Creativity and Discovery

The Work of Gregor Mendel

Gregor Mendel

In the summer of 1878, Abbot Gregor Mendel was visited in his monastery by the horticulturalist C.W. Eichling, representing a French seed company. The 22-year old Eichling was touring Central Europe, and had been urged to visit Mendel's collection of pea plants at his monastery in the town of Brno in what is now called the Czech Republic. At the age of 56, Mendel had been nearly five years removed from his scientific work with pea plants, having been so preoccupied with the daily operations of a large monastery that he could only spend rare free hours in his garden.

On Eichling's visit, Mendel showed him the grounds and his beehives, and of course his beds of pea plants. The plants, Mendel admitted, had been crafted to suit the monastery's food needs. The beds featured 25 varieties, many of them a “hybrid” – the offspring of two different types of peas – consisting of wild-grown plants mixed with the local sugar-pod types. Eichling wondered how this unassuming monk could really claim to possess custom-made plants. Mendel responded, “It is just a little trick, but there is a long story connected with it which it would take too long to tell.” The Abbott then continued the tour of his monastery, ignoring Eichling's requests for the rest of the story. When Eichling left, he asked a customer why Mendel had been so reluctant to reveal his account, and was told that Mendel was “one of the best clerics,” but “not a soul believed his experiments were anything more than the maundering of a charming putterer.” About 20 years later, this “charming putterer” would be hailed for developing two ideas that we now accept as fundamental laws of inheritance.[1]

Born Johann Mendel in 1822 in the village of Hynčice (also in what is now the Czech Republic), he lived a peasant's life for many years. In grade school he was pointed out as a gifted child, and sent off to boarding school in the German speaking town of Opava. His parents could barely afford the bill, and his occasional gifts from home came in the form of bread loaves. To pay for housing, Mendel tutored other students. Earning top grades, he gained a great deal of self-discipline throughout his youth, but such pressure burdened him with broken nerves that would haunt him for the rest of his life. Unable to secure a job as a full-time teacher after graduation, he returned home a beaten man and spent a year on his parents' farm. In 1841 he was accepted to the University of Olomouc, in a Czech speaking town. Attending University was a tough decision for Mendel – in addition to hardly speaking a word of Czech, his father had been injured and the farm was in real danger of collapsing. Mendel opted to continue his education.

At Olomouc, Mendel fervently pursued a degree that included work in mathematics, physics, philosophy and ethics. He made good relationships with his professors and again earned top marks. After his two year degree, though, his life went into a very different direction than he had expected. When Mendel had decided to leave the family farm, his sister took charge. When she married while he was away at the university, her new husband gained the farm. In the contract handing over control of the farm to Mendel's new brother-in-law, a clause stipulated that Johann would receive a handsome annual sum of money in return for entering the priesthood. Luckily for Johann, his physics professor at Olomouc had been a member of an Augustinian Monastery. With his grades and his teacher's reference, in 1843 Johann was accepted at the Augustinian Monastery in Brno without so much as meeting the elders. There he would be christened “Gregor,” and as long as he performed his clerical duties, he was free to study whatever he wished. While faithful, Mendel obviously did not take vows purely because he felt driven to serve God.

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> ***Life at the Monastery provided time for Mendel to study and, years later, to investigate the heredity of pea plants. The word “scholar” comes from the Latin word “scholee” which means “leisure time”. Today we hardly think of conducting scholarly work as “leisure”. However, historically, doing science and other forms of scholarship was associated with leisure time.***

The popular image of monastery life is painted such that monks are quiet, reserved creatures that pray the whole day and interact little with the outside world. This was not the case at Brno. Mendel's duties involved visits with the sick and poor and attending regular church services. Furthermore, the Brno monastery had an extensive collection of rocks, minerals, and plants collected by monks while on their travels. Most important, the monastery had an excellent library, stocked with books of all types, and a librarian willing to procure any needed volumes. Mendel used these resources extensively, hoping to procure a certificate to become a full-time teacher.

