

## Notes on the Circulation of Epistemic Images

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## Notes on the Circulation of Epistemic Images

Dr. Nina Samuel

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### Abstract

Three cases of image circulation in the sciences, two from complex dynamics and one from microscopy, are discussed. The article deals with failed circulations, suspected errors, interdisciplinary communication, notebooks of scientists, the role of media shifts, mathematics and materiality, human perception, pictorial norms and conventions. It analyses how images circulate through different thought collectives and visual cultures. All three examples show different strategies of how images that break with visual traditions have been reintegrated into epistemic circulations and become “boundary objects” that are both robust and flexible.

### Zusammenfassung

Der Artikel diskutiert drei wissenschaftliche Bildzirkulationen in der komplexen Dynamik und der Mikroskopie. Im Zentrum stehen gescheiterte Zirkulationen und Fehlervermutungen, verschiedene Denkkollektive und visuelle Kulturen, die Herausforderungen interdisziplinärer Kommunikation in Notizbüchern oder vor dem Hintergrund von Medienumbrüchen, das Verhältnis von Mathematik und Materialität und von Wahrnehmung und Bildkonventionen. Die Beispiele zeigen unterschiedliche Strategien, wie Bilder, die mit visuellen Traditionen brechen, in epistemische Zirkulationen reintegriert und zu „Grenzobjekten“ werden, die sowohl robust als auch flexibel sind.

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## Introduction

This article follows the circulation of images in science through a close reading of three case studies from the late 20<sup>th</sup> and early 21<sup>st</sup> centuries. Situated in the area of physics, mathematics, and cell biology, all analyzed images are part of a transition: from a linear to a nonlinear paradigm in dynamical systems theory, from optical to digital magnification in microscopy, and from cubic to quadratic equations in complex analysis. In all three cases, the circulation of images serves a communicative function that is either fostered or hindered by deliberately designed aesthetics. The relationship between different media techniques and between computer graphics and hand drawing plays a central role. The article is based on the basic assumption that images are not mere illustrations of work done by other means, but tools for experimental discovery in their own right. Thus, the case studies illuminate key aspects of this epistemic function: to challenge and encourage critical thinking and seeing, and to act as visual thresholds for theory formation.

## Circulation through Visual Consistency

The sheet, filled with sketches and notes, is not comprehensible at first sight (Fig. 1). The drawing in the upper left quarter is striking, with curves and loops in red, grey and blue, expressively drawn, and small arrows illustrating a development over time. The schematic blue ‘spiderweb’ to the right is embedded in a text that relates the drawings to the theory of non-linear differential equations introduced under the term ‘Arnold Diffusion,’ which describes the transition of dynamical systems from stable to chaotic states. In this field of research “chaotic attractors” play a particularly important role. They give mathematical chaos a concise and highly organized form.<sup>1</sup>

<sup>1</sup> Unless otherwise mentioned, translations are mine.

Attractors are geometric formations within a phase space that represent all potentially realizable final states of a dynamic system. While any point in a phase space can be a possible initial state of a system, how it ends (i.e. how it stabilizes) determines the shape of the attractor. Attractors are symbolic representations of the long-term outcome of a dynamical system. For more details on the pictorial history of chaotic attractors and other shapes of chaos, see: Nina Samuel, *Die Form des Chaos. Bild und Erkenntnis in der komplexen Dynamik und der fraktalen Geometrie* (Paderborn: Wilhelm

The illustration is taken from a notebook of the Japanese engineer and mathematician Yoshisuke Ueda. It was created during his first meeting with the American physicist Joseph Ford in 1978, who visited him in Japan. Both scientists belonged to different disciplines, to different research traditions within the theory of complex systems and, they didn’t speak each other’s language.<sup>2</sup>

Nevertheless, the researchers found an alternative yet very effective form of communication on this sheet: while Ueda made the drawings with colored pencils, Ford completed the part written in blue. What deserves special attention is what is missing on the page: there is not a single mathematical formula. The sketching of the forms and the noting down of some core sentences were sufficient for the two researchers to exchange views on their different approaches and to find common ground. The drawings were used as a visual Esperanto—a universal language, thanks to which Ueda and Ford were able to overcome not only their language barriers, but also the boundaries of their disciplines. It was this graphic conversation between Ueda and Ford that set off a circulation so that Ueda’s discovery, the so-called “Japanese attractor,” was able to go beyond disciplinary and language boundaries.

At the end of the 1970s, the various approaches to the theory of complex systems began to converge through increased personal exchange between research collectives and disciplines. Circulation no longer took place primarily privately and between individuals, but became increasingly institutionalized.

After the meeting with Ford, Ueda accepted the invitation to participate in two important conferences in the USA in 1979: the conference *New Approaches to Nonlinear Problems in Dynamics* in Asilomar, California, organized by Philip J. Holmes, and the *International Conference on Nonlinear*

Fink, 2014). The first and third cases are translated, shortened and reworked extracts from my dissertation.

<sup>2</sup> Ford was primarily concerned with conservative, energy-preserving systems, which included the movement of the celestial bodies and the three-body problem considered by Henri Poincaré. Ueda, on the other hand, studied the behavior of dissipative systems that only remain in motion when energy is supplied, such as pendulums with friction.

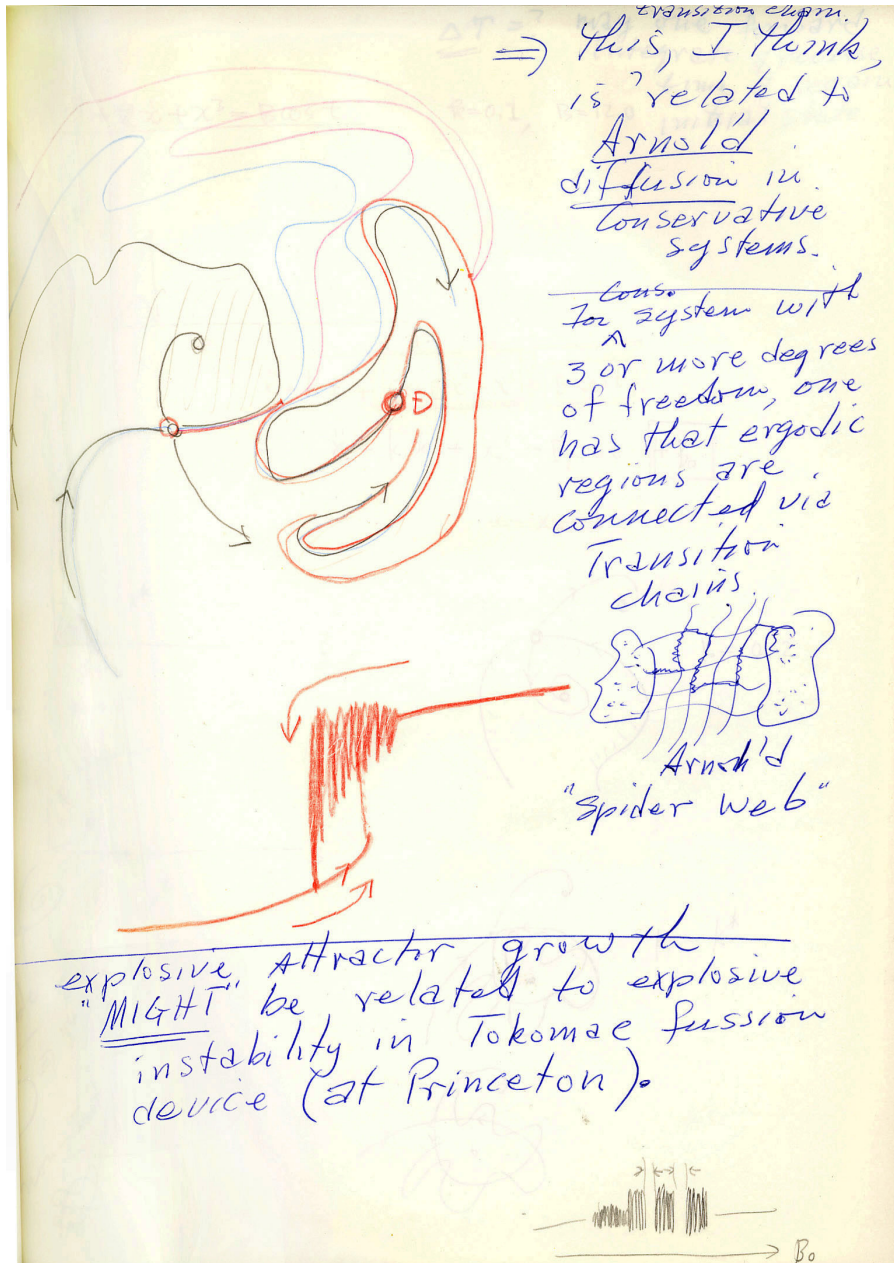


Figure 1. Yoshisuke Ueda and Joseph Ford. Drawings during a meeting in 1978, page from a sketchbook by Yoshisuke Ueda. Courtesy of Yoshisuke Ueda.

