Visual Thinking by Scientists ©

Anecdotal reports

There are many anecdotal reports on the importance of visual thinking by scientists. Perhaps the best known visual discoveries are the benzene ring and the helical structure of DNA. Friedrich Kekule envisioned the benzene ring as a snake biting its own tail. Computing can facilitate this experience.

> "*The most striking - and a unique - feature of the mind is the acceptance and use of things as symbols standing for other things. Symbols may stand for, refer to, or mean other things which may or may not lie within the world of physics. .... In this sense we find the mind in computing machines*". Richard L. Gregory in Mind of Science

Max Planck reinforces the idea how human reasoning coincides with, but exists independent of, the world of physics:

> "*My original decision to devote myself to science was a direct result of the discovery which has never ceased to fill me with enthusiasm since my early youth - the comprehension of the far from obvious fact that the laws of human reasoning coincide with the laws governing the sequences of the impressions we receive from the world about us; that, therefore, pure reasoning can enable man to gain an insight into the mechanism of the later. In this connection, it is of paramount importance that the outside world is something independent from man, something absolute, and the quest for the laws which apply to this absolute appeared to me as the most sublime scientific pursuit in life*". Max Planck in Scientific Autobiography.

Even more vivid was Albert Einstein's explanation how human reasoning includes visual thinking.

> "*The words or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined. .... This combinatory play seems to be the essential feature in productive thought before there is any connection with logical construction in words or other kinds of signs which can be communicated to others*". Albert Einstein in a letter to Jacques Hadamard.

A more contemporary example of visual thinking is given by James Gleick from "The Life and Science of Richard Feynman", Vintage Books, New York, 1992.

> "*Visualization - you keep repeating that*", he (Feynman) said to another historian, Silvan S. Schweber, who was trying to interview him.
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> Feynman continues: "*What I am really trying to do is bring birth to clarity, which is really a half-assedly thought-out-pictorial semi-vision thing. I would see the jiggle-jiggle-jiggle or the wiggle of the path. Even now when I talk about the influence functional, I see the coupling and I take this turn - like as if there was a big bag of stuff - and try to collect it in away and to push it. It's all visual. It's hard to explain.*"
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> Schweber: "*In some ways you see the answer - ?*"
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> Feynman: "*The character of the answer, absolutely. An inspired method of picturing, I guess. Ordinarily I try to get the pictures clearer, but in the end the mathematics can take over and be more efficient in communicating the idea of the picture.*"
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> "*In certain particular problems, that I have done, it was necessary to continue the development of the picture as the method before the mathematics could be really done.*"
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> The reader can witness how Feynman developes the theory of quantum electro-dynamics (Q.E.D.) using visual thinking, referred to above as "*a half-assedly thought-out-pictorial semi-vision thing*", in his Douglas Robb Memorial Lectures at the University of Auckland, New Zealand, 1979.

Feyman would often refer to how he used a graphical approach in his thinking but was at a loss to explain, when studying turbulent flow, how a variety of behaviors (three-dimensional structures) were observed to be "*hidden*" within but yet predicted by the same equations. Consequently it was difficult to explain how others could reproduce his visual thinking. This conflict was demonstrated in a summary on modeling viscous fluid flow (Chpt 41, The Flow of Wet Water, The Feynman Lectures on Physics, 1964), Feyman provides an example of Couette flow (41-6) that was used to explain the formation of different wavey "*barber pole*" formations of vortices that start out as bands of vortices caused by a differential rotation between two concentric cylinders. Feynman was fascinated how different three-dimensional vortice structures result from different rates of rotation, e.g. Reynolds numbers, while the equations and boundary conditions are unchanged: "*And no one knows why!*". Feyman concludes,

> "*The main lesson to be learned by all this is that a tremendous variety of behavior is hidden in the simple set of equations (41.23). All the solutions are from the same equations, only with different values of R (Reynolds number). We have no reason to think that there are any terms missing from these equations. The only difficulty is that we do not have the mathematical power to analyze them except for very small Reynolds numbers -- that is, in the completely viscous case. That we have written an equation does not remove from the flow of fluids its charm or mystery of its surpise.*"

