The Technological Fact of Counterfactuals

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That secondly, the medium of the imaginary must be optical follows not only from the primacy of gestalt *recognition, but also, and more elegantly, from Cartesian geometry.*[1]

In 1946 the philosopher Nelson Goodman argued that if we lacked the »means for interpreting counterfactual conditionals« we could »hardly claim to have any adequate philosophy of science«.[2] On its face this is a troubling assertion. Intuitively, a philosophy of science is concerned with facts and the frameworks through which we understand the experimental settings that legitimize and structure those facts. In their most common construction as ›thought experiments,‹ however, which assume unobservable, impossible, or nonexistent conditions for the sake of exploring the outer limits of possible states, counterfactuals are closely tied to the materialities of experimentation from which they seem to depart. From Galileo to Werner Heisenberg, thought experiments may have worked counter-to-facts, but what made them ›experiments‹ rather than artifacts of the subjunctive case was their reliance on the standards and operations of real instruments. What is more, those instruments were historically optical technologies, defining legitimate spaces of counterfactual possibility as images.

Thought experiments have remained fixtures of philosophical and scientific reasoning since the Eleatics, but only acquired their name in an 1897 paper by the physicist, psychologist, and philosopher of science, Ernst Mach.[3] In his essay, Mach claimed that thought experiments were not only critical to the production of scientific knowledge, but that they were a »necessary *pre-condition* of physical experiments.«[4] There was, however, a seeming paradox in his insistence on the

1 Friedrich Kittler: The World of the Symbolic—A World of the Machine, in: John Johnston (ed.): Literature, Media, Information Systems, New York 2012, p. 138.
2 Nelson Goodman: Fact, Fiction, and Forecast, Cambridge, MA 1983, p. 3.
3 Ernst Mach: Über Gedankenexperimente, in: Zeitschrift für den physikalischen und chemischen Unterricht 10 (1897), pp. 1-5. The revised and expanded version to which I refer is in Ernst Mach: Erkenntnis und Irrtum. Skizzen zur Psychologie der Forschung [EuI], Leipzig 1906, pp. 183-200.
4 Ibid., p. 187.

importance of thought experiments. Mach was deemed a »positivist«—a designation that implied an investment in empirical evidence as the be-all-end-all of the knowable world. And not only was he seen as a positivist, he was equally exalted and reviled as the high priest of positivism. Georg Lukács denounced impoverished forms of realism as »Neo-Machism,« the logical positivists of the Vienna Circle named an extension of their group the »Ernst Mach Society,« and his reputation became bound to the losing side of a debate in which he criticized Max Planck and others for granting the atom »a reality outside of thought.«[5] Mach's legacy was inseparably, if mistakenly, linked to a bloody-minded belief in direct observation as the final standard in the legitimacy of scientific claims.

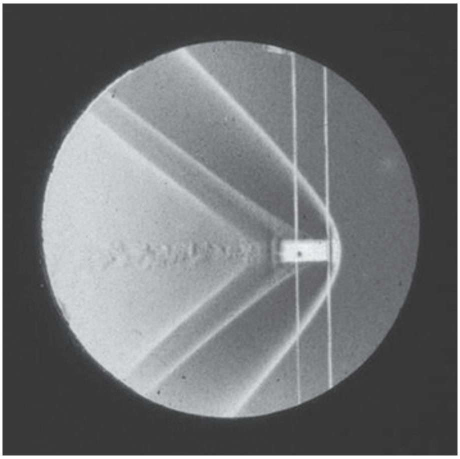

Fig. 1: Ernst Mach, supersonic projectile, Schlieren image, 1888

This is what makes his interest in thought experiments so remarkable. How could a figure who dismissed all supra-empirical concepts in physics as »mere thought-things« (EuI, p. 418) or »means of thinking«[6] also believe that in certain cases counterfactual thought experiments could be »so certain and decisive« (EuI, p. 188) that they required no further experimentation?[7] How could counterfactuals—assumptions that were definitionally outside of the realm of direct observation—be squared with the demand for empirical, and ideally optical, verification? The answer turns out not to arise despite his positivism, but because of it.

Mach is perhaps best known for the iconic photographs he made with Peter Salcher beginning in 1886 depicting shockwaves dramatically arcing from the tips of supersonic projectiles. These photographs and similar images he made later with his son Ludwig Mach received broad international attention in scientific publications well into the twentieth century and contributed to a general cultural enthusiasm about the ability of imaging technologies to reveal objects and events beyond the threshold of human perception. For Futurists like Giacomo Balla, the photographs

5 Georg Lukács: Reportage oder Gestaltung? (1932), in: Probleme des Realismus I: Essays über Realismus. Georg Lukács Werke, vol. 4, Neuwied 1971, p. 62; Ernst Mach: Die Mechanik in ihrer Entwicklung (1883), Leipzig 1908, pp. 552f.

6 Mach: Die Mechanik in ihrer Entwicklung (as note 5), p. 552.

7 On this point Mach agrees with Pierre Duhem, who warned in his *La Théorie physique: Son objet et sa structure* (1906) against treating thought experiments as if they were physical experiments and their »*postulates* as *facts*.«

offered a visual vocabulary for articulating the extra-sensory speed of modern machinery and they have been subsequently canonized alongside the work of Eadweard Muybridge, Étienne-Jules Marey, and Arthur Mason Worthington as part of a larger revolution in vision. [8] As the apotheosis of a machine-driven technological regime that began in the second half of the nineteenth century, the photographs have been credited with »radical rearrangements of perceptual ›truths‹ made possible by machinic speeds.«[9] As such they have been historicized according to their participation in an epochal transformation in modes of seeing that rendered »invisible things visible.«[10]

On their own, however, the individual, turbid, 9mm images did not show very much. Mach commented in a January 1886 letter to Salcher that he wanted to »optically verify« the air compression at the tip of a supersonic projectile in order to test a hypothesis presented by Henri-Frédéric Melsens's, but the significance of the images was not in their visual affirmation of an object or event.[11] Prior to his work with Salcher, Mach had already made images that »visualized« both shockwaves and bullets using experimental methods similar to those they would use in 1886. The real revelation made possible by the later photographs concerned general principles governing supersonic fluid dynamics that were enabled by optics, not vision. *Seeing* the bullets was not the issue, as slow bullets were also too fast to view unaided. Positioning these photographs within an upheaval in visuality, even where its transformation was »radical,« obscures the degree to which optical tech-

8 For more on this and issues related to the visual vocabulary instated by Mach, see Christoph Asendorf: Parabeln und Hyperbeln. Über die Kodierung von Kurven, in: Christoph Hoffmann and Peter Berz (eds.): Über Schall. Ernst Machs und Peter Salchers Geschoßfotographien, Göttingen 2001, pp. 357–380; cf. Peter Weibel: Beyond Art. A Third Culture. A Comparative Study in Cultures, Art, and Science in 20th Century Austria and Hungary, Vienna 2005.

