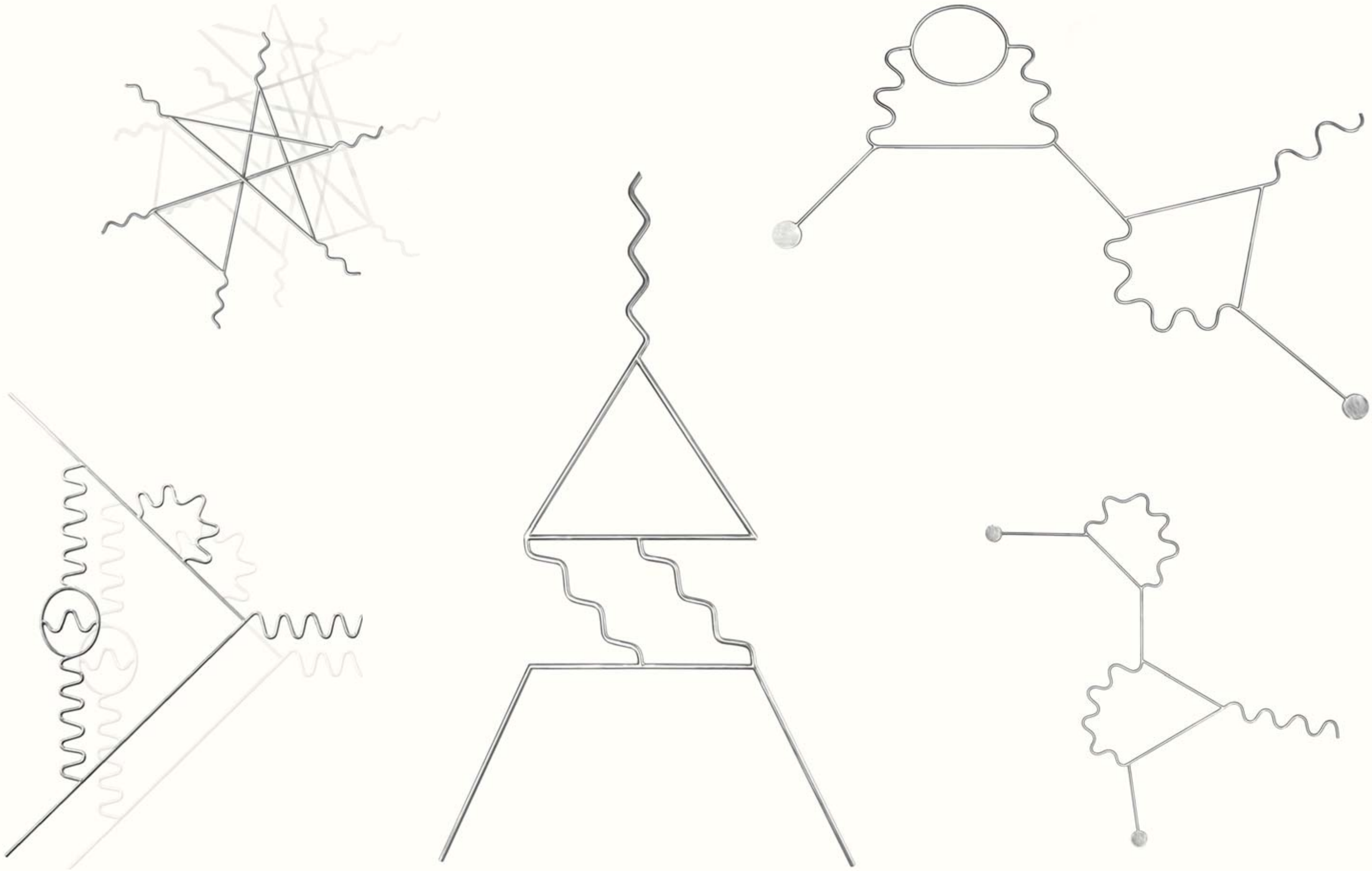
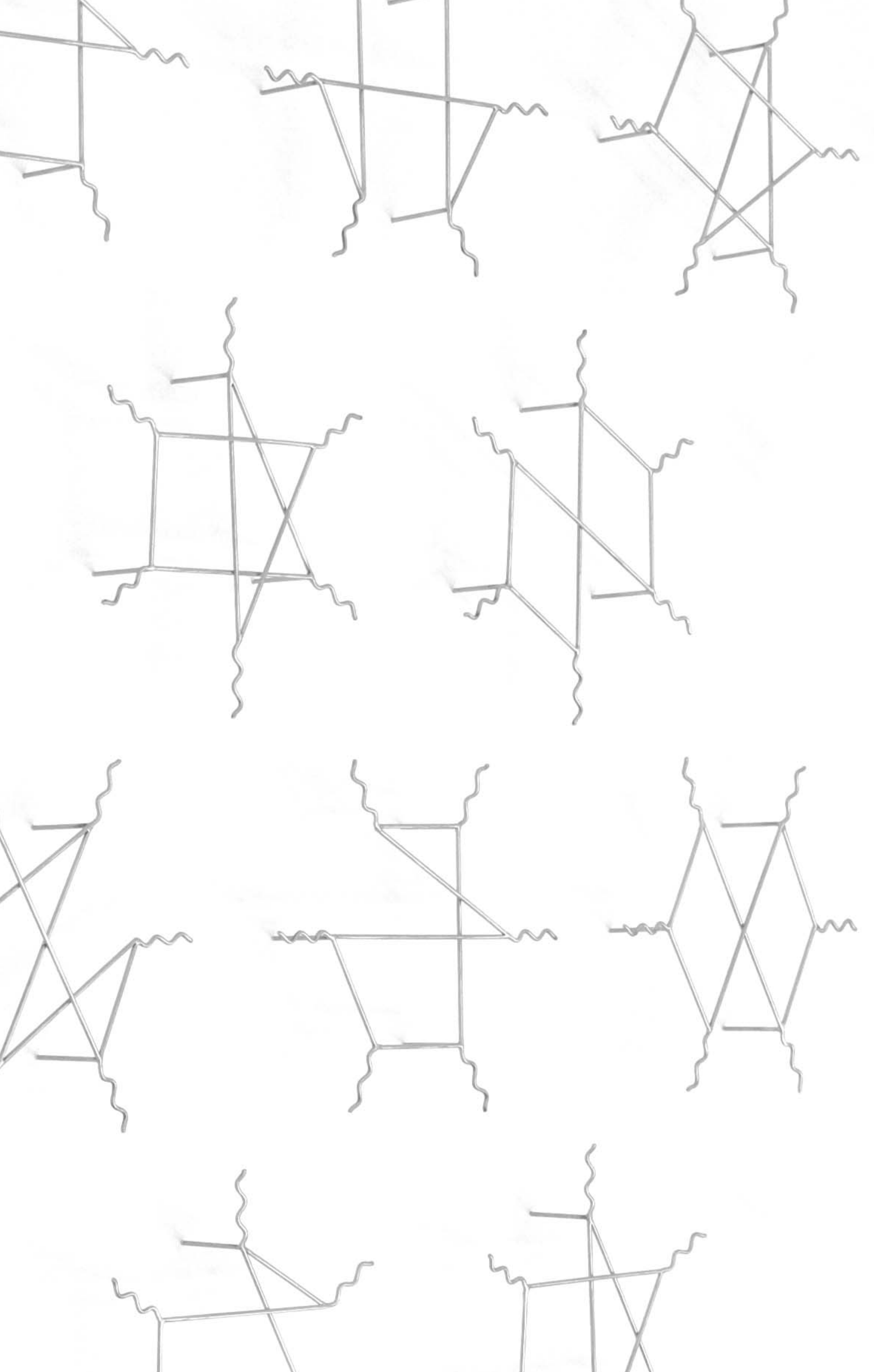


EDWARD TUFTE ALL POSSIBLE PHOTONS

THE CONCEPTUAL AND COGNITIVE ART OF FEYNMAN DIAGRAMS

ET MODERN 547 WEST 20TH STREET NEW YORK



Edward Tufte's wall-mounted sculptures, *All Possible Photons,* generate an enormous multiplicity of three-dimensional optical experiences of line, light, airspace, color, shadow, form.

