Constructing scientific culture in the 5G era: Historical lessons from the first discovery of a virus

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Abstract
This article examines how scientists from various periods, countries and disciplines worked together to identify the tobacco mosaic virus, which is a rod-shaped protein–RNA complex. The process by which that came about was one of persistent and reflective collective learning. Examination of this history reveals that under conditions in which repeated experiments were unable to be properly performed, and no adequate queries from within the scientific community or communications among scientists were available, highly uncertain novel phenomena were susceptible to inaccurate interpretations and predictions. In view of that, it is suggested that only by encouraging queries within the scientific community and embracing alternative opinions can differences in scientific understanding be calibrated to increase the number of fundamental scientific and technological innovations. Only by promoting academic democracy and establishing dialogue on the basis of equality can we prevent substantial deviations in scientific understanding, proposed by scientific authorities, from inhibiting scientific development. With respect to China, this article holds that, in the age of the internet and the dawning era of 5G, Chinese scientists ought to recognise and confront the limitations of scientific research, examine the cumulative nature of scientific understanding in a more general way, establish a dialogue mechanism among researchers on the basis of equality, allow for the inherent error-correction mechanism within the scientific community, and actively take part in the construction of scientific culture.

Keywords
Academic democracy, deviations in understanding, scientific culture, scientific discovery, tobacco mosaic virus

Due to the limitations in scientific research and the cumulative nature of scientific knowledge, an understanding of a novel phenomenon can only be achieved after a long process of investigative research. In view of this, it is quite understandable that a plethora of competing opinions have been presented regarding the origins, nomenclature, testing, prevention and treatment of coronavirus disease 2019 (COVID-19).

In the absence of shared findings from repeated experiments, and of channels for in-depth queries and communication between scientists active in laboratory research, scientific understanding together with concomitant predictions on novel phenomena are highly susceptible to variation and negative deviation. In a
previous study, I investigated the process by which the tobacco mosaic virus (TMV) was first discovered (Zhou, 2020a). Building upon those findings, this paper draws on the history of the discovery of TMV as a case study to demonstrate how the scientific community might circumvent certain deviations in understanding of novel phenomena by embracing the persistent and reflective process of collective learning.

1. The discovery of filterable pathogens

Until the late 20th century, the germ theory of disease, which was postulated by French microbiologist Louis Pasteur (1822–1895) and German microbiologist Robert Koch (1843–1910), remained the most widely accepted disease theory (Zhou, 2015). Under its influence, German agricultural chemist Adolf Mayer (1843–1942) discovered that tobacco mosaic disease (TMD) was infectious (Mayer, 1886). However, due mainly to the low resolution of the optical microscopes that were used at that time (only 200 nanometres), there was no way for Mayer to know that the causative agent of TMD was a submicroscopic particle; that is, a filterable pathogen.

It was Russian plant physiologist Dmitri Ivanovsky (1864–1920) who eventually discovered that the causative agent of TMD could pass through a bacterial filter (Lustig and Levine, 1992). However, in 1892, when Ivanovsky – who was then still a young student – made this discovery, it did not occur to him that this causative agent was neither a bacterium nor derived from a bacterium. Failing to recognise this filterable pathogen as a new type of pathogen, Ivanovsky did not immediately conduct in-depth follow-up research (Toriyama, 2008).

That is quite understandable given that, at that time, it was widely accepted by the scientific community that all infectious diseases were caused by either bacteria or bacterially secreted toxins. For instance, in 1897, foot-and-mouth disease virus was first discovered by German microbiologists Friedrich Loeffler (1852–1915) and Paul Frosch (1860–1928), who recognised it as a new pathogen that could pass through a bacterial filter. Nevertheless, they were reluctant to abandon the ‘one bacterium, one disease’ theory postulated by their mentor, Koch. Therefore, they continued to identify foot-and-mouth disease virus as a kind of ‘minutest organism’; that is, they still considered it to be in essence a bacterium, only much smaller (Loeffler and Frosch, 1964).

In 1898, Dutch bacteriologist Martinus Beijerinck (1851–1931) used the most advanced Chamberland filter available at the time to filter liquid extracted from tobacco leaves with TMD. He found that the filtrate was infectious and subsequently observed that it could permeate agar gel while still retaining its infectivity. Based on those findings, Beijerinck (1898) held that the causative agent of TMD was a novel pathogen entirely distinct from bacteria, which he called ‘contagious living fluid’ (*contagium vivum fluidum*).