9 Jonathan Crary: Suspensions of Perception. Attention, Spectacle, and Modern Culture, Cambridge, MA 2001, p. 142.

10 Klaus Hentschel: Visual Cultures in Science and Technology. A Comparative History, New York 2014, p. 385.

11 Ernst Mach to Peter Salcher, Prague (January 25, 1886), republished in Hoffmann and Berz (eds.): Über Schall (as note 8), p. 21. On this see John Blackmore: Ernst Mach: His Work, Life, and Influence, Berkeley 1972. The experiments were designed to explain why two reports were often heard when high-velocity guns were fired and, relatedly, to refute Melsens's hypothesis that the crater-like wounds from French Chassepôt-bullets during the Franco-Prussian War were not caused by exploding munitions, which were illegal after the 1868 Treaty of St. Petersburg, but were instead the result of compressed air. Nearly ten years before Mach heard Melsens's presentation in Paris, the results had been published in *Sur les plaies produites par les armes a feu, sur quelques effets de la pénétration des projectiles dans divers milieux et sur l'impossibilité de la fusion des balles de plomb qui frappent les hommes ou les chevaux,* Brussels 1872.

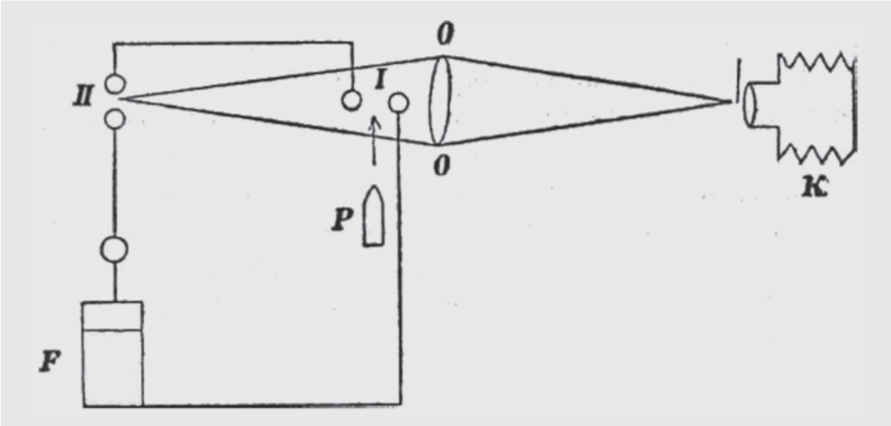

Fig. 2: Ernst Mach and Peter Salcher, Experimental diagram

nologies opened a space of modality as distinct from vision—a space concerned with the world of all possible states rather than merely observable ones.

Mach himself was never present for the execution of the experiments that yielded the initial photographs.[12] Through a mail correspondence with Mach, Salcher designed and implemented the experimental setup at the Naval Academy in Fiume in which, as the projectile passed in front of a lens that focused an image on a small silver bromide plate, it tripped wires that activated a flash battery whose spark provided the illumination. Unlike typical photographs that might depict the fluid medium as uniform or transparent, the images were made using the Schlieren method that inserted a knife-edge between the lens and the image plane, which caused differences in density to be expressed as areas of relative darkness or lightness.[13] The resulting images flattened the world into empirical abstractions that could be analyzed mathematically. They reduced the ostensible wonders of photography to an angle calculated in relation to the projectile's velocity and the speed of sound. Strictly speaking, the two-dimensional shapes that Mach used to perform a trigonometric analysis did not exist in the world. The bowed form of the shockwave propagating ahead of the bullet that would be used to derive the »Mach Angle« and the famous »Mach Number« were largely the result of an experimental photographic setting that was based on a comparison of differences between photographs, not on indexical affirmation of objects in the world. It was

12 Ernst Mach: Bemerkungen über wissenschaftliche Anwendung der Photographie, in: Ernst Mach: Populär-Wissenschaftliche Vorlesungen, Leipzig 1903, p. 131.

13 Schlieren photography was developed by August Toepler, Salcher's professor at the University of Graz.

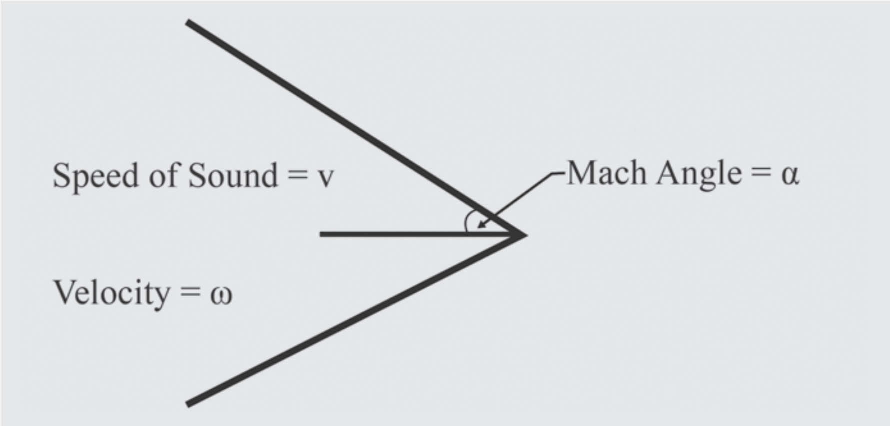

Fig. 3: Mach Angle

an artifact of an optical process whose value was less about showing what *was* (the bullet at supersonic speeds), and more about creating empirically valid conditions of abstraction for understanding what *could be*.