Made from stainless steel and air, the artworks grow out of Richard Feynman's famous diagrams describing Nature's subatomic behavior. Feynman diagrams depict the space-time patterns of particles and waves of quantum electrodynamics. These mathematically derived and empirically verified visualizations represent the space-time paths taken by all subatomic particles in the universe.

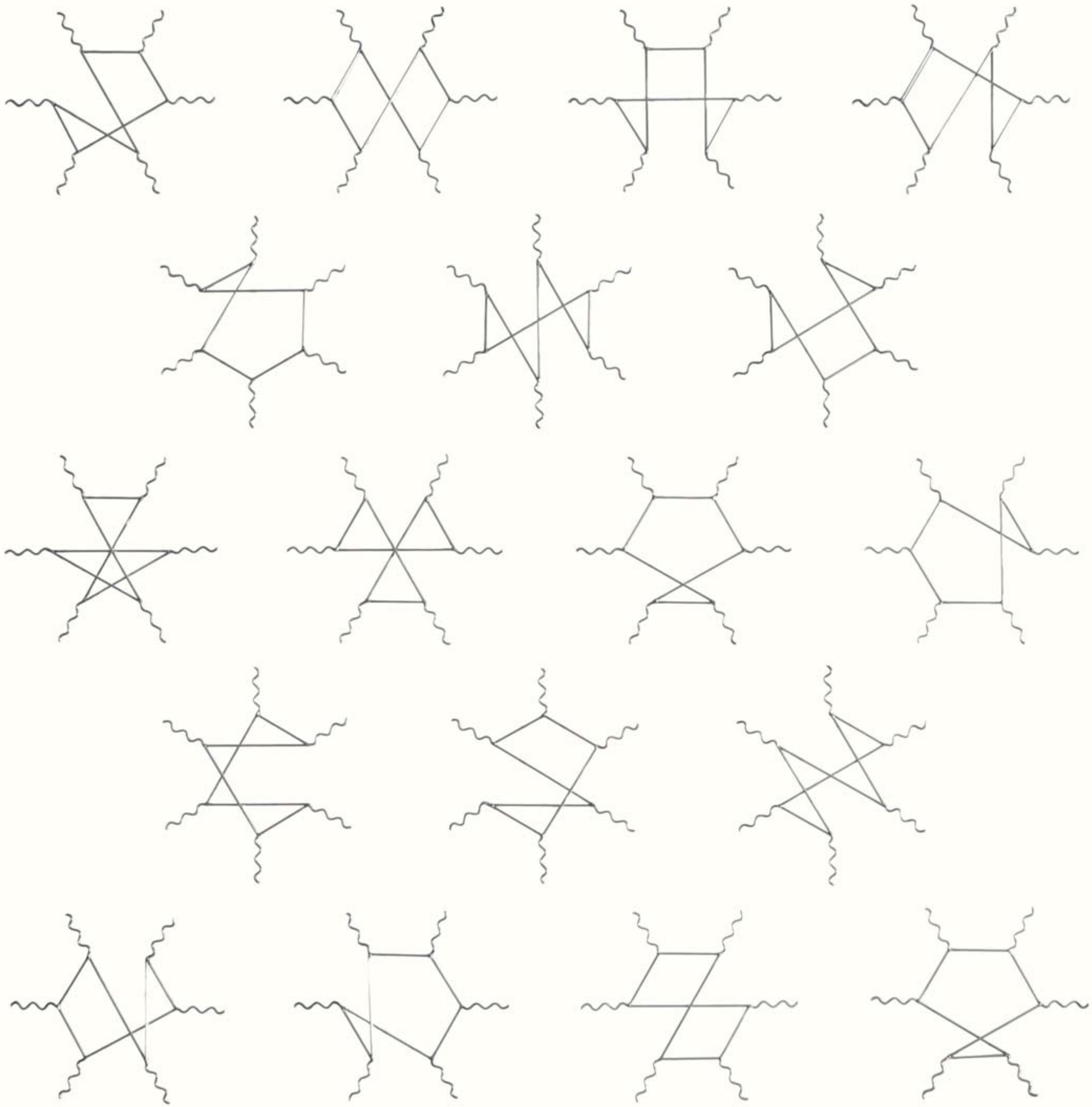
The resulting conceptual and cognitive art is both beautiful and true. Along with their art, the stainless steel elements of *All Possible Photons* actually *represent something:* the precise activities of Nature at her highest resolution.

Gathered together, as in the 120 diagrams showing all possible space-time paths of 6-photon scattering, the stainless steel lines (and their variable shadow, airspace, light, color, form) reveal the endless complexities that result from multiplying and varying fundamental elements.

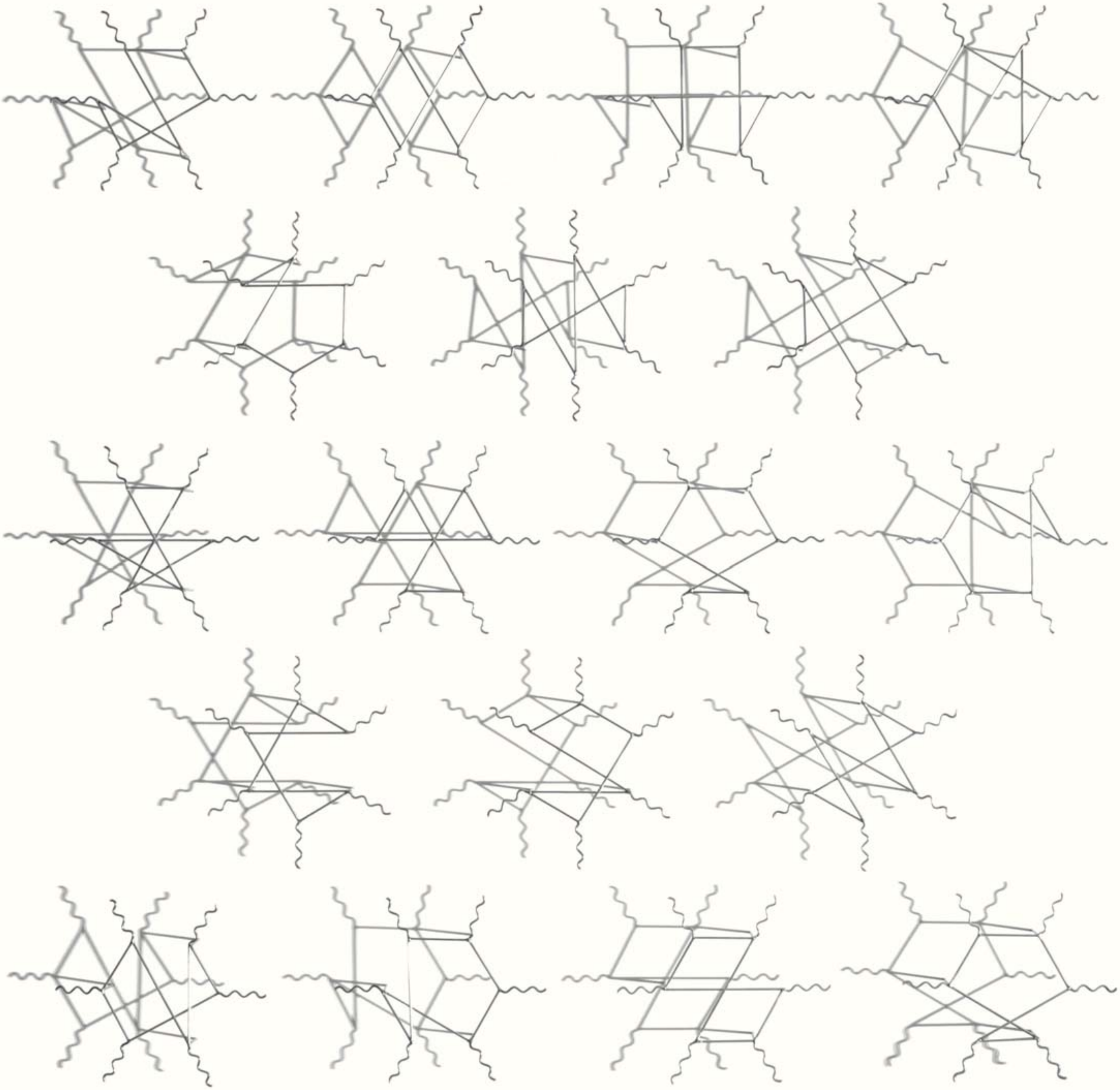
"How beautiful it was then," writes Italo Calvino about a time of radiant clarity in cosmic prehistory, "through that void, to draw lines and parabolas, pick out the precise point, the intersection between space and time when the event would spring forth, undeniable in the prominence of its glow."

