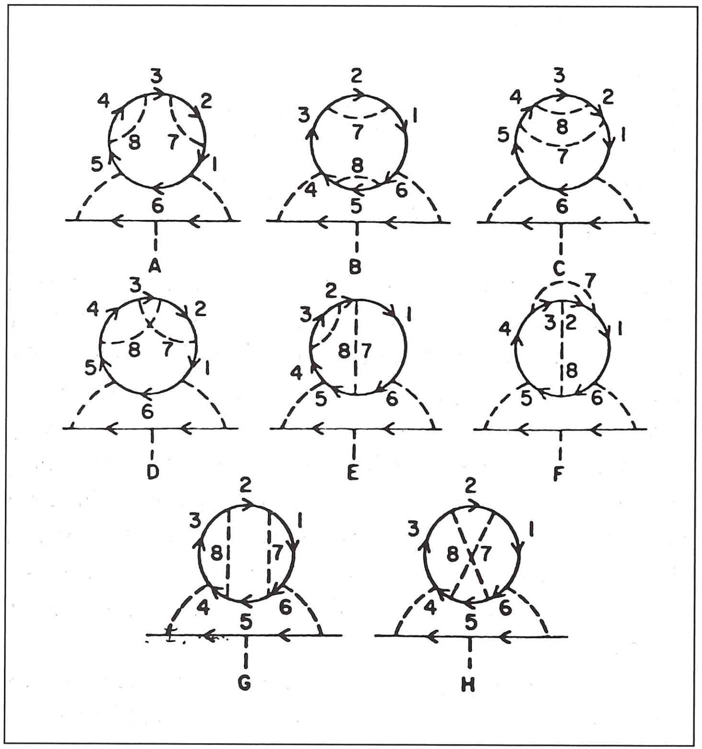
Other kinds of visibilities emerged, mutated, shifted. Paul Dirac, often called the "theorist's theorist" came from a modest Bristol background and received the worker's heavily geometric technical training typical at the turn of the century in England. Geometry, in fact, became his touchstone, and his key to moving up and out of his origins.

[7] _ On visualization in quantum mechanics, see A.I. Miller, Visualization Lost and Regained: The Genesis of the Quantum Theory in the Period 1913-27, in Judith Wechsler (ed.), *On Aesthetics in Science*, The MIT Press, Cambridge, MA, 1978.

[8] _ Miller, op. cit.; on Heisenberg: David Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg*, Freeman, San Francisco, 1992; and on Schrödinger: Walter Moore, *Schrödinger: Life and Thought*, Cambridge University Press, Cambridge, 1989.

[9] _ Heisenberg letter to Pauli, cited in Miller, op. cit., p. 89.

As he raced through the university in Bristol towards Cambridge University and through Cambridge towards the physics of the Continent, Dirac found his geometry less and less valued. Among the Cambridge mathematicians, Godfrey Harold Hardy was just then fulminating against what he considered the destructive, useless Tripos exams. For years those examinations had run on tradition, sorting students from the top-rated wrangler on down, demanding geometrical-visual and mnemonic skills that Hardy considered antiquated. At the same time, looking towards the continent, Dirac found in the young Heisenberg a guide to a new mechanics that had no more time for the visual than Hardy had in mathematics.



Feynman Diagrams / eight-order vertices obtained by insertion of sixth-order (single electron loop) vacuum polarization subdiagrams in a second-order vertex / © from: T. Kinoshita, W.B. Lindquist, Eighth-order Magnetic Moment of the Electron. I. Second-order Vertex containing Second-, Fourth-, and Sixth-order Vacuum Polarization Subdiagrams, Physical Review D, 27, 4, 1983, pp. 867-868, on p. 868

Each line and vertex in a Feynman diagram corresponds to a calculational rule. So to draw the possible ways in which particles interact is already to set up a precise mathematical problem. The Feynman diagrams shown here are just some of the hundreds that T. Kinoshita and his group used to calculate one of the most precise theoretical predictions in all of physics, the magnetic strength of an electron.

In the face of this new anti-visualism, Dirac soon came to be known for his ascetic, logically crystalline work. Throughout his books and papers on the new quantum theory, diagrams are as rare as hens' teeth. Yet behind the curtain all was different. Squirreling his private calculations into the recesses of his rooms, Dirac scrawled hundreds of geometrical pages. Diagrams spilled over into the margins and down the page. Pedagogy and metaphysics, on the public side, kept to a strict logical-analytical exposition, cleansed of images. Meanwhile, in the private domain, in the realm of the epistemic, pictures ruled.[10]

Over and over this clash has repeated itself over three distinct axes: How visual-intuitive should teaching be? What role does visualization play in discovery? What is the reality-status of the picture? When physicists tried to use quantum mechanics to understand a force at the quantum level (such as the electric field in terms of photons), the fault line resurfaced. Just after World War II, Richard Feynman developed a way to use pictures to imagine how quantum field theory worked. He said, in effect: Do you want to know how an electron goes from A to B? Then consider all the ways that you can draw diagrams of electrons, their emission and absorption of photons, and the intermediate production of electron-positron pairs. Each piece of the diagram corresponded to a calculation rule, so when you finished drawing you had a straightforward mathematical problem to solve. Soon physicists were as facile with these diagrams as they had been with electronic schematics.[11] For Julian Schwinger that was just the problem. Schwinger, then at Harvard, hated Feynman's diagrams. As far as Schwinger was concerned, the diagrammatics taught physicists to treat theory as an assembly of modules, a process that could proceed without thinking. Pictures

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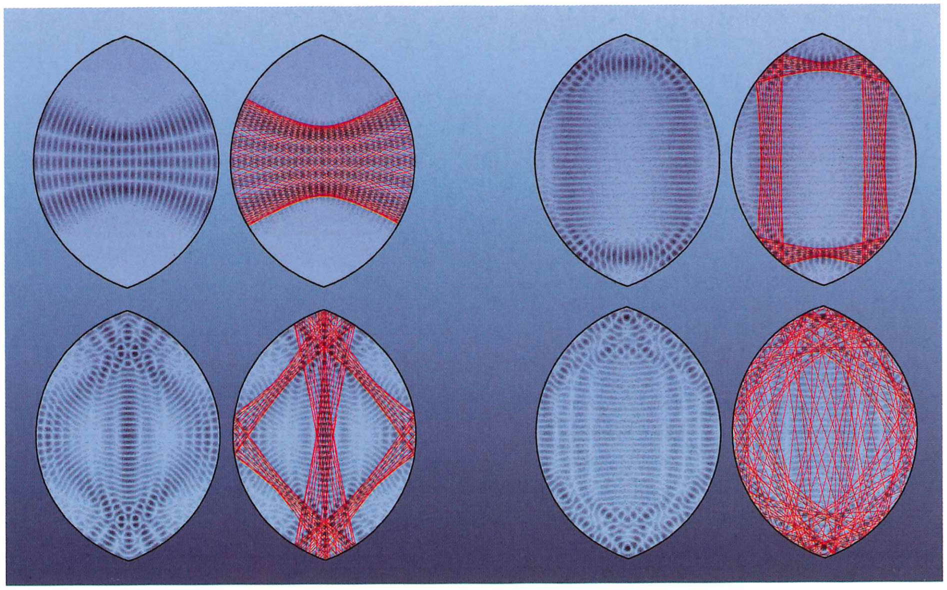
[10] _ Peter Galison, The Suppressed Drawing: Paul Dirac's Hidden Geometry, in *Representations*, Fall, 2000, pp. 145-166.

[11] _ Silvan Schweber, *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga*, Princeton University Press, Princeton, 1994; Peter Galison, Feynman's War: Modelling Weapons, Modeling Nature, in *Studies in the History and Philosophy of Modern Physics*, 29, 1998, pp. 391-434; David Kaiser, Stick-Figure Realism: Conventions, Reification, and the Persistence of Feynman Diagrams, 1948-1964, in *Representations*, 70, 2000, pp. 49-86.



Eric J. Heller / Correspondence / 1997 / LightJet Digital Imager / © Eric J. Heller

Correspondence between the quantum waves (black) and classical motion (red).

reduced calculations to algorithmic routines. Inevitably perhaps, computers would calculate a process. All you need do was to shift around the lines and nodes with a light pen on a cathode-ray tube. Schwinger dismissed this plug-and-play theorizing the way older car mechanics look down on their younger successors who think engine repair means sticking a jack into a microcircuit and ordering a replacement over the Internet. By black-boxing physical processes, thought more traditional physicists, their younger colleagues had lost a grasp of the inner workings of physics. Feynman, Schwinger often lamented, had "brought quantum field theory to the masses." For the formal, methodical Schwinger, that was the kiss of death.