The empirical image-making technologies so critical to the understanding of »facts« from the seventeenth century through the nineteenth century were equally important to conceiving of states that did not or could not exist. Technologies that helped inaugurate what Lorrain Daston and Peter Galison have referred to as the »regulative« ideal of »mechanical objectivity« in the nineteenth century, in which machines seemed to »offer images uncontaminated by interpretation,« also introduced material operations that regulated the imagination of possible states.[14] Mach's contributions straddled the distinction between a »mechanical objectivity« that was wedded to impassive images and »structural objectivity,« which abandoned the conceit of representation and »empirical images« altogether.[15] Mechanical images for Mach were also structural, offering a template for conceiving of states that were not observable.

Mach's engagement with the matter of counterfactual thought experiments demonstrates that, rather than treating reality as reducible to our observations, as is so often assumed of so-called positivists, the technologies that grant images of the world offer standards for assessing the validity of states that have no objects. In general, scientific photographs exacerbated the tendency towards ontological

14 Lorraine Daston and Peter Galison: Objectivity, New York 2007, p. 171. Daston and Galison are unambiguous in claiming that the various notions of objectivity they detail are not about revealing »unvarnished facts,« but about eliminating »a common enemy: subjectivity,« p. 257.

15 Ibid., p. 317.

thinking through a seduction to a belief in the power of images to reveal the existence of properties, states, or objects that would otherwise remain unseen. In this techno-progressive model, the instruments get better and the objects get more abundant. For Mach and Salcher, however, photography did not serve »as a tool for recording the ›invisible,‹« but instead offered a methodology for detecting »differences between the pictures due to adjustments in the setup.«[16] By establishing a logic of pictorial relations these images did define the real, but in such a way that it could account for modalities that had not yet and might never come into existence.

Counterfactuality emerged as an essential figure of scientific thinking alongside the proliferation of optical instruments at the end of the sixteenth and beginning of the seventeenth centuries. As the story goes, Euclid had put forth an extramission theory of vision in his *Optica*, believing that vision was the result of rays emitted from the eyes. This was only refuted by Alhazen in the eleventh century, although the appearance of objects would continue to be attributed to perpendicular rays entering the eye throughout the medieval period.[17] For all of their advances, the reception of Alhazen by perspectivists like Roger Bacon, John Peckam, and Witelo could not account for the »focusing properties of lenses,« which made the resolution of a coherent image appear on a single plane.[18] In other words, vision continued to be understood as the interaction between an object and an observer until its understanding was displaced to the study of lenses following Johannes Kepler.[19] Lenses fundamentally changed subject-object relations by relocating the principles of observation from the inherent properties of either an object or the observer to the regularities of light passing through a medium. While this may have contributed to a new theory of vision, the core insight for my purposes was not about how humans see, but about how the operations of external devices revolutionized the nature of ›observation.‹

The divergence of vision and optics based on optical technologies corresponded with the rise of counterfactual modes of scientific exploration. In one of the most famous cases, Galileo revised the longstanding Aristotelian theory of falling bodies using a thought experiment whose theoretical »optic« was closely related to the telescope. The telescope did not allow falling objects to be seen better, but instead initiated the possibility of counterfactual abstractions that privileged gen-

16 Christoph Hoffmann: Representing Difference. Ernst Mach and Peter Salcher's Ballistic-photographic Experiments, in: Endeavor 33/1 (2009), pp. 21f.

17 Cf. David C. Lindberg: Theories of Vision from Al-Kindi to Kepler, Chicago 1976.

18 Ibid., p. 194.

19 Ibid., p. 195. Kepler's role in the various lineages stemming from Alhazen is a source of dispute. See A. Mark Smith: From Sight to Light: The Passage from Ancient to Modern Optics, Chicago 2015.

eral principles over concrete particulars. The explosion of optical instrumentation that began in the Renaissance, while often connected to a triumph in the powers of vision, is the ligature that unites the history of counterfactual exploration. This extends from Galileo to Mach's various meditations on thought experiments, which themselves borrowed heavily from the logic of his photographic experiments on ballistics. For Mach, the mental images that got arranged and recombined to explore counterfactual modalities were »images of the facts [*Abbilder der Tatsachen*]« in the sense of mechanical copies, invoking the language of his photographic experiments as a template for drawing the contours of the knowable, but perhaps not yet extant world (EuI, p. 187).

In the early twentieth century, the nature of the image would also become a shibboleth for a distinctly modern commitment to a probabilistic, »structural,« and anti-positivistic »*Weltbild*« that placed Mach at odds with the winning side of theoretical physics. While Max Planck and others critical of Mach spoke actively of the need for a unifying »world picture,« it was no longer a picture based on optics, which created imaginary, geometric spaces of possibility linked to the production of two-dimensional images. Planck's world picture was radically anti-imagistic, even while it appropriated the concepts of optics to account for its own understanding of possibility, modality, and contingency. In this way, it seems that Mach's commitments to images may not have been so wrong, recognizing at some level that notions of counterfactuality were historically inseparable from the optical technologies that propelled them.

1. From Vision to Optics

What Galileo's telescope enforced was not an enhanced supremacy of the human powers of observation as one of many »visual prostheses,« but a necessity for leaving the confines of empirical observation, precisely through empirical instrumentation.[20] Hans Blumenberg deals with this beautifully when he notes the Galilean telescope's impact on the »reversal of the postulate of visibility.«[21] The revelation of four of Jupiter's moons, additional stars in the Pleiades, and the general expansion of the field of observable celestial objects did as much to underscore the limitations of visibility as it did to magnify the powers of vision. Optical instruments in this outlook had the effect of undermining faith in the powers of vision for capturing the real, which fled farther away from the searchlight of our gaze with each revela-

20 Paul Virilio: The Vision Machine, translated by Julie Rose, Bloomington 1994, p. 4.

21 Hans Blumenberg: The Genesis of the Copernican World, translated by Robert M. Wallace, Cambridge, MA 1987, p. 621.

tion. With the disappointments of vision, however, came expanded fields of optical possibility informed by geometries that no one could witness.