*Dynamics* in New York, to which Ford invited some of the most important pioneers in the field to come together in one place for the first time.<sup>3</sup> Ueda was able to present his attractor to a larger audience

<sup>3</sup> For the conference held in Asilomar, California, 9–14 December 1979, see Philip Holmes, ed., *New Approaches to Nonlinear Problems in Dynamics* (Philadelphia 1980). At the subsequent conference in New York, 17–21 December 1979, Benoît Mandelbrot, Mitchell Feigenbaum and Edward N. Lorenz took part, among others, cf. Robert H.G. Helleman, ed., *Nonlinear Dynamics*, *Annals of the New York Academy of Sciences* 357 (New York 1980).

and from then on, it became a well-known shape in the mathematical community. Both meetings were equally summits, turning points and driving forces that released new impulses and synergies. From the late 1970s onwards, a stabilization and reconfiguration of concepts began, which in many cases presupposed the existence of pictorial representations and was accompanied by a circulation of images. The conference in New York organized

by Ford was significant in this context not only because it brought together many of the most important protagonists in the field, but also because three disciplinary groups of scientists (mathematicians, natural scientists, and engineers) met who had been working on similar issues for years, but in most cases, did not even know about each other. All those scientists were on the pursuit of the same phenomenon in different ways: the impossibility of long-term predictability of dynamical systems due to their sensitive dependence on the initial conditions. This basic definition of a dynamic unpredictability, already formulated by Henri Poincaré in the 19<sup>th</sup> century, was confirmed starting in the 1960s by computer experiments, which initiated a profound break with common modeling practices.<sup>4</sup>

However, the circulation of scientific images from the world of research to different contexts can never be taken for granted. It is always subject to a complex network of preconditions and constraints that must be met in order to be set in motion.

When Bruno Latour defined scientific representations as “immutable and combinable mobiles,”<sup>5</sup> he assumed that scientists invent objects in such a way that they have the property of being able to be transported and distributed, while at the same time they must retain an unchangeable core, a kind of semantic framework, which makes them presentable, readable, and combinable with one another. They must therefore be robust enough not to lose their meaning through circulation and transfer, yet flexible or adaptable enough to function in scientific communication. But how does their aesthetic appearance influence their function as communication devices, or: in which way is it enabling or disabling circulation?

A closer examination of Ueda’s process of discovery of mathematical chaos offers insights into this question.

<sup>4</sup> Henri Poincaré, “Sur le problème des trois corps et les équations de la dynamique,” *Acta Mathematica* 13, no. 1 (1890): 1–270. See Samuel Nina, “Henri Poincaré und der chaotische Wirbelsturm der Erkenntnis. Zur Performanz mathematischen Denkens,” *STUDIA UBB. Philosophia*, 57, no. 1 (2012): 59–91.

<sup>5</sup> Bruno Latour, *Science in action: how to follow scientists and engineers through society* (Cambridge: Harvard Univ. Press, 1987): 227.

Ueda had come across the phenomenon he had sketched out for Ford seventeen years earlier, in 1961, rather by chance when he was a doctoral student in Kyoto (Fig. 2). This sheet documents Ueda’s research with analogue computers during the early 1960s. In front of a light-grey round, a jagged contour consisting of dark dots stands out on the graph paper. The computer images produced in this way posed new challenges to research in complex dynamics: the visible had to be related to mathematical theory. Mathematical work required a new kind of visual competence and literacy. Such expertise seemed to be particularly important given the results of Ueda’s experiment.

In the beginning, Ueda didn’t know how to evaluate his results, which was surprising because of its unexpected shape:

It was nothing like the smooth oval closed curves [...] but was more like a broken egg with jagged edges. [...] [D]uring asynchronous phase, the shattered egg appeared more frequently than the smooth closed curves and [...] the order of the dots which drew the shattered egg was totally irregular and seemingly inexplicable.<sup>6</sup>

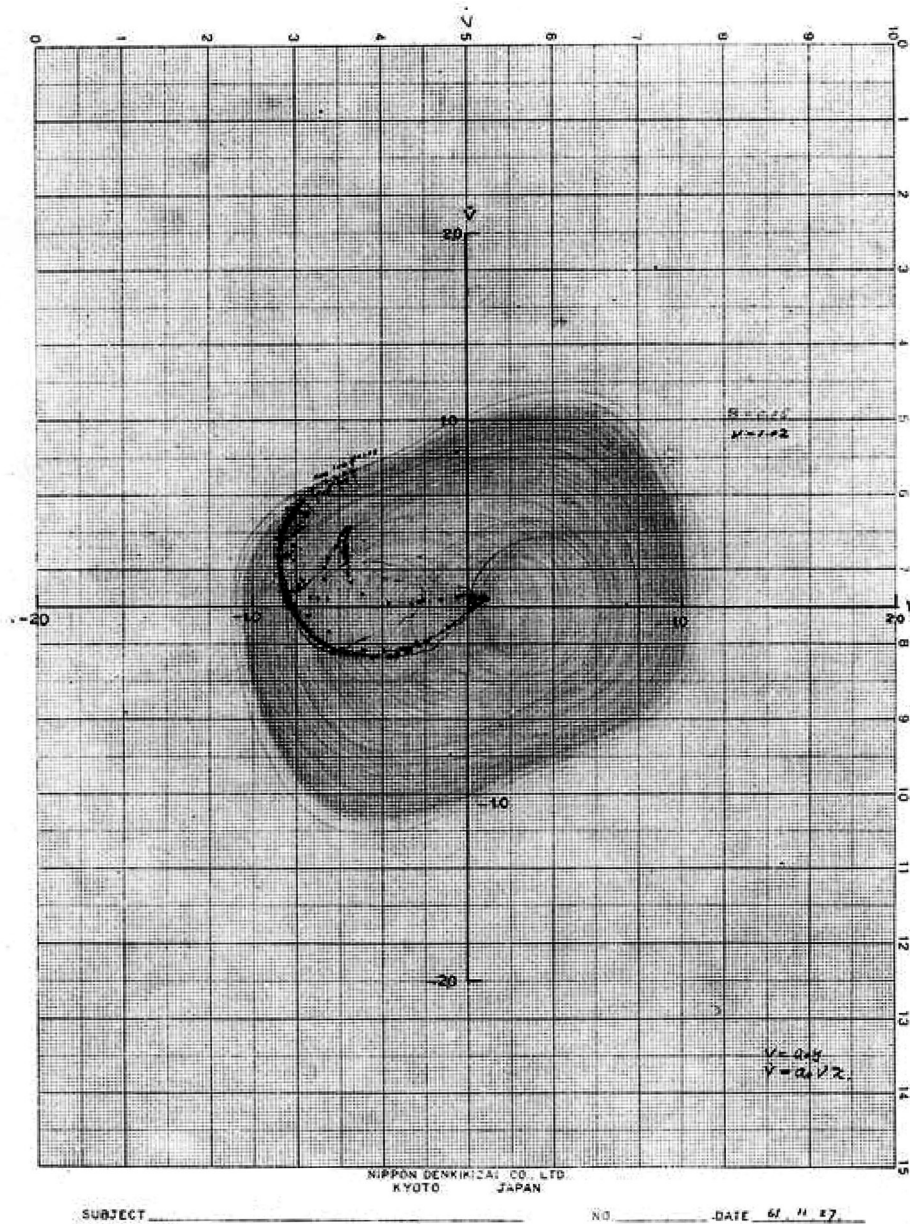
The perception and judgement of form was therefore based on aesthetic expectations that were disappointed: Ueda’s confusion was related to the arrangement of the black dots within the light-grey round. While Ueda anticipated the image of a regular, smooth oval as a result, he was instead confronted with a shape that reminded him of a “broken egg.” This recalls the new quality of computer-assisted research in complex dynamics as described by historians of science David Aubin and Amy Dahan Dalmedico as “surprise images with suggestive power.”<sup>7</sup>

However, in order to gain an understanding of the form, it required more than contemplation but rather a manual editing. With the help of a dark pencil, Ueda emphasized the hooks and he erased

<sup>6</sup> Yoshisuke Ueda, “Strange Attractors and the Origin of Chaos,” *Nonlinear Science Today* 2, no. 2 (1992): 1–16; Ueda, “Strange Attractors,” 4.

<sup>7</sup> David Aubin and Amy Dahan Dalmedico, “Writing the History of Dynamical Systems and Chaos: Longue Durée and Revolution, Disciplines and Cultures,” *Historia Mathematica* 29 (2002): 302.



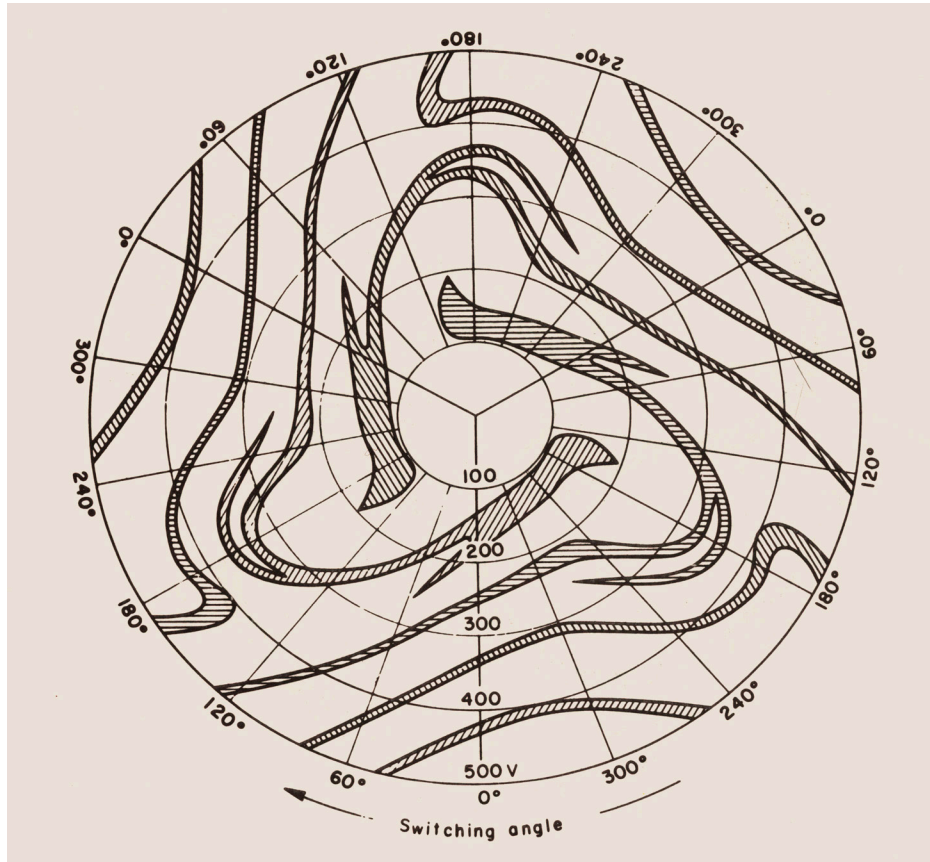


**Figure 2.** Yoshisuke Ueda. Graphic result of an analog computer simulation, manually edited page from the sketchbook, 1961. Source: Ueda, Yoshisuke. "Strange Attractors and the Origin of Chaos." *Nonlinear Science Today* 2, no. 2 (1992): 3.