So Schwinger laid down the law, forbidding his doctoral students to use Feynman's diagrammatic calculations. Needless to say, the students quickly learned to calculate with Feynman vision in private, and then to translate their results into the bare formalism their advisor demanded. De jure, aniconic; de facto, iconic. And yet a commitment towards one kind of visualization is not necessarily a commitment to them all. As Feynman turned his sights towards Einstein's general theory of relativity, he was not at all interested in continuing the geometrical views of Einstein – or of his own teacher John Wheeler, who later published a gigantic diagram-crammed volume on what he called "geometrodynamics." Geometry may well have been Einstein's guide, said Steven Weinberg (following Feynman's approach), but it was now nothing but a roadblock isolating gravity from insights gained in the rest of physics. When he was done smashing the idols, the diagrams were completely gone: Weinberg's text does not have a single one.[12]

The long struggle over visualization in quantum mechanics has continued. Ever since the time of Bohr, Heisenberg, and Schrödinger, physicists have taken as gospel the idea that, within certain limits, quantum mechanics should reproduce classical mechanics. Formally known as the correspondence principle, this grounding of quantum mechanics in the classical provided a test of the new theory's validity. In addition, the correspondence principle gave an intuitive understanding of

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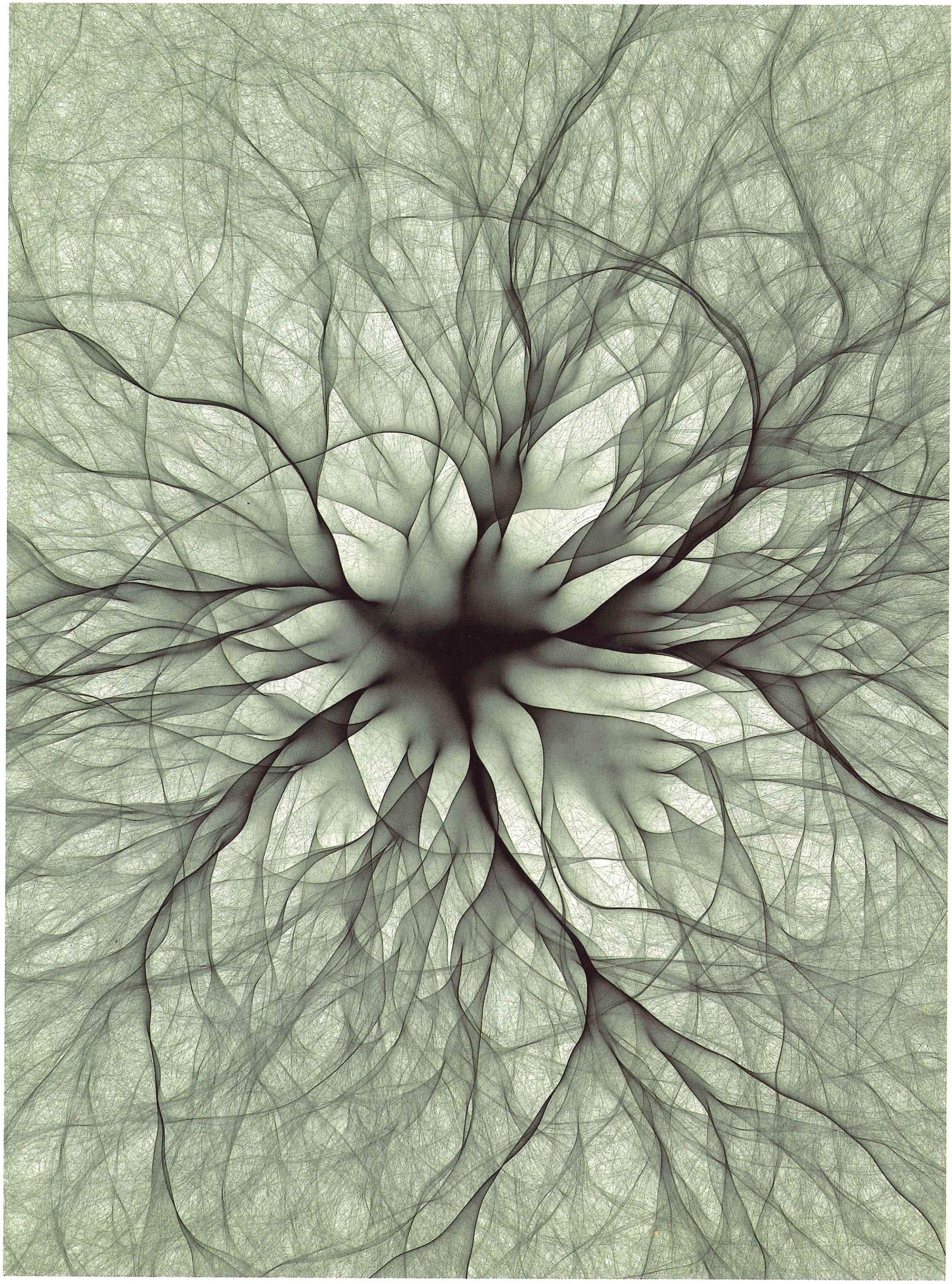
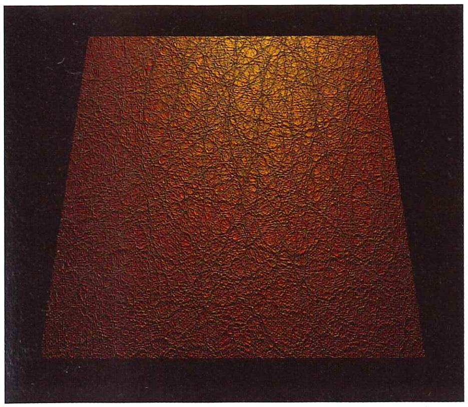
[12] _ Charles W. Misner, Kip S. Thorne, and John A. Wheeler, *Gravitation*, W.H. Freeman, San Francisco, 1973; Steven Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, John Wiley, New York, 1972, p. vii. On Feynman and gravity: David Kaiser, A Psi is just a Psi? Pedagogy, Practice, and the Reconstitution of General Relativity, 1942-1975, in *Studies in History and Philosophy of Modern Physics*, 29, 1998, pp. 321-338.

Art of Physics, Physics of Art / Eric J. Heller's work began as an effort to explore the relation between classical and quantum physics. Over the last years he has expanded his interest in images both in his physics and in his artistic careers. Heller: »There is a connection, a feedback from the science to the art and back again. In me, this has happened many times and has led to new scientific discoveries through the attempt to produce art. In the viewer and also in me, I strive for a feedback of a different kind, namely, I want the scene being rendered to evoke emotion and familiarity; this the viewer can project back onto the science behind the image to sense the power and mystery in the world of quantum mechanics and the microscopic chaos which is just under the surface.«

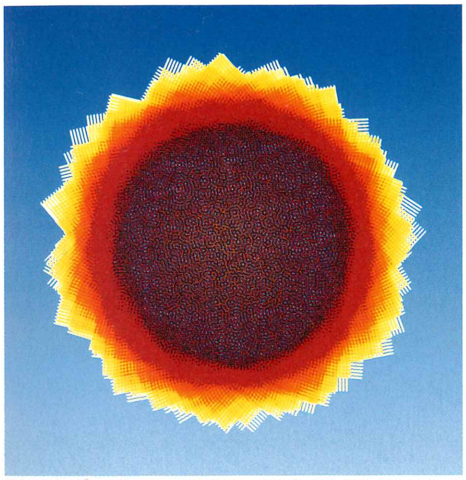


Eric J. Heller / Transport II / 2000 / LightJet Digital Imager / © Eric J. Heller

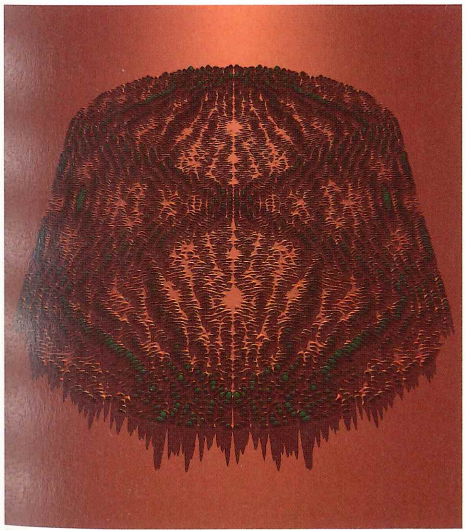
Electrons launched from the center in all directions fan and then form branches, as indirect effects of traveling over bumps