In one of the most discussed thought experiments from his *Discorsi* (1638), Galileo is credited with decisively upending Aristotelian mechanics, »without further experiment«—that is, through counterfactual thought experiment.[22] The Aristotelian dogma that heavy bodies fall faster than lighter ones, as found in the *Physics*, against contemporary intuitions, was actually »based on sense-perception« and was »decidedly ›non-mathematical.‹«[23] In this view, the appearance of motion was a process of change in the *object* itself rather than the more abstract notion of a change in the relative position of bodies with respect to one another. As Alexandre Koyré commented, »Aristotelian physics does not admit the right, or even the possibility, of identifying the concrete world-space of its well ordered and finite Cosmos with the ›space‹ of geometry,« and it is therefore »impossible to try to subject these different realms to the same laws—and perhaps especially—to the same laws of motion.«[24] Common sense »is—as it always was—medieval and Aristotelian.«[25] This means that the conditions necessary for the revised Galilean vision of space and movement must be attributed to artificial, even counterintuitive presuppositions that forced one out of the realm of common sense.

Galileo's attack on the standing Aristotelian framework required a counterfactual imaginary. The telescope, with its simple arrangement of a convex and a concave lens in a tube, was the vehicle for just such an imaginary precisely because it erased »the coordinates of natural vision, the natural view, the natural eye.«[26] This was confirmed in a letter to his sister's husband, Benedetto Landucci, in his report to the Doge of Venice in the summer of 1609, in which he wrote that his new instrument was built upon the »most recondite speculations in perspective.«[27]

22 Galileo Galilei: Dialogues Concerning Two New Sciences, translated by Henry Crew and Alfonso de Salvio, New York 2010, p. 62.

23 Alexandre Koyré: Metaphysics and Measurement, translated by R.E.W. Madison, Langhorne, PA 1992, p. 5. Perhaps the best description of »natural« motion occurs in Book 8, Part 4 of Aristotle's *Physics*.

24 Koyré: Metaphysics and Measurement (as note 23), p. 6.

25 Ibid., p. 5.

26 Joseph Vogl: Becoming-media: Galileo's Telescope, translated by Brian Hanrahan, in: Grey Room 29 (Winter 2008), pp. 17f. For a more complete history of the politics and discourse surrounding the development and circulation of early telescopes see Massimo Bucciantini, Michele Camerota, and Franco Giudice: Galileo's Telescope: A European Story, translated by Catherine Bolton, Turin 2015; Mario Biagioli: Galileo's Instrument of Credit: Telescopes, Images, Secrecy, Chicago 2006.
Galileo Galilei: Opere di Galileo Galilei, vol. 2, Milan 1832, p. 126. The larger context for this incredible comment is discussed in Eileen Reeves: Galileo's Glassworks: The Telescope and the Mirror, Cambridge, UK 2008.

27 Galilei: Opere di Galileo Galilei (as note 26), p. 126.

The telescope was not so much an instrument of vision as a perspective constructed by an artificial apparatus (»*artifizio*«) that defied rather than supported natural vision.[28] Moreover, it was based on speculations (»*recondite speculazioni*«), and was therefore not a mere re-presentation of the world in its present state, but in all of its possibility.[29]

In *De Motu*, the early manuscripts on motion he began writing around 1590, there is no »discussion of uniform motion […] or related topics« that get elaborated in his later work and which represented the coup against Aristotle.[30] Despite already conducting physical experiments with inclined planes in 1591, and attacking the Aristotelian position on motion, *De Motu* »generally adheres to Aristotelian explanatory principles,« such as the tendency of bodies to seek out their »natural« place.[31] A counterfactual expression of what was already right in front of him was only articulated after his 1610 *Sidereus Nuncius* documenting his observations with the telescope, but it was not on account of more exhaustive physical experimentation.[32] The »*thought experiment*« from which the radically divergent concept of space-time emerged, as Jacques Lacan noted of Huygens and the isochronic clock, was »a hypothesis embodied in an instrument.«[33] Consequently, »if the instrument is constructed to confirm the hypothesis, there is no need whatever to do the experiments which confirms it, since the very fact that it works confirms the hypothesis.«[34] The reciprocal dependence between the material operations of medium and the symbolic realm of theory that made sense of those operations delimited spaces of possibility and actuality, but in such a way that they were ultimately inseparable. Everything that could exist could also signify. But a state's ability to signify (and thus be imagined) did not necessarily mean that it existed, just that it accorded with and could be made sense of with the instrumentation.

28 Ibid., p. 126.

29 Ibid.

30 Stillman Drake: Essays on Galileo and the History and Philosophy of Science, vol. 1, Toronto 1999, p. 213.

31 David Marshall Miller: Representing Space in the Scientific Revolution, Cambridge, UK 2014, p. 11. See also W.C. Humphreys: Galileo, Falling Bodies and Inclined Planes. An Attempt at Reconstructing Galileo's Discovery of the Law of Squares, in: The British Society for the History of Science 3/3 (June 1967), pp. 225-244.

32 Stillman Drake: Galileo at Work. His Scientific Biography, Mineola, NY 1978, p. 55; Galileo Galilei: Sidereus Nuncius, Venice 1610, translated by Albert Van Helden, Chicago 1981.

33 Jacques Lacan: Seminar of Jacques Lacan, Book II: The Ego in Freud's Theory and in the Technique of Psychoanalysis, 1954–1955, translated by Jacques-Alain Miller, New York 1988, p. 298.

34 Ibid.

For Galileo as for Mach 250 years later, the transition from facts to counterfactuals was built upon the move from *real* bodies and dynamic analysis to abstract geometries and kinematic analysis that emphasized an idealized set of spatial relationships. This had a number of ramifications, the first of which was that it privileged possible states over existing ones. And secondly, it constituted those relationships as images. The turn to kinematic analysis, concerned with pure geometries of motion, seems to reappear wherever the epistemic boundary between the actual and the possible reasserts itself. Possibility was a picture, which created a pressure to broaden the epistemic scope of images to encompass states that could be judged true without being seen. In his philosophical-historical examination of the relationship between the possible and the actual, Ernst Cassirer built a bridge from Galileo to Mach regarding exactly this question:

»Even in this plurality of possible starting-points, it is evident that the ›picture‹ [*Bild*] that we form of the reality of nature is not dependent on the data of sense perception alone, but upon the intellectual views and postulates that we bring to it […] It is the task of physical investigation to advance from these sensuous measures, which are satisfactory for practical purposes, to the *realities* indicated and expressed through them.«[35]

He continues, specifically addressing what he takes to be Mach's ideas about the relationship between laws and observation:

