RECOGNIZING GALOIS GROUPS S_n AND A_n

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> If you now give me an equation that you have chosen at will, and you wish to know whether or not it is solvable by radicals, I will have nothing to do other than to indicate to you the way to respond to your question, without wishing to charge either myself or anyone else with doing it. In a word, the calculations are impractical. [...] But most of the time in applications [...] one is led to equations all of whose properties one knows beforehand: properties by means of which it will always be easy to answer the question by the rules which we shall expound. E. Galois [2, pp. 227, 229].

1. Introduction

If $f(X) \in K[X]$ is a separable irreducible polynomial of degree n and G_f is its Galois group over K (the Galois group of the splitting field of $f(X)$ over K), then the group G_f can be embedded into S_n by writing the roots of $f(X)$ as $r_1, \ldots, r_n$ and identifying each automorphism in the Galois group with the permutation it makes on the r_i's.

Whether thinking about G_f as a subgroup of S_n in this way really helps us compute G_f depends on how well we can conjure up elements of G_f as permutations of the roots.

For instance, when $K = \mathbf{Q}$ there is a fantastic theorem of Dedekind that tells us about the Galois group as a permutation group if we factor $f(X)$ mod p for different prime numbers p. If

$$f(X) \equiv \pi_1(X) \cdots \pi_m(X) \bmod p$$

where the $\pi_i(X)$'s are distinct monic irreducibles mod p, with $d_i = \deg \pi_i$, then Dedekind's theorem says there is an element in the Galois group of $f(X)$ over $\mathbf{Q}$ that permutes the roots with cycle type $(d_1, \ldots, d_m)$.

Example 1.1. Let $f(X) = X^6 + X^4 + X + 3$. Here are the factorizations of $f(X)$ modulo the first few primes:

$$\begin{aligned}
f(X) &\equiv (X+1)(X^2+X+1)(X^3+X+1) \bmod 2, \\
f(X) &\equiv X(X+2)(X^4+X^3+2X^2+2X+2) \bmod 3, \\
f(X) &\equiv (X+3)^2(X^4+4X^3+3X^2+X+2) \bmod 5, \\
f(X) &\equiv (X^2+5X+2)(X^4+2X^3+3X^2+2X+5) \bmod 7, \\
f(X) &\equiv (X+6)(X^5+5X^4+4X^3+9X^2+X+6) \bmod 11, \\
f(X) &\equiv (X^2+8X+1)(X^2+9X+10)(X^2+9X+12) \bmod 13.
\end{aligned}$$

From the factorizations modulo 2 and 3, Dedekind's theorem says G_f, as a subgroup of S_6, contains permutations of cycle type $(1, 2, 3)$ and $(1, 1, 4)$ (namely a 4-cycle). The factorization mod 5 does not tell us anything by Dedekind's theorem, because there is a multiple factor. From the later primes, we see G_f contains permutations of the roots with cycle types $(2, 4)$, $(1, 5)$ (a 5-cycle), and $(2, 2, 2)$.

Actually, before using Dedekind's theorem we have to know $f(X)$ is irreducible over $\mathbf{Q}$. That irreducibility can be read off from the factorizations above, since a factorization over $\mathbf{Q}$ can be scaled to a (monic) factorization over $\mathbf{Z}$. If $f(X)$ were reducible over $\mathbf{Q}$ then it would have a factor in $\mathbf{Z}[X]$ of degree 1, 2, or 3. From $p = 7$ (or 13) we see there is no linear factor. From $p = 11$ there is no quadratic factor. From $p = 3$ (or 5 or 7 or 11 or 13) there is no cubic factor.

It is important to remember that Dedekind's theorem does not correlate information about the permutations coming from different primes. For instance, permutations in G_f associated to the factorizations mod 2 and 11 each fix a root, but we can't be sure if these are the same root.

Example 1.2. Let $f(X) = X^6 + 15X^2 + 18X - 20$. Here are its irreducible factorizations modulo small primes:

$$\begin{aligned}
f(X) &\equiv X^2(X+1)^4 \bmod 2,\\
f(X) &\equiv (X^2+1)^3 \bmod 3,\\
f(X) &\equiv X(X+3)^5 \bmod 5,\\
f(X) &\equiv (X+5)(X+6)(X^2+5X+5)^2 \bmod 7,\\
f(X) &\equiv (X+1)(X^5+10X^4+X^3+10X^2+5X+2) \bmod 11,\\
f(X) &\equiv (X^3+2X^2+4X+10)(X^3+11X^2+11) \bmod 13.
\end{aligned}$$

It is left to the reader to explain from these why $f(X)$ is irreducible over $\mathbf{Q}$. We can't determine anything about G_f from the factorizations at the primes $p \le 7$ since there $f(X)$ mod p has repeated factors. From $p = 11$ and $p = 13$, we see G_f contains permutations of the roots of $f(X)$ with cycle types $(1, 5)$ (a 5-cycle) and $(3, 3)$.