Eric J. Heller / Monolith / 2000 / LightJet Digital Imager / © Eric J. Heller / perspective of random wave in two dimensions

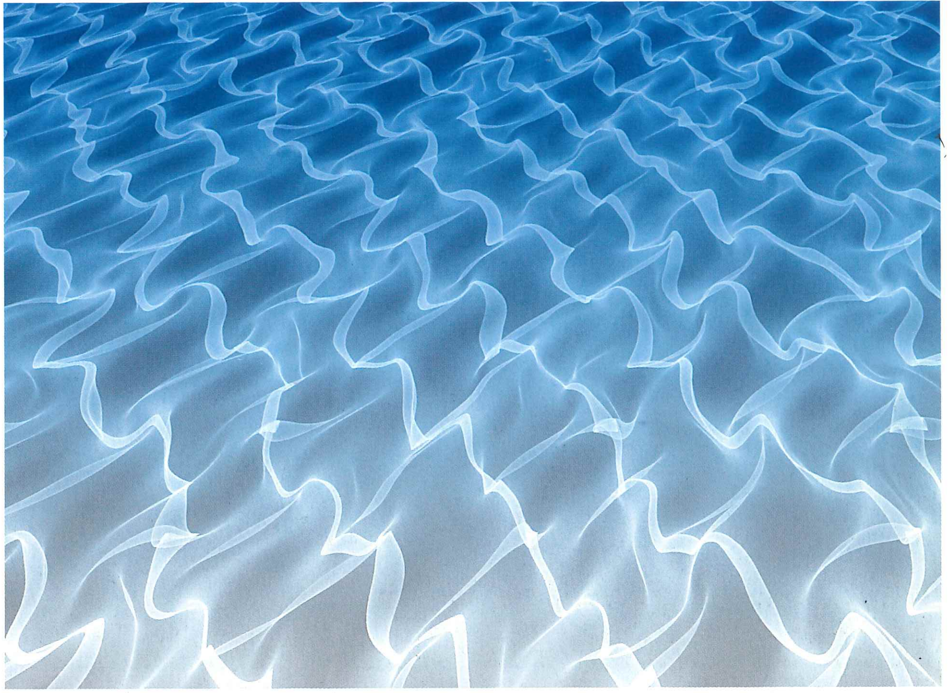


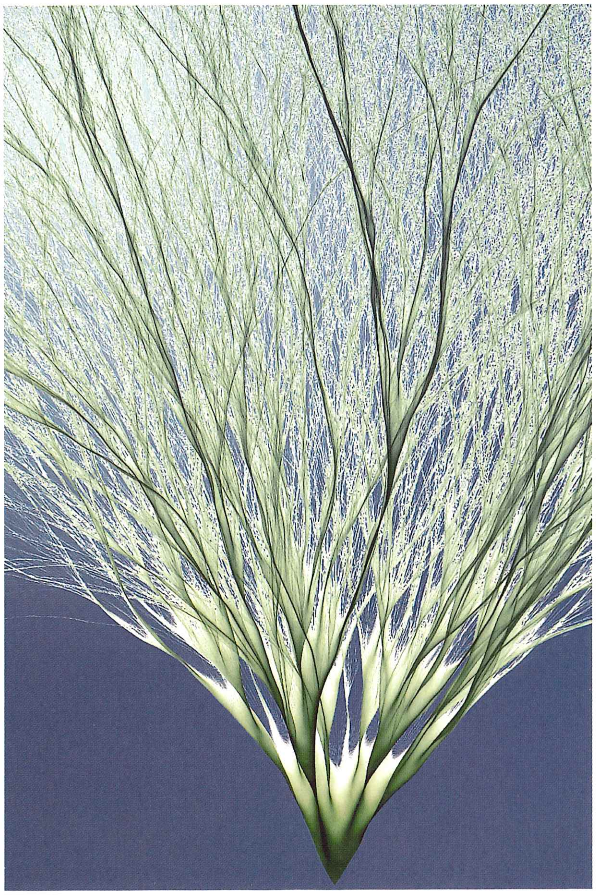
Eric J. Heller / Random Synthesis / 2000 / LightJet Digital Imager / © Eric J. Heller / lines produced by the addition of wave sets produce a random wave in the central region



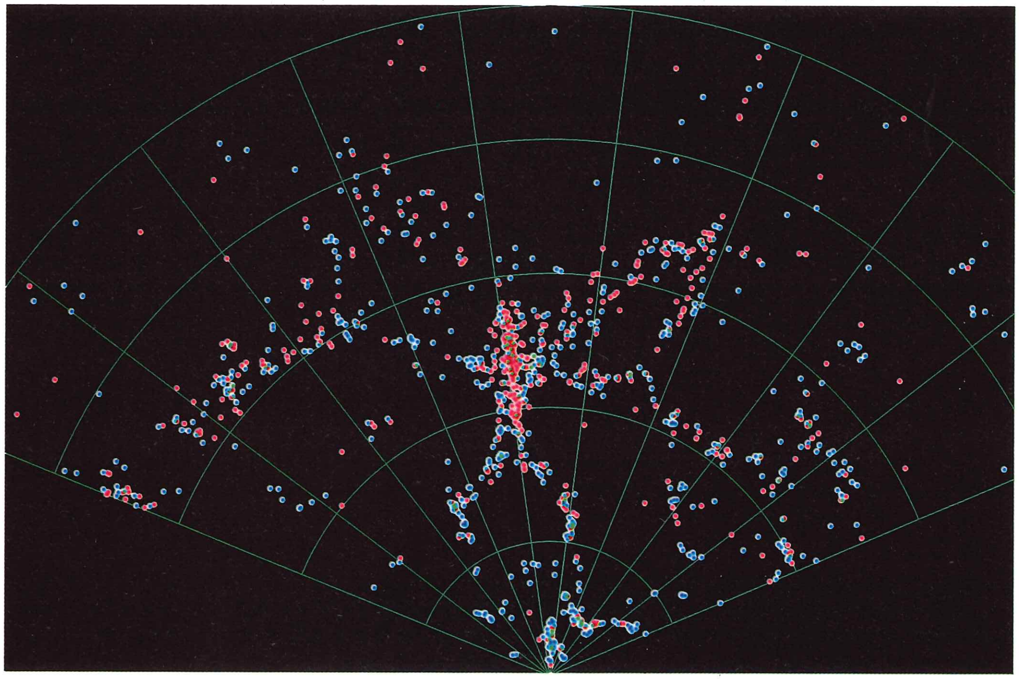
Eric J. Heller / Double Diamond / 2000 / LightJet Digital Imager / © Eric J. Heller / scarred quantum wave function in a stadium shaped enclosure

Eric J. Heller / Caustic I / 2001 / LightJet Digital Imager / © Eric J. Heller / three dimensional caustics formed on a flat sea-bottom by light passing through two consecutive wavy surfaces



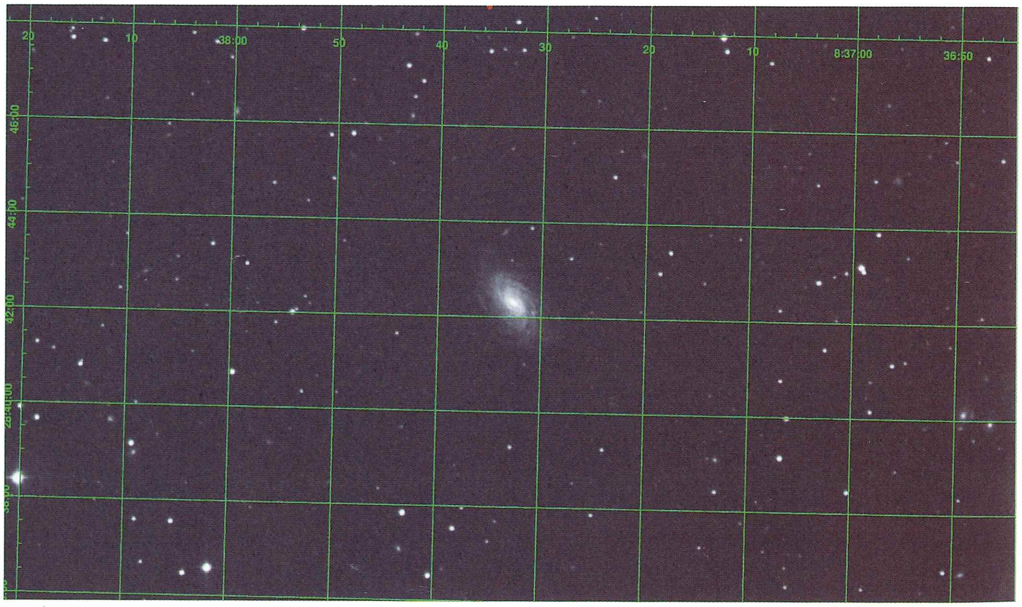


Eric J. Heller / Transport IV / 2000 / LightJet Digital Imager / © Eric J. Heller / electrons injected at the bottom form branches caused by riding over hills and valleys induced by charged atoms which donated the electrons