»In this solution to the problem offered by Mach, the consequences of the empiristic view is drawn with great energy. According to this view, every scientifically valid judgment gains its meaning only as an assertion concerning a concrete, factually present existence. […] The fundamental theoretical laws of physics throughout speak of cases that are never given in experience, nor can be given in it; for in the formula of the law the real object of perception is replaced by its ideal limit. The insight gained through them never issues from consideration of the real alone, but from the possible conditions and circumstances; it includes not only the actual, but also the ›virtual‹ process. […] Galileo, at least, leaves no doubt that the principle [of inertia], in the sense that he takes it, has not arisen from the consideration of a particular class of empirically real movements.«[36]

Cassirer powerfully acknowledges that the empirically observable and the possible are inseparable from a pictorial mode of reasoning, but he seems to misrecognize the nature of Mach's positivistic leanings. Placing »picture« in quotation marks,

35 Ernst Cassirer: Substance and Function and Einstein's Relativity, translated by William Curtis Swabey and Marie Collins Swabey, Mineola, NY 2015, pp. 170f.

36 Ibid., pp. 230–231, 232.

Cassirer points to the fact that the vision one achieves through kinematic analysis is not of actual movements. But nevertheless the principles at work are constituted pictorially and, as Ernst Mach himself notes of the route Galileo took to »fully grasp the law of inertia,« he arrived at his position through »abstraction.«[37]

This view onto the evolution of thought experiments links them rather closely to the history of linear perspective. Like other images, the »reality« of counterfactual thought experiments has been judged according to historically specific conditions of verisimilitude. Thomas Kuhn writes, »the new understanding produced by thought experiments is not an understanding of *nature* but rather of the scientist's *conceptual apparatus*« involving »one condition of verisimilitude.«[38] What is realistic (as opposed to »real«) in science, as in art, is not so much a matter of what the world looks like, as it is of how instruments allow the world to become seen. Similarly, what the world *could* look like is a function of the possibilities for depicting it. The question of an image's veracity is largely one of perspective.

Not only was the geometric function of Galileo's telescope »essentially based on the same Euclidean optical model as Alberti's perspective,« but the standards for the judgment of beauty and knowledge were equally governed by optical instruments.[39] Devices, both real and heuristic, including Leon Battista Alberti's *fenestra aperta*, the *camera obscura*, Dürer's perspective apparatuses, peepholes, and Brunelleschi's mirror, have been credited with initiating and governing the explosion of linear perspective in the *Quattrocento* by mathematically regulating the organization of pictorial space. As just one example, Friedrich Kittler argues that the »*camera obscura* made the revolutionary concept of a perfect perspective painting possible« by calculating »trigonometrical functions completely automatically, simply because it focused light into a single bundle of straight lines and then allowed them to follow their course.«[40] Likewise, the »trigonometrical functions« revealed

37 Ernst Mach: Der Begriff, in: Mach: Erkenntnis und Irrtum (as note 3), p. 138.

38 Thomas Kuhn: A Function for Thought Experiments, in: The Essential Tension. Selected Studies in Scientific Tradition and Change, Chicago 1977, p. 242.

39 Samuel Y. Edgerton: The Mirror, the Window, and the Telescope. How Renaissance Linear Perspective Changed Our Vision of the Universe, Ithaca 2009, p. 9. Martin Kemp argues that Galileo's interpretation of what he saw in his »perspective tube« (telescope) was structured by his familiarity with visual analysis and Renaissance treatises on perspective in addition to his training in perspective by Ostilio Ricci, cf. Martin Kemp: Seen/Unseen. Art, Science, and Intuition from Leonardo to the Hubble Telescope, Oxford 2006. Samuel Edgerton also notes Galileo's familiarity with perspective literature like Wenzel Jamnitzer's *Perspectiva corporum regularum* (Nuremburg 1568). See Samuel Edgerton: Galileo, Florentine »Disegno,« and the »Strange Spottednesse« of the Moon, in: Art Journal 44/3 (Autumn 1984), pp. 225–232.

40 Friedrich Kittler: Optical Media. Berlin Lectures 1999, translated by Anthony Enns, Cambridge, UK 2010, p. 52.

through Mach and Salcher's Schlieren photographs, not the supposed indexical properties of those images, were what would define the realities of fluid dynamics.

The properties of individual objects that lead the human observer to treat them as distinct and autonomous were therefore submitted to a higher representational force—that of light as projected on a two-dimensional plane by an optical device. Objects were no longer depicted in their idiosyncratic relations to other autonomous objects. They emerged as coordinates in »an infinite, mathematically homogenous space« that manufactured a pictorial and representational unity in which objects appeared.[41] The totalizing force of abstraction put into action with linear perspective negated the real, empirical differences between objects as pre-constituted entities, supplanting them with an infinite number of coordinates on a seemingly infinite grid. But this also meant that the truth conditions and standards of verisimilitude no longer hinged exclusively on the details of empirical observation, something that would be even more fully realized at the end of the nineteenth century.

2. Ernst Mach: Learning Not to See

Prior to Mach and Salcher's ballistics photographs, Mach had produced images of all of the objects and events that their images were celebrated for depicting—both bullets and shockwaves. Beginning in 1875 he undertook a series of experiments on shockwaves, theorizing their irregular interference patterns recorded on soot covered glass plates as what are now called »Mach reflections.«[42] Similarly, in 1885 he and his student Josef Wentzel also recorded the propagation of shockwaves photographically using the Schlieren method.[43] Mach had thus already achieved »very delicate pictures« of shock waves and a »picture of a projectile« from a »target pistol« with a velocity of around 240 m/s »without any difficulties.«[44] However, it became clear to him that the phenomena in which he was interested could only appear with a »projectile speed exceeding 340 m/s.«[45] It may be »less spectacular«

41 John White: The Birth and Rebirth of Pictorial Space, Cambridge, MA 1987, p. 124. For more on differences between competing methodologies in the history of geometric perspective see Filippo Camerota: Renaissance Descriptive Geometry. The Codification of Drawing Methods, in: Wolfgang Lefevre (ed.): Picturing Machines 1400–1700, Cambridge, MA 2004, pp. 175–208.

42 Ernst Mach and Josef Wentzel: Ein Beitrag zur Mechanik der Explosionen, in: Sitzungsberichte der Kaiserlichen Akademie der Wissenschaft zu Wien 92 (1885), pp. 625–638.