parts of the curves. The jagged shape that peeled out of the computer graphics in this way was not only an aesthetic surprise, but also such a deviation from everything previously known that Ueda at first thought it must be the result of a computer bug, a technical error: "My first concern was that my analog computer has gone bad."<sup>8</sup>

<sup>8</sup> Ueda, "Strange Attractors," 4.

But as the shape kept appearing throughout the experiments, Ueda tried to convince his doctoral supervisor Chihiro Hayashi to let him publish it. The equations Ueda studied were Hayashi's specialty, an internationally renowned expert in the field of dynamical systems. The projects of his doctoral students such as Ueda had to continue the tradition of his own research. In Hayashi's nonlinear world, chaos did not yet exist for dynamical systems, but only periodic and quasi-periodic oscillations.



**Figure 3.** Chihiro Hayashi. Drawing of subperiodic oscillations, 1956. Source: Hayashi, Chihiro. "Initial conditions for certain types of nonlinear oscillations." In *Proc. Symp. Nonlinear Circuit Analysis*, 6: 86. Brooklyn, 1956.

Hayashi had published numerous drawings on the topic that are impressive in their exact execution and can be described as icons of 'pre-chaotic non-linearity' (Fig. 3).

His drawings were strikingly similar in their aesthetics: spiral constructions oriented towards a clear center and embedded in compositions of concentric circles. Those gently bent lines, regular and balanced, were considered the hallmark of quasi-periodic oscillations. But even more important was the adherence to a symmetrical structure in most of the pictures.

This can be witnessed in the following instance of self-censorship: in 1963, Hayashi and his colleague Yoshikazu Nishikawa concluded that "asymmetrical systems" also existed (Fig.4).<sup>9</sup>

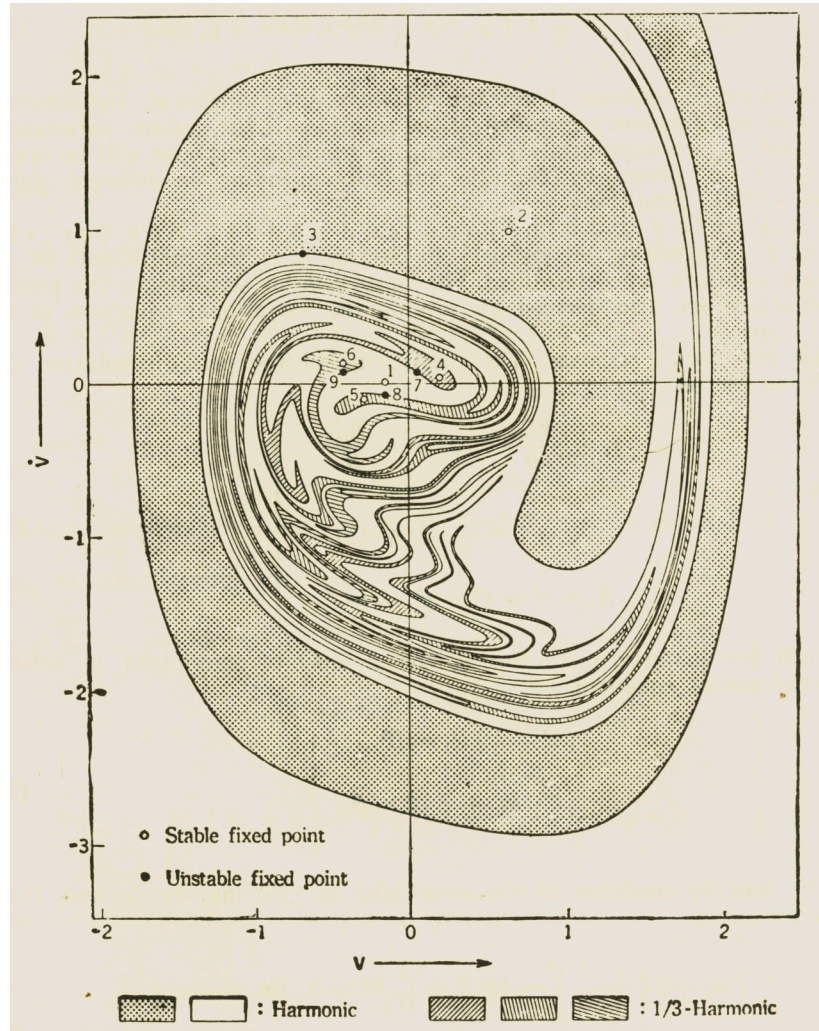
<sup>9</sup> Chihiro Hayashi and Yoshikazu Nishikawa, "Initial conditions leading to different types of periodic solutions for Duffing's equation," in *Proc. Int. Symp. Nonlinear Oscillations 2* (Kiew 1963), 386.

In the middle of a coordinate system there is a roundish structure with irregular curves inside. It is a phase-space portrait and marks different initial states of the investigated dynamic equation, which are called attraction areas. The fate of this aesthetic exception is telling: although the result did not even show a chaotic system, the irregular form must have been so unpleasant for Hayashi, that he intentionally left it out of his major publication of 1964.<sup>10</sup>

Initially, the same censorship mechanism also prevented the publication of Ueda's discovery. Hayashi's visual expectation filtered what could be perceived, even if something else showed up repeatedly. The jagged shape was not compatible with the accepted aesthetics of the time. This led to the "broken egg" being sorted out as a technical "accident of representation," thus preventing the passage from

<sup>10</sup> Chihiro Hayashi, *Nonlinear Oscillations in Physical Systems* (New York: Princeton Univ. Press, 1964). Cf. Ueda, "Strange Attractors," 5.





**Figure 4.** Chihiro Hayashi and Yoshikazu Nishikawa. Drawing of an “asymmetrical system,” 1963. Source: Hayashi, Chihiro, and Yoshikazu Nishikawa. “Initial conditions leading to different types of periodic solutions for Duffing’s equation.” In *Proc. Int. Symp. Nonlinear Oscillations*, 2: 386. Kiew, 1963.

laboratory to publication.<sup>11</sup> In addition, the strict hierarchy in the working group made it impossible to publish without the consent of his supervisor. Ueda could therefore be described as a discoverer without discovery. Circulation was stopped, due to a preconfigured mode of perception.

The question of whether seeing determines the limits of knowledge can hence also be answered the other way around: in this case, prior knowledge determined perception, and prevented circulation. What Henri Bergson once formulated for thinking

also proves to be true for seeing: “Our mind has an irresistible tendency to consider the idea it most frequently uses to be the clearest.”<sup>12</sup> The philosopher of science Gaston Bachelard used Bergson’s phrase to introduce his “epistemological obstacle,” which he also called a “counter-thought.”<sup>13</sup> According to Bachelard, such obstacles are necessary preconditions for the emergence of new insights. They constitute a battleground between a creative and a conservative instinct. This battle carries the danger that the mind becomes sluggish: “The value itself is opposed to the circulation of values. This means an

<sup>11</sup> On “accidents of representation” in the photochemical domain, see Peter Geimer, “Was ist kein Bild? Zur Störung der Verweisung,” in *Ordnungen der Sichtbarkeit: Fotografie in Wissenschaft, Kunst und Technologie*, ed. Peter Geimer, 313–41 (Frankfurt am Main: suhrkamp, 2002).

<sup>12</sup> As cited in Gaston Bachelard, *Epistemologie. Ausgewählte Texte* (Frankfurt am Main: Ullstein, 1974), 172.

<sup>13</sup> Bachelard, *Epistemologie*, 170–187.



idleness factor for the mind. Sometimes a dominant idea can polarize a mind in its totality.”<sup>14</sup> Questions of standardization form an antipole to circulation, from which new things emerge.