The difficulty that we do not have the complete mathematical power to analyze and envision these different behaviors (three-dimensional structures) led Feyman to speculate on how the future may produce a method to envision these structures within the context of "*understanding the qualitative content of the equations*". To understand the "*qualitative content of equations*" it is necessary to first read and study the ideas used in the creation of the equations developed in chapters 40 and 41. You don't need a Ph.D. in Physics to appreciate the anectodal evidence of Feynman's visual thinking. However Feynman's lectures in chapters 40 and 41 did target undergraduate physics students who had already taken their freshman and sophomore physics and calculus courses. So at least an undergraduate level education, perhaps more, is needed as a foundation to develop such methods of understanding. It is within this context Feynman is fascinated with but hopes to resolve this conflict and envision his science.

> "*The next great era of awakening of human intellect may well produce a method of understanding the qualitative content of equations. Today we cannot. Today we cannot see that the water flow equations contain such things as the barber pole structure of turbulence that one sees between rotating cylinders. Today we cannot see whether Schroedinger's equation contains frogs, musical composers, or morality - or whether it does not. We cannot say whether something beyond it like God is needed, or not. And so we can all hold strong opinions either way.*"

Until such graphical methods of understanding are developed, the emphasis was to see these various structures by just using graphical tools without requiring an understanding of ideas used in the development of these equations. In this case results lack reproducibilty in the scientific sense, and so we are all entitled to our own opinions when we analyze and interpret information embedded in equations or massive data sets by just using graphical tools. With such graphical methods of understanding, together with graphical tools, scientists will "see" the content of their equations and results will be reproducible in a scientific sense. And so we seek reproducible graphical methods, not tools, that allow scientists to "*see*" and understanding the content hidden within their equations or massive simulation/experimental data sets. It is important that scientists create these graphical methods within the context as they understand their science. Recall Feynman's anecdotal report: "*In certain particular problems, that I have done, it was necessary to continue the development of the picture as the method before the mathematics could be really done.*" Do such scientific reproducible graphical methods exist?

Scientific reproducible results

Although informative and perhaps inspirational, anectodal reports are not instructive in the sense that they do not allow the reader to reproduce these insightful experiences. There are however some examples where visual thinking was developed by scientists as a graphical method and published which enabled other scientists to reproduce geometric physical property relationships within the scientific context that they were created. In these cases creation of graphical property relationships transcends the use of graphics for presentation. Creation of these graphical methods becomes a cognitive experience that was used to understand and then develop the underlying theory. This idea was demonstrated by J. Willard Gibbs in his first two historic publications, "Graphical Methods in the Thermodynamics of Fluids" and "A Method of Geometrical Representation of the Thermodynamic Properties of Substances by Means of Surfaces", Transactions of the Connecticut Academy, Vol. II, Part 1, pp. 309-342 and Part 2, pp. 382-404, 1873, respectively. In the first publication, Part 1, Gibbs' objective, as the title implies, developes graphical methods that provide insight into the thermodynamic properties governed by the first and second laws of thermodynamics:

> "*Although geometrical representations of propositions in the thermodynamics of fluids are in general use, and have done good service in disseminating clear notions in this science, yet they have by no means received the extension in respect to variety and generality of which they are capable. So far as regards a general graphical method, which can exhibit at once all the thermodynamic properties of a fluid concerned in reversible processes, and serve alike for the demonstration of general theorems and the numerical solution of particular problems, it is the general if not the universal practice to use diagrams in which the rectilinear co-ordinates represent volume and pressure. The object of this article is to call attention to certain diagrams of different construction, which afford graphical methods coextensive in their applications with that in ordinary use, and preferable to it in many cases in respect of distinctness or of convenience.*"

After carefully developing various reversible thermodynamic "graphical methods", pp. 310-341, Gibbs concludes:

