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Évariste Galois

Évariste Galois (/ɡæl'wɑː/;[1] French: [evaʁist galwa]; 25 October 1811 – 31 May 1832) was a French mathematician and political activist. While still in his teens, he was able to determine a necessary and sufficient condition for a polynomial to be solvable by radicals, thereby solving a problem standing for 350 years. His work laid the foundations for Galois theory and group theory,[2] two major branches of abstract algebra, and the subfield of Galois connections. He died at age 20 from wounds suffered in a duel.[3]

Contents

Life

Early life

Galois was born on 25 October 1811 to Nicolas-Gabriel Galois and Adélaïde-Marie (born Demante).[2][4] His father was a Republican and was head of Bourg-la-Reine's liberal party. His father became mayor of the village[2] after Louis XVIII returned to the throne in 1814. His

Évariste Galois

A portrait of Évariste Galois aged about 15

Born	25 October 1811 Bourg-la-Reine, French Empire
Died	31 May 1832 (aged 20) Paris, Kingdom of France
Nationality	French
Alma mater	École préparatoire (no degree)
Known for	Work on the theory of equations and Abelian integrals
Scientific career	
Fields	Mathematics

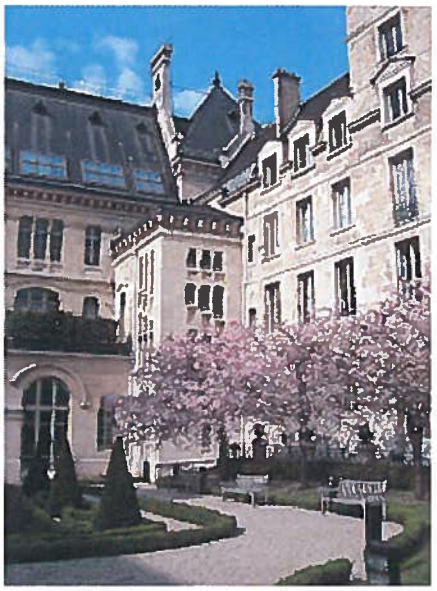
mother, the daughter of a jurist, was a fluent reader of Latin and classical literature and was responsible for her son's education for his first twelve years. At the age of 10, Galois was offered a place at the college of Reims, but his mother preferred to keep him at home.

In October 1823, he entered the Lycée Louis-le-Grand,[5] and despite some turmoil in the school at the beginning of the term (when about a hundred students were expelled), Galois managed to perform well for the first two years, obtaining the first prize in Latin. He soon became bored with his studies and, at the age of 14, he began to take a serious interest in mathematics.[5]

He found a copy of Adrien-Marie Legendre's *Éléments de Géométrie*, which, it is said, he read "like a novel" and mastered at the first reading. At 15, he was reading the original papers of Joseph-Louis Lagrange, such as the *Réflexions sur la résolution algébrique des équations* which likely motivated his later work on equation theory, and *Leçons sur le calcul des fonctions*, work intended for professional mathematicians, yet his classwork remained uninspired, and his teachers accused him of *affecting* ambition and originality in a negative way.[4]

Influences Adrien-Marie Legendre, Joseph-Louis Lagrange

Signature



The Cour d'honneur of the Lycée Louis-le-Grand, which Galois attended as a boy.

Budding mathematician

In 1828, he attempted the entrance examination for the École Polytechnique, the most prestigious institution for mathematics in France at the time, without the usual preparation in mathematics, and failed for lack of explanations on the oral examination. In that same year, he entered the École Normale (then known as l'École préparatoire), a far inferior institution for mathematical studies at that time, where he found some professors sympathetic to him.

In the following year Galois' first paper, on continued fractions,[6] was published. It was at around the same time that he began making fundamental discoveries in the theory of polynomial equations. He submitted two papers on this topic to the Academy of Sciences. Augustin-Louis Cauchy refereed these papers, but refused to accept them for publication for reasons that still remain unclear. However, in spite of many claims to the contrary, it is widely held that Cauchy recognized the importance of Galois' work, and that he merely suggested combining the two papers into one in order to enter it in the competition for the Academy's Grand Prize in Mathematics. Cauchy, an eminent mathematician of the time, though with political views that were at the opposite end from Galois', considered Galois' work to be a likely winner.[7]

On 28 July 1829, Galois' father committed suicide after a bitter political dispute with the village priest.[8] A couple of days later, Galois made his second and last attempt to enter the Polytechnique, and failed yet again.[8] It is undisputed that Galois was more than qualified; however, accounts differ on why he failed. More plausible accounts state that Galois made too many logical leaps and baffled the incompetent examiner, which enraged Galois. The recent death of

his father may have also influenced his behavior.[4]

Having been denied admission to the Polytechnique, Galois took the Baccalaureate examinations in order to enter the École Normale.[8] He passed, receiving his degree on 29 December 1829.[8] His examiner in mathematics reported, "This pupil is sometimes obscure in expressing his ideas, but he is intelligent and shows a remarkable spirit of research."