Mendel's teaching career, however, never took off. While praised for his classroom teaching, he couldn't pass the very tough certification exams. Taking the exams over four times, he failed for a variety of reasons, mostly because he limited his studies to what was on hand at the monastery. Another time, Mendel's nerves got him so riled up he couldn't finish his test and just walked out. By 1851, Mendel had resigned himself to being a substitute teacher in a monastery.

However, later that year the natural history teacher at Brno Technical School took ill, and Mendel stepped in. He taught over a hundred students a day and did so well that he was hired on full-time. When the Abbot of the Brno monastery later learned that Mendel hadn't passed the certification exams, he made a merciful move. The Abbot decided to send Mendel to the University of Vienna to sharpen his education.

Vienna proved incredibly important for Mendel's future. His experimental physics class was taught by Professor Christian Doppler, for whom the Doppler Effect is named. Doppler used a textbook he had written himself, which included emphasis on probability. This unanticipated encounter with ideas regarding probability likely influenced Mendel's interpretation of his later experiments with pea plants. Furthermore, as a minister, Mendel's education included a broad category of coursework including botany, zoology, and anthropology. He finished his degree in 1854, returning to the monastery and immediately commencing his work on peas.

At the time Mendel began his scientific work, discussions regarding heredity had already been very active for a century. Well known figures in science like Erasmus Darwin (Charles' grandfather), the Comte de Buffon (who developed convincing ideas regarding the earth's age) and Carl Linnaeus (who developed a classification system whose basic framework is still used today) had speculated on the subject. Erasmus Darwin, for example, put forth the idea that if a man thought about himself during sex, the offspring would be male; if he thought about his wife, then the offspring would be female.

Early investigations into heredity were done with animals. Plants were not used in hybridization experiments until the 1700s. In *Origins of Mendelism,* Olby maintains this was likely due to the difficulty natural scientists had in accepting that plants sexually reproduced. In observing the great number of pollen grains dusting the few seed chambers of a plant, J.G. Siegesbeck, Professor of Botany at St. Petersburg, was compelled to say, "What man will ever believe that God Almighty should have introduced such confusion, or rather such shameful whoredom, for the propagation of the reign of plants. Who will instruct young students in such a voluptuous system without scandal?"

Carl Linnaeus (1707-1788) not only believed it, he made the plant's sexual organs the basis for his system of plant classification. After some observation of various plants, Linnaeus concluded that any plant showing a combination of characteristics from those of two known species must be hybrids. Linnaeus proposed a "two-layer theory of heredity," in which the outer layer, containing the leaves and the rind of the stem, was inherited from the father, and the inner layer, containing the central part of the flower and the pith of the stem, was inherited from the mother. The notion that humans could artificially create new species came as a shock to eighteenth-century naturalists. Nature was supposed to be orderly and harmonious, but if humans could indeed make a new species whenever desired by simply crossbreeding existing species, chaos would follow.

When Mendel began his investigations into heredity in 1856, the publication of Charles Darwin's *Origin of Species* was still three years in the future. The transmutation (or 'evolution') of species was an old idea that was periodically discussed, but it was not prevalent in the scientific community. Linnaeus, a devout Christian, was willing to accept that God's creatures could procreate and make new species. He noted that plants also had sexes, and that when two different kinds of plants produced a new offspring (or 'hybrid'), it was good enough to be considered a new species. As such, his original list of classified species was filled with hybrid plants that today would not be considered species because those hybrids could not have viable offspring. So at the time Mendel began his work, scientists were thinking about heredity and were considering the idea that new species might result from procreation. However, precisely how characteristics were transferred from parents to offspring remained a complete mystery.

What stimulated Mendel and others to begin investigating the mechanism of heredity was prior work regarding the fertility of hybrids. Almost 100 years earlier, around 1760, Joseph Koelreuter, a German, began mating hybrids with other hybrids. He filled all the space he could spare with potted plants acquired from all corners of the globe. He even wrote Linnaeus asking him for seeds of hybrids. Koelreuter made two important observations. The first was that not all hybrids could produce offspring, and the second was that when hybrids were mated, many offspring looked like the parents, but some appeared to be a new species. How could one set of parents create identical offspring and a new species all at once?