In addition to coining that phrase, Beijerinck also referred several times to the filterable TMD pathogen as a ‘virus’ (Bos, 1999). The term ‘virus’ comes from Latin, and its literal meaning is ‘viscous liquid, toxin’. In late medieval English, ‘virus’ primarily denoted ‘the venom of snakes’. In view of that, it is quite understandable that after Beijerinck adopted the term ‘virus’ to refer to filterable pathogens and noted that this type of pathogen was a kind of ‘contagious living fluid’, Ivanovsky and others raised serious doubts about his view (Okada, 2004). This is explained by the fact that, constrained by previous experience, it was almost unthinkable that the fluid, which was not composed of particles, could replicate in the same way as unicellular bacteria. In 1903, Ivanovsky successfully demonstrated via several experiments that this new type of pathogen probably consisted of particles, although he was not able to observe them under optical microscopes; nor was he able to cultivate this new type of pathogen *in vitro*.

2. Identification of TMV as a non-bacterial particle

At the beginning of the 20th century, an increasing number of scientists began to conduct research on TMV. Electron microscopes became commercially available only after 1939, and earlier studies on TMV had to rely on a wide variety of now outdated equipment and methods. In that period, the key research questions were whether TMV consisted of particles and, if it did, whether it was a micro-organism.
In 1902, Albert F Woods (1866–1948), an expert in the plant industry from the United States Department of Agriculture, postulated that TMD arose from increased activity of oxidase in leaves (Helvoort, 1991). His younger colleague, Harry A Allard (1880–1963), who ran follow-up experiments on Woods’s research in 1916, questioned Woods’s postulation. World War I was in full swing at that time, and Allard could not obtain a Chamberland filter in Europe. Fortunately, Burton E Livingstone had invented a device that monitored soil moisture, and it happened to be constructed from a porous cup mainly made of micas that were buried in the soil. The cup was easy to obtain in the United States, and Allard used it as a substitute for a Chamberland filter.

Eventually, Allard discovered that, after being filtered through the porous cup, liquid extracted from leaves with TMD contained highly active oxidase. Despite that, the filtrate was non-infectious, indicating that the porous cup had filtered out the TMD pathogen. This incidentally yet decisively proved that the TMD pathogen was a particle that could be absorbed by micas. Allard (1916) also discovered that the pathogen remained highly infective after treatment with 45%–50% ethanol, which was part of the precipitation process.

Allard’s research attracted the attention of Benjamin M Duggar (1872–1956), a famous American plant physiologist and a pioneer of plant pathology. Duggar had designed several comparative TMV experiments (for example, grinding experiments) (Duggar and Armstrong, 1923) and, based on them, he developed the modern conception of the virus, which he used to refer to submicroscopic particles capable of self-replication in living cells. He also posited that the size of TMV was on the same scale as an erythrocyte (Walker, 1982). Eventually, the understanding of TMV as a kind of submicroscopic particle became widely accepted, although the exact nature of the virus remained unknown.

In 1935, American biochemist Wendell Meredith Stanley (1904–1971), who was working for the Rockefeller Institute for Medical Research and later received the Nobel Prize in chemistry in 1946, obtained TMV crystals with the help of the most advanced enzymatic crystallisation techniques available in America. He claimed that the virus was a kind of protein, and its relative molecular mass was a few millions (Stanley, 1935). His new conception of the virus was at odds with chemistry’s mainstream understanding of life and its basic materials, in which self-replication was a unique capacity. If, as suggested by his new conception, protein as a chemical substance was also capable of self-replication, what was the boundary between living things and non-living things? What, after all, was life?

Stanley’s research has been the target of much criticism, including that from British plant pathologists Frederick Charles Bawden and Norman Wingate Pirie. Together, they countered Stanley’s experimental conclusions with indisputable empirical facts. Experiments they conducted in 1936 demonstrated that, as well as a large amount of protein, TMV also contained a small quantity of RNA. They did not realize that this small quantity of RNA was TMV’s genetic material but, based on the anisotropy of TMV’s protein–RNA complex, they inferred that TMV was a rod-shaped particle (Bawden et al., 1936). In 1939, with assistance from Helmut Ruska (1908–1973), German biochemist Gustav Adolf Kausche (1901–1960) made the first observation of TMV under the first commercially available electron microscope and confirmed that it was a rod-shaped particle (Kruger et al., 2000). Despite that, Kausche and his contemporaries failed to accurately describe the size of TMV (Harrison and Wilson, 1999).

3. Lessons from the first discovery of a virus

It took 40 years from the filtration experiments conducted in 1898, which identified TMV as a filterable pathogen, to the determination in 1939, via electron microscopy, that TMV is a submicroscopic rod-shaped particle. During that period, countless scientists contributed to the understanding of the virus. Without this process of persistent and reflective collective learning that involved scientists from various countries and disciplines, it is virtually inconceivable that researchers would have discovered the virus – which is unobservable under the most advanced optical microscope – within such a short period.