He submitted his memoir on equation theory several times, but it was never published in his lifetime due to various events. Though his first attempt was refused by Cauchy, in February 1830 following Cauchy's suggestion he submitted it to the Academy's secretary Joseph Fourier,[8] to be considered for the Grand Prix of the Academy. Unfortunately, Fourier died soon after,[8] and the memoir was lost.[8] The prize would be awarded that year to Niels Henrik Abel posthumously and also to Carl Gustav Jacob Jacobi. Despite the lost memoir, Galois published three papers that year, one of which laid the foundations for Galois theory.[9] The second one was about the numerical resolution of equations (root finding in modern terminology).[10] The third was an important one in number theory, in which the concept of a finite field was first articulated.[11]

Augustin-Louis Cauchy reviewed Galois' early mathematical papers.

Political firebrand

Galois lived during a time of political turmoil in France. Charles X had succeeded Louis XVIII in 1824, but in 1827 his party suffered a major electoral setback and by 1830 the opposition liberal party became the majority. Charles, faced with abdication, staged a coup d'état, and issued his notorious July Ordinances, touching off the July Revolution[8] which ended with Louis-Philippe becoming king. While their counterparts at the Polytechnique were making history in the streets during *les Trois Glorieuses*, Galois and all the other students at the École Normale were locked in by the school's director. Galois was incensed and wrote a blistering letter criticizing the director, which he submitted to the *Gazette des Écoles*, signing the letter with his full name. Although the *Gazette*'s editor omitted the signature for publication, Galois was expelled.[12]

Battle for the Town Hall by Jean-Victor Schnetz. Galois, as a staunch republican, would have wanted to participate in the July Revolution of 1830 but was prevented by the director of the École Normale.

Although his expulsion would have formally taken effect on 4 January 1831, Galois quit school immediately and joined the staunchly Republican artillery unit of the National Guard. He divided his time between his mathematical work and his political affiliations. Due to controversy surrounding the unit, soon after Galois became a member, on 31 December 1830, the artillery of the National Guard was disbanded out of fear that they might destabilize the

government. At around the same time, nineteen officers of Galois' former unit were arrested and charged with conspiracy to overthrow the government.

In April 1831, the officers were acquitted of all charges, and on 9 May 1831, a banquet was held in their honor, with many illustrious people present, such as Alexandre Dumas. The proceedings grew riotous, and Galois proposed a toast to King Louis Philippe with a dagger above his cup, which was interpreted as a threat against the king's life. He was arrested the following day but was acquitted on 15 June 1831.[8][12][13]

On the following Bastille Day (14 July 1831), Galois was at the head of a protest, wearing the uniform of the disbanded artillery, and came heavily armed with several pistols, a rifle, and a dagger. He was again arrested.[8] On 23 October, he was sentenced to six months in prison for illegally wearing a uniform.[8][14][15] He was released on 29 April 1832. During his imprisonment, he continued developing his mathematical ideas.

Final days

Galois returned to mathematics after his expulsion from the École Normale, although he continued to spend time in political activities. After his expulsion became official in January 1831, he attempted to start a private class in advanced algebra which attracted some interest, but this waned, as it seemed that his political activism had priority.[4][7] Siméon Poisson asked him to submit his work on the theory of equations, which he did on 17 January 1831. Around 4 July 1831, Poisson declared Galois' work "incomprehensible", declaring that "[Galois'] argument is neither sufficiently clear nor sufficiently developed to allow us to judge its rigor"; however, the rejection report ends on an encouraging note: "We would then suggest that the author should publish the whole of his work in order to form a definitive opinion."[16] While Poisson's report was made before Galois' July 14 arrest, it took until October to reach Galois in prison. It is unsurprising, in the light of his character and situation at the time, that Galois reacted violently to the rejection letter, and decided to abandon publishing his papers through the Academy and instead publish them privately through his friend Auguste Chevalier. Apparently, however, Galois did not ignore Poisson's advice, as he began collecting all his mathematical manuscripts while still in prison, and continued polishing his ideas until his release on 29 April 1832,[12] after which he was somehow talked into a duel.[8]

Siméon Poisson reviewed Galois' paper on equation theory and declared it "incomprehensible".