Stick-Man Universe / 1986 / after de Lapparent, Geller, Huchra / graphics by Michael Kurtz

A slice of the nearby universe in which red points are elliptical galaxies which populate the cores of rich clusters of galaxies; they have little gas or dust. Blue points are spiral galaxies like our own Milky Way. In this plot, the vertex is the position of the Milky Way. Distance increases in the radial direction with more distant galaxies located toward the outer curved edge of the plot. Right ascension (the celestial longitude) runs along the curved boundary. This image was part of Geller and her group's first three-dimensional galactic mapping. It was only when thousands of galaxies were laid out in this and related 3D-images (here about a thousand galaxies), that the distribution of galaxies became clear: galaxies were concentrated as if on the surface of soap bubbles.



Positioning the Galaxy: Palomar Sky Survey Plate / Palomar Observatory Sky Survey / © Palomar Observatory Sky Survey supported by the National Geographic Foundation

The first step in the mapping process was to use the Zwicky catalog of galaxies (from the Palomar Sky Survey Plates) to determine the coordinates of those galaxies Geller and her collaborators wanted to study.

the relation between the quantum and ordinary worlds. But correspondence calculations have, since the beginning of quantum theory, been calculable only at certain relatively simple points of contact. Recently physicists have begun to ask this question again, this time coupling chaotic classical mechanics chaos to the power of the computer. Unlike Poincaré in the 1890s, physicists using computers *could* draw chaotic behavior. And unlike the situation in the 1920s, detailed pictorial representations of complex classical systems could be compared with their quantum analogues.

One of the leaders of this field of calculation-intensive quantum chaos has been physicist Eric J. Heller, who has pursued a remarkable range of visual techniques for studying the relationship of classical chaotic phenomena to their quantum analogues. In his computer-generated *Correspondence* he showed how a lemon-shaped box would contain a classical electron bouncing from its sides (images in the left column of each four-lemon cluster). Then on the right hand column of each foursome (in red), he let the computer plot the likelihood of finding a quantum electron at each spot. The two sides of the comparison are strikingly similar. In that visually recognizable similarity lies, for Heller, a powerful *pictorial* demonstration of the link between the classical and quantum worlds.[13]

No one in the physics community had much doubted the correspondence principle. Yet before pictures like these it was almost impossible to capture the relation of the quantum and classical worlds in such qualitative richness.

The icon clash began when these pictorial methods took on phenomena that were *not* understood. One struggle enveloped *Monolith*, where Heller looked at underlying chaotic classical systems in which electrons would bounce around in completely random directions like mad BB bullets. A quantum version analogue set waves traveling in random directions; it is this chaotic superposition of waves that appears in *Monolith*. Physicists had applied analytic techniques, (techniques without images), to this kind of situation, and some hard-liners claimed that such a ground-up view yielded all there was to know about such systems. But Heller and his group saw something in these images that had not been noticed in the strict calculationists' reckoning: the random skein of almost straight "tracks" criss-crossing the picture. Following from this purely pictorial observation came another. In tiny flat gases of electrons (more precisely gases confined to a mere micron while bathed in a weakly random electric field) electrons tended to flow for long stretches along concentrated channels. This "branched flow" had features that only emerged when Heller began creating ultra-high-resolution pictures like these for artistic display. *Transport IV* is one image in which branched flow is visible as the electrons flow from the center, focus, defocus, and focus again.

Some of Heller's claims have been controversial precisely because they relied largely on images for backing. Back in 1983, he had been looking at the pictures his computer was spewing out of a chaotic quantum system. (*Doublediamond* is a version of that original image.) While poring over these images, he noticed that there was a darkened area in the picture – indicating a strong likelihood of finding an electron – precisely along certain periodic (self-repeating) trajectories of classical physics. With a short theoretical demonstration, he published the image, expecting that the picture itself would go a long way towards persuading his colleagues of the effect's reality. It didn't and controversy followed for a good ten years. As a result of support that came from more recent statistical studies, the effect known as "scarring" is now one of the standard features of quantum chaos. But it is not unusual that it took a straight non-visual demonstration to clinch the argument for many in the physics community. At the turn of the twenty-first century it remains the case that if you ask a variety of physicists (or astrophysicists) whether simulation-generated pictures are sufficient to make a demonstration, you are more likely to get a fight than a chorus.

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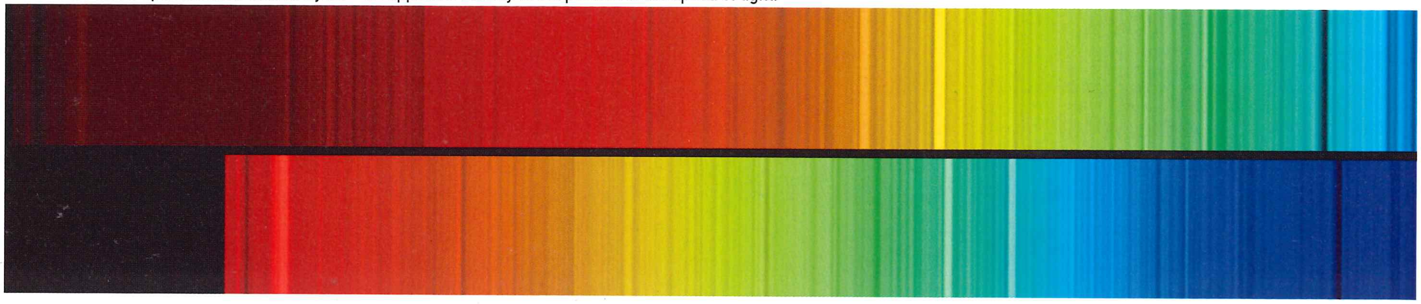
[13] On Heller and the problem of reductionism see M. Norton Wise and David C. Brock, The Culture of Quantum Chaos, in *Studies in the History and Philosophy of Modern Physics*, 29, 1998, pp. 369-389.

Galactic Red Shift / courtesy Margaret Geller and Michael Kurtz
In an expanding universe, the further an object is from us, the redder its spectrum appears to us (and the faster it appears to be receding). In the two images shown here, one is of the unshifted spectrum of a galaxy, and the other of the same spectrum red-shifted by 0.1 - an apparent velocity of ten percent of the speed of light.