Koelreuter provided the following interesting explanation: in nature, species remain fixed and like parents give birth to like offspring, but when humans interfere is when the 'unnatural' crosses appear.

While Koelreuter's explanation is no longer accepted, his work was important for questioning one of the major ideas regarding heredity, called “preformation.” Preformation stated that an exact miniature replica of the parent existed inside sperm cells or ovum cells. Therefore, exact blueprints were passed on in each generation, with slight changes depending on the influence of either the male sperm or female egg – not both. The idea of preformation had survived to Koelreuter's day even though the microscope had been invented almost one-hundred years earlier. Despite failure to see the miniature replicas of parents in the sex cells, the preformation idea lived on because it explained why so many species had more or less identical offspring. Taking his extensive examples, Koelreuter measured key points on his hybrid plants, and argued that his results could only occur if *both* the male and female were involved in heredity. Mendel had extensively read Koelreuter's work, and it influenced the way he thought about heredity. Franz Unger, a professor of plant physiology at Vienna, was yet another influence on Mendel's thinking. Unger rejected the idea that species were stable and, in contrast to Koelreuter, proposed that variations arise in natural populations.

So at the time Mendel graduated from the University of Vienna, his thinking regarding heredity would be influenced by the following ideas:
(1) new 'species' can appear in the form of hybrids,
(2) great difficulty existed in explaining why these hybrids gave rise to new hybrids, and
(3) whatever the mechanism of heredity, it involved both the male and the female.

After graduation in 1854, Mendel again filled a substitute teaching position in Brno, teaching over a hundred students a day. He took the teaching certification test again. His nerves broke and he stormed out of the examination room. Again he failed.

In the summer of 1856, in between clerical duties and teaching (at Brno they chose to ignore the teaching certification exam failure), Mendel began his research on pea plants of the genus *Pisum*. He favored these plants for their purity and more easily observed characteristics. Mendel's experiments followed from a speculative idea that he had already formulated. His crucial conjecture that no one had previously considered “was simply the prediction of the number of different forms that would result from the random fertilization of two kinds of 'egg cells' by two kinds of pollen grains.”[2] In other words, Mendel postulated the existence of what he called “factors” for each characteristic, and that these factors responsible for different variations of a trait would not occur together in the same sex cell. Mendel did not know what these factors were, but his idea had observable consequences as illustrated in Figure 1.

FIGURE 1

Ratio of progeny expected from the random cross of two kinds of egg cells and two kinds of pollen grains.

	T	t
T	TT	Tt
t	Tt	tt

If equal numbers of two kinds of egg cells existed (one for long stem length, the other for short stem length) were randomly fertilized by two kinds of pollen grains (one for long stem length, the other for short stem length), and if long stem length was dominant to short stem length, then the resulting ratio of progeny would be 3 long:1 short. These predictions are what Mendel set out to test.

1. Explain how Mendel's thinking shows both a gradual progression from prior ideas regarding heredity and also a break from those prior ideas.

Mendel used varieties of the genus *Pisum* that he had tested for purity of type. That is, through self-fertilization crosses, he determined that particular plants were “true-breeding” (only contained one factor) for certain characteristics. This was a crucial step, for, as Mendel wrote, “The value and utility of any experiment are determined by the fitness of the material to the purpose for which it is used…”. He then began making strategic crosses between plants. But rather than simply observing what resulted (as his predecessors had done), he *counted* the number of each kind of progeny resulting from his crosses.

The simplest illustration of Mendel's work is his crosses between short and long stem pea plants. Beginning with true-breeding long stem length plants (6-7 feet high) and true-breeding dwarf plants (3/4 to 1 ½ feet high), he crossed them together. The offspring that resulted from the crossbreeding (called the F_1 generation) all had long stems. Mendel did not know what in the sex cells caused pea plants to have long or short stems, but proposed that whatever caused the plants to have long stems somehow overpowered whatever caused pea plants to have short stems. That is, the long stem factor was *dominant* and dwarfness, which did not show up in this F_1 generation, was caused by a *recessive* factor.