To varying degrees, many TMV researchers have reported valid and valuable conclusions, but there
are also reports indicating shortcomings in some methodologies and conclusions. That is quite understandable, given the common wisdom that no methodology or report is infallible and no scientist’s opinion is completely indisputable. If the scientific community had raised no doubts about the methodologies and reports of TMV researchers, or, even worse, if the community had idolized those researchers as scientific gods, it is almost certain that our understanding of the virus would have been much delayed, and the development of the discipline of microbiology would have been severely hindered.

If most historical scientific advances are flawed in one way or another, and if every scientist is potentially prone to errors when interpreting their research results, then what kind of perspective should we adopt with regard to scientific knowledge and scientists? Furthermore, will contemporary scientists turn out to be highly susceptible to deviations in scientific understanding, as their historical colleagues were, even in areas that they believe they know a great deal about? If the answer proves to be yes, is it the case that we can never be too cautious when evaluating the latest scientific discoveries and the public policies informed by those discoveries?

History teaches us that irrational trust of any scientific theory and quasi-religious worship of scientific authority are no help to in-depth explorations of the unknown, the discovery of scientific truths, or even the efficient resolution of many of the practical conundrums we are currently facing. Truths abound in a world of rational questioning, whereas fallacies rule in a world of blind acceptance. I believe that only by encouraging questioning and embracing criticisms can deviations in scientific understanding be calibrated and scientific and technological innovations be boosted.

The sequence of events that culminated in the discovery of TMV demonstrates that scientific advances are most successfully progressed by way of cumulative waves. That is, many of the key scientific discoveries throughout history have not been made by god-like science-supermen in the blink of an eye; instead, they were possible only through years of persistent effort made by waves of scientists. One conceivable role for science-supermen, if they do exist, is to predict and guide the future directions of science. A handful of science-supermen or star scientists would not be sufficient to bear complete responsibility for the entire scientific enterprise, considering its magnitude and complexity. Moreover, the identification of star scientists typically requires a long process of repeated screening and time-consuming evaluation. Therefore, establishing mechanisms for dialogues between equals, communication among peers and cooperation among fellow colleagues is an urgent task that must be confronted.

Zhou (2020b) once wrote:

Only by promoting academic democracy and establishing dialogues on the basis of equality, can we, on the one hand, avoid genuine insights of scientists being overlooked, and on the other hand prevent any authority’s deviations in scientific understanding from hindering scientific development.

The meaning of a sentence is never clear if it remains unspoken, and the validity of reasoning is never made clear if it is never questioned. In consideration of this, the most effective way to question experimental or faulty opinions and theories in the scientific community is not through protecting their godlike status by suppressing criticism of them, but by arriving at more penetrating hypotheses, groundbreaking experimental results and persuasive theories about them. Blindly suppressing opposing opinions and imprudently establishing experimental theories as authoritative all too easily constrains the development of new scientific ideas and negatively affects future scientific advances, with the result that opportunities for genuine scientific discovery are severely hampered.

In order to establish long-term mechanisms of communication and cooperation within the scientific community, we first need to establish a discourse system that scientists from all over the world can understand and agree upon. We must avoid relegating communications to our own separate small circles. Instead, we should create digital and concrete communication platforms capable of facilitating real-time and efficient communications among scientists throughout the world. Looking back at the process of the discovery of TMV, it is apparent that, had scientists from Germany, Russia, the Netherlands, the United States and the United Kingdom not maintained
their scientific activities in accordance with the planetary consequences of their collective research on TMD, no network of such a gigantic scale would have been established, and hence no collective intellectual capacity of such strength would have been fostered.

4. Conclusion and discussion

The current COVID-19 pandemic marks yet another round in the battle between humanity and viruses. As with our confrontations with other novelities, such as a new technology or a new application of an existing technology, the ongoing battle against COVID-19 is replete with risk and uncertainty. Under these circumstances, no single country or scientist can guarantee a rapid, valid, in-depth and comprehensive understanding of COVID-19 in the near future. Even when such an understanding is attained, the path from that theoretical understanding to effective clinical treatment and successful vaccination remains uncertain. In view of that, it is vital for both the scientific community and the general public to accept that science is not magic; that is, science is not born into truth but progresses by way of painstaking and time-consuming effort. Nevertheless, that is no reason for pessimism about science because, as has been widely accepted already in the philosophy of science, science is by no means infallible. Put in more familiar terms, science is a process of trial and error.