3. The Conflicted Image

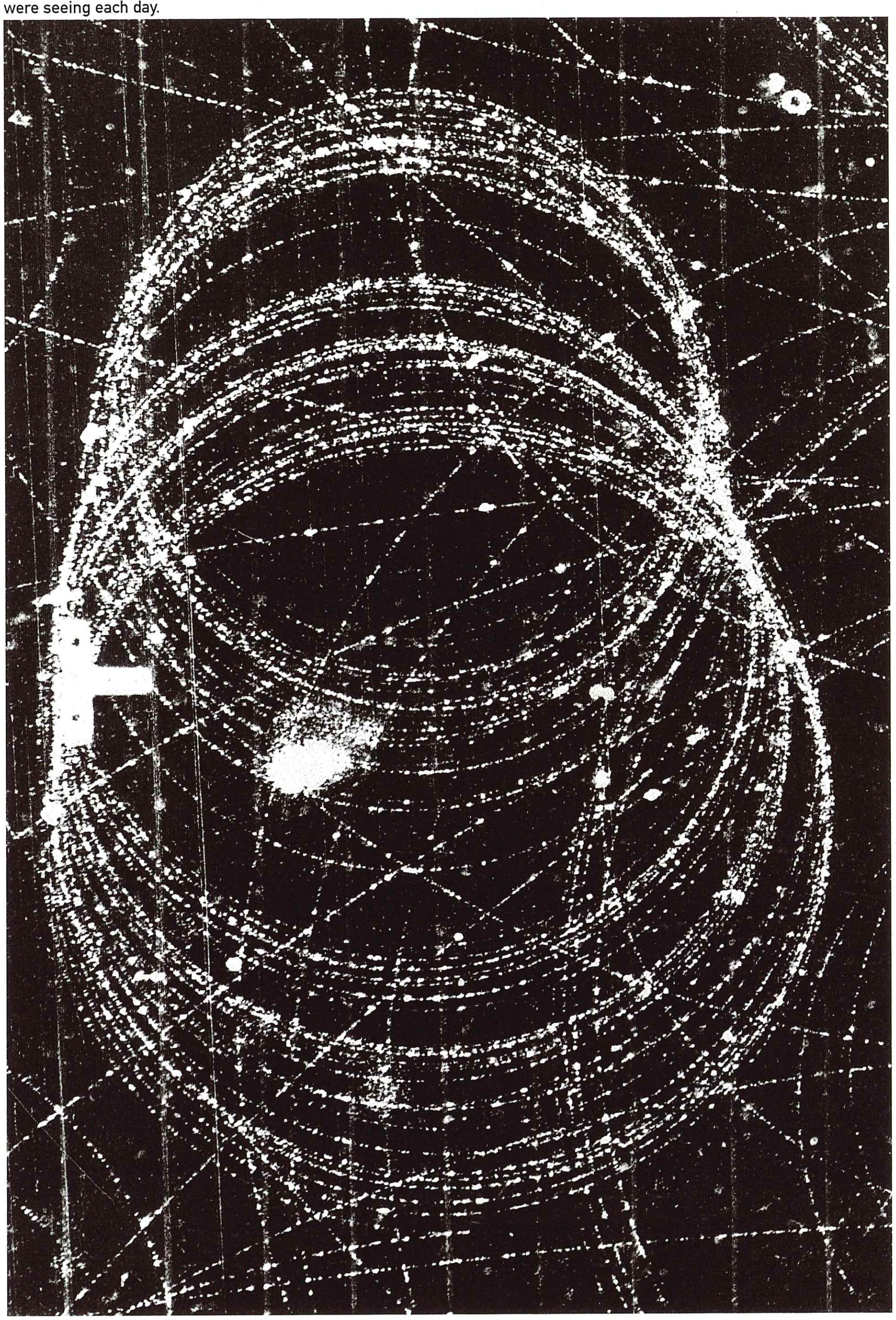
Among the astrophysicists who were inclined to credit the visual with real weight is Margaret Geller. She, as much as anyone, has used images to back a crucial claim about the physical universe. To widespread astonishment, she and her colleagues showed that galaxies seem to be clustered as if on the surface of soap bubbles. But coming to and sustaining that conclusion relied in the first instance on *picturing* what was happening deep in the universe, followed by non-visual statistical studies, followed by more picturing. Recognizing a pattern was one thing. Bringing the broader community of astrophysicists along required a continuing alternation between imaging and more formal analyses: “Images,” Geller says, “are not sufficient in themselves.”

Visualization in astronomy has a long history of being both celebrated and challenged – for decades people tried, without much success, to sort the spectra of stars by strict protocol. Others emphasized the ability of humans (and some much more than others) to seize the pattern of the spectral lines so as to accurately put stars in their proper type-bin. In Geller’s case one of the most effective pieces of evidence she and her colleagues mustered were visual plots like that shown in the image *Stick-Man Universe,* and a moving, three-dimensional version of this image in the computer-generated video that allowed the viewer to “walk” around the galaxy cluster. But images alone were never enough – neither for Geller and colleagues nor for the wider community of astronomers and astrophysicists.

It is worth following the sequence of transformations that lay behind the production of a computer-generated video image that so strikingly showed the flat clustering of galaxies. Geller and her colleagues began with the galaxy catalogs that had been made from the Palomar Sky Survey by the famously irascible Caltech astronomer Fritz Zwicky. Each glass plate covered 36 degrees of the northern sky; from catalogs and plates the astronomers knew where in the sky to look for each of the galaxies in their study.

With those celestial latitude and longitude positions in hand, Geller and her colleagues could then direct the telescope to the right portion of the sky, technicians did the observing and took the data. With those data in hand, Geller and her co-workers then used the red-shift to figure out how far away particular galaxies were from earth (Hubble’s law). More precisely: When galactic light hits a spectrograph, a grating breaks the light up into its constituent colors and the amount of light at each different wavelength is digitally recorded. Each element has its own characteristic pattern of bands of light – this much in a particular portion of the red, that much in a band of yellow, and so on. Hydrogen, the simplest and, what is important, most abundant of all elements, leaves its signature clearly stamped in the light emitted by almost every galaxy. But because the universe is expanding, the wavelength of any light is stretched, making it redder. (Think

Cloud Chamber Atlas / © from: W. Gentner, H. Maier-Leibnitz, W. Bothe, Atlas typischer Nebelkammerbilder mit Einführung in die Wilsonsche Methode, Julius Springer, Berlin, 1940, p. 51, fig. 43
Physicists made and produced images like this one to provide a template against which they could gauge the events they were seeing each day.



of holding one end of a vibrating string in each hand while slowly moving your hands apart.) In particular, as space expands, the hydrogen spectrum emitted by distant galaxies reddens, giving rise to an apparent separation velocity between the galaxies.

Hubble's law relates redshift (apparent separation velocity) to distance; Geller and her team applied that law and showed, astonishingly, that in their survey the galaxies were not at all homogeneously distributed throughout space. (Or more precisely, they showed that in a properly conducted survey the redshifts of galaxies were not evenly scattered among the possible redshifts, but instead strikingly clustered.) By moving from the Palomar Survey and Zwicky's catalog to the spectrum and then through Hubble's law and the theory of the expanding universe, Geller's group could plot a three-dimensional map of the galaxies' positions. It is these data that they then plotted and inserted into the computer to produce a video clip of a "walk" through the galaxies.

The astronomers found two remarkable features: first, that the distribution of galaxies was not even approximately smooth throughout space. Instead, the galaxies concentrated as if on the surfaces of vast bubbles. Said another way, there were vast voids in space in which hardly a galaxy was to be found. Second, Geller's group found what they called The Great Wall, a fantastically large and flattened cluster of galaxies exhibiting a filamentary internal structure – spanning a billion-light year swath across the sky with a wafer-thin width of (only) twenty million light years. It was as if you expected a population of miniature galaxies to be scattered evenly through a four-foot cube, but instead found the collection held in strands within a region the shape of a sheet of plywood one inch thick and four feet on a side.

Bubble Chamber Scanning / © Lawrence Berkeley Laboratory, Bubble Chamber
During the 1950s and early 1960s, Luis Alvarez and his group at Lawrence Berkeley Laboratory introduced factory-style physics not only in the building and running of the bubble chamber, but in the analysis of data as well. Shift-work, quality control, and efficiency reports all became routine as scanners (like the woman shown here) evaluated and measured the bubble chamber images, preparing the information for entry into the computers.

Picturing mattered. To follow the lay of the galaxies it was not enough to have two-dimensional photographs of galaxies, crucial though they were. Nor were the catalogued coordinates of those plates sufficient. Nor were (in and of themselves) the various spectra. Even the thousand three-dimensional coordinates derived by way of Hubble's Law did not yet reveal the pattern. Re-visualization – first by plotting on paper and then by computer – initially forced the clustering to stand out. Then a back and forth between visualizable evidence and statistical analysis: new data meant new possibilities for rendering the information visually striking, and at the same time made possible the computation of new kinds of statistical, non-visualizable, correlations. By the time Geller and her collaborators produced the computer simulation of a walk through the galaxies, and accompanied it by mathematical correlations, the oscillation between the human eye and the statistical calculation made the effect as striking and as evident as the nose on your face. New theories began vying for the honor of explaining this new map of space. Image to data to image to data to image to theory.

At the heart of experimental microphysics lies a not unrelated tension between picture and proposition; on one side the desire to image the microworld; and on the other the equally powerful longing to escape the image. Decorating

Cloud Chamber / 47 x 47" / Forschungszentrum Karlsruhe GmbH

Spark Chamber / built in 1999 / metal, Plexiglas electronic / 79 x 43.3 x 31.4" / weight 700 kg / Zeuthen, DESY Instrument to produce proof of cosmic radiation

the cover of textbooks and imprinted into our cultural imagination are the wispy tracks of cloud chambers, nuclear emulsions, and bubble chambers. The cloud chamber, that prototype of all other visualization machines in microphysics, emerged from Victorian technologies that aimed to reproduce nature in miniature. Here was the world *in vitro*, one that displayed miniature storms, table-top volcanoes, room-sized glaciers. At first, C.T.R. Wilson, the inventor of the cloud chamber, had just this in mind: a chamber (that is a controlled space or room) in which he could manufacture clouds, fog, rain. Into the series – camera lucida, camera obscura, dust chamber – came the cloud chamber, the camera nebulosa.[14]

Once Wilson found that he could produce tracks (long trailing clouds) that followed the trajectory of charged particles, physicists began to assemble a new kind of technology, one organized to sort phenomena. This classificatory mechanism relied on a centuries-old tradition of medical atlases: atlases of skulls, atlases of hands, atlases of X-rays. In these compendia the budding physician would, in the simplest case, find "normal" anatomy. The idea was that by looking at these images, organs, bones, or microscope slides would stand out if they were different, that is if they were pathological. For the physicist the cloud chamber atlas functioned similarly: if the image found departed dramatically from the normal, then pay attention. But while deviation from the normal marked the "pathological" for the physician, deviation from the normal signaled "discovery" to the physicist.