Once we know some cycle types of permutations in G_f, as a subgroup of S_n, we can often prove G_f has to be S_n or A_n because G_f is a transitive subgroup of S_n (each root of $f(X)$ can be carried to every other root by G_f, which is what being transitive means) and there are several theorems in group theory saying a transitive subgroup of S_n containing certain cycle types has to be A_n or S_n.

2. Statement of Theorems and Some Applications

Here are theorems giving conditions under which a transitive subgroup of S_n is A_n or S_n.

Theorem 2.1. *For $n \ge 2$, a transitive subgroup of S_n that contains a transposition and a p-cycle for some prime $p > n/2$ is S_n.*

Theorem 2.2. *For $n \ge 3$, a transitive subgroup of S_n that contains a 3-cycle and a p-cycle for some prime $p > n/2$ is A_n or S_n.*

By Bertrand's postulate (proved by Chebyshev), for $n \ge 2$ there is a prime p such that $n/2 < p \le n$, so every S_n for $n \ge 2$ contain a p-cycle for some prime $p > n/2$. Since a cycle of odd length is even, every A_n for $n \ge 3$ contains a p-cycle for some prime $p > n/2$. So the hypotheses of Theorem 2.1 and 2.2 are satisfied by S_n for $n \ge 2$ and A_n for $n \ge 3$: they are transitive subgroups of themselves and have a p-cycle for some prime $p > n/2$.

We will illustrate these theorems with examples in $\mathbf{Q}[X]$. Whether or not the discriminant of an irreducible polynomial in $\mathbf{Q}[X]$ is a square tells us when its Galois group is in A_n or not. So if we want to check whether the Galois group is big (A_n or S_n), first determine if the discriminant is a square, which tells us which group (A_n or S_n) to aim for. Theorems 2.1 and 2.2 are directly applicable to Galois groups over $\mathbf{Q}$ using Dedekind's theorem.

Example 2.3. Let $f(X) = X^6 + X^4 + X + 3$, as in Example 1.1. Its discriminant is $-13353595 < 0$, which is not a square and we'll show the Galois group over $\mathbf{Q}$ is S_6. We saw in Example 1.1 that the Galois group contains permutations of the roots with cycle types (1,2,3), (1,1,4), (2,4), (1,5), and (2,2,2). In particular, there is a 5-cycle in the Galois group. By Theorem 2.1 (with $n = 6$ and $p = 5$), $G_f = S_6$ provided we show G_f contains a transposition. None of the cycle types we found is a transposition, but the third power of a permutation with cycle type $(1, 2, 3)$ is a transposition (why?). Therefore G_f contains a transposition.

The cycle types we used, $(1, 2, 3)$ and $(1, 5)$, came from the factorizations of $f(X) \bmod 2$ and $f(X) \bmod 11$. In principle the "right" way to show G_f contains a transposition is not by the trick of cubing a permutation of type $(1, 2, 3)$, but by finding a prime p at which $f(X) \bmod p$ has distinct irreducible factors of degree 2, 1, 1, 1, and 1. You'll have to wait a while for that. Such a factorization occurs for the first time when $p = 311$:

$$f(X) \equiv (X + 7)(X + 118)(X + 203)(X + 244)(X^2 + 50X + 142) \bmod 311.$$

Example 2.4. Let $f(X) = X^7 - X - 1$. The first few factorizations of $f(X) \bmod p$ are as follows:

$$\begin{aligned} f(X) &\equiv X^7 + X + 1 \bmod 2, \\ f(X) &\equiv (X^2 + X + 2)(X^5 + 2X^4 + 2X^3 + 2X + 1) \bmod 3, \\ f(X) &\equiv (X + 3)(X^6 + 2X^5 + 4X^4 + 3X^3 + X^2 + 2) \bmod 5. \end{aligned}$$

Since $f(X) \bmod 2$ is irreducible, $f(X)$ is irreducible over $\mathbf{Q}$. Its discriminant is $-776887 < 0$, so we'll try to show $G_f = S_7$. The mod 2 factorization says G_f contains a 7-cycle on the roots. The factorization mod 3 gives us a permutation in G_f of cycle type $(2, 5)$, whose 5th power is a transposition, so $G_f = S_7$ by Theorem 2.1. (The first prime p such that $f(X) \bmod p$ has a factorization of "transposition type" $(1, 1, 1, 1, 1, 2)$ is 191, so it's faster to use the power method on the (2,5)-permutation to show G_f contains a transposition.)