ET *All Possible 6-Photon Scattering (120 Space-Time Feynman Diagrams)* 2012
stainless steel 17.5 x 7.3 x .2 feet or 5.3 x 2.3 x .1 meters (detail)

Without shadow light, the artwork reads as precise lines on a flat surface. But since all the 18 elements are supported off the wall, they cast shadows. (A good definition of sculpture is *artwork that casts shadows.*) These shadows are shown on the adjacent page.



18 Space-Time Feyman Diagrams of 6-Photon Scattering 2012
stainless steel 4.1 x 4.2 x .2 feet
or 1.3 x 1.3 x .1 meters



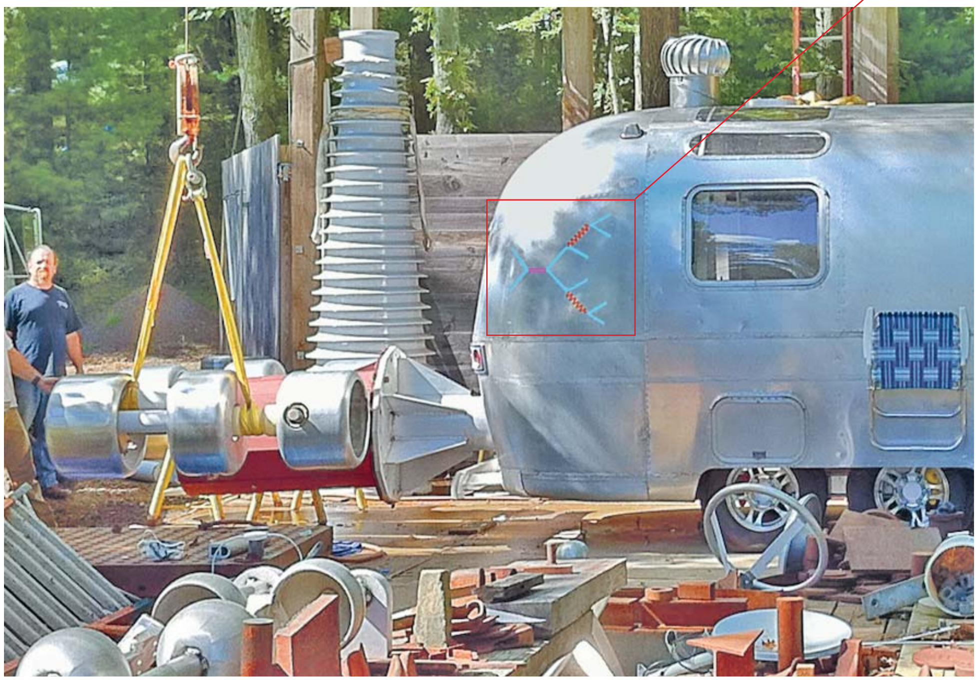
With light, the same artwork yields a luscious complexity: flat shadows interacting with 3D stainless steel lines to create Escher-impossible apparent objects in 3-space.

And when the light shifts in color, intensity, and angle of incidence, so the reflections from the steel lines and their shadows continually respond, vary, shift. These diverse optical experiences created by light are all for free, the happy by-products of light meeting sculpture.

Alas the complex airspaces created by the steel lines and their wall shadows *can only be seen by being there*. Sculpture's interface is reality.

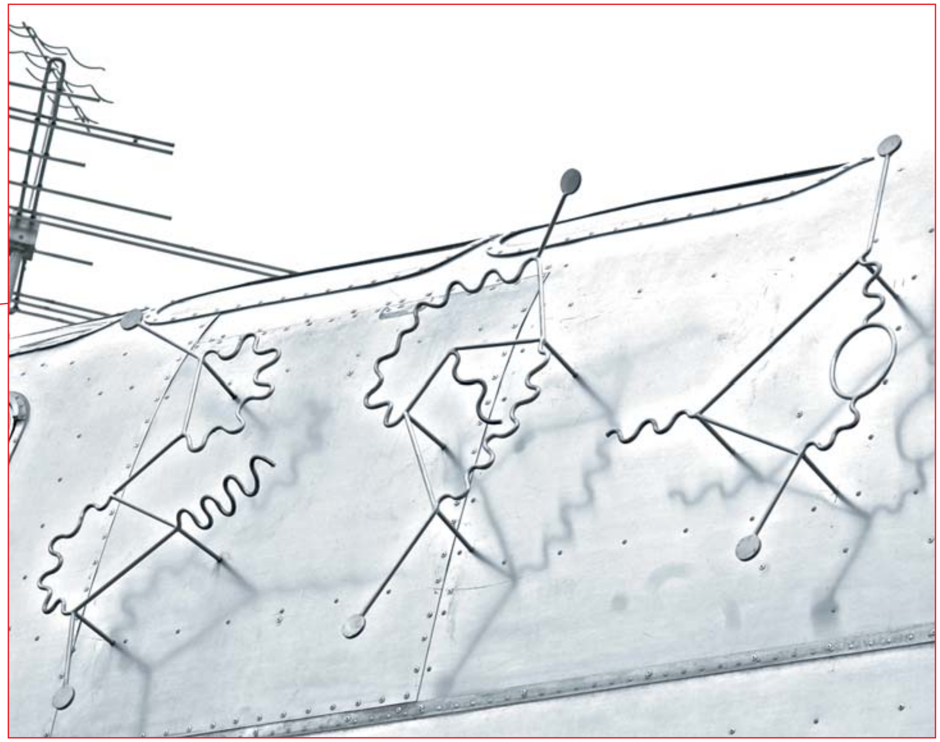
Rocket Science 2 (Lunar Lander) 2009
steel, aluminum, porcelain length 70 feet or 21 meters, height 35 feet or 11 meters

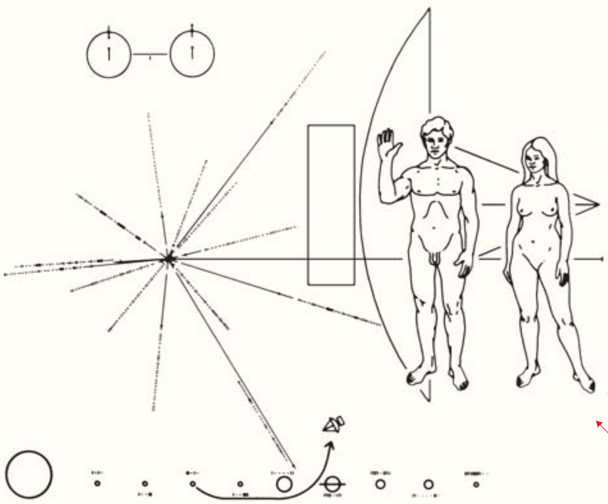
Rocket Science 3 (Airstream Interplanetary Explorer) 2011
steel, aluminum, stainless steel, electronics length 84 feet or 26 meters, height 31 feet or 9 meters



Since Feynman diagrams describe the universal operations of Nature's laws, they can communicate throughout the universe. Both sides of the *Airstream Interplanetary Explorer* show Feynman diagrams that may well communicate with intelligent life anywhere. Better the cosmopolitan verbs of Nature's laws on spacecraft than the local proper nouns of national flags, earthly Gods and Goddesses, and government agency logos. For interplanetary exploration, better to send smart machines and emblematic Feynman diagrams than human beings and their lawn chairs, toilets, and teddie bears.

And for the cosmological entertainment of intelligent beings wherever whenever, prankish illusory violations of Nature's laws make jokes that travel well – as in the Pioneer Space Plaque redesign at right.