Other image-making devices soon followed. Nuclear emulsions were simply sheets of film that particles would traverse leaving tracks to be developed. Bubble chambers were great vats of liquid hydrogen or other liquids that would boil along the tracks of passing particles. As the technologies of image production shifted, much carried forward into the analysis of images.

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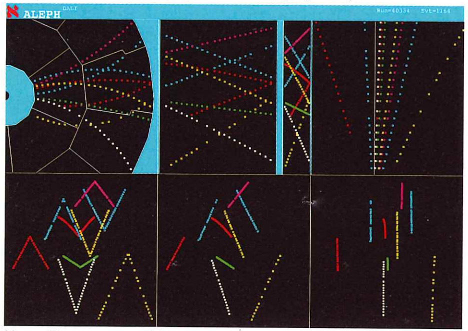
[14] _ This and the following discussion of particle physics experiments is drawn from Peter Galison, *Image and Logic: A Material Culture of Microphysics*, University of Chicago Press, Chicago, 1997.

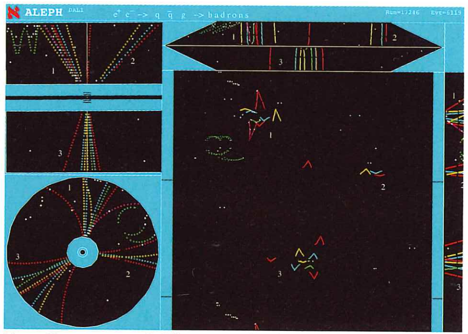
Digits into Pictures

It is not just that images pass into abstraction; the images themselves encode a wide range of abstract features. In a picture used in high-energy physics the »helpful distortions« are many – the uses of colored areas, »wire frame« outlines, transformations to make smaller inner chambers look larger, fish-eye perspectives to make better use of the visual field – to name but a few. Hans Drevermann and his collaborators at CERN belong to the growing community of physicists concerned with visual display. Addressing the often-discussed question, »Is there a future for pictorial representations?« they say »yes,« but caution that »the price to be paid is the use of more abstract representations. If one is ready to accept this complication, visualization of events will continue to serve as a helpful tool for representation and analysis.« These »abstract images« indicate several ways in which physicists manipulate images, pulling them from the more representational towards the more abstract.

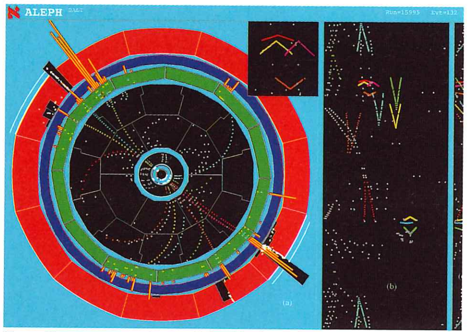
Conventional to abstract V-plot / a series of mathematical transformations performed on images to alter the »representational« spirals of particles moving in the magnetic field of a detector into »V«-shapes that are much easier to grasp / partially modified by Hans Drevermann / © from H. Drevermann, D. Kuhn, B. S. Nilsson, Is There a Future for Event Displays? http://www1.cern.ch/Explorator/EDisplay/Chapter-7.html



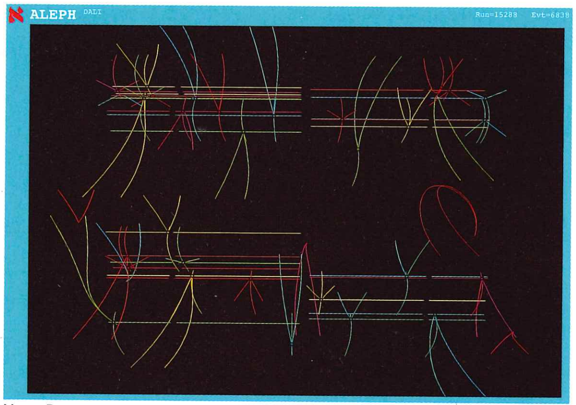
Hans Drevermann / from xy to V-plot: y/x, (/(, (/(compressed, (/z, v-plot, half of v-plot=((/(+(/(), (/(



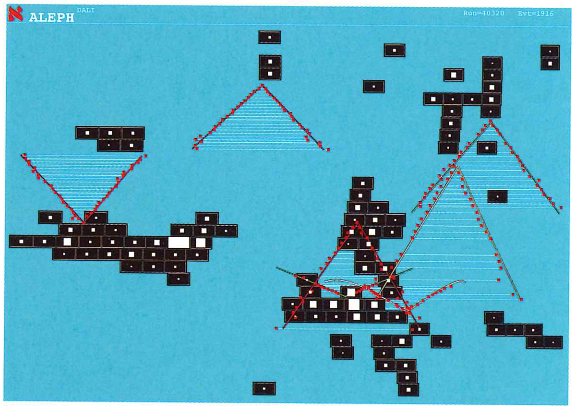
Hans Drevermann / different projections of the same event: (/z, r/(, y/x, V-plot, (/(, where (, r, and (are by (2=x2+y2, r2=x2+y2+z2, tan(()=z/(respectively



Hans Drevermann / use of the V-plot: y/x, v-plot, (/(

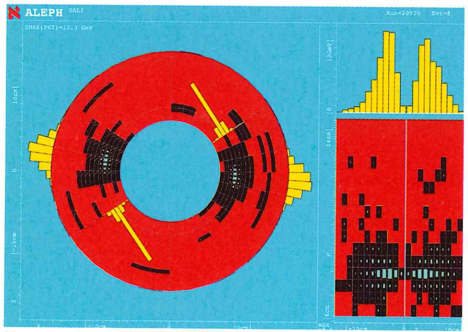


Hans Drevermann / use of the V-plot to connect TPC tracks to vertex detector

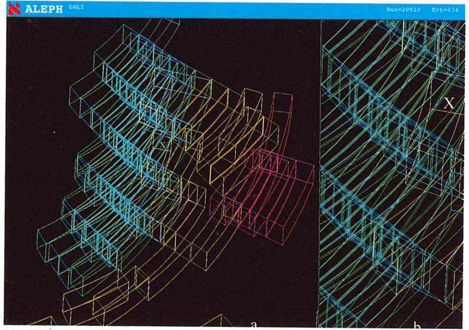


Hans Drevermann / use of the V-plot to connect TPC tracks to calorimeter data

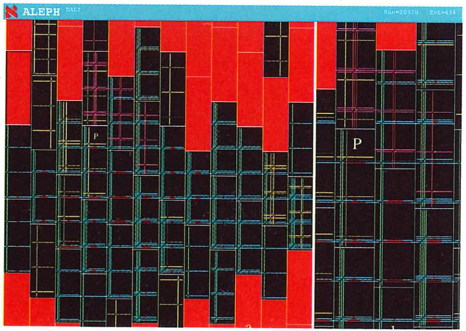
A different kind of transformation that alters the spatial disposition of detector cells into a so-called »puzzle-plot« that aided physicists in understanding the relation of the physics of the event / partially modified by H. Drevermann, from H. Drevermann, D. Kuhn, B. S. Nilsson, Is There a Future for Event Displays, http://www1.cern.ch/Explorator/EDisplay/Chapter-7.html



Hans Drevermann / front (Y/X) and side ((/Z) view of a silicon calorimeter



Hans Drevermann / conventional (3D) picture of the silicon calorimeter



Hans Drevermann / abstract puzzle plot of the silicon calorimeter

But almost at once, in every one of these new laboratories, the images themselves begin to dissolve, morphing into other forms. A flash of light and three cameras would capture a complex trail of bubbles in stereo relief. Then a scanner projected the pictures one by one onto a table, where she (almost inevitably *she* during the 1950s and 1960s) clicked a mouse-like device to enter space coordinates. Digitized, the information flowed into a computer which then crunched the data into idealized mathematical curves; from those curves the computer spat out punch cards with the particles' identities and properties. At first by hand and later by computer, the morass of numbers could finally be reassembled into new images: bar graphs or the so-called Dalitz plots where an entire picture would be reduced to a single black dot. The physicists could then ask: Did the dots cluster? Did the bar graph show one peak or perhaps two? An invisible physical process made bubbling tracks, tracks to numbers, numbers back to pictures. Those pictures in turn could themselves be analyzed back into numbers.