The resulting tall hybrid plants were then self-fertilized, thus creating the next or F_2 generation. When the F_2 progeny matured, most were tall, but some were short. This was just what others had observed, but unlike previous explanations for this phenomenon, Mendel was interested in how the number of each compared. Upon counting the members of this F_2 progeny, Mendel interpreted the numbers as exhibiting a certain constancy, averaging three talls to one short, or a 3:1 ratio. Table 1 below contains Mendel's published numbers of tall and short F_2 progeny as well as the results of the same type of crosses with other characteristics that Mendel conducted in pea plants.

Note that the numbers do not reflect a precise 3:1 ratio. While some crosses gave results that were almost exactly that ratio, other results were further from it. Moreover, Mendel's published paper made reference to additional crosses he performed, but whose numerical results were

TABLE 1

Mendel's F_2 Experimental Results.[3]

Characteristic	F2 Progeny Results				Ratio
Seed shape	Round	5,474	Angular	1,850	2.959:1
Cotyledon color	Yellow	6,022	Green	2,001	3.010:1
Seed coat color	Colored	705	White	224	3.147:1
Pod shape	Inflated	882	Constricted	299	2.950:1
Pod color	Green	428	Yellow	152	2.816:1
Flower position	Axial	651	Terminal	207	3.145:1
Stem length	Tall	787	Short	277	2.841:1
Total	**Dominant**	**14,949**	**Recessive**	**5,010**	**2.984:1**

not reported. The results above were selected by Mendel for presentation, and were likely chosen because they best illustrate his proposed ideas regarding heredity. Varying levels of ambiguity is part of all scientific work, and those who do research must make judgments to make sense of that ambiguity. Mendel's crucial interaction with and interpretation of his data is apparent in: 1) his having to observe and judge which categories the outcomes of his crosses belonged, 2) his choice of which data to present publicly, and 3) the way he identifies and reacts to anomalous data. Moreover, one biographer of Mendel, Viteslav Orel, wrote:

> In generalizing that the segregation ratio was 3:1, Mendel…pointed out that this figure was only apparent when a large number of observations was involved. Where the number of observations was small, quite different results might be obtained; by way of example he stated that in one plant he found 43 round seeds and only two [rough] ones. The other extreme of random occurrence was a plant which yielded 20 seeds with the dominant yellow color and 19 with the recessive green color.[4]

Mendel wasn't fudging his data. Scientists must make sense of data, and this entails interpretive judgments, because data doesn't tell scientists what to think. Over time, the wider scientific community will decide to what extent an individual scientist's decisions hold up to scrutiny, and this reduces, but does not eliminate subjectivity in science.

2. How does Mendel's work illustrate that observation and data analysis is not objective (i.e. scientists "see" through the lens of their theoretical commitments)?

Mendel next allowed these F_2 plants to fertilize themselves. All progeny resulting from the self-fertilization of the F_2 recessive parents exhibited, as expect, the recessive trait. The self-fertilization of the F_2 parents exhibiting the dominant trait yielded a more complex result. Mendel proposed that two-thirds of the F_2 individuals expressing the dominant trait should be hybrids and the remaining one-third should be true-breeding, giving a ratio of 2:1. He tested this by allowing the dominant F_2 plants to self-fertilize, and then observing the expressed traits of the F_3 generation. Table 2 presents Mendel's experimental results in regards to the expected 2:1 ratio.

These results again illustrate that research findings must be interpreted. For instance, Fairbanks and Rytting write that when Mendel noted that one of his crosses yielded results he thought were not in line with the predicted ratio, "he repeated the experiment and obtained results that were more acceptable to him."[6] Data is always interpreted in light of other data, prevailing ideas, hunches, and other factors. Mendel's extensive empirical research into plant hybridization provided evidence supporting his idea that factors for particular characteristics are transmitted individually in sex cells (what we today refer to as the law of segregation). Mendel also reported that when he crossed plants that were hybrids of two or three different traits, those traits assort independently of one another (what we today refer to as the law of independent assortment). Interestingly, Mendel applied his idea of segregation *only* to hybrids. This is evident in his representing factors in hybrids with a two-letter designation (e.g. Tt), but his representing true-breeding plants with only one letter (e.g. T or t instead of TT or tt). But his work illustrated how the development of hybrids could be accounted for by the segregated transfer of factors. Of course, Mendel had no idea what these factors were, or how they were passed from parents to