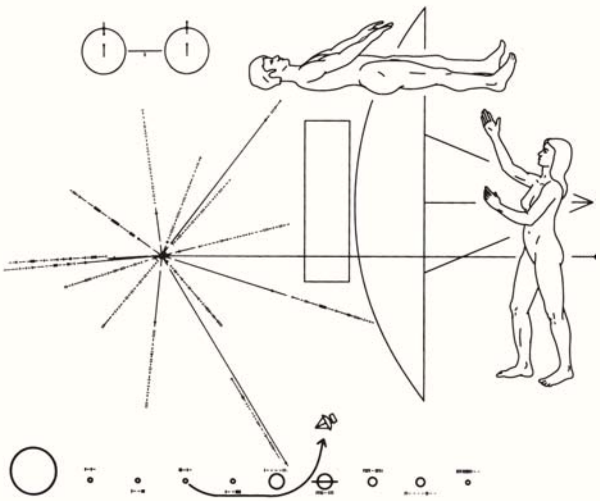




THE PIONEER SPACE PLAQUE: A COSMIC PRANK

Magic, the production of entertaining illusions, has an appeal quite independent of the local specifics of language, history, or culture. In vanishing objects or levitating assistants, conjurers amaze, delight, and even shock their audiences by the apparent violation of the universal laws of nature and our daily experience of those laws.

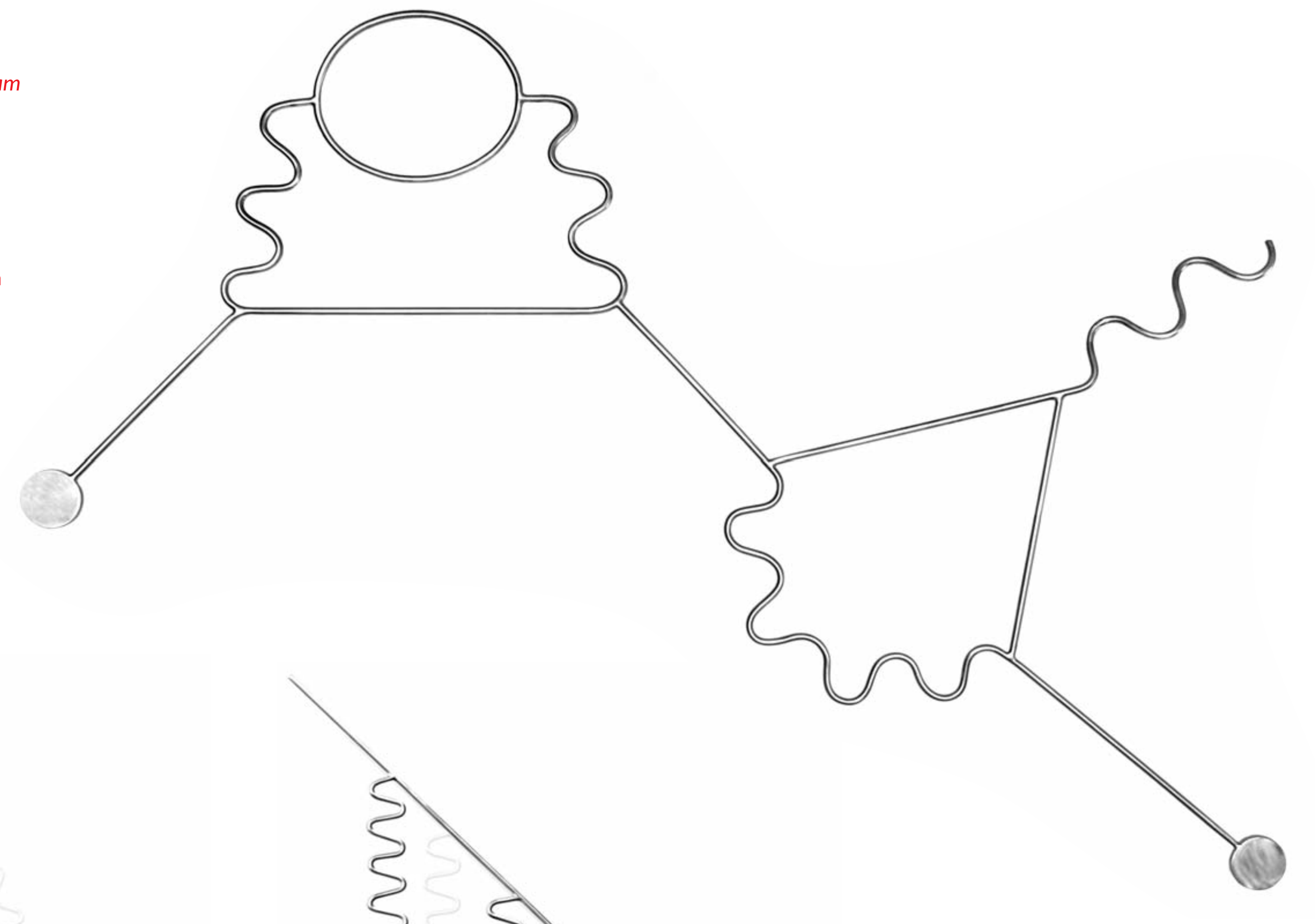
Since the principles of physics hold everywhere in the entire universe, magic is conceivably a cosmological entertainment, with the wonder induced by theatrical illusions available to and appreciated by all, regardless of planetary system. Accordingly the original plaque placed aboard the Pioneer spacecraft for extraterrestrial scrutiny billions of years from now might have escaped from its conspicuously anthropocentric gestures by showing instead the universally familiar Amazing Levitation Trick.