In many ways, recognising experimental errors is even more scientifically valuable than the production of new scientific discoveries because, in certain circumstances, recognising a fallacy requires an innovative or sometimes even a revolutionary perspective. Historically, perspectives of this kind have predicted so-called scientific revolutions, which in turn can elevate our scientific understanding to new levels. Therefore, pessimism about science because of its built-in fallibility is unnecessary, and there is no doubt that eventually we will achieve an in-depth understanding of COVID-19.

We cannot idly sit and wait with wishful expectations because, as with most scientific (or even human) endeavours, COVID-19 research is a complex process that involves twists and turns along the way. Estimations and expectations about that research therefore have to be made alongside research practices, and they are inevitably fated to be, in most cases, relatively short-sighted. As common wisdom indicates, irrationally high expectations bring about disproportionally deep disappointment – a circumstance that has been demonstrated many times over during the current COVID-19 epidemic. Due to specific incorrect deductions scientists made during the early stages of COVID-19 research, and due also to the fact that the development of vaccines and medicine has proceeded at a much lower speed than the public has been led to expect, we are now witnessing public reproaches against scientists, especially against the positive contributions made by Chinese scientists in the current international battle against COVID-19.

Before the internet era, communications announcing the latest scientific discoveries were largely confined to the scientific community. The public in general had little inkling of the existence of many exciting scientific achievements until they had been put to practical application and become part of everyday life. However, that situation has been completely overturned in the internet era. Today, access to internet has been broadened, and 5G technology has already been applied in a multitude of commercial settings. Against this background, few scientific discoveries can remain secret. In theory, the public can easily become informed of many discoveries if they so desire, and the fact is that they do desire to be informed, especially about medical discoveries. Once people are familiar with such discoveries and believe that they have understood them, they often then share their understanding with more people – an activity that is easy and efficient thanks to the power of modern social media. With more and more laypeople either directly learning about original scientific discoveries or indirectly hearing about them from others who share their learning of those discoveries, an interesting phenomenon has emerged in which more and more laypeople become, knowingly or not, involved in scientific discourses that were previously confined within the scientific community.

The involvement of laypeople in scientific discourses has had a variety of effects, both positive and negative. Despite all of the potential good brought about by the public’s involvement in science, science remains a professional area of expertise, and laypeople...
have not undergone strict training in science in any comparable way. More importantly, as well as the ability to manage advanced scientific theories and methods, scientific training fosters the nurturing of the proverbial ‘scientific spirit’. One important component of the scientific spirit is its requirement that scientific research must invariably be based on facts, while the public tends to base its opinions on value judgements. Because of that, when a scientist’s honest and factual description does not live up to the public’s value expectations, that scientist is likely to be a target of public reproach. Or, when a scientist makes invalid scientific assertions that are themselves in opposition to the public’s value expectations, that scientist is likely to receive a considerable amount of social pressure from the public.

These are all new problems that arise with the public’s involvement in science, and they could hardly have been foreseen by scientists who were active in the initial TMV research. Notably, public involvement can benefit scientific development in many ways (e.g. through the early identification of ethical problems), but that is not to say that the public’s involvement should be unlimited or can take any particular form whatsoever. The bottom line is that any scientific dispute is and can only be about facts, and not about the values associated with those facts or about the value of the scientists who uncovered them. Without sticking to that bottom line, we expose scientists to considerable risk of internet violence and, more importantly, we invite irrationality into the rational enterprise of science. It should not be forgotten that science is power, and the most alarming way to abuse that power is to hand it over to irrationality. If public abuse of the power of science caused all scientists to focus more on public opinions about their research rather than on the research itself, then would we still have any chance to discover further truths?

As well as the concerns described above, another problem derived from the public’s involvement in science is that laypeople are prone to criticize, while they simultaneously create gods and worship them. That is especially true in relation to the internet. Understandably, once a scientist has been worshipped as a scientific god by the public, it is very hard for that scientist to maintain an objective evaluation of their own academic capacity. Once they believe that they really are a scientific god beyond question or challenge, it is very likely that they will then misguide the direction of science into a place that they wishfully and subjectively believe to be best for scientific investment.

Science is fallible, progressive and professional. In the era of social media, when all of our voices can be heard indiscriminately, Chinese scientists confront the limitations of scientific research, the cumulative nature of scientific understanding and the context-dependent nature of scientific knowledge. They should actively construct their own mechanisms for dialogue, communication, cooperation and error-correction among themselves. Only by doing so can they circumvent problems arising from the public’s involvement in science through, for example, the internet. Every Chinese scientist is responsible for the construction of the future scientific culture in the dawning era of 5G, with its ever-higher speed, larger capacity and wider range of connections.

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