Galois' fatal duel took place on 30 May.[17] The true motives behind the duel are obscure. There has been much speculation as to the reasons behind it. What is known is that five days before his death, he wrote a letter to Chevalier which clearly alludes to a broken love affair.[7]

Some archival investigation on the original letters suggests that the woman of romantic interest was a Mademoiselle Stéphanie-Félicie Poterin du Motel,[18] the daughter of the physician at the hostel where Galois stayed during the last months of his life. Fragments of letters from her, copied by Galois himself (with many portions, such as her name, either

obliterated or deliberately omitted), are available.[19] The letters hint that Mlle. du Motel had confided some of her troubles to Galois, and this might have prompted him to provoke the duel himself on her behalf. This conjecture is also supported by other letters Galois later wrote to his friends the night before he died. Galois' cousin, Gabriel Demante, when asked if he knew the cause of the duel, mentioned that Galois "found himself in the presence of a supposed uncle and a supposed fiancé, each of whom provoked the duel." Galois himself famously exclaimed: "I am the victim of an infamous coquette and her two dupes."[12]

Much more detailed speculation based on these scant historical details has been interpolated by many of Galois' biographers (most notably by Eric Temple Bell in *Men of Mathematics*), such as the frequently repeated speculation that the entire incident was stage-managed by the police and royalist factions to eliminate a political enemy.[14]

As to his opponent in the duel, Alexandre Dumas names Pescheux d'Herbinville,[13] who was actually one of the nineteen artillery officers whose acquittal was celebrated at the banquet that occasioned Galois' first arrest.[20] However, Dumas is alone in this assertion, and if he were correct it is unclear why d'Herbinville would have been involved. It has been speculated that he might have been du Motel's "supposed fiancé" at the time (she ultimately married someone else), but no clear evidence has been found supporting this conjecture. On the other hand, extant newspaper clippings from only a few days after the duel give a description of his opponent (identified by the initials "L.D.") that appear to more accurately apply to one of Galois' Republican friends, most probably Ernest Duchatelet, who was imprisoned with Galois on the same charges.[21] Given the conflicting information available, the true identity of his killer may well be lost to history.

Whatever the reasons behind the duel, Galois was so convinced of his impending death that he stayed up all night writing letters to his Republican friends and composing what would become his mathematical testament, the famous letter to Auguste Chevalier outlining his ideas, and three attached manuscripts.[22] Mathematician Hermann Weyl said of this testament, "This letter, if judged by the novelty and profundity of ideas it contains, is perhaps the most substantial piece of writing in the whole literature of mankind." However, the legend of Galois pouring his mathematical thoughts onto paper the night before he died seems to have been exaggerated.[7] In these final papers, he outlined the rough edges of some work he had been doing in analysis and annotated a copy of the manuscript submitted to the Academy and other papers.

Early in the morning of 30 May 1832, he was shot in the abdomen,[17] abandoned by his opponents and seconds, and was found by a passing farmer. He died the following morning[17] at ten o'clock in the Hôpital Cochin (probably of peritonitis), after refusing the offices of a priest. His funeral ended in riots.[17] There were plans to initiate an uprising during his funeral, but during the same time frame the leaders heard of General Jean Maximilien Lamarque's death, and the rising was postponed without any uprising occurring until 5 June. Only Galois' younger brother was notified of the events prior to Galois' death.[23] He was 20 years old. His last words to his younger brother Alfred were:

> "Ne pleure pas, Alfred ! J'ai besoin de tout mon courage pour mourir à vingt ans !"
> (*Don't cry, Alfred! I need all my courage to die at twenty!*)

On 2 June, Évariste Galois was buried in a common grave of the Montparnasse Cemetery whose exact location is unknown.[17][15] In the cemetery of his native town – Bourg-la-Reine – a cenotaph in his honour was erected beside

The Galois memorial in the cemetery of Bourg-la-Reine. Évariste Galois was buried in a common grave and the exact location is still unknown.

the graves of his relatives.[24]