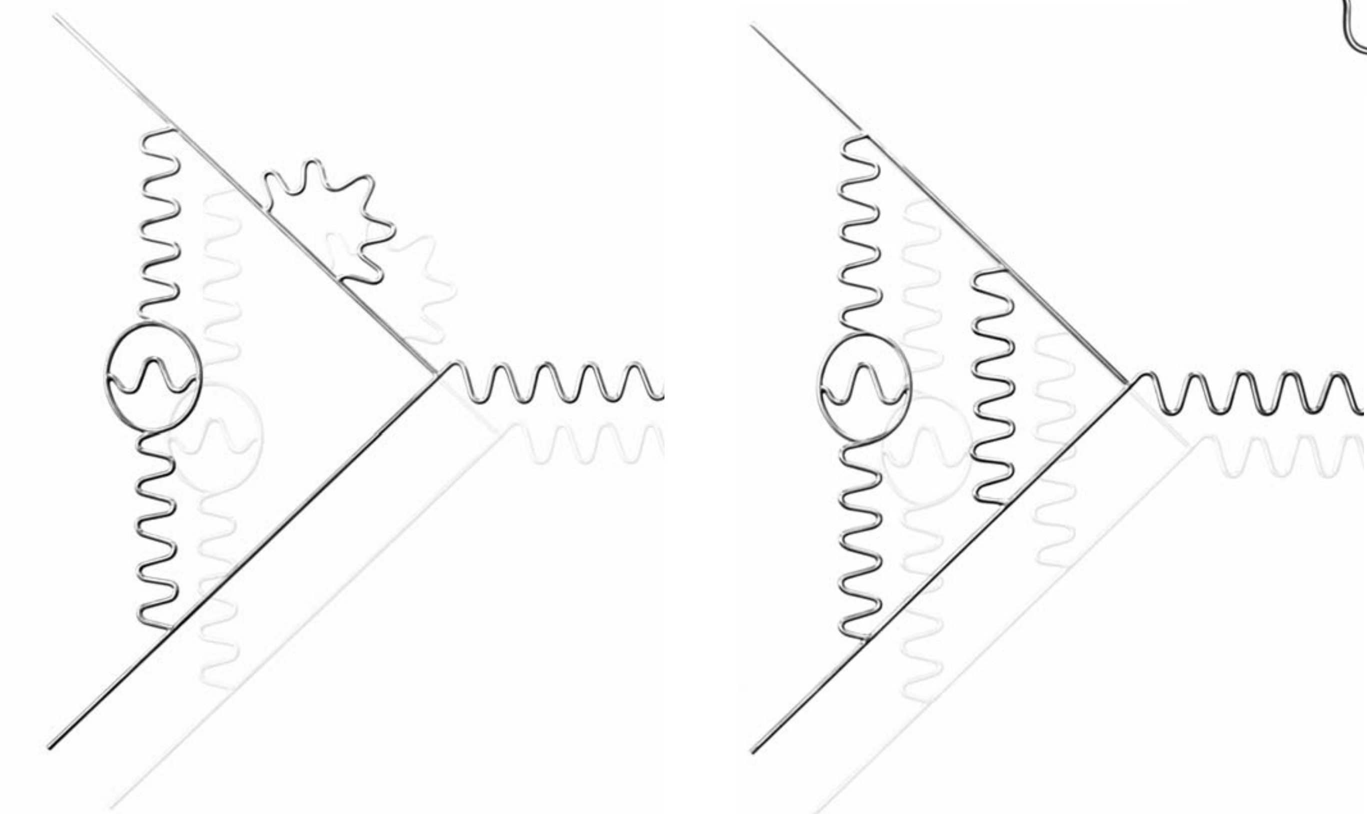


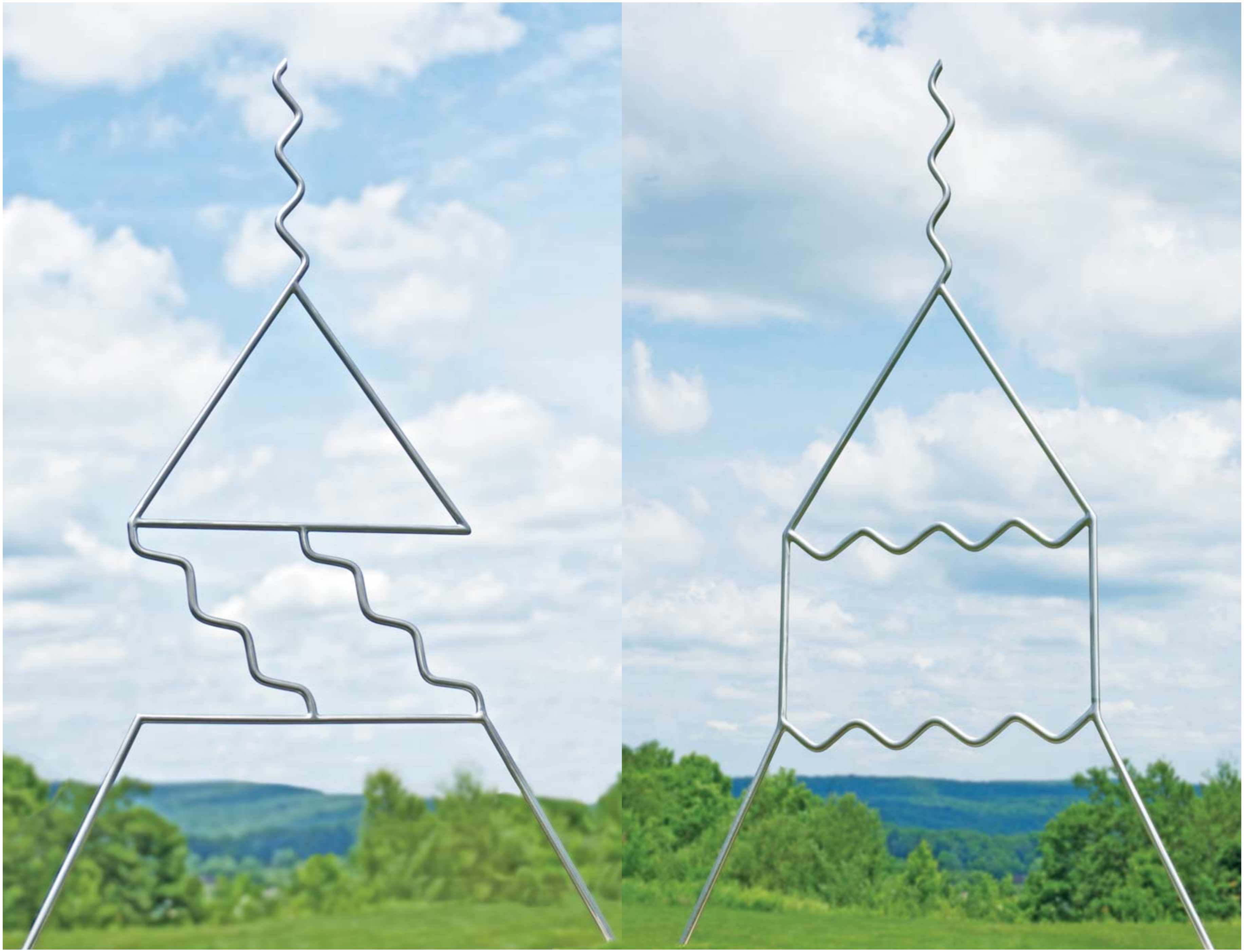
The Pioneer Space Plaque: A Cosmic Prank 2010 digital print, animation electronics 6.9 x 2.2 x .5 feet or 2.1 x .7 x .2 meters

Torqued Space-Time Feynman diagram
2012 stainless steel
6.1 x 8.1 x 1 ft or 1.9 x 2.5 x .3 m

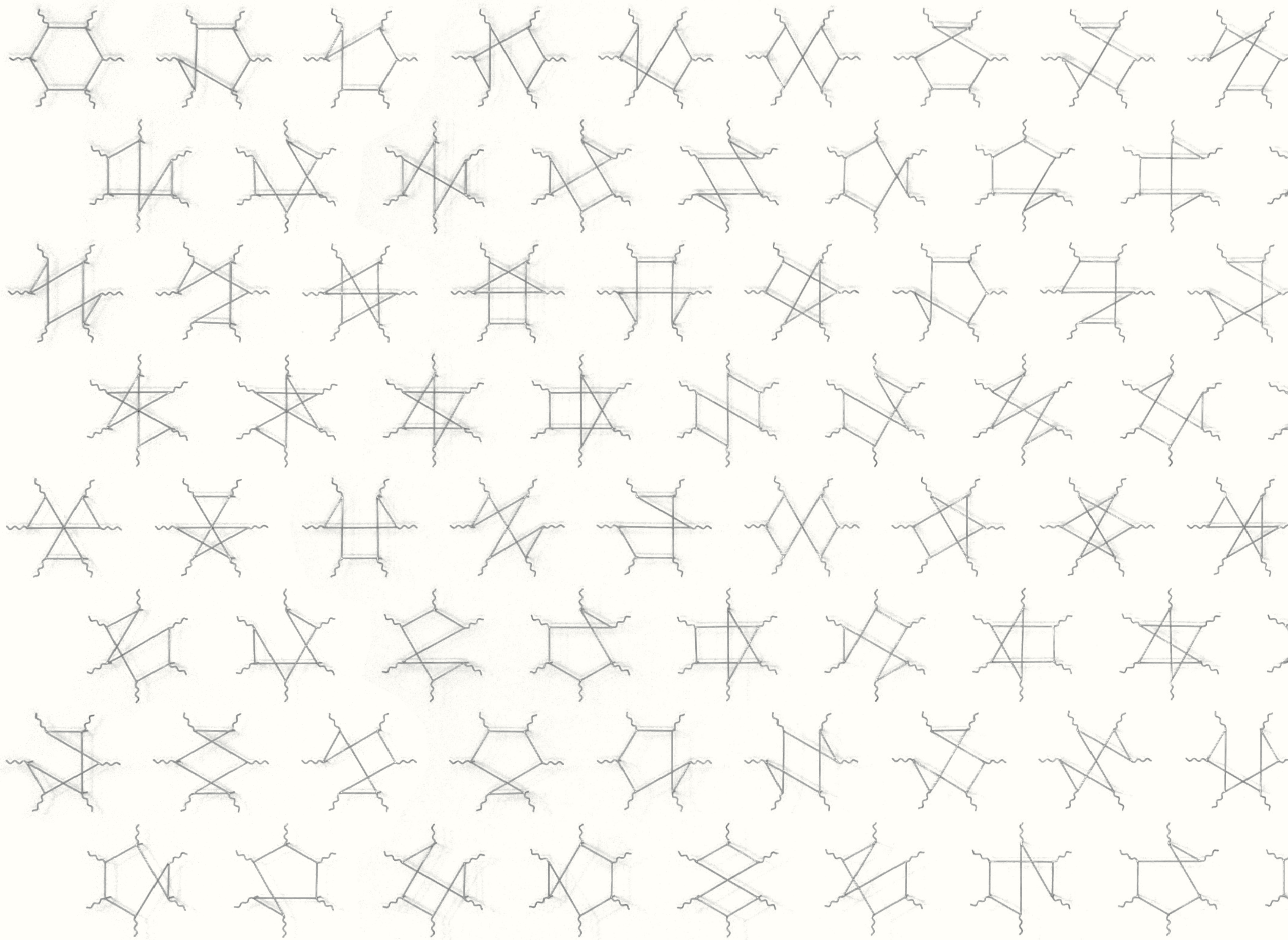
2 Space-Time Feynman diagrams
2012 stainless steel pair
8.9 x 4.5 x .3 ft or 2.7 x 1.4 x .1 m