Apart from aesthetic expectations, technical instruments can also stand in the way of circulation. From the time he joined the Kyoto working group, it was Ueda who made most of the drawings for Hayashi’s publications, as he was considered a particularly skillful draughtsman. However, his designs were by no means mere results of a computer graphic device or traces of a technical experimental system. Ueda developed a remarkable hybrid technique to merge the data provided by the analog computer with his hand drawn analysis of the dynamics. This would have been unthinkable without years of training his eye in the interpretation of analog graphics. At the same time, this training could also be described in terms of education: none of these sketches were freehand drawings. On the contrary, Ueda used standardized drawing instruments with which he had been familiar for many years: a specific sort of rulers, called French Curves. These flat, solid templates for drawing various smooth curves through a series of fixed points were created in the spirit of industrialization in the middle of the 19<sup>th</sup> century, when the demand for technical drawing increased.<sup>15</sup> Initially also known as “design pistols,”<sup>16</sup> they were used in a wide range of applications, from mathematics education to fashion design, architecture, and engineering drawing. They show variable curvatures at their outer and inner edges and exist in a great variety of materials and shapes, while their main shapes are ellipse, hyperbolas, parabolas, and spirals.<sup>17</sup> The usage of French Curves was a technique Ueda was trained in during his apprenticeship as an electrical engineer.<sup>18</sup>

In her definition of chemical formulas as ‘paper tools’, the historian of science Ursula Klein noticed the effect of a dependence of the tools used on the

development of theories and came to the conclusion: “[Tools] relate to culturally and socially embedded human goals; they embody human goals and they react back on them and shape them.”<sup>19</sup> This can also be applied to the style developed in Hayashi’s working group. The design of the drawings was both shaped and limited by the standardization of the technical drawing tools. The French Curves used by Ueda favored a certain aesthetic. They were auxiliary devices to approximate a continuous curve without jumps or discontinuities and thus not neutral: The mathematical property of continuity is inscribed in their construction. The shape of a “broken egg” lay outside their normalized forms of representation. They were tools which, through their own design, also helped to shape aesthetic expectations – and thus also influenced the chances of circulation.

Both standardized aesthetic expectations and standardized drawing devices can act as a filter for theory production. They can lead to processes of collective ex- and inclusion, which the physician and biologist Ludwik Fleck subsumed under the concept of ‘thought style’ (Denkstil), which meant a “directed perception, with corresponding mental and factual processing of what is perceived.”<sup>20</sup> At another point he even described it pointedly as “thought compulsion [. . .]: the totality of mental readiness, the readiness for such and not for other ways of seeing and acting.”<sup>21</sup> Speculations about errors are related to the role of trained observation in “thought collectives:”<sup>22</sup> the scientific observation is “above all caused by a certain training, by a certain scientific tradition. [. . .] [T]he emergence of the ability to perceive certain figures [. . .] is accompanied by the dwindling of the ability to perceive certain others. [. . .] From the intentional abstraction of certain figures to the inability to perceive them, it is thus a continuous transition.”<sup>23</sup> The result of an

<sup>14</sup> Ibid., 172.

<sup>15</sup> Brian J. Lunday, “French Curves,” in *Hands on History. A Resource for Teaching Mathematics*, ed. Amy Shell-Gellasch, 63-69 (Washington: Mathematical Association of America, 2007). Curve rulers also became known as Burmester templates, after the German mathematician Ludwig Burmester (1840-1927).

<sup>16</sup> Ibid., 65.

<sup>17</sup> Ibid., 64.

<sup>18</sup> Based on an email exchange with mathematician Bruce Stewart in 2009.

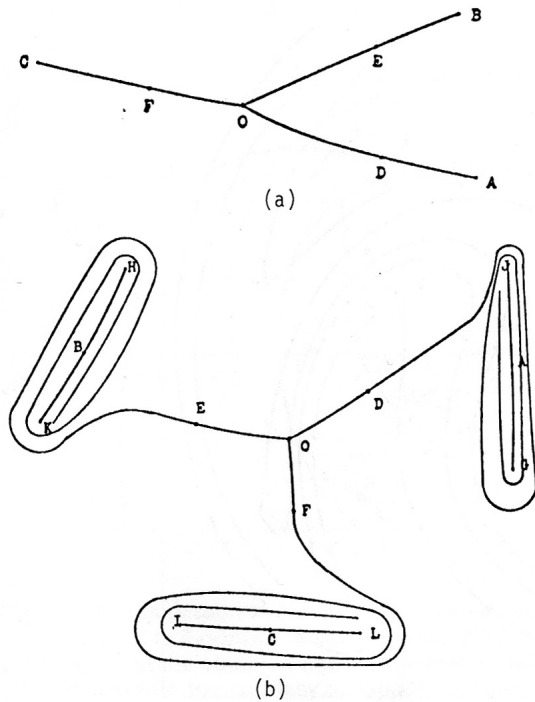
<sup>19</sup> Ursula Klein, “Paper Tools in Experimental Cultures,” *Studies in History and Philosophy of Science* 32, no. 2 (2001): 265, 297.

<sup>20</sup> Ludwik Fleck, *Die Entstehung und Entwicklung einer wissenschaftlichen Tatsache: Einführung in die Lehre vom Denkstil und Denkkollektiv* (Frankfurt am Main: suhrkamp, 1980), 130.

<sup>21</sup> Ibid., 85.

<sup>22</sup> For a definition of a “thought collective,” see Ibid., 54f.

<sup>23</sup> Ludwik Fleck, “Über die wissenschaftliche Beobachtung und die Wahrnehmung im Allgemeinen,” in *Erfahrung und Tatsache. Gesammelte Aufsätze* (Frankfurt am Main: suhrkamp, 1983), 61f.

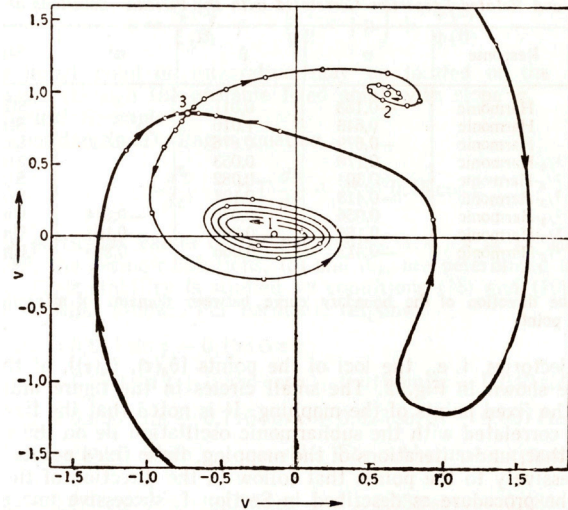


**Figure 5.** Norman Levinson. “Examples of maximum finite invariant domains,” drawing, from: *The Annals of Mathematics*, 1944. Source: Ueda, Yoshisuke. “Strange Attractors and the Origin of Chaos.” *Nonlinear Science Today* 2, no. 2 (1992): 9.

observation can take many forms depending on the observer. Obstacles to perception were particularly formed by existing standards, which also circulated and determined what led to the emergence and development of a scientific fact in a thought collective. In analogy to Fleck’s compulsion to think, there is also a compulsion to see: The eye’s gaze through the theory can censor the image and hinder circulation.

Nevertheless, there was a way for Ueda to get his result published after all so that his chaotic attractor could become widely known among experts. It is related to a different form of circulation in science that had not been addressed so far. You could call them inner or internal circulations, referring to already existing images from other contexts that a scientist encounters during research and that actively influence his thinking and theory formation. For Ueda, it was a discovery in 1966 of a twenty-year old drawing by mathematician Norman Levinson (Fig. 5).

He described this decisive situation in terms of a Eureka effect: “The moment I understood the

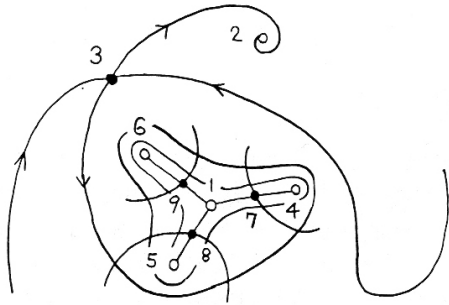


**Figure 6.** Toshiaki Murakami. “The loci of some image points of the invariant curves,” drawing, 1963. Source: Ueda, Yoshisuke. “Strange Attractors and the Origin of Chaos.” *Nonlinear Science Today* 2, no. 2 (1992): 6.

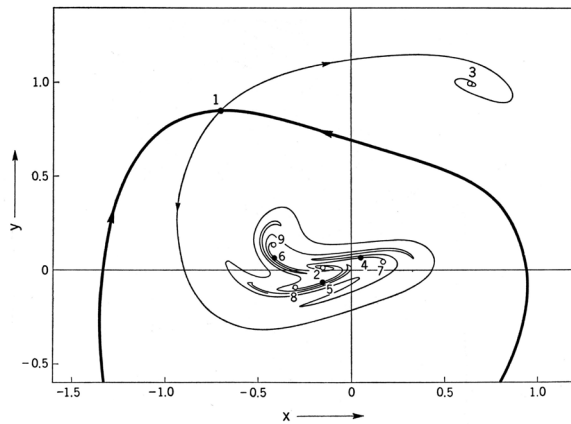
meaning of these figures, I thought ‘This is it!’ It solved a long-standing mystery for me.”<sup>24</sup> Ueda’s discovery concerned the arrangement of the so-called invariant manifolds, i.e. the parts with attracting or repelling properties around the area of the attractor. Years earlier, Hayashi’s group had already been studying these manifolds, which at a certain point formed an even spiral (Fig. 6). Now, with the help of Levinson’s drawing and the accompanying numerical calculations, Ueda was able to present a new organization of these lines, which he subsequently sketched out himself (Fig. 7). Lewinson’s drawing re-shaped Ueda’s own mental and material representations of the folding mechanism: it can be clearly seen that Ueda adapted Levinson’s folding and rotation mechanism instead of the spiral. In mathematical terms, this was Ueda’s first conscious contact with a chaotic topology – a homoclinic point, where forces that expand and contract act simultaneously, and by doing so, can generate chaos.<sup>25</sup>

<sup>24</sup> Ueda, “Strange Attractors,” 9. From Henri Poincaré to Benoît Mandelbrot and to Yoshisuke Ueda – the brilliant flash of inspiration is a leitmotif in the autobiographical testimonies of scientists over the centuries. It would be a desideratum to compare these narrative structures with long-established topics of artists’ myths, see Ernst Kris and Otto Kurz, *Legend, Myth, and Magic in the Image of the Artist: A Historical Experiment* (New Haven: Yale Univ. Press, 1979).