Some physicists, led by Luis Alvarez, insisted that human scanners and human physicists look at the pictures. Only the trained eye, he believed, would recognize the new and unexpected. Only a person facing an image would pluck the "zoo-on" out of the vast sea of unexceptional results. Others, driven largely by the group around Lew Kowarski at CERN, insisted that the image ought to be removed as much as possible from the process, scanned by computers. People looking at pictures were, he believed, prone to error and should be eliminated "function by function" from the analysis of the physics. At Karlsruhe in 1964, the two sides gathered, and fought:

> K. Ekberg: "I would like to ask a question of principle which touches on the point that one might wish to do the first scanning of these pictures automatically. Now it is surely so that many important discoveries have been made because scientists have noticed something, which they did not expect. Something new which they could not explain from their previous knowledge. Now we surely can't program computers and automatic devices for this sort of thing?"

Kowarski allowed that perhaps people could call interesting pictures up from the millions that would be archived. Then another physicist intervened even more pained:

> Herwig Franz Schopper: "This point of view frightens me a little because it would mean that, in a few years, if one wants to do a high energy experiment, one would not go to start a new experiment but would just go into the archives, get a few magnetic tapes, and start to scan."

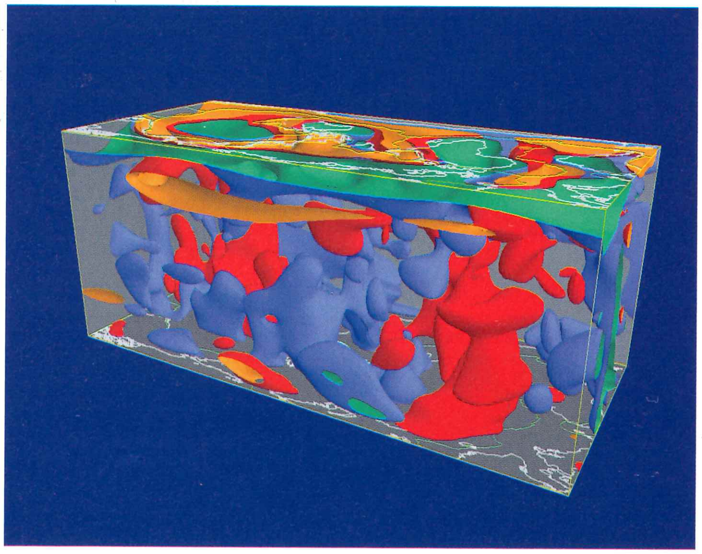
Even within the image tradition, the picture was always on the verge of being resorbed by the computer, snatched from human eyes and transmuted back into the whirl of numbers.

As these new imaging technologies of physics rose to prominence, other competing machines offered data without any pictorial product. Pictures, some physicists lamented, had something nineteenth century about them. Couldn't devices be built that took the world directly to the computer, that fully by-passed the millions of pictures spewing out of cloud and bubble chambers? Geiger counters could click, for example, when a particle passed – sending an electrical pulse to a counter. Spark chambers flashed when particles traversed them, wire chambers became sensitive enough to pick up even the tiny amounts of ionized gas left in the wake of a passing particle. With the help of a computer, machinery could use time and space measurements to reconstruct the event. These were technologies that, in the first instance, produced not images but statistical data, though statistical data quickly converted back into images.

One can find statistical experiments without any images at all. Suppose, for example, you want to find out whether cosmic rays can penetrate a block of lead. One way to proceed might be this: place a Geiger counter on either side of the lead block, and wire up the system so that it only sends a pulse to a counter if *both* Geiger counters fire within a very short amount of time. Say that twenty pulses get counted, on average, per minute. The question arises: could the coincidental firing of the two counters be an artifact, the arrival not of a single penetrating particle but of two independent particles that happen to hit the two counters in the same short amount of time? To control for this possibility, the experimenter might measure the total number of hits on each counter and figure out the likelihood of an "accidental" coincidence. For the sake of our example that might be ten per hour. Then the conclusion that particles *are* penetrating the lead is not based on any individual coincidence – any particular coincidence might be due either to a single particle *or* to two independent hits. No, in the end the argument is statistical: there is a statistical *excess* of coincidences beyond that expected by the background.

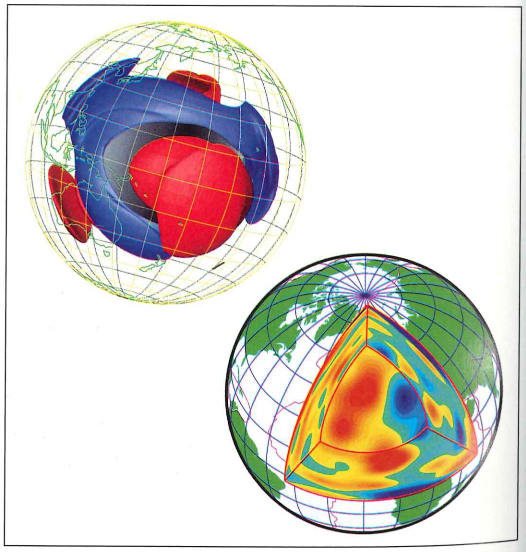
Image experiments served wonderfully to track individual events; logic experiments often had the edge in treating aggregates. Individual events for some physicists carried persuasive force precisely because they could "see" into the whole of the process, as if, some said, they could peer directly into the submicroscopic world. They hated not knowing what went on between the counters, resisted the indirect, inferential process of statistical reasoning. The "logicians" by contrast claimed that arguments by solid statistics stood on vastly firmer ground. "Anything can happen once," they grumbled. Science, the anti-imagers asserted, lies in the ability to manipulate and control phenomena, in the behavior of the many, not in the comportment of the few. Science, the image-defenders retorted, lies in the receptive, objective, singular medium of film.

In many ways, this image/logic split highlights, in the laboratory itself, the gulf between the desperate search for the individual image and the equally insistent attempt to avoid reliance on anything pictorial. Epistemically, this is an argument repeated over and over, in field after field. Doctors (and now the courts) slam into each other as they measure case studies versus epistemological studies. Geology had its era of qualitative studies against quantitative ones, seismology opposed to morphology. In the post-World War II years, astronomers often felt that they had to evaluate claims from radio astronomy against the established knowledge of optical

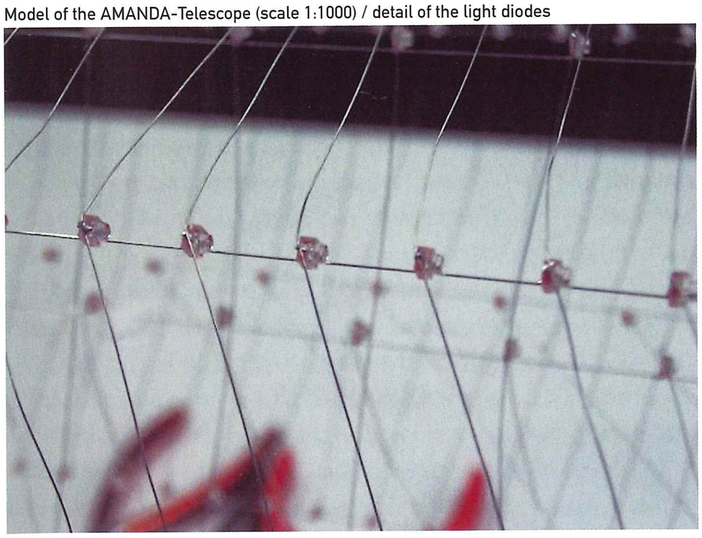


Imaging the Interior of the Earth / courtesy Adam M. Dziewonski and Goran Ekstrom

Geology, long divided between the quantitative seismologists and the morphological, more visual approach began to come together at the technical level with seismographic imaging. Borrowing from years of work on nuclear magnetic imaging- and analog techniques on materials-geophysicists, led by Adam M. Dziewonski, began to produce images like these of the interior of the earth, all the way down to the solid core. The colors in the pictures indicate the different velocities with which seismic waves travel through the earth.