43 Ibid.

44 Ernst Mach: Über Erscheinungen an fliegenden Projektilen, in: Ernst Mach: Populär-Wissenschaftliche Vorlesungen, Leipzig 1903, p. 359.

45 Ibid.

than the idea of visualizing something too fast to catch a glimpse of unaided, but the more important result of the photographs was the »observation that the speed of sound is a fundamental threshold for all dynamical processes in gases,« and that the relative values of these processes could be understood geometrically.[46]

The early miniature photographs did not offer a gateway into a realm of things hitherto unseen.[47] The high-speed photographs optically transformed the projectile's triggering of the flash battery and passing of the lens into a series of relationships that could only be understood trigonometrically, that is to say, as relationships between idealized shapes.[48] As a projectile approaches and exceeds the speed of sound a shockwave forms in a cone shape extending from the head of the object out and towards its rear. From his previous work on blast waves, acoustics, and owing to his familiarity with the Schlieren method, Mach was able to recognize the form as a shockwave rather than the compressed air mass suggested by the Belgian physicist and chemist Louis Melsens. However, an individual photograph was not sufficient on its own to produce a scientific ground shift. The photographs had to be idealized and compared.

The lasting impacts of these images was the formalization of a series of relationships between the speed of sound, which is relative to the elasticity of the medium through which it travels, the velocity of the projectile, and the angle of the shockwave relative to the imagined flight path of the projectile. Mach expressed this relationship using the equation $\sin \alpha = v/\omega$ where α was the angle of the shockwave relative to the axis of the flight path, v was the speed of sound in a given medium, and ω stood for the velocity of the projectile.[49] Unlike the tendency to understand these photographs as showing us some *thing* (a bullet or a shockwave), what they really show us is a relationship brought about through optics.

With the help of a Leeson double refraction goniometer, a device employing a prism to measure angles often used in the assessment of gemstones, Mach measured the difference in the angles of the shockwaves.[50] While one could claim that these relationships exist in nature, they do not exist as a trigonometric function, which requires the optical abstraction instituted by the Schlieren apparatus. Strictly

46 Christoph Hoffmann: The Pocket Schedule: Note-Taking as a Research Technique. Ernst Mach's Ballistic-Photographic Experiments, in: Frederic L. Holmes, Jürgen Renn, and Hans-Jörg Rheinberger (eds.): Reworking the Bench: Research Notebooks in the History of Science, Dordrecht 2003, p. 183.

47 Hoffmann: Representing Difference (as note 16), p. 18.

48 Ernst Mach and Peter Salcher. Photographische Fixirung der durch Projectile in der Luft eingeleiteten Vorgänge, in: Sitzungsberichte der Kaiserlichen Akademie der Wissenschaft zu Wien 95 (April 21, 1887), pp. 277–291.

49 Ibid., p. 282.

50 Ibid., pp. 284f.

speaking, *there is no Mach Angle*. It is an effect of a two-dimensional rendering of density differences that are transformed into simple geometries that are then compared among multiple images. There is no doubt that the images showed something that could not be seen, but their main effect was also bound to something that was not shown. The geometries governing the actual and the possible emerged from interstices between images to define the real.

One experimental image on its own is not a picture of the world. As Christoph Hoffmann notes, a single image did not »provide the central insight.«[51] The technological implements of ›positivist‹ experimentation in the case of Mach did not amass facts in the hopes of building a world model to scale. They were difference engines—producing distinctions between the images themselves, the images and what was observed, and between what was depicted and what was assumed. As he argued in his essay on thought experiments, it was only through the »reproduction of facts« [*Nachbildung der Tatsachen*] (EuI, p. 187) that an order could be established among individual images that could define, but should not to be confused with, the world itself.[52] Image machines systemized differences such that proof was a process of reproduction, using the gaps between images as the quantifiable measure of the real. These were images that disaggregated objects into an endless series of differences. In this way the »bullet frozen in the moment of the experiment is a knot in the network of a wild metonymy« that is tamed, consolidated, and distributed »among experimentally relative hybridities.«[53] In one of several reflections on the function of photography in scientific experiments Mach recognized the optical displacement of the truth conditions from objects to continuities of shape:

»If we have collected a great quantity of physical observational data such that we have nevertheless exhausted them with the conception [*Anschauung*] taken from direct sensation, such data must remain bound to those points. How great by contrast is the abundance, the breadth, the concentration of the conception, when we depict [*darstellen*] the totality of the observational data through a diagram [*Kurve*]! And how greatly the intellectual use is facilitated. Registering apparatuses and registering methods are used in physics, in meteorology, indeed in all natural sciences and in this way photography finds its many applications.«[54]

51 Hoffmann: Representing Difference (as note 16), p. 22.

52 Mach frequently played on the term »image« (*Bild*) when thinking about evidence and experimentation. The term »*Nachbildung*« here frames reproduction as a process for creating an »after« (*nach*) »image« (*Bild*).

53 Anselm Haverkamp: Chaos by Design. The Light-Sound Constellation, in: MLN 118/3 (2003), pp. 688–703: 699.

54 Mach: Bemerkungen über wissenschaftliche Anwendung der Photographie (as note 12), p. 131.

The German »*Kurve*« captures something more than just »diagram« or »graph« in that it also means »curve«—the word Mach uses to describe the shock arc visible in his projectile photographs. The graph or line becomes a metonymic expression of the sum relations among the points and likewise delimits areas or directions of infinite possibility in the interstices between those points. For Mach, photographs did not magnify, fix, or copy objects in space-time, but participated in the construction of space-time itself. The emergence of objects against the seemingly stable background of their measure was actually a part of the definition of that background as determined by the experimental order. Any sense of potentiality, contingency, or modality was thus tied at a deep level to operations of the optical and mechanical devices that established a space within which ›things‹ emerged.