<sup>25</sup> See Ueda, “Strange Attractors,” 9. Strictly speaking, this is a variant, the heteroclinic point. However, a heteroclinic point is related to the homoclinic point. They differ only in their fixed points. Both represent a characteristic topological feature of chaos.



**Figure 7.** Yoshisuke Ueda. Corrected schematic diagram, drawing, 1966. Source: Ueda, Yoshisuke. "Strange Attractors and the Origin of Chaos." *Nonlinear Science Today* 2, no. 2 (1992): 9.



**Figure 8.** Yoshisuke Ueda and Chihiro Hayashi. Calculated fixed points and invariant curves, ink drawing, 1968. Source: Hayashi, Chihiro: "Solution of Duffing's Equation Using Mapping Concepts," reprinted in: Hayashi, Chihiro. *Selected Papers on Nonlinear Oscillations* (Osaka 1975), 156.

With the help of his updated sketch, Ueda finally succeeded in convincing Hayashi of the correctness of his findings, and in 1968 he published with him an updated version of the spiral (Fig. 8), which incorporated Ueda's construction. The subtlety of Ueda's idea lay in a visual mediation between symmetry and asymmetry: his Levinson-inspired scheme (Fig. 7) was built around a clear center, similar to the spiral (Fig. 6), but in its concrete application to the equations, it produced an asymmetrical form (Fig. 8). It is not without reason that this form recalls the drawing for Ford described at the beginning (Fig. 1): in Ueda's sketch of 1978, this very core idea of a stretched and refolded space of a chaotic attractor was concentrated.<sup>26</sup>

<sup>26</sup> Ueda probably drew the "Japanese attractor" in the sketch for Ford, which he discovered somewhat later than the "Broken Egg" attractor, but which has the same structural elements, although it is based on a different equation (based on an email conversation with mathematician Bruce Stewart in 2009).

Levinson's drawing had the function of a 'symbolic boomerang,' metaphorically speaking, which acted on the experimentally obtained result by making it understandable and, eventually, circulating it. Although Ueda's drawing of the Levinson-inspired rotating mechanism is not strictly speaking a chaotic attractor; it opened the view, sensitized the eye to new forms and thus created the conditions for later circulation through different scientific communities and disciplines. It was only after this success that Ueda himself finally dared, at the time of the student protests in Kyoto, 1969/70, and during a period of absence of his professor Hayashi to submit his own research to a professional journal in which he cautiously mentioned his discovery for the first time.<sup>27</sup> As he stated in retrospect, it was the "democratic atmosphere that prevailed on campus" after the turmoil of the demonstrations that may have inspired him to this action of intellectual liberation from his doctoral supervisor.<sup>28</sup>

The exploration of the boundary between presumed error and expected result, the initial classification of results as incorrect and the subsequent reintegration of the rejected into theory are some of the constants in the history of complex dynamics. However, there are many different ways of dealing with suspicious results. In Ueda's case, an image that was initially judged to be a technical error could only be integrated into the circulation of science if its visual consistency with existing pictorial traditions and aesthetic preferences was emphasized on a structural level,

In this sense, the image had to function as a "boundary object," – as defined by the sociologists Susan Star and James Griesemer: "[To translate between viewpoints, we need boundary objects that] are both adaptable to different viewpoints and robust enough to maintain identity across them."<sup>29</sup> Ueda's chaotic shape had successfully become such a "boundary object." It had become robust (symmetry

<sup>27</sup> See *Ibid.*, 12.

<sup>28</sup> Yoshisuke Ueda, "Strange Attractors and the Origin of Chaos," in *The Chaos Avantgarde. Memories of the Early Days of Chaos Theory*, ed. Ralph Abraham and Yoshisuke Ueda, 23-55, here: 45 (Singapore: World Scientific Publishing, 2000).

<sup>29</sup> Susan Leigh Star and James R. Griesemer, "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39," *Social Studies of Science* 19 (1989): 387.

based) and adaptable at the same time (incorporating the new paradigm). This concept is related to Latour's "immutable and combinable mobiles"<sup>30</sup> quoted above. Both notions address the question how images migrate through different "thought collectives."<sup>31</sup> The following two examples will show the further conditions under which a circulation through such knowledge spaces can take place.

### Circulation as Negotiation Process

The challenges of image circulation for scientific communication become especially obvious when a major paradigm shift – like the one from periodic to chaotic oscillations – or a major media shift takes place. In cell biology, such a media shift happened around 2006–2012, when a new microscopic visualization technique was introduced, namely localization microscopy.<sup>32</sup> This technique was promising to make visible intracellular structures that are more than six times smaller than the limits of optical resolution (i.e. 30 nanometers instead of 200).<sup>33</sup>

On the question of image circulation, however, the decisive factor is the transformation of a specimen into a visual representation. In standard fluorescence microscopy, each image is generated by a single exposure and the image can be viewed directly by the eye or captured by a device or photographic film. The scientist can look through the microscope and observe the imaging process. In contrast to this, in localization microscopy, the principle of image acquisition is based entirely on gathering a huge amount of data sets through continuous measurement. The scientist obtains only a data matrix. Not until a second step can an image be generated based on a translation of the array of

numbers into spatial relations and colors. Thus, the imaging process is split up into a preceding data acquisition procedure and a subsequent image generation.

In the first years after its invention in 2006, the technique was not yet standardized or accessible to members of biological labs. Most of the scientists who produced those images were not biologists, but physicists specialized in applied optics and information processing. Physicists developed the instruments, techniques and algorithms that were used to visualize biological cell structures. They took commissions from biologists (as well as from material scientists) and subsequently discussed the results with them. But they were not the 'end users.' They rather took up an intermediary status between two scientific cultures and thus between two different "cultures of seeing."<sup>34</sup>

Those different cultures of seeing emerge through different scientific practices. For example, a biologist could very quickly decide whether a suspicious detail in an image is an artefact or a new discovery by comparing it with one of the oldest microscopy techniques that have been around since the 17<sup>th</sup> century: bright-field light microscopy. It is part of the daily routine of biologists working in a wet lab, who use the bright-field light microscope to check samples and count cells in cultures. However, since this older imaging technique is by no means part of the common working practice of physicists specializing in applied optics and localization data, they would probably evaluate details in their microscopic images quite differently. It is the heterogeneous familiarization with microscopic visions, grounded in the practice of the lab, that informs and distinguishes the different biological and physical "cultures of seeing."<sup>35</sup>

When it comes to the interdisciplinary circulation of images, these different cultures of seeing can

<sup>30</sup> Latour, *Science in action*, 227.

<sup>31</sup> Fleck, *Entstehung und Entwicklung*, 54f.

<sup>32</sup> The first decisive steps towards localization microscopy were taken by three research teams in the United States (Eric Betzig et al., "Imaging Intracellular Fluorescent Proteins at Nanometer Resolution," *Science* 313, no. 5793 (2006): 1642–45; Samuel T. Hess et al., "Ultra-High Resolution Imaging by Fluorescence Photoactivation Localization Microscopy," *Biophysical Journal* 91, no. 11 (December 1, 2006): 4258–72; Michael J. Rust et al., "Sub-diffraction-limit imaging by stochastic optical reconstruction microscopy (STORM)," *Nat Meth* 3, no. 10 (October 2006): 793–96.

<sup>33</sup> For a survey on fluorescence microscopy and on the high hopes that the new 'nanoscopic' methods have raised in the early years, see Stefan W. Hell, "Far-Field Optical Nanoscopy," *Science* 316, no. 5828 (May 25, 2007): 1153–58, and Alberto Diaspro, *Optical Fluorescence Microscopy From the Spectral to the Nano Dimension* (New York: Springer, 2010).

<sup>34</sup> For microscopy, this term was introduced by Thomas Schlich, "Repräsentationen von Krankheitserregern. Wie Robert Koch Bakterien als Krankheitsursache dargestellt hat," in *Räume des Wissens. Repräsentation, Codierung, Spur*, ed. Hans-Jörg Rheinberger, Michael Hagner and B. Wahrig-Schmidt, 170 (Berlin: Akademie-Verlag, 1997).

<sup>35</sup> This second case study is a shortened and reworked version of: Nina Samuel, "Images as tools. On visual epistemic practices in the biological sciences," *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences* 44, no. 2 (June 2013), 225–236.



have a significant impact. Because biologists are mainly trained to understand cells by interpreting microscopic images, physicists need to translate their aniconic measurements into forms that are comprehensible for the Biology community, rather than delivering the data as, for example, a histogram or a graph. Their challenge is ‘to give the biologists something to see’ that they can relate to their own practical experience on ‘what cells look like.’<sup>36</sup> To facilitate this process, expectations are often exchanged through interdisciplinary communication: in many cases the biologists indicate beforehand, based on their experience, how the investigated biological structures should roughly look, or what features physicists should try to highlight in the images. To the same degree, physicists help to interpret the visual results based on what they discovered through additionally obtained data.

The philosopher Paul Virilio suggested that errors and accidents are an integral part of new technologies, and that they must therefore always be considered in conjunction with the new modes of failure they produce.<sup>37</sup> Assuming that the new technologies cannot exist at all without such accidents, they must also play a decisive role for questions of circulation. Therefore, it is necessary to take a closer look at what goes on in cases of potential miscommunication or misinterpretation: how does the scientific community attempt to avoid them and what does this reveal about the circulation of images in the sciences?