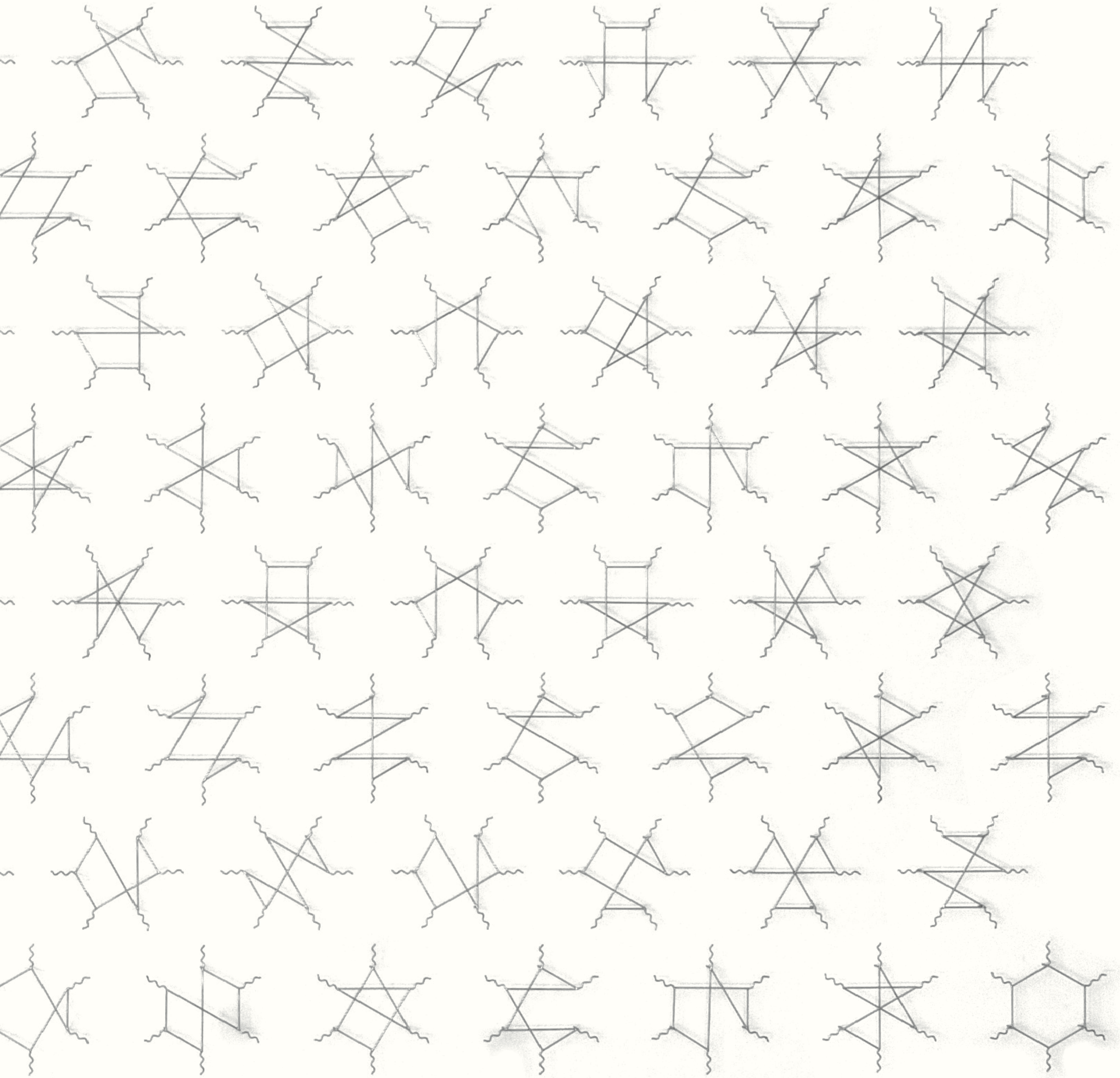


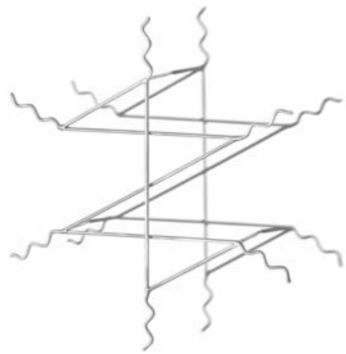


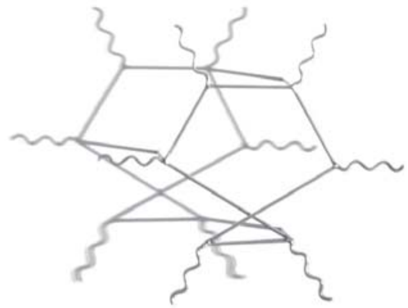
2 Space-Time Feynman Diagrams (Aztec) 2012 stainless steel 30.5 x 49 x 3.5 in or .8 x 1.2 x .1 m

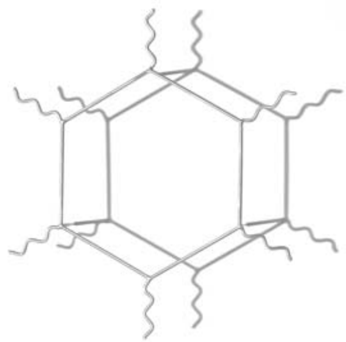


All Possible 6-Photon Scattering (120 Space-Time Feynman Diagrams) 2012 stainless steel 17.5 x 7.3 x .2 feet or 5.3 x 2.3 x .1 meters









FEYNMAN DIAGRAMS

Edward Tufte, *Beautiful Evidence* (2006), pages 76-77.

With differentiated lines similar to maps and old electronic schematics, Richard Feynman's famous diagrams for quantum electrodynamics depict complex ideas. Based on a dictionary and elaborate syntax, the diagrams portray interactions of photons, electrons, positrons, their many colleagues and anti-colleagues by means of visual reasoning, logical enumeration, and mathematical operations. Behind the scenes, extensive calculations are at work; in 1983, the magnetic moment of an electron was computed to 12 significant digits using 900 diagrams with 100,000 terms.

Serving simultaneously as images, equations, and verbal summaries, Feynman diagrams are multimodal and thus, in practice, often modeless. For example, this double-page layout below from Martinus Veltman's *Diagrammatica: The Path to Feynman Diagrams* combines diagrams, their parallel mathematical equations, and a verbal narrative. Veltman points out that the "situation in quantum electrodynamics is more complicated," *which we knew before we started.* These pages below have an elegant