By the time that Mach first visited Salcher in Fiume in April of 1887, the experimental arrangement responsible for the first photos had already been disassembled.[55] What remained of the initial events were pictures—pictures that had been fully divorced from a fantasy of verification through reference or correspondence. If one can speak of objects at all in such a situation, the objects were the photographs themselves, although their meaning resided between rather than within their frames. Mach explicitly locates difference as the engine that drives scientific discovery and the principle that allows one to move between factuality, theory, and possibility. »For a theory,« he writes, »always puts in the place of a fact something *different*, something more simple, which is qualified to represent it in some *certain* aspect, but for the very reason that it is different does *not* represent it in other aspects.«[56] This is anything but a reductionistic theory of science, offering a dynamic epistemology of permanently shifting relationships that sees facts as generative rather than conclusive. Moreover, his truth model is an optical one, taking explicit cues from the relationships between geometry and optics:

»No one will seriously imagine for a moment that a real circle with angles and sines actually performs functions in the refraction of light. Everyone, on the contrary, regards the formula $\sin\alpha/\sin\beta=n$ as a kind of geometrical model that *imitates in form* the refraction of light and *takes its place* in our mind.«[57]

The same trigonometric devices made possible by the materialities of high-speed photography are separate from the »real« they define, even as they are treated as having been derived from it. In this optokinetic understanding of the approxima-

55 Christoph Hoffmann and Peter Berz: Mach/ Salchers Versuch: Anordnung, Durchführung, in: Hoffmann and Berz (eds.): Über Schall (as note 8), p. 23.

56 Ernst Mach: Facts and Mental Symbols, in: The Monist 2/2 (January, 1892), p. 201.

57 Ibid., pp. 201-202.

tions of mind that offer conceptual and intellectual continuities where there would otherwise be an infinite series of possible points, theoretical sense is derived from the relationship that optical instruments bear to the perfect shapes of geometry.[58] The difference between the image and what it was presumed to depict were insuperable. The regularities that allowed one to move from the discrete points of empirical observation to a smooth picture of the world could only be found in the operations of the optical media through which pictures of the world came into focus.

3. Optical versus Statistical Pictures

Among the many things for which Ernst Mach is famous, one of the most notable was his role in an acrimonious standoff with Max Planck between 1908 and 1911.[59] Mach was vehemently criticized by Planck and others for being a positivist, an epithet as nebulous as it was derogatory. The term was intended to characterize the position of Mach and his sympathizers as a retrograde movement against the tide of theoretical physics around 1900, which no longer relied on ›appearances‹ for the verification of things like atoms.[60] At its core, the contest between the worldviews represented by Planck and Mach was one about the nature of pictures as the essential mark of epistemological legitimacy. For Planck it would be a »*Weltbild*« (world picture) where, as we have seen, for Mach it was the arrangement of »*Abbilder*« (images in the sense of mechanical copies).

The first exchange in the volley, issued by Planck in his 1908 lecture in Leiden, entitled *The Unity of the Physical World Picture* (*Die Einheit des physikalischen Weltbildes*), highlights the stakes of this clash about the physical world as pictorial in nature.[61] Planck took aim at Mach and precisely on the matter of the image's function

58 Kittler too associates this optokinetic thinking with the episteme around 1900 and relates it particularly to Edmund Husserl's phenomenology in Friedrich Kittler: Aufschreibesysteme 1800/1900, Munich ³1995, p. 283.

59 John Blackmore offers a comprehensive view of the exchanges between Mach, Planck, and Einstein in John Blackmore: Ernst Mach Leaves »The Church of Physics,« in: The British Journal for the Philosophy of Science 40/4 (December 1989), pp. 519–540.

60 Einstein was deeply influenced by Mach's 1883 *Mechanik* and in his obituary for Mach in 1916 he wrote »Mach clearly recognized the weak sides of classical mechanics and was not far from postulating a general theory of relativity; and already a half century in advance!« Albert Einstein: Ernst Mach, in: Physikalische Zeitschrift 17/7 (1916), pp. 101-104: 103.

61 Max Planck: The Unity of the Physical World Picture – Section 4 (1908/1909), in: John Blackmore (ed.): Ernst Mach—A Deeper Look: Documents and New Perspectives, Dordrecht 1992, pp. 127–132.

for defining scientific knowledge. In place of the images that had defined the positivistic worldview, theoretical physics offered »nothing other than *unity*, unity in reference to all individual parts of the picture« that could only be achieved by embracing a »physical world picture« that allowed physicists to make »conclusions going *beyond direct observation* which can *never be tested by human observation*.«[62] Here Planck identified an internal distinction between two kinds of picture—one that was a mathematical model whose legitimacy rested on its internal coherence defining both the actual and the possible, and the other an empirical image, defining only the actual.

Planck then exaggerated Mach's epistemology into a kind of naïve realism, in which »there are no other realities than one's own perceptions.«[63] This relegated Mach to an impoverished form of empiricism. »Machian positivism,« as Planck describes, was the »philosophical result« of an »unavoidable disillusionment« with the coupling of »the discovery of the energy principle« and a »mechanistic world view.«[64] This acted as a counterpoint to the eruption of statistics, which made the potential position and momentum of atoms and electrons something that it was not just unnecessary to organize and imagine geometrically, but *impossible* to visualize. This was an epochal conflict that would be indirectly theorized soon after by Martin Heidegger in his essay *Die Zeit des Weltbildes* (*The Age of the World Picture*). [65] The modern age, as he argued, is distinguished from the medieval period through the »projection« (*Entwurf*) of a »circumscribed object-sphere« (*umgrenzter Gegenstandsbezirk*) in which everything that is—everything that is *object*ive—stands in a systematic relation to everything else; it is framed, as a picture.[66] The totality of these existing and possible relationships, which define human's difference from and view onto the world for the first time *as subjects*, is a »worldview« or »view onto the world« (*Weltanschauung*). The *Weltanschaunung* is a picture (*Bild*), not in the sense of »replica« (*Abklatsch*) or copy, but instead the »world itself, the world as such,« the world as a single realm, adhering to universal rules by which objects emerge as part of a coherent system that allows them to be »grasped.«[67] It is the fact of the world becoming an image that makes way for this development.

62 Ibid., p. 128 [Emphasis mine].

63 Ibid., p. 129.

64 Ibid., p. 130.

65 Martin Heidegger: Die Zeit des Weltbildes (1938), in: Martin Heidegger: Holzwege. Gesamtausgabe, vol. 5, Frankfurt am Main 1977, pp. 75–96; Martin Heidegger: The Age of the World Picture, translated by William Lovitt, in: Martin Heidegger: The Question Concerning Technology and Other Essays, New York 1980, pp. 115–154.