New technologies like localization microscopy trigger new moments of ambiguity, indecisiveness, and quandary. The physicist David Baddeley researched about the problem of how to find the best and most workable method to “translate this list [of data] into some form of image.”<sup>38</sup>

Baddeley presents and compares three different methods to render localization data as images (Fig. 9). He confronts the typical Gaussian rendering

(left) with two alternatives that differ particularly through the different design of the contour lines between square and rounded. Most importantly, he discusses the gap between the density of informational data that can technically be collected by the instrument and the amount of data that can practically be visualized in these three images. Here, Baddeley comes to a surprising conclusion: images that imitate the optical effect of wide-field microscopy most perfectly (Fig. 9a) work best in interdisciplinary communication but, unfortunately, they are also the ones that fail most dramatically in transmitting a maximum of the possible data volume.<sup>39</sup>

Baddeley classified methods like the so-called “quad-tree visualization” (Fig. 9b) as most efficient in terms of their potential to contain a high density of data. But unfortunately, their appearance comes just too close to the tessellated aesthetics of early computer games, recalling pixelated, square-cut Atari images – reminiscent of the computer games pioneer of the 1970s – more than biological and cellular structures. These patterns simply do not belong to the formal repertoire that biologists were trained to read as biological information. If the data were handed over to the biologists in the format of b, the image would most likely lead to an interdisciplinary communication blackout: unable to make sense of them, the biologists might just as well return the images to the physicist.

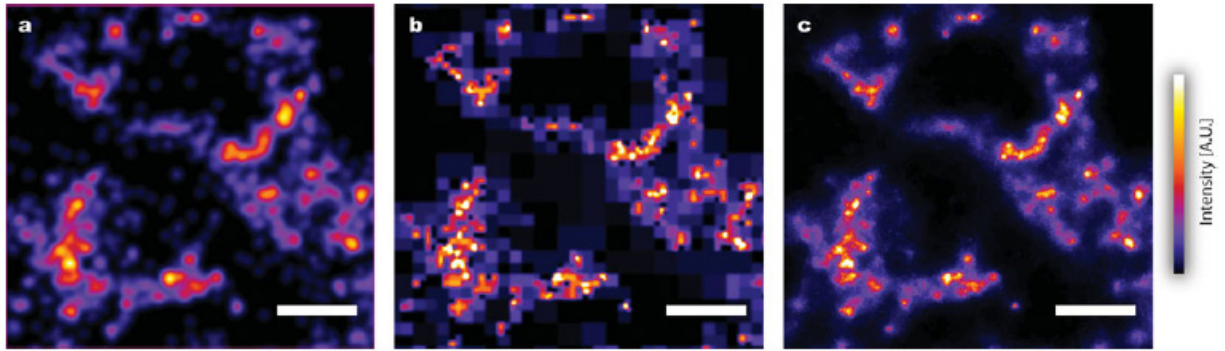
The biologists’ objections were related to the readability of the images. Such pictorial readability was established by familiarization through practice. Images whose aesthetic manifestations – e.g. shapes, colors, lines, transitions – were not familiar to them from their daily routines in the laboratory could not be deciphered and associated with known cell shapes. Such a process of getting used to a new kind of pictures could take quite a long time, as confirmed by the physicist Rainer Kaufman, who has worked intensively on this topic: “You generally can count on it taking about ten years until a newly developed microscopic technique is generally ‘accepted’ and widely and routinely used by

<sup>36</sup> This account is based on interviews with physicist Rainer Kaufman, see Samuel, “Images as tools,” 232f.

<sup>37</sup> Paul Virilio, “Der Urfall (accidens originale),” *Tumult. Zeitschrift für Verkehrswissenschaft*, no. 1 (1979): 77–82.

<sup>38</sup> David Baddeley et al., “Visualization of Localization Microscopy Data,” *Microscopy and Microanalysis* 16, no. 01 (2010): 64.

<sup>39</sup> *Ibid.*, 68.



**Figure 9.** David Baddeley. Application of visualization methods to experimental localization microscopy data. a: conventional visualization by Gaussian rendering; b: quad-tree based rendering; c: visualization based on triangulation. 2010. Source: Baddeley, David, Mark B. Cannell, und Christian Soeller. "Visualization of Localization Microscopy Data." *Microscopy and Microanalysis* 16, no. 01 (2010): 71.

biologists."<sup>40</sup> Before this change took place, however, their respective "culture of seeing"<sup>41</sup> determined what the images had to look like so that it could be read and understood.

To work properly as an interdisciplinary communication device and as a boundary object, the square-cut pattern in b had to be modified to look fuzzier again and thus to familiarize the biologist with the unknown (Fig. 9c), to the utmost regret of the physicists who lamented the loss of information density. New instruments are calibrated against older ones, and the impressions of known techniques need to be replicated for interdisciplinary agreement in order to avoid miscommunication between different fields.

This results in an obvious dilemma and involves continuous negotiation between the data and human perception. Physicists have to design images that, on the one hand, resemble the aesthetics of blurry, wide-field microscopy enough to enable interdisciplinary communication, while on the other hand, these images have to be sharp and precise enough to convey as much of the newly gained information about the specimen as possible. In the course of this process, physicists even face the challenge of taking action against human nature itself: Baddeley states that the eye has the natural tendency to see "spurious structure[s] in what is essentially noise."<sup>42</sup>

<sup>40</sup> Rainer Kaufman, quoted in Samuel, "Images as tools," 233.

<sup>41</sup> Thomas Schlich, "Repräsentationen," 170.

<sup>42</sup> Baddeley et al., "Visualization," 69.

So much the worse since the images preferred by biologists, the Gaussian renderings (Fig. 9a), can increase this perceptual disposition.

The aesthetic struggle to find the right form of visualization amounts to an epistemic one that becomes part of the process of discovery, replication, and agreement in science. In the case of localization microscopy, the struggle to find the perfect compromise between the amount of hidden data and the visible surface has a sizable impact on the actual design of the microscopic images that circulate between physicists and biologists.

In order to circulate, the microscopic image becomes an aesthetic and epistemic battleground between data, the psychology of perception, and imagination: physicists design the images to guide the perception of the biologists and to minimize the chance of misinterpretation and miscommunication. However, the decision about what counts as right or wrong is naturally based on their own interpretation of the relation of imaging technique and biology, and on their previous communication with the biologists. The resulting image always bears traces of this process and compromise. Star and Griesemer provide a lucid description of this situation: "When participants in the intersection worlds create representations together, their different commitments and perceptions are resolved into representations—in the sense that a fuzzy image is resolved by a microscope. This resolution does not mean consensus. Rather, representations, or inscriptions, contain at every stage the traces of

multiple viewpoints, translations, and incomplete battles.”<sup>43</sup>

Circulation in times of media shifts requires a visual taming of the unexpected. This means a conscious adaptation of well-known and trained ways of seeing, and standardized image traditions.

## Circulation and Materiality

The third case study is dedicated to the early history of images circulations of the probably most famous symbol of chaos theory: the Mandelbrot set. Simply put, the Mandelbrot set defines a realm within the complex number field that is distinguished, above all in the margins, by an impressively ornamental – and self-similar – variety, and for that reason is all the more impressive, since the formula it is based on seemed simple even to non-mathematicians.

Benoît Mandelbrot, the mathematician after whom this symbol was named, spent most of his life working and researching at IBM. It is possible to distinguish two phases in his research. In the first one, that took place at his employer in 1979, Mandelbrot devoted himself exclusively to the graphic depiction of complex non-quadratic equations, called cubic polynomials. The greatest initial difficulties resulted from his having to deal with a new kind of pictures in mathematics; pictures that needed to be carefully studied. During this first phase of playful experimentation with the new shapes, Mandelbrot produced an extensive series of black-and-white graphics, of which at least 150 sheets are still preserved (Fig. 10).<sup>44</sup>

They document how comprehensive his experiments were and how difficult it was to make anything visible at all. An equation’s complexity was often reflected in an apparitional blurring of the contours. Very frequently, the picture simply remained white, and nothing at all, or just a few spots, could be seen. Mandelbrot acknowledged in retrospect that, in certain areas in the series, it might already have been

possible to recognize the familiar bulbous shape of the Mandelbrot set: “I did see those elements in 1979 but could not organize and describe them. Therefore, they remained undiscovered.”<sup>45</sup> Once again we have a separation between perception and recognition, something that repeatedly determines the history of image circulations. A few outlines were clearly recognizable, but the majority disintegrated into irregular cloudlike spots: “Throughout, I felt like someone trying to photograph the Cheshire cat in *Alice in Wonderland* at the very moment it is about to disappear.”<sup>46</sup> Given these unresolved ambivalences, it is not surprising that these images did circulate at the time: Mandelbrot did not publish them because it was simply not possible to make sense of them or to “clean up their theory.”<sup>47</sup>

Seeing and discovering have to be sharply distinguished as two distinct phases of sense impressions: the mere availability of the new visualization tool, the computer, was not enough. The history of the Mandelbrot set can neither be disassociated from the requisite technology nor attributed to it alone. This becomes especially obvious during the next research phase that took place while Mandelbrot was guest professor at Harvard University during the winter semester of 1979/80. There, working under less ideal technical conditions – using what he called the “most miserable equipment in academia,”<sup>48</sup> he focused on assumedly simpler quadratic equations with a single variable parameter. Hence, what he expected was a simple, unambiguous result. Yet what appeared was unlike anything he had experienced before. As he recalls in retrospect, the first pictures “looked awful: filled with apparent specks of dust that the Versatec printer produced in abundance. . . . I was motivated to sniff out the ramifications of those specks of dirt.”<sup>49</sup> (Fig. 11)

<sup>45</sup> Benoît Mandelbrot, “Two nonquadratic rational maps devised from Weierstrass doubling formulas,” in *Fractals and Chaos. The Mandelbrot Set and Beyond. Selected Works of Benoît B. Mandelbrot. Companion to The Fractal Geometry of Nature* (New York: Springer, 2004), 157.