> "*In the foregoing discussion, the equations which express the fundamental principles of thermodynamics in an analytical form have been assumed, and the aim has only been to show how the same relations may be expressed geometrically. It would, however, be easy, starting from the first and second laws of thermodynamics as usually enunciated, to arrive at the same results without the aid of analytical formulae, to arrive, for example, at the conception of energy, of entropy, of absolute temperature, in the construction of the diagram without the analytical definitions of these quantities, and to obtain the various properties of the diagram without the analytical expression of the thermodynamic properties which they involve. Such a course would have been better fitted to show the independence and sufficiency of a graphical method, but perhaps less suitable for an examination of the comparative advantages or disadvantages of different graphical methods.*"

Evidently, according to Gibbs, the equation of state derived at the begining of his first paper was not as insightful as the graphical method. Interesting. To understand how the thermodynamic relationship of properties can be better understood graphically without the analytic experessions it is necessary to actually read and study Gibbs 1873 publications. After reading these two publications James Clerk Maxwell created a "sculptured" surface in 1874 showing the thermodynamic graphical relationship of energy, entropy, and volume, described in detail by Gibbs, but never drawn. Maxwell also graphically reproduced and extended Gibbs' original graphical method by constructing lines of temperature and pressure mapped onto his sculptured surface in figure 26d, pg 207, *Theory of Heat*, 1904, without using any mathematical relations as recommended by Gibbs. This is quite an endorsement, coming from Maxwell the mathematician. This also demonstrates scientific reproducibility. Maxwell used clay and plaster to make a "sculpture", a graphical model of the graphical method. It was 1874, there were no graphical tools. Maxwell sent one of three sculptures to Gibbs at Yale in 1874 which is enclosed in a dusty display case next to an oil drum. Another of Maxwell's sculptures can be viewed in a display case at Cavendish Laboratory at Cambridge. It is interesting to note that the graphical method, originally developed by Gibbs, was done so independent of any graphical tools. With todays computer technology we have focused on using graphical tools, not developing graphical methods within the scientific/mathematical context understood by the scientist. A brief web summary describes how Gibbs' graphical method is related to a generalized graphical method used to envision total derivatives without reference to graphical tools. Another web site, created by Professor Kenneth Jolls and Dr. Daniel Coy, summarizes Gibbs' graphical method and highlights Dr Coy's Ph.D. dissertation, "Visualizing thermodynamic stability and phase-equilibrium through computer graphics", Iowa State University, 1993. These web sites and Dr. Coy's dissertation exemplifies how others can learn about Gibbs' graphical method and create energy-entropy-volume surfaces as originally described by Gibbs and graphically reproduced by Maxwell.

Although it was Gibbs intention to develop "*graphical methods coextensive in their applications*", selecting a specific example such as the thermodynamic theory of state should encourage us to seek other examples and perhaps other general graphical methods coextensive in their applications. Too often scientists stop once they find their specific example. Perhaps there are other interesting graphical methods that can be used to envision scientific information. This idea is presented as the theme in the class notes for ESM4714, "Scientific Visual Data Analysis and Multimedia: Create the graphical method -- discover the science".