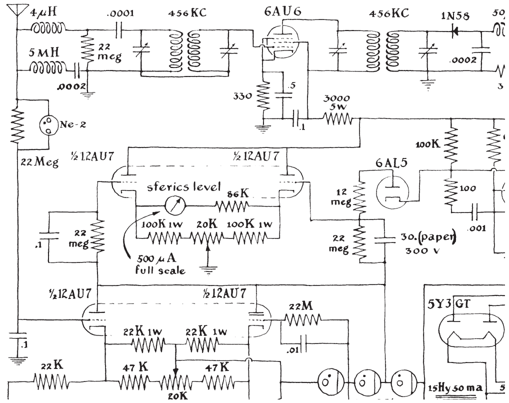
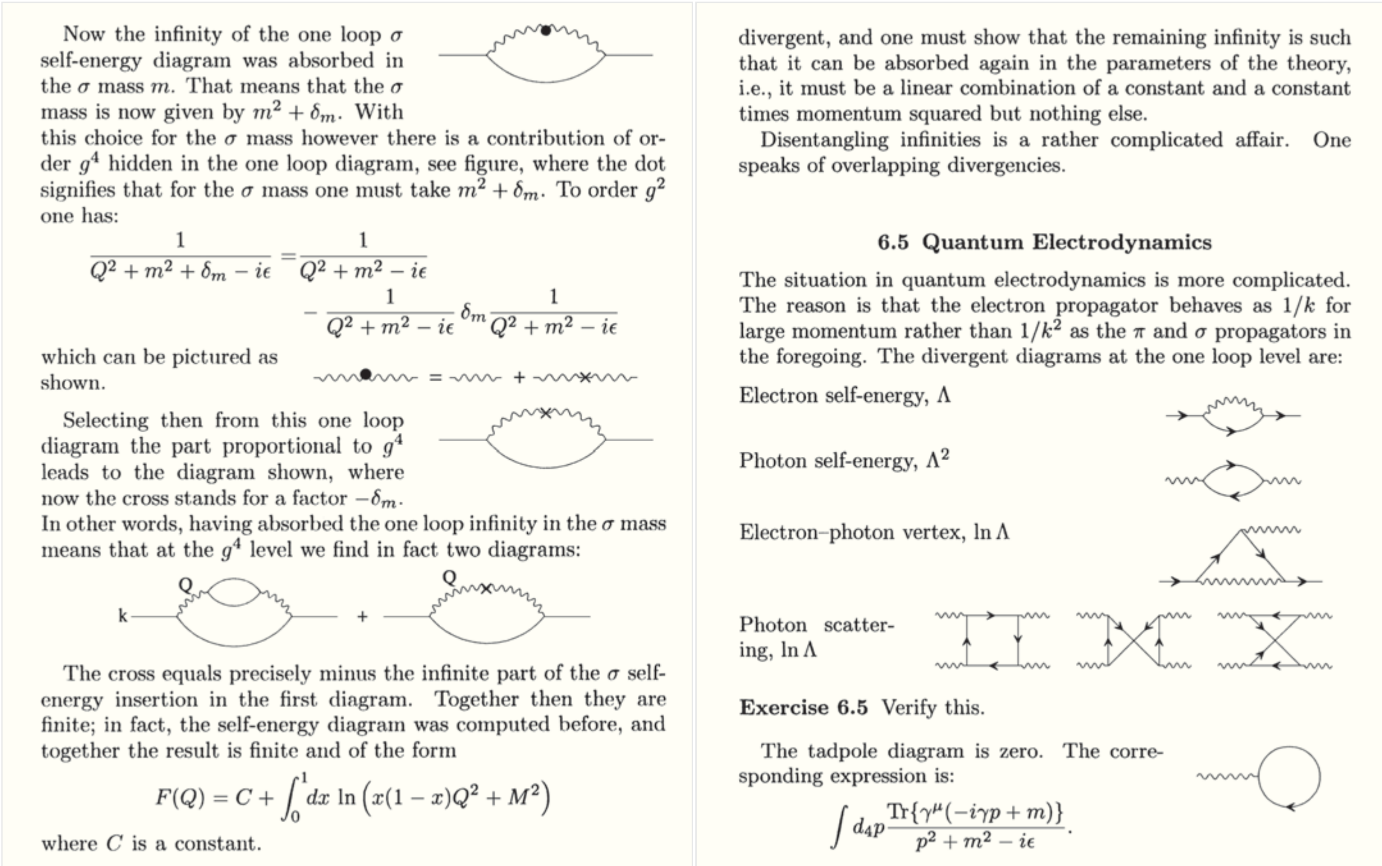


Illustration by Roger Hayward, in C. L. Stong, *The Amateur Scientist* (New York, 1960), 287.

Martinus Veltman, *Diagrammatica: The Path to Feynman Diagrams* (Cambridge, 1994), 150–151.



Now the infinity of the one loop σ self-energy diagram was absorbed in the σ mass m. That means that the σ mass is now given by $m^2 + \delta_m$. With this choice for the σ mass however there is a contribution of order g^4 hidden in the one loop diagram, see figure, where the dot signifies that for the σ mass one must take $m^2 + \delta_m$. To order g^2 one has:

$$\frac{1}{Q^2+m^2+\delta_m-i\epsilon} = \frac{1}{Q^2+m^2-i\epsilon} - \frac{1}{Q^2+m^2-i\epsilon}\delta_m\frac{1}{Q^2+m^2-i\epsilon}$$

which can be pictured as shown.

Selecting then from this one loop diagram the part proportional to g^4 leads to the diagram shown, where now the cross stands for a factor $-\delta_m$. In other words, having absorbed the one loop infinity in the σ mass means that at the g^4 level we find in fact two diagrams:

The cross equals precisely minus the infinite part of the σ self-energy insertion in the first diagram. Together then they are finite; in fact, the self-energy diagram was computed before, and together the result is finite and of the form

$$F(Q) = C + \int_0^1 dx \ln\left(x(1-x)Q^2 + M^2\right)$$

where C is a constant.

divergent, and one must show that the remaining infinity is such that it can be absorbed again in the parameters of the theory, i.e., it must be a linear combination of a constant and a constant times momentum squared but nothing else.

Disentangling infinities is a rather complicated affair. One speaks of overlapping divergencies.

6.5 Quantum Electrodynamics

The situation in quantum electrodynamics is more complicated. The reason is that the electron propagator behaves as $1/k$ for large momentum rather than $1/k^2$ as the π and σ propagators in the foregoing. The divergent diagrams at the one loop level are:

Electron self-energy, Λ

Photon self-energy, Λ^2

Electron–photon vertex, $\ln\Lambda$

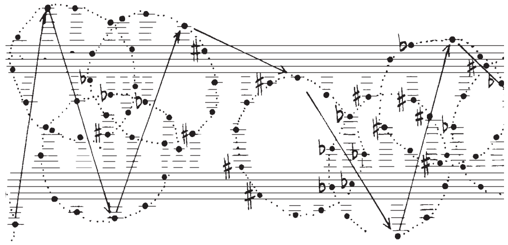
Photon scattering, $\ln\Lambda$

Exercise 6.5 Verify this.

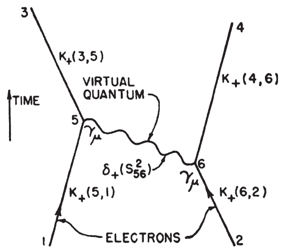
The tadpole diagram is zero. The corresponding expression is:

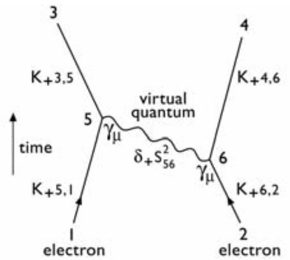
$$\int d_4p \frac{\mathrm{Tr}\{\gamma^\mu(-i\gamma p+m)\}}{p^2+m^2-i\epsilon}.$$

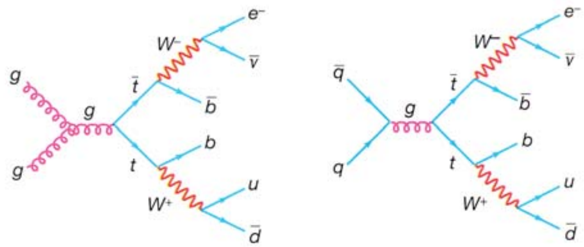
visual precision, similar to John Cage's artistic musical scores. Veltman introduces *Diagrammatica* with a note indicating that behind the graceful page layout is a thoughtful mathematical physicist and book designer: "This book is somewhat unusual in that I have tried very hard to avoid numbering the equations and figures. This [keeps] all derivations and arguments closed in themselves, and the reader needs not to have fingers at eleven places to follow an argument."[1]



John Cage, detail from *Concert for piano and orchestra, 1958,* solo for piano, 9.







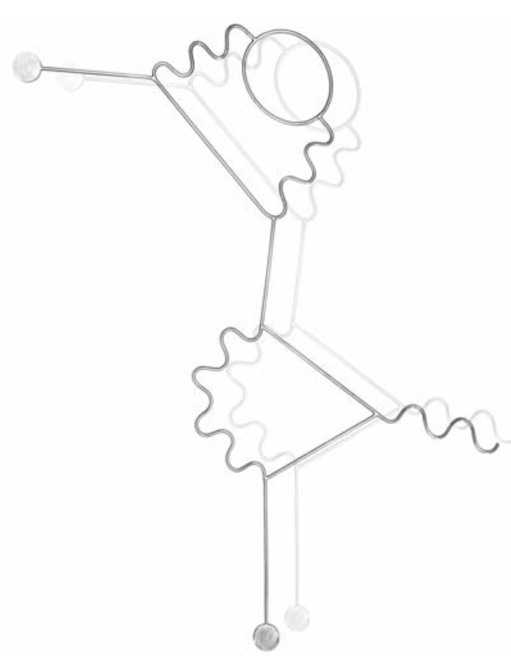
Feynman diagram on the Airstream Interplanetary Explorer.