66 Ibid., p. 83.

67 Ibid., p. 89.

That is to say, it is the principles of optics that forced the world of splendid, irreconcilable textures into a single perspectival relationship that could be called objective.

This same reasoning informs Planck's idea of the »*Weltbild,*« even though or precisely because the objects and phenomena his conception is meant to validate *cannot be seen*. For Planck »the Real« that was the object of his statistical world picture was entirely independent of the possibility for being visualized.[68] Yet the issue for Mach was also not about seeing or sensing. It was a resistance to the hypostatization of objects, all of which were provisional. For Mach »there is no immutable thing [*Ding*] in nature.«[69] A »thing« is rather »an abstraction, the name of which is a symbol for a complex of elements, whose changes we disregard.«[70] Mach's positivism was not *object*ive. Objects were temporary constellations composed of material processes not essentially different from those according to which they were registered. For Mach truth resided in the picture one composed, even where such a picture depicted no existing objects. The stabilizing principle that allowed him to associate one observed event with similar observed events required the »reproduction of facts.«[71] This is underscored by the fact that Mach uses undeniably similar language to describe counterfactuals, calling them »copies of the facts [*Abbilder der Tatsachen*],« (EuI, p. 187) suggesting that facts and counterfactuals derived equally from the operations of the instruments that (re)produced them.

Planck's world picture of »colorless particles« did not have a perspective, as it required no observer and no »lens,« optical or otherwise.[72] This was a »perversity [*Verkehrtheit*]« for Mach, as it was both probabilistic and simultaneously invested in the existence of »hypothetico-fictive« entities on which the tentative coherence of its mathematical model depended.[73] While Mach claimed that »no one has any objection« to these provisional, »unifying systems in physics« he could also not »deny [his] aversion to hypothetico-fictive physics.«[74] Part of the confusion in interpreting Mach's well-developed epistemology is that his opposition to the ob-

68 Planck: The Unity of the Physical World Picture (as note 61), p. 131.

69 Mach: Die Mechanik in ihrer Entwicklung (as note 5), p. 473.

70 Ibid.

71 Ibid., p. 474.

72 Ernst Mach: Die Leitgedanken meiner naturwissenschaftlichen Erkenntnislehre und ihre Aufnahme durch die Zeitgenossen, in: Physikalische Zeitschrift 11 (1910), pp. 599-606: 602. The partial English translation of this article and Planck's response on Mach's theory of physical knowledge can be found in Blackmore (ed.): Ernst Mach Leaves »The Church of Physics« (as note 59), pp. 133-146.

73 Mach: Die Leitgedanken meiner naturwissenschaftlichen Erkenntnislehre (as note 72), p. 602.

74 Ibid.

jects of Planck's objectivity was received as an expectation that one be able to see them as a condition of their existence.[75]

The new epistemological regime Mach rejected was a statistical one. Planck's reception of the work of J.W. Gibbs and Ludwig Boltzmann in statistical mechanics and thermodynamics was methodologically at odds with Mach's commitment to kinematic analysis. Where the behaviors of mechanical systems in kinematics were evaluated as idealized geometries—and thus tied to the evolution of optical devices—in statistical mechanics the state of a system was calculated probabilistically based on the measure of energy and temperature. At the same time, the probability of a certain state did assume the actual *existence* of individual atoms, which in the nineteenth and early twentieth century still could not be observed. In other words, one could not say for certain that a specific state was the case (something Mach could accept), but nevertheless required that one believe that unobservable entities existed (something Mach could not accept).

This was especially evident in Mach's vigorous and eventually reputation-damaging opposition to the atom. Where Mach seems to diverge from the vogue of early twentieth century physics is in the belief that a reality based on atoms, which categorically excluded certainty with respect to objects, could nevertheless demand that one affirm the existence of those objects. Clarifying his position as one that is anything but that of a naïve realist he wrote:

»I can only say that my ›Positivism‹ has not been rightly judged if it is viewed as a reaction to the failures of atomistic speculation. Even if the kinetic physical world picture, which in any case I consider hypothetical without intending thereby to degrade it, could ›explain‹ *all* physical appearances, I would still hold that the diversity of the world has not been exhausted…«[76]

Mach and Planck were in fact closer to one another in their *Weltbild* than either admitted publically, which is perhaps why Einstein commented in a letter to Mach with a somewhat elegiac regard for an old master:

»You have had such an influence on the epistemological views of the younger generation of physicists that even your current opponents, such as, e.g., Herr Planck, would un-

75 Paul Feyerabend for example defends Mach from mischaracterizations of his epistemology in the »transition from a critical *philosophy* to a *sense-data dogmatism*,« remarking that »Mach was either not read at all or read with little care.« Paul K. Feyerabend: Knowledge, Science and Relativism. Philosophical Papers, vol. 3, edited by John Preston, Cambridge, UK 1999, p. 133.

76 Mach: Die Leitgedanken meiner naturwissenschaftlichen Erkenntnislehre (as note 72), p. 605.

doubtedly have been declared to be ›Machists‹ by the kind of physicists that prevailed a few decades ago.«[77]

The ostensible source of friction was the nature of the image each understood as defining the *Weltbild*. That is, the technologically informed structures according to which an image could be understood as defining both the actual and the possible—the factual and counterfactual. This was the point at which possibility became probability instead of geometry. And it was here that the ›world picture‹ was divorced with finality from the technological regimes imposed by optical technologies.

Picture Credits:

Fig. 1. Ernst Mach, supersonic projectile, Schlieren image, 1888.

Fig. 2. Ernst Mach and Peter Salcher, Experimental diagram, in: Photographische Fixirung der durch Projectile in der Luft eingeleiteten Vorgänge, in: Sitzungsberichte der Kaiserlichen Akademie der Wissenschaft zu Wien, vol. 95 (April 21, 1887).

Fig. 3. Mach Angle

77 Cited from a letter from Einstein to Mach on August 9, 1909, cf. Don Howard: Point Coincidences and Pointer Coincidences. Einstein on the Invariant Content of Space-Time Theories, in: Hubert Goenner, Jürgen Renn, Jim Ritter and Tilman Sauer (eds.): The Expanding Worlds of General Relativity, Boston/Basel/Berlin 1999, pp. 463–500: 474.