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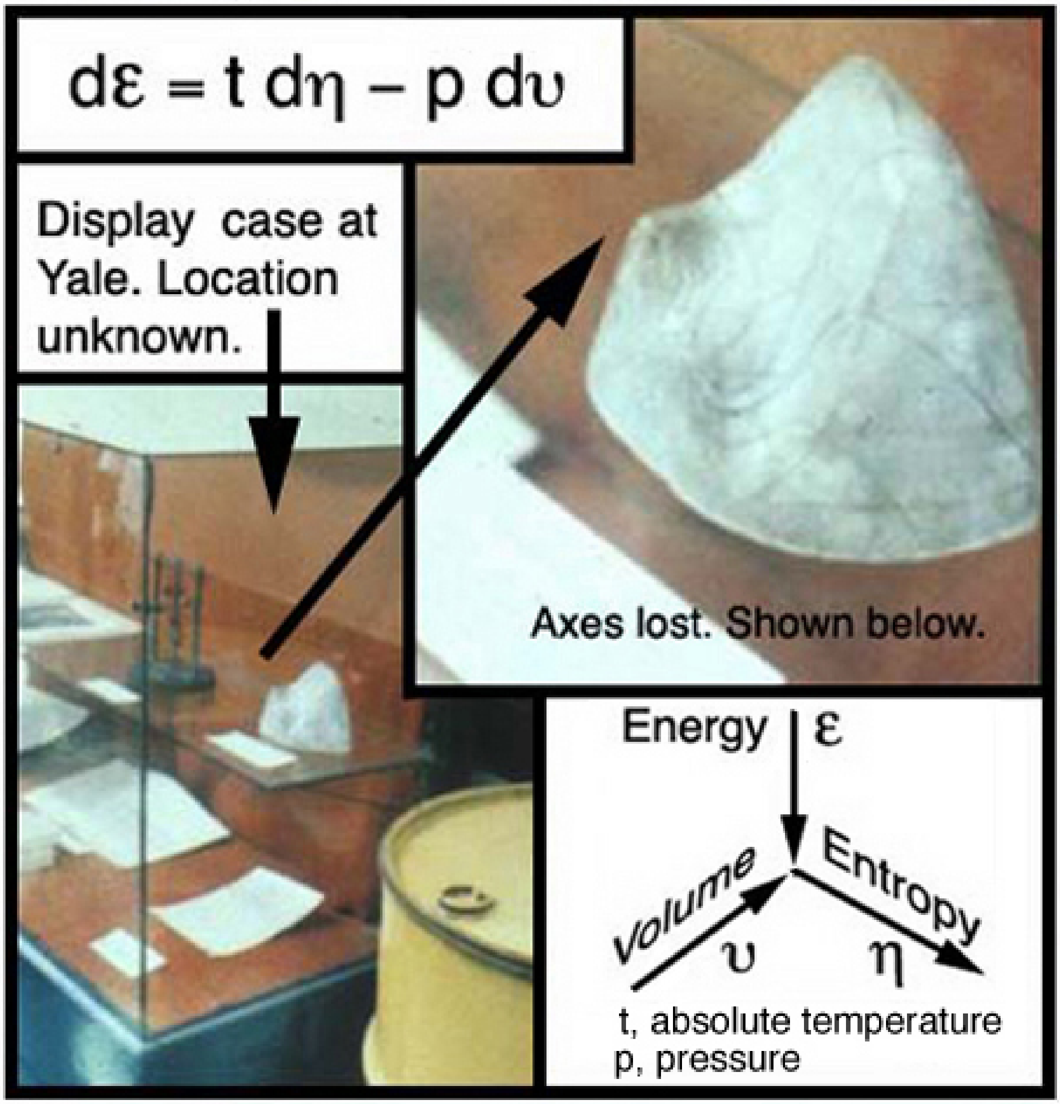
http://www.sv.vt.edu/classes/ESM4714/methods/vizthink.html

Scultpture: Display case Cavendish Laboratory in Cambridge, England.

Maxwell's "sculpture" of J.W. Gibbs visual model of thermodynamic properties of water published in Transactions of the Connecticutt Academy of Arts and Sciences Vol. II, "Graphical Methods in the Thermodynamics of Fluids", Part 1 pp. 309-342, "A Method of Geometrical Representation of the Thermodynamic Properties of Substances by Means of Surface", Part 2 pp.382-404,1873

http://www-outreach.phy.cam.ac.uk/camphy/museum/area1/images/cabinet1_2.jpg

Image modified. Original image taken from Thomas G. West web page
http://krasnow.gmu.edu/twest/maxwell_visual.html



Clay model of J. Willard Gibbs visual mental model a "graphical method" showing solid, liquid and gaseous states, created by James Clerk Maxwell and sent to Gibbs in NewHaven, 1874, which now gathers dust in an isolated display case at Yale next to a trash bin.