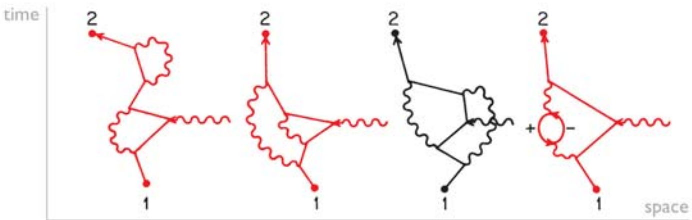
Produced by mechanical drawing, the first published Feynman diagram (above left) commits the classic design error of *equal line weight for all visual elements.* In the original at left, naive arrows serve as pointer lines *and* as traces of quantum dynamics, just as dimension lines sometimes get mixed up with object lines in architectural plans. In my redesign next to the original, pointer lines prove unnecessary other than for time's arrow. More recent Feynman diagrams use color lines similar to road maps.

An endlessly useful strategy in analytical design is to extend the scope of a good design element: increasing the dimensionality of the space the element resides in, enhancing resolution of the element, multiplying elements, integrating the element into various displays. Such is the history of Feynman diagrams, as below on 2 space-time grids multiple quantum dancers move about, described by Feynman's words beneath:

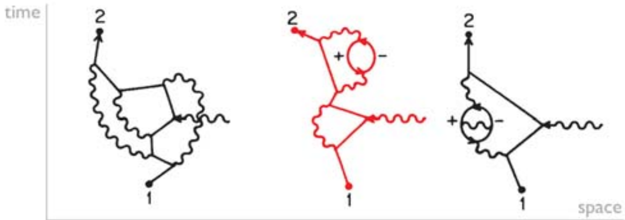
[1] Veltman, *Diagrammatica,* xii.

Far left: R. P. Feynman, "Space-time approach to quantum electrodynamics," *Physical Review,* 76 (1949), 776. Color diagrams: DØ Collaboration, "A precision measurement of the mass of the top quark," *Nature,* 429 (10 June 2004), 638–641. Below: Richard P. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton, 1985), 117–118. For history, see David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago, 2005).





Laboratory experiments became so accurate that further alternatives, involving four extra couplings (over all possible intermediate points in space-time), had to be calculated, some of which are shown here. The alternative on the right involves a photon disintegrating into a positron-electron pair, which annihilates to form a new photon, which is ultimately absorbed by the electron.



Calculations are presently going on to make the theoretical value even more accurate. The next contribution to amplitude, which represents all possibilities with six extra couplings, involves 70 diagrams, 3 of which are shown here. As of 1983, the theoretical number was 1.00115965246, and the experimental number was 1.00115965221.

Shown in red at left, 4 Feynman diagrams were translated into stainless steel sculptures.

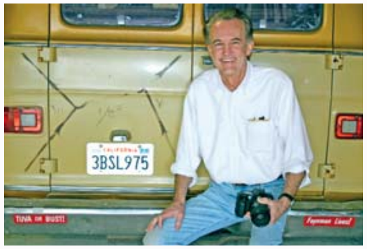
The Feynman-Tufte Principle

A visual display of data should be simple enough to fit on the side of a van **By MICHAEL SHERMER**

I had long wanted to meet Edward R. Tufte—the man the *New York Times* called "the da Vinci of data" because of his concisely written and artfully illustrated books on the visual display of data—and invite him to speak at the Skeptics Society science lecture series that I host at the California Institute of Technology. Tufte is one of the world's leading experts on a core tool of skepticism: how to see through information obfuscation.

But how could we afford someone of his stature? "My honorarium," he told me, "is to see Feynman's van."

Richard Feynman, the late Caltech physicist, is famous for working on the atomic bomb, winning a Nobel Prize in Physics, cracking safes, playing drums and driving a 1975 Dodge Maxivan adorned with squiggly lines on the side panels. Most people who saw it gazed in puzzlement, but once in a while someone would ask the driver why he had Feynman diagrams all over his van, only to be told, "Because I'm Richard Feynman!"



EDWARD R. TUFTE, master of design analysis, poses next to a Feynman diagram on Feynman's van depicting the interaction of photons and electrons.

Feynman diagrams are simplified visual representations of the very complex world of quantum electrodynamics (QED), in which particles of light called photons are depicted by wavy lines, negatively charged electrons are depicted by straight or curved nonwavy lines, and line junctions show electrons emitting or absorbing a photon. In the diagram on the back door of the van, seen in the photograph above with Tufte, time flows from bottom to top. The pair of electrons (the straight lines) are moving toward each other. When the left-hand electron emits a photon (wavy-line junction), that negatively charged particle is deflected outward left; the right-hand electron reabsorbs the photon, causing it to deflect outward right.

Feynman diagrams are the embodiment of what Tufte teaches about analytical design: "Good displays of data help to reveal knowledge relevant to understanding mechanism, process and dynamics, cause and effect." We see the unthinkable and think the unseeable. "Visual representations of evidence should be governed by principles of reasoning about quantitative evidence. Clear and precise seeing becomes as one with clear and precise thinking."

The master of clear and precise thinking meets the master of clear and precise seeing in what I call the Feynman-Tufte Principle: a visual display of data should be simple enough to fit on the side of a van.

As Tufte poignantly demonstrated in his analysis of the space shuttle *Challenger* disaster, despite the 13 charts prepared for NASA by Thiokol (the makers of the solid-rocket booster that blew up), they failed to communicate the link between cool temperature and O-ring damage on earlier flights. The loss of the *Columbia,* Tufte believes, was directly related to "a PowerPoint festival of bureaucratic hyperrationalism" in which a single slide contained six different levels of hierarchy (chapters and subheads), thereby obfuscating the conclusion that damage to the left wing might have been significant. In his 1970 classic work *The Feynman Lectures on Physics,* Feynman covered all of physics—from celestial mechanics to quantum electrodynamics—with only two levels of hierarchy.

Tufte codified the design process into six principles: "(1) documenting the sources and characteristics of the data, (2) insistently enforcing appropriate comparisons, (3) demonstrating mechanisms of cause and effect, (4) expressing those mechanisms quantitatively, (5) recognizing the inherently multivariate nature of analytic problems, (6) inspecting and evaluating alternative explanations." In brief, "information displays should be documentary, comparative, causal and explanatory, quantified, multivariate, exploratory, skeptical."

Skeptical. How fitting for this column, opus 50 for me, because when I asked Tufte to summarize the goal of his work, he said, "Simple design, intense content." Because we all need a mark at which to aim (one meaning of "skeptic"), "simple design, intense content" is a sound objective for this series. SA

Michael Shermer is publisher of Skeptic *(www.skeptic.com) and author of* Science Friction.

MICHAEL SHERMER (*Tufte with Feynman van*); BRAD HINES

In addition to the *All Possible Photons* wall sculptures, Edward Tufte has constructed 70 large-scale landscape artworks, including *Twigs* (series of 6), *Escaping Flatland* (10), *Rocket Science* (3), and *Megaliths of Silence* (40 large stone works so far).

ET wrote, designed, and self-published 4 books on data science, visual thinking, and analytical design: *The Visual Display of Quantitative Information, Envisioning Information, Visual Explanations*, and *Beautiful Evidence*. *The New York Times* described ET as the "da Vinci of data" and *Business Week* as the "Galileo of graphics." He served as a professor at Princeton University and Yale University for 33 years, and in 2010 was appointed by the President to the Recovery Independent Advisory Panel.

He has received 7 honorary degrees, and is a fellow of the American Academy of Arts and Sciences, the Guggenheim Foundation, and the Center for Advanced Study in the Behavioral Sciences.

ET's sculpture fields are on 266 acres in Connecticut. Accounts of the work are at www.tufte.com.

Feynman diagrams painted by Richard Feynman on his van in 1975. Garage storage, Long Beach, California, 2004.

EDWARD TUFTE ALL POSSIBLE PHOTONS

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