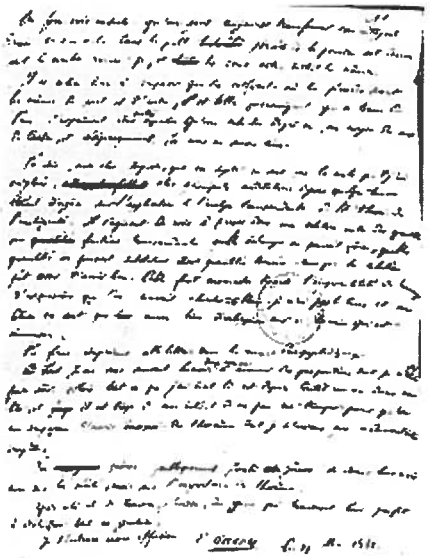
In 1843 Liouville reviewed his manuscript and declared it sound. It was finally published in the October–November 1846 issue of the *Journal de Mathématiques Pures et Appliquées*.[25][26] The most famous contribution of this manuscript was a novel proof that there is no quintic formula – that is, that fifth and higher degree equations are not generally solvable by radicals. Although Abel had already proved the impossibility of a "quintic formula" by radicals in 1824 and Ruffini had published a solution in 1799 that turned out to be flawed, Galois' methods led to deeper research in what is now called Galois theory. For example, one can use it to determine, for *any* polynomial equation, whether it has a solution by radicals.

Contributions to mathematics

From the closing lines of a letter from Galois to his friend Auguste Chevalier, dated May 29, 1832, two days before Galois' death:[22]

> *Tu prieras publiquement Jacobi ou Gauss de donner leur avis, non sur la vérité, mais sur l'importance des théorèmes.*
>
> *Après cela, il y aura, j'espère, des gens qui trouveront leur profit à déchiffrer tout ce gâchis.*
>
> (Ask Jacobi or Gauss publicly to give their opinion, not as to the truth, but as to the importance of these theorems. Later there will be, I hope, some people who will find it to their advantage to decipher all this mess.)

Within the 60 or so pages of Galois' collected works are many important ideas that have had far-reaching consequences for nearly all branches of mathematics.[27][28] His work has been compared to that of Niels Henrik Abel, another mathematician who died at a very young age, and much of their work had significant overlap.



The final page of Galois' mathematical testament, in his own hand. The phrase "to decipher all this mess" ("déchiffrer tout ce gâchis") is on the second to the last line.

Algebra

While many mathematicians before Galois gave consideration to what are now known as groups, it was Galois who was the first to use the word *group* (in French *groupe*) in a sense close to the technical sense that is understood today, making him among the founders of the branch of algebra known as group theory. He developed the concept that is today known as a normal subgroup. He called the decomposition of a group into its left and right cosets a *proper*

decomposition if the left and right cosets coincide, which is what today is known as a normal subgroup.[22] He also introduced the concept of a finite field (also known as a Galois field in his honor), in essentially the same form as it is understood today.[11]

In his last letter to Chevalier[22] and attached manuscripts, the second of three, he made basic studies of linear groups over finite fields:

- He constructed the general linear group over a prime field, GL(ν, p) and computed its order, in studying the Galois group of the general equation of degree p^ν.[29]
- He constructed the projective special linear group PSL(2,p). Galois constructed them as fractional linear transforms, and observed that they were simple except if p was 2 or 3.[30] These were the second family of finite simple groups, after the alternating groups.[31]
- He noted the exceptional fact that PSL(2,p) is simple and acts on p points if and only if p is 5, 7, or 11.[32][33]

Galois theory

Galois' most significant contribution to mathematics is his development of Galois theory. He realized that the algebraic solution to a polynomial equation is related to the structure of a group of permutations associated with the roots of the polynomial, the Galois group of the polynomial. He found that an equation could be solved in radicals if one can find a series of subgroups of its Galois group, each one normal in its successor with abelian quotient, or its Galois group is solvable. This proved to be a fertile approach, which later mathematicians adapted to many other fields of mathematics besides the theory of equations to which Galois originally applied it.[27]

Analysis

Galois also made some contributions to the theory of Abelian integrals and continued fractions.

As written in his last letter,[22] Galois passed from the study of elliptic functions to consideration of the integrals of the most general algebraic differentials, today called Abelian integrals. He classified these integrals into three categories.

Continued fractions

In his first paper in 1828,[6] Galois proved that the regular continued fraction which represents a quadratic surd ζ is purely periodic if and only if ζ is a reduced surd, that is, $\zeta > 1$ and its conjugate η satisfies $-1 < \eta < 0$.

