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We now look at a particularly important example of a Galois extension of $\mathbf{Q}$, namely a *cyclotomic extension* $C_n = \mathbf{Q}(e^{2\pi i/n})$ for some n. This is the splitting field of the polynomial $x^n - 1$ over $\mathbf{Q}$, since the roots of $x^n - 1$ are clearly the powers of $\alpha_n = e^{2\pi i/n}$. We begin by recalling that $x^n - 1$ is the product of the *cyclotomic polynomials* $\Phi_d(x)$ as d runs over the positive divisors of n, where $\Phi_d(x)$ the unique monic polynomial whose roots are exactly the primitive dth roots of 1 in $\mathbf{C}$. It follows easily by (strong) induction on n that $\Phi_n(x)$ is a monic polynomial with integer coefficients; its degree is $\phi(n)$, the number of positive integers less than n and relatively prime to it, or equivalently the order of the multiplicative group $\mathbf{Z}_n^*$ of units in $\mathbf{Z}_n$. The main result is that $\Phi_n(x)$ *is irreducible in* $\mathbf{Z}[x]$ *for any* n. To prove this suppose for a contradiction that $\Phi_n(x)$ factors as $f(x)g(x)$ where $f(x), g(x)$ are monic with integer coefficients, $g(x) \neq 1$, and $f(x)$ is irreducible. Then every one of the $\phi(n)$ primitive nth roots of 1 in $\mathbf{C}$ is a root of $f(x)$ or $g(x)$ but not both, whence there is a prime number p no dividing n and a primitive nth root α of 1 such that α is a root of $f(x)$ while α^p is a root of $g(x)$. By irreducibility $f(x)$ must then divide $g(x^p)$ in $\mathbf{Z}[x]$, since both of these polynomials have α as a root; denoting by $\bar{f}(x), \bar{g}(x)$ the respective reductions of $f(x), g(x)$ modulo p, we get that $\bar{f}(x)$ divides $\bar{g}(x^p) = (\bar{g}(x))^p$ in $\mathbf{Z}_p[x]$. But then $x^n - 1$ would have to have a repeated root in its splitting field over $\mathbf{Z}_p$ (since both $\bar{f}(x), \bar{g}(x)$ divide $x^n - 1$ in $\mathbf{Z}_p[x]$); this is a contradiction, since the derivative nx^{n-1} of $x^n - 1$ clearly has no roots in common with $x^n - 1$ over any field. Now we know that all the powers $e^{2\pi im/n}$ of $e^{2\pi i/n}$ are roots of the same irreducible polynomial $\Phi_n(x)$ over $\mathbf{Z}$ or $\mathbf{Q}$, as m runs over the elements of $\mathbf{Z}_n^*$; it follows for any such m that there is a unique automorphism of C_n sending α_n to α_n^m, so that the Galois group of C_n over $\mathbf{Q}$ is exactly $U_n = \mathbf{Z}_n^*$; in particular, it is abelian (and cyclic if n is prime, or a power of an odd prime). More generally, the splitting field of $x^n - 1$ over any field of characteristic not dividing n is a subgroup (possibly proper) of U_n and so is abelian.

It follows for any n that any field K between $\mathbf{Q}$ and C_n that is Galois over $\mathbf{Q}$ has an abelian Galois group (being a quotient of U_n). It is a remarkable fact that the converse holds: *any finite abelian extension of* $\mathbf{Q}$, *that is any finite Galois extension of* $\mathbf{Q}$ *with abelian Galois group, lies in* C_n *for some* n. This result, called the Kronecker-Weber Theorem, at first sight seems flatly impossible: if for example p is a prime number, how can the quadratic extension $\mathbf{Q}(\sqrt{p})$ of $\mathbf{Q}$, with Galois group $\mathbf{Z}_2$, lie in any C_n? In fact, a fairly simple direct calculation shows that it lies in C_{4p}; extending this, it is not difficult to show directly that any quadratic extension of $\mathbf{Q}$ indeed lies in a cyclotomic extension. Now suppose that p is an odd prime number of the form $2^m + 1$ for some m; it then turns out that m must itself be a power of 2, and in fact the there are only five known examples, corresponding to the values $m = 1, 2, 4, 8, 16$. Then the cyclotomic extension C_p has degree $\phi(p) = p - 1 = 2^m$ over $\mathbf{Q}$ and its Galois group is cyclic of this order. There is an obvious descending chain of subgroups starting from U_p and ending at 1, each having index 2 in its predecessor; applying the Galois correspondence we get an inreasing chain of fields starting at $\mathbf{Q}$ and ending at

C_p with each a quadratic extension of its predecessor. The quadratic formula then guarantees that each field can be obtained from its predecessor by adjoining a single square root. But now there is a simple geometric construction which starts from a line segment of a specified length a and constructs one of length $\sqrt{a}$ using only straightedge and compass; in a similar manner, starting with a given point $a+bi$ in the complex plane (together with the origin $0 = 0+0i$) and using only straightedge and compass, one can construct a second point $c+di$ with $(c+di)^2 = a+bi$. The upshot is that *the complex number $e^{2\pi i/p}$, or equivalently a regular p-gon inscribed in a unit circle, can be constructed using only compass and straightedge for any such p.* It was Gauss's discovery of this fact (for $p = 17$) that convinced him to go into mathematics as a profession. More recently a rather anal-retentive German professor by the name of Hermes wrote a manuscript for how this could be done explicitly for $p = 65537$, the largest known prime of the form $2^m + 1$. This took ten years to produce and the manuscript is carefully preserved under glass in Göttingen today.

More generally (and more interestingly) one could ask for which n is there a formula for the roots of any polynomial over $\mathbf{Q}$ of degree n using only rational numbers, mth roots (for any m, not just $m \leq n$), and field operations. We will see that such a formula exists for $n = 3$ or 4, but not any higher n; the proof will use the simplicity of the alternating group A_n for any $n \geq 5$.