TABLE 2

Ratio of hybrid to pure-breeding dominant individuals in F2 generation[5]

Characteristic	F2 Individuals				Ratio
Seed shape	Heterozygous	372	True-breeding	193	1.927:1
Cotyledon color	Heterozygous	353	True-breeding	166	2.127:1
Total for seed traits	**Heterozygous**	**725**	**True-breeding**	**359**	**2.019:1**
Seed coat color	Heterozygous	64	True-breeding	36	1.778:1
Pod shape	Heterozygous	71	True-breeding	29	2.448:1
Pod color	Heterozygous	60	True-breeding	40	1.500:1
Flower position	Heterozygous	67	True-breeding	33	2.080:1
Stem length	Heterozygous	72	True-breeding	28	2.571:1
Pod color (repeat)	Heterozygous	65	True-breeding	35	1.985:1
Total for plant traits	**Heterozygous**	**399**	**True-breeding**	**201**	**1.985:1**

offspring. But his empirical work did not support the preformationist idea that the entire organism was transferred to an offspring).

3. Many students today choose not to pursue science careers, thinking that science does not require creativity. How does Mendel's original idea, approach to testing that idea, and his analysis of data illustrate that science is a creative endeavor?

Mendel's biographer Orel asserts that the three important contributions made to science by the *Pisum* experiments were these:
1) The application of mathematics in research into heredity;
2) The elucidation of the basic mechanism of fertilization in connection with heredity; and
3) The application of probability to the production of germ cells in the fertilization process, and in the transmission of parental traits to offspring.[7]

However, Mendel's research did not immediately revolutionize thinking regarding heredity, and only a few scientists really took Mendel's research to heart.

4. Consider that Mendel's ideas involved "factors" for particular traits, and the application of mathematics and probability to biological systems. Why might scientists in Mendel's time have found each of these ideas difficult to accept?

In 1868, Gregor Mendel was appointed Abbot of the Brno Monastery. Overtaken by the daily work of maintaining a monastic order, Mendel quit his pea experiments and slowly withdrew from scientific circles. He spent the last years of his life under increased stress, taking up cigar smoking to calm his nerves. For the better part of a decade he fought a new ecclesiastical tax with would have taken 10% of the monastery's funds. On his death in 1884, the local paper wrote, "His death deprives the poor of a benefactor, and mankind at large of a man of the noblest character, one who was a warm friend, a promoter of the natural sciences, and an exemplary priest."[8]

In 1900, Mendel's work was 'rediscovered.' While it had never really been lost, his results resonated with some vocal scientists. They hailed him as being the discoverer of what they now called 'genes,' the microscopic entities thought to be responsible for transmitting information from parent to offspring. This idea angered one biologist, T.H. Morgan so much that in 1910 he set out working with fruit flies to disprove Mendel's ideas. After much research, however, Morgan changed his mind, realizing that certain characteristics in fruit flies were indeed transmitted as individual units and linked by gender. Over the next thirty years as the field of genetics developed, the name Mendel continuously appeared as its founder.

[1] Story taken from Robert Olby, *Origins of Mendelism* [2nd Ed] (Chicago: University of Chicago Press, 1985), 90; and Viteslav Orel, *Gregor Mendel: The First Geneticist*, trans. Stephen Finn (Oxford: Oxford University Press, 1996), 259.
[2] Olby, 101.
[3] Fairbanks, D.J. & Rytting, B. (2001). Mendelian Controversies: A Botanical and Historical Review. *American Journal of Botany*, 88(5), 737-752., p. 739.
[4] Orel, 102.
[5] Fairbanks, D.J. & Rytting, B., p. 739
[6] Fairbanks, D.J. & Rytting, B., p. 740.
[7] Orel, 178.
[8] Olby, 106.

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Partial support for this work was provided by the National Science Foundation's Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. 0618446. Project Principal Investigator: Michael P. Clough. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.