<sup>46</sup> *Ibid.*, 161.

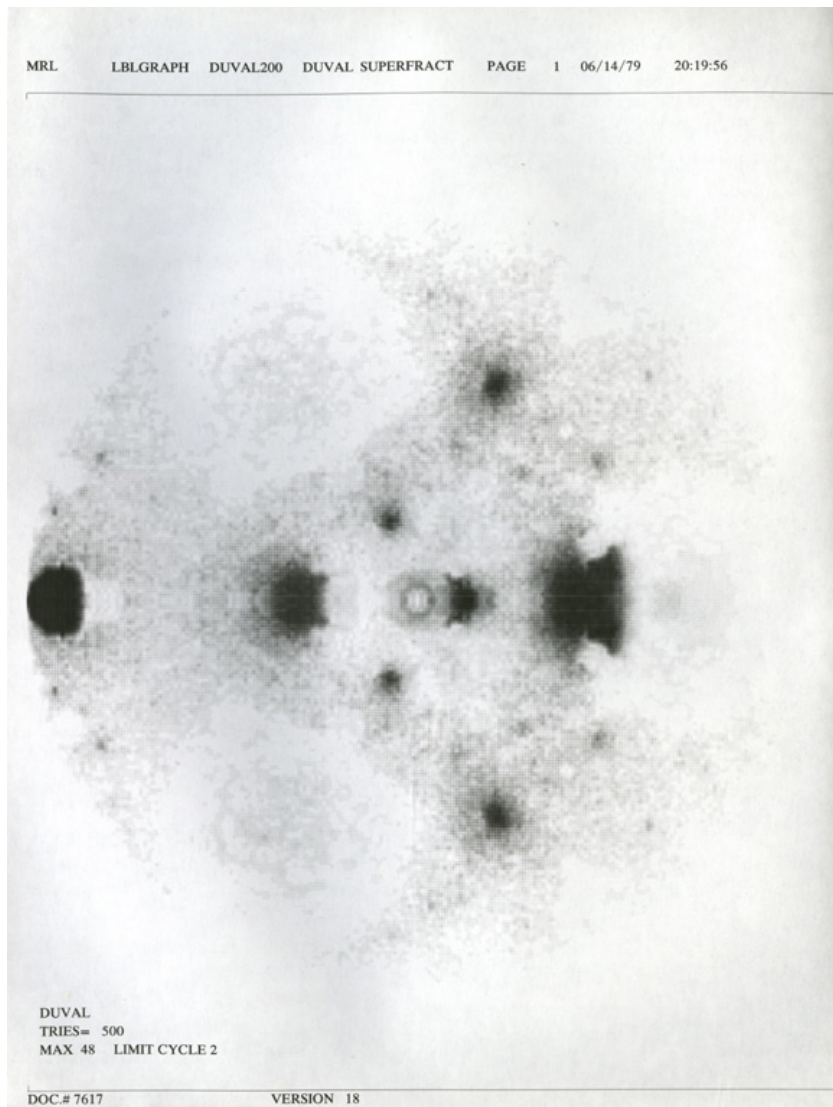
<sup>47</sup> *Ibid.*, 157f.

<sup>48</sup> Benoît Mandelbrot, “Fractals and the Rebirth of Iteration Theory,” in *The Beauty of Fractals. Images of Complex Dynamical Systems*, ed. Heinz-Otto Peitgen and Peter H. Richter (Berlin, Heidelberg: Springer, 1986), 151.

<sup>49</sup> Benoît Mandelbrot, *Fractals and Chaos. The Mandelbrot Set and Beyond. Selected Works of Benoît B. Mandelbrot. Companion to The Fractal Geometry of Nature* (New York: Springer, 2004), 23.

<sup>43</sup> Star and Griesemer, “Institutional Ecology,” 412f.

<sup>44</sup> For more examples of images and more details on Mandelbrot’s process of discovery, see Nina Samuel, ed., *The Islands of Benoît Mandelbrot: Fractals, Chaos, and the Materiality of Thinking* (New York: Yale University Press, 2012). This third case study contains extracts of this publication.

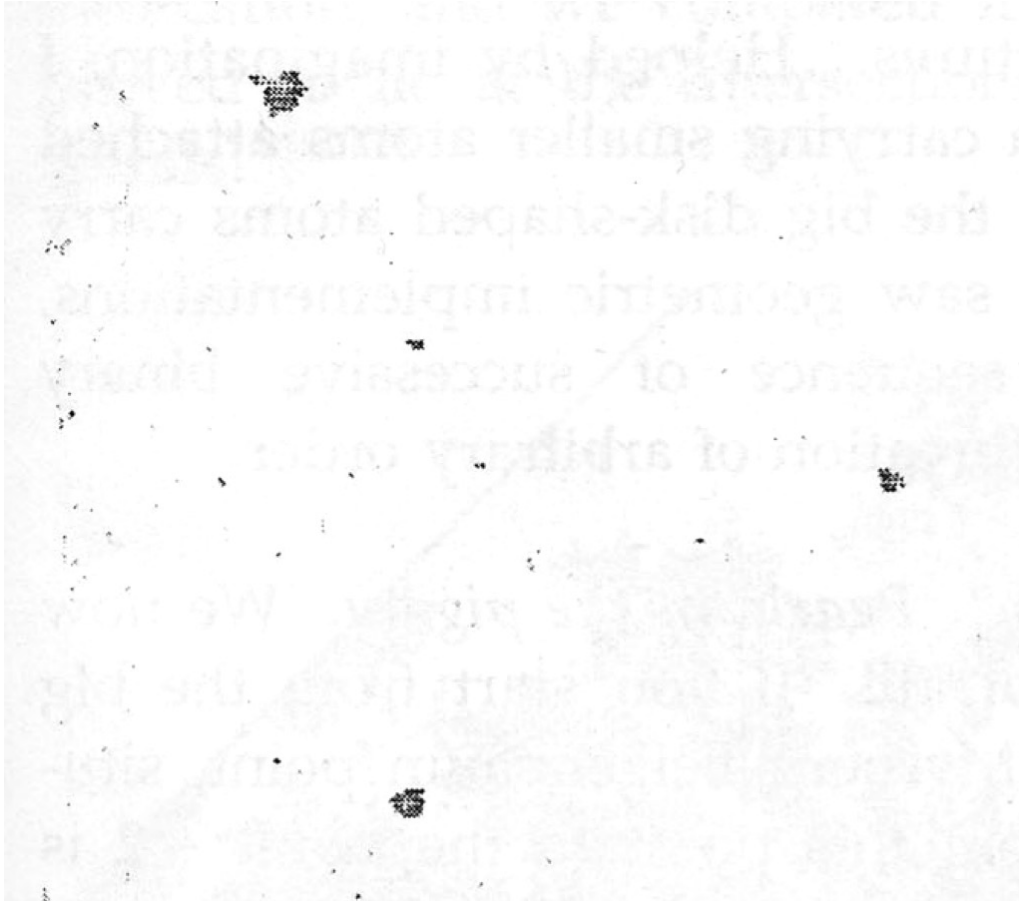


**Figure 10.** Benoît Mandelbrot and Mark R. Laff, programmer. Investigations in the complex plane of iterated cubic polynomials, series of over 150, 1979. IBM. Computer-generated prints on photographic paper. Source: Samuel, Nina, ed. *The Islands of Benoit Mandelbrot: Fractals, Chaos, and the Materiality of Thinking*. New York: Yale University Press, 2012, 73.

According to all reports the monitor at Harvard was subject to constant malfunctions and the decrepit printer made it uncertain what one was really seeing. Were the specks in fact dirt or “dust”? Were they smears and blots of the sort that the machine produced in abundance or visualizations of mathematics? What was technical bug and what was quadratic equation? The image itself had become suspicious and rose questions about its pictorial status. For the moment the boundary between image and non-image, between mathematics and materiality, was blurred. The specks

could be the result of either poor-quality printing or mathematical calculations of these “simple” formulas. Their origin was unclear. In order to distinguish between image and non-image, Mandelbrot decided to examine the specks more closely, and to that end employed the computer as a microscope. It was only his perception of symmetries in the “dirt” that elevated the specks’ ‘reality probability’ and suggested that the specks belonged to mathematics: “Since bona fide dirt is not symmetric, both kinds of specks demanded to be blown up for close inspection. . . . The symmetric points





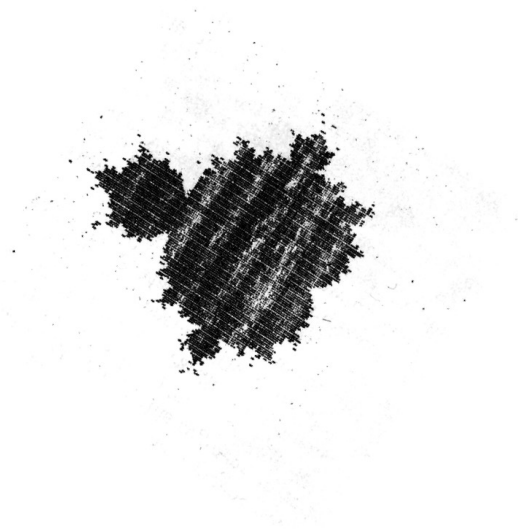
**Figure 11.** Benoît Mandelbrot. Investigations in the complex plane of iterated quadratic polynomials, detail from computer graphic. Harvard, Spring 1980. Source: Mandelbrot, Benoît. *Fractals and Chaos. The Mandelbrot Set and Beyond. Selected Works of Benoît B. Mandelbrot. Companion to The Fractal Geometry of Nature*. New York, 2004, 13.

had more chances of being real.”<sup>50</sup> From a series of enlarged pictures it was determined that some of the specks were in fact dirt from the machinery, but others proved to be self-similar copies of the basic shape (Fig. 12). The presumed glitch was thus transformed into a decisive discovery.