Model of the AMANDA-Telescope (scale 1:1000) / detail of the light diodes

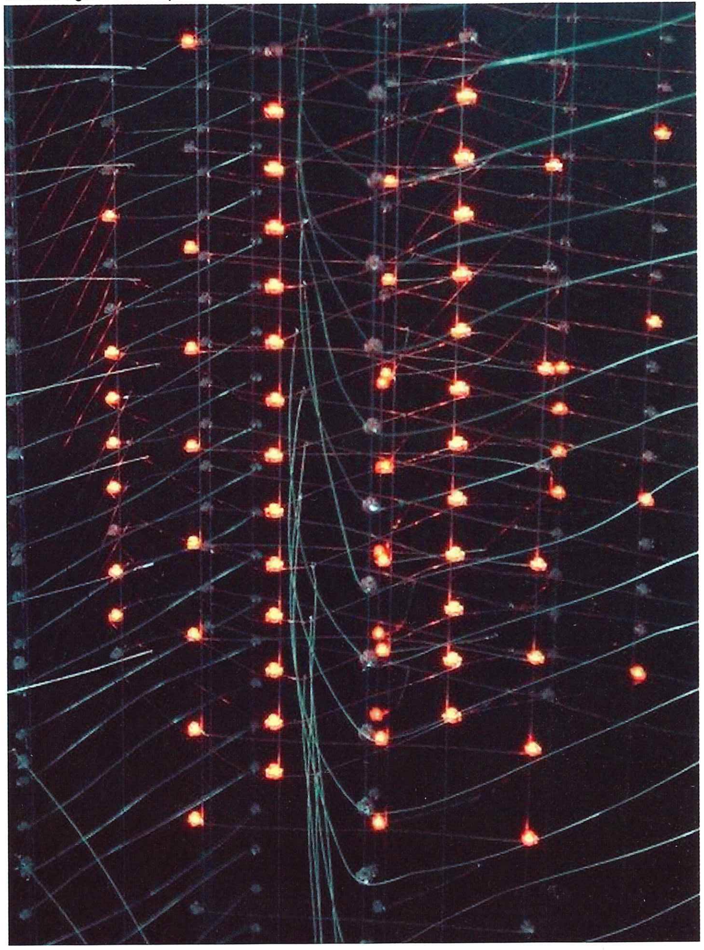


astronomy. Do you trust the X-ray or the stethoscope? Would you put your money on the morphology of open faces of rocks or seismological data? Bit by bit over the last few decades there has been a remarkable transformation in all these binaries. In each instance the image followers found themselves manipulating data banks, and the numerical-logicians found themselves gazing into the face of a picture. In the science of the very small, physicists have even brought cognitive science into their strategies for the visual display of digital data – the need to visualize crossed with the need for manipulable "logic"-based data.

Tomographic techniques in medicine and electronics have created a vast new industry in medical imaging: CAT scans, MRI scans; new modes of visualization have seized one discipline after another as image-producing software migrated between fields. For example, seismology, once the least visible of all the earth sciences was, by century's end, yielding seismically-generated pictures of the earth's mantle and inner structures all the way down to the solid core of the planet.

Soon, the cycle of fragmentation and consolidation began again as earth scientists began dissecting their images not just for the qualitative work but for further quantitative analysis bearing on the detailed structure of the core, plate dynamics, and much more.

Light clouds drifting below the surface of the ice are shown through the light amplifier submerged in the ice of the South Pole. Every light diode stands for a light sensor. The time that the light cloud requires to travel across the telescope is reduced ten-millionfold.



4. Between Eye and Mind

In conclusion it may be that the most significant development in the laboratory of the last fifty years has been the fusion of pictures and numbers into the production of the manipulable image. Controllable digitized images were built by computers from statistics and formed into pictorial renditions of non-visible worlds.

But with these examples in mind, we can come back to re-assess, critically, the conflicted ideals with which we began: "We must have images, we cannot have images." After tracking the endless drive back and forth between images and data, it becomes clear that the powerful drive to images and the equally forceful pressure towards analysis never completely stabilized scientific practice. Quite the contrary: neither the "pictorial-representative" nor the "analytic-logical" exist as fixed positions. Instead, across a wide span of the special sciences, we see that the image itself is constantly in the process of fragmenting and re-configuring. No doubt this has long been so, back deep into the history of scientific images of Etienne Jules Marey or even to the shifting forms of diagrams in the Renaissance. But now, ever more intensively, the routinization of analog-to-digital and digital-to-analog conversions has made the flickering exchanges routine: image to non-image to image. No longer only set in motion at moments of crisis, we find that ordinary, every-day science propels this incessant oscillation:

> "Images scatter into data, data gather into images."

Bubble chamber images fragment into digitized measurements; measurements re-arrange into mathematically-described tracks; tracks splinter back into numerically-coded particle properties; particle properties reform into new kinds of image displays. Such movements back and forth across the pictorial/analytic divide are, I believe, woven deep into physics, not just in epochal battles of the intuitionists and logicians (or of Heisenberg and Schrödinger), but instead in the quotidian details of practice in astrophysics, in geodynamics, even in medicine.

Joseph Koerner has written in this volume about a seemingly paradoxical subject: the image of the iconoclast. But he shows that it is far too simple to gloss the *Bildersturm* as a conflict between image worshipers and image destroyers. Instead, he finds on one side sixteenth century Protestant iconoclasts who surrounded themselves with a vast new armamentarium of images: carnivalesque depictions of their opponents, idols ostentatiously punished and preserved, pictorial renditions of the errors of this-worldliness. Pushed to the limit, even Luther began arguing that faith inevitably led to "images ... within my heart" as surely as "my face naturally delineates itself on the water, when I look into it." On the other side there are Luther's Catholic opponents who are also after the transcendental. For the defenders of the older order, the faithful are never actually worshiping the wooden hand of Christ, they are using those images as a spiritual ladder. As each upward step is taken, it is pushed away; images slip into non-images. As Koerner puts it, image makers become image breakers, and image breakers become image makers.

Caroline Jones finds the oscillation between image-wanting and image-refusing to be even greater. Abstract art, as she points out, is from the onset saturated with micro-iconoclasms: cancellations, unravellings, destructions. After all, the modernist canvas is forever depicting its abstraction. It is a project that can only make sense insofar as the abstraction is not an abstraction from *all possible images* but an abstraction from a specific feature (representation or depth or surface or perspective). Barnett Newman's expanses of color refused to mime the physical world – and at the same time the canvasses celebrated the phenomenal self that must, when facing such a color plane, confront its existence. We are always, Jones says, caught between the desire for present magic in *this* canvas and the absent abstraction to which it is supposed to point. Dario Gamboni takes as emblematic Komar and Melamid's crane-hoisted Lenin statue. Like that construction, Gamboni sees artwork perpetually suspended between restoration and destruction.

Quite generally, this exhibition explores a problem common to both art and science: the haunting oscillation between the concrete and abstract. Indeed, as we have seen, for these last hundred and fifty years or so, a great range of scientific specialties have struggled to find a way to cross the divide. Perhaps just because of these conflicted crossings we ought to rethink the gap that is supposed to separate them. Maybe the concrete and abstract ought not be seen as pitting the sublunary world against the superlunary one, the finite, pictorial, and material against the infinite, logical, and abstract. For as soon as the problem is phrased that way we are launched on a futile search for a relation between two evacuated poles. Instead, suppose we took the material as never to be completely non-abstract – objects are never just objects to us. We cannot ever speak (or paint or calculate) without metaphoric abstraction. At the same time the abstract is never completely so; even in the coldest reaches of mathematical physics we will always (borrowing from Luther), find the image of our face in still water. Not abstract against the concrete, but rather shifting historical realizations of concrete-abstraction or abstract-concreteness.

What of the putative battle between iconoclasm and inconophilia? In field after field, from geometry to quantum mechanics, from astrophysics to microphysics, the richness of the image and the austerity of the numerical are always falling into each other. One wonders how this state of instability so often comes to be seen as a battle of fixed positions. A bit of physics comes to mind. General relativity gives a fascinating description of an object falling into a black hole. As the object approaches the event's horizon – the point of no return – an outside observer sees that object slow down as it approaches the horizon, its image gradually shifting towards the red. Eventually the scene of the falling object freezes in dimming redness at just the instant it passes beyond the visible. That scene resembles ours. Just when the scientific image moves towards abstraction we are left with the last glimpse of a frozen picture and ignore what happens next. At just that moment when the abstract-logical becomes pictorial, we forget the picture to celebrate that last remembered moment of non-image. It is all too easy to forget the incessant traffic back and forth between the scientific-artistic desires to grasp with eyes open and shut.