In fact, Galois showed more than this. He also proved that if ζ is a reduced quadratic surd and η is its conjugate, then the continued fractions for ζ and for $(-1/\eta)$ are both purely periodic, and the repeating block in one of those continued fractions is the mirror image of the repeating block in the other. In symbols we have

$$\zeta = [\overline{a_0; a_1, a_2, \ldots, a_{m-1}}]$$
$$\frac{-1}{\eta} = [\overline{a_{m-1}; a_{m-2}, a_{m-3}, \ldots, a_0}]$$

where ζ is any reduced quadratic surd, and η is its conjugate.

From these two theorems of Galois a result already known to Lagrange can be deduced. If $r > 1$ is a rational number that is not a perfect square, then

$$\sqrt{r} = \left[a_0; \overline{a_1, a_2, \ldots, a_2, a_1, 2a_0} \right].$$

In particular, if n is any non-square positive integer, the regular continued fraction expansion of $\sqrt{n}$ contains a repeating block of length m, in which the first $m - 1$ partial denominators form a palindromic string.

See also

- Group theory
- List of things named after Évariste Galois
- Niels Henrik Abel

Notes

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External links

- Works by Évariste Galois (https://www.gutenberg.org/author/Galois,+Évariste) at Project Gutenberg
- Works by or about Évariste Galois (https://archive.org/search.php?query=%28%28subject%3A%22Galois%2C%20Évariste%22%20OR%20subject%3A%22Évariste%20Galois%22%20OR%20creator%3A%22Galois%2C%20Évariste%22%20OR%20creator%3A%22Évariste%20Galois%22%20OR%20creator%3A%22Galois%2C%20É%2E%22%20OR%20title%3A%22Évariste%20Galois%22%20OR%20description%3A%22Galois%2C%20Évariste%22%20OR%20description%3A%22Évariste%20Galois%22%29%20OR%20%28%221811-1832%22%20AND%20Galois%29%29%20AND%20%28-mediatype:software%29) at Internet Archive
- O'Connor, John J.; Robertson, Edmund F., "Évariste Galois" (http://www-history.mcs.st-andrews.ac.uk/Biographies/Galois.html), *MacTutor History of Mathematics archive*, University of St Andrews.
- The Galois Archive (http://www.galois-group.net/) (biography, letters and texts in various languages)
- Two Galois articles, online and analyzed on *BibNum* : "Mémoire sur les conditions de résolubilité des équations par radicaux" (1830) (link (https://www.bibnum.education.fr/mathematiques/algebre/memoire-sur-les-conditions-de-resolubilite-des-equations-par-radicaux))[for English analysis, click 'A télécharger']; "Démonstration d'un théorème sur les fractions continues périodiques" (1829) (link (https://www.bibnum.education.fr/mathematiques/algebre/demonstration-d-un-theoreme-sur-les-fractions-continues-periodiques)) [for English analysis, click 'A télécharger']
- Genius and Biographers: The Fictionalization of Evariste Galois (https://www.jstor.org/stable/2320923) by Tony Rothman doi:10.2307/2320923 (https://doi.org/10.2307%2F2320923) Pdf (https://sites.tufts.edu/histmath/files/2015/11/rothman.pdf)
- La vie d'Évariste Galois by Paul Dupuy (http://www.galois-group.net/dupuy/index.php) The first and still one of the most extensive biographies, referred to by every other serious biographer of Galois
- Œuvres Mathématiques (https://www.irphe.fr/~clanet/otherpaperfile/articles/Galois/N0029062_PDF_1_84.pdf) published in 1846 in the *Journal de Liouville*, converted to Djvu format by Prof. Antoine Chambert-Loir at the University of Rennes.
- Alexandre Dumas, Mes Mémoires (http://www.dumaspere.com/pages/bibliotheque/chapitre.php?lid=m3&cid=204), the relevant chapter of Alexandre Dumas' memoires where he mentions Galois and the banquet.
- Évariste Galois (https://www.genealogy.math.ndsu.nodak.edu/id.php?id=55176) at the Mathematics Genealogy Project
- Theatrical trailer of University College Utrecht's "Évariste – En Garde" (http://www.phys.uu.nl/~witte/EvaristeTheatricalTrailer3.wmv)

- A piece of music dedicated to Evariste Galois (https://www.youtube.com/watch?v=J7X4W7kKW8g) on YouTube

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