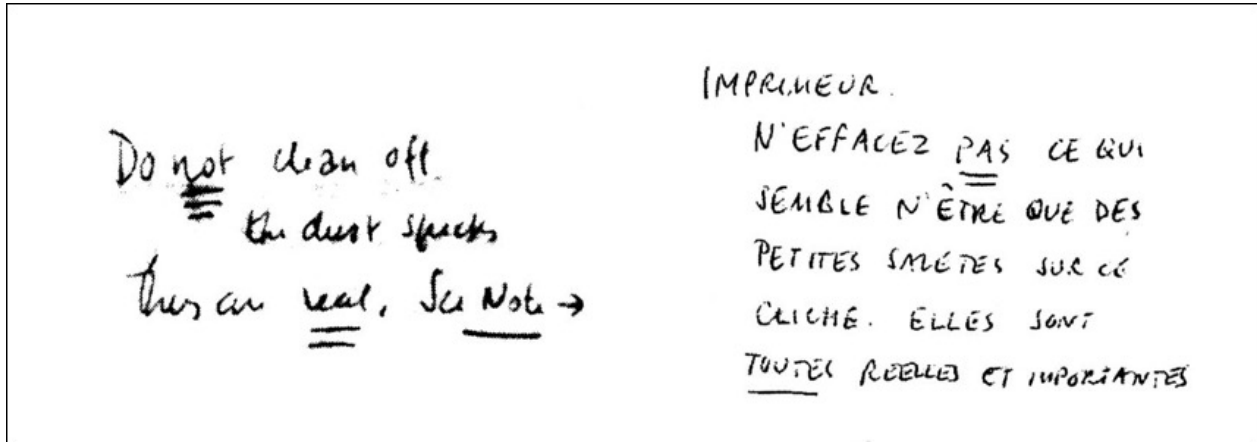
This is how the famous symbol of chaos theory was finally discovered, and soon afterwards Mandelbrot decided to prepare his first publication on this topic in the *Annals of the New York Academy of Sciences*. One of his central hypotheses was the detachment of the small specks from the central main form. He therefore called them “disconnected portions.”<sup>51</sup>

<sup>50</sup> *Ibid.*, 14.

<sup>51</sup> Benoît Mandelbrot, “Fractal aspects of the iteration of  $z \rightarrow \lambda z(1-z)$  for complex  $\lambda$  and  $z$ ,” in *Nonlinear Dynamics*, ed. Robert H. G. Helleman, *Annals of the New York Academy of Sciences* 357 (New York: New York Academy of Sciences, 1980), 250.



**Figure 12.** Benoît Mandelbrot. Investigations in the complex plane of iterated quadratic polynomials, large magnification from computer graphic. Harvard, Spring 1980. Source: Mandelbrot, Benoît. *Fractals and Chaos. The Mandelbrot Set and Beyond. Selected Works of Benoît B. Mandelbrot. Companion to The Fractal Geometry of Nature*. New York, 2004, 13.



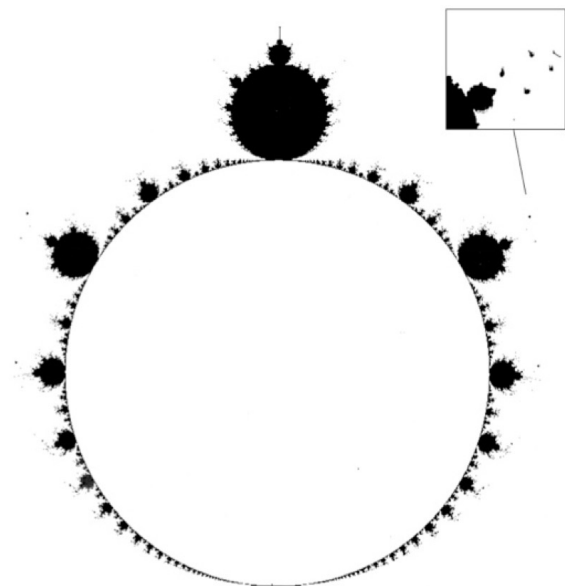
**Figure 13.** Benoît Mandelbrot. “Notes on Working Equipment from the Years 1980–81.” Source: Mandelbrot, Benoît. *Fractals and Chaos. The Mandelbrot Set and Beyond. Selected Works of Benoit B. Mandelbrot. Companion to The Fractal Geometry of Nature.* New York, 2004, 22.

However, setting the circulation in motion was not so easy, precisely because of the similarity of his discovery to tiny pieces of matter. Because the small, surrounding spots were deceptively similar to interference or printer smudges, they were repeatedly removed by conscientious computer lab and print shop employees. For that reason, in the years 1980/81 Mandelbrot got in the habit of posting warnings on his output equipment (Fig. 13): “Don’t clean off the dust specks, they are real.”<sup>52</sup> According to his own reports, the fact that his early pictures were in constant danger of being erased had infuriated him again and again.

But the worst was yet to come. Despite all his warnings and attempts to protect the tiny details of his graphics, the ultimate disaster happened at the very moment his image first made it into the publishing chain. His main discovery, the small specks, which were small copies of the whole, had been completely removed by the editors because they were judged to be unwanted printing errors – or, in Mandelbot’s own words: “Horrors! It is now free of specks! . . . Clearly, gremlins in the printing business had . . . [repeated] that evil deed.”<sup>53</sup>

What happened in the following was particularly remarkable with regard to the question of the circulation of images. To protest against the failed circulation of his correct image and to mitigate the

<sup>52</sup> Mandelbrot, *Fractals and Chaos*, 22.  
<sup>53</sup> *Ibid.*, 22.



**Figure 14.** Benoît Mandelbrot. Offprint of the first publication of the Mandelbrot set, 1980, with specks drawn by hand. Courtesy John Hubbard. Source: Samuel, Nina, ed. *The Islands of Benoit Mandelbrot: Fractals, Chaos, and the Materiality of Thinking.* New York: Yale University Press, 2012, 40.

damage, Mandelbrot drew the small specks by hand in the offprint versions of his article, which he sent to colleagues (Fig. 14). This practice could be described as micro-circulation – or counter-circulation – as opposed to macro-circulation, which took place through the official publishing houses.

But there is also a tragic twist in this story around the first circulations: while Mandelbrot had decided to trust the appearance of the “disconnected portions” as uncontested truth in the article, two years

later the French mathematician Adrien Douady mathematically confirmed that the opposite was true – that they were in fact attached to the main shape by invisible lines.<sup>54</sup> But since Mandelbrot saw no connecting lines during his experiments and had confidence in his computer, he did not believe in their existence and reaffirmed this in his drawings, which then microcirculated in the mathematical community. One could also say that the material side of the mathematical object was more important than the analytical proof. Mandelbrot's famous (and often quoted) dictum "seeing is believing"<sup>55</sup> changed during these events to "drawing is believing": the digital form had to circulate as a drawing in order to be considered existing and real.

## Conclusion

As can be seen in the last example, circulation is an essential part of the material formation of knowledge in science: for Mandelbrot, his materialized mathematical proof – although in the end false – had to circulate in order to exist. Circulation in science can never be understood simply by looking at the history of publications; one must take into account the notebooks of the scientists (Ueda), the counter- or micro-circulations (Mandelbrot), and the rejected images that are held back to enable interdisciplinary communication (Baddeley).

Pictorial norms and conventions function as a solid filter in two directions: first, they influence whether a result is taken into account or considered a technical error; second, they determine the border between the expected and the unexpected, the accepted and the contested result. However, tiny traces – or "specks of dust and dirt" – on the interface between the world of thinking and the world of things can be enough to 'seduce' the mind during these epistemic circulations.

All three examples show different strategies through which images that break with visual conventions and

traditions have been integrated into the circulation of scientific knowledge and became "boundary objects"<sup>56</sup> that are robust and flexible at the same time:

- 1) first, through an attempt to generate visual consistency on a structural level,
- 2) second, through a negotiation process between data and human perception,
- 3) and third, through an emphasis on visual discontinuity, a conscious break with traditions, but simultaneously relying on the material character of the mathematical object.

All three examples show how difficult it can be to maintain a distance between what the eye sees and what can be proved analytically. As the story of a struggle for agreement between observation and theory, the examples illustrate how necessary it is for the eye to be schooled on pictures and how risky the thinking can be that pictures inspire. It thereby says something not only about mechanisms of circulation in science but also about the fundamental ambiguity of visual perception.

<sup>54</sup> Adrien Douady and John Hamal Hubbard, "Itération des polynômes quadratiques complexes," *Comptes Rendus (Paris)* 194–I (1982): 123–26.

<sup>55</sup> Benoit B Mandelbrot, *The Fractal Geometry of Nature* (San Francisco: W.H. Freeman, 1982), 21.

<sup>56</sup> Star and Griesemer, "Institutional Ecology," 387.