Example 2.5. Let $f(X) = X^7 - 7X + 10$. Here are factorizations mod 2 and 3:

$$\begin{aligned} f(X) &\equiv X(X + 1)^2(X^2 + X + 1)^2 \bmod 2, \\ f(X) &\equiv (X^2 + 2X + 2)(X^5 + X^4 + 2X^3 + 2X + 2) \bmod 3. \end{aligned}$$

We can't say anything from the mod 2 factorization since there's a multiple factor. The mod 3 factorization gives us a permutation in G_f of cycle type $(2, 5)$, whose square is a 5-cycle and whose fifth power is a transposition. Since $5 > 7/2$, this means $G_f = S_7$ by Theorem 2.1, right?

Wrong: we forgot to check $f(X)$ is irreducible in $\mathbf{Q}[X]$, and in fact it isn't:

$$f(X) = (X^2 - X + 2)(X^5 + X^4 - X^3 - 3X^2 - X + 5).$$

So our arguments about G_f were bogus. You must always check first that your polynomial is irreducible.

Example 2.6. Let $f(X) = X^6 + 15X^2 + 18X - 20$. From Example 1.2, we know $f(X)$ is irreducible over $\mathbf{Q}$ and its factorization mod 11 gives us a 5-cycle in the Galois group over $\mathbf{Q}$. Since $\operatorname{disc} f = 2893401000000 = 1701000^2$, $G_f \subset A_6$. To prove $G_f = A_6$ using Theorem

2.2, we just need to find a 3-cycle. The factorization mod 13 in Example 1.2 gives us an element of order 3, but not a 3-cycle. We get a 3-cycle in G_f from factoring $f(X)$ mod 17:

$$f(X) \equiv (X+2)(X+9)(X+10)(X^3+13X^2+7X+15) \bmod 17.$$

Example 2.7. Let $f(X) = X^7 - 56X + 48$. It's irreducible mod 5, so $f(X)$ is irreducible over $\mathbf{Q}$ and G_f contains a 7-cycle on the roots. The discriminant is 265531392^2, so $G_f \subset A_7$. Theorem 2.2 tells us $G_f = A_7$ once we know there is a 3-cycle in G_f. The factorization

$$f(X) \equiv (X^2+9X+5)(X^2+17X+17)(X^3+20X^2+18X+3) \bmod 23$$

gives us a permutation in the Galois group of cycle type $(2, 2, 3)$, whose square is a 3-cycle.

3. Proofs of Theorems

Proof. (of Theorem 2.1) This argument is adapted from [1]. Let G be a transitive subgroup of S_n containing a transposition and a p-cycle for some prime $p > n/2$. For a and b in $\{1, 2 \ldots, n\}$, write $a \sim b$ if $(ab) \in G$ (that is, either $a = b$ so (ab) is the identity permutation, or $a \neq b$ and there is a 2-cycle in G exchanging a and b). Let's check $\sim$ is an equivalence relation on $\{1, 2, \ldots, n\}$.

Reflexive: Clearly $a \sim a$ for all a.

Symmetric: This is clear.

Transitive: Suppose $a \sim b$ and $b \sim c$. We want to show $a \sim c$. We may assume a, b, and c are distinct (otherwise the task is trivial). Then (ab) and (bc) are transpositions in G, so $(ab)(bc)(ab) = (ac)$ is in G.

Our goal is to show there is only one equivalence class: if all elements of $\{1, 2, \ldots, n\}$ are equivalent to each other than every transposition (ab) lies in G, so $G = S_n$.

The group G preserves the equivalence relation: if $a \sim b$ then $ga \sim gb$ for all g in G. (For $g \in G$ and $1 \leq i \leq n$, we write gi for $g(i)$.) This is clear if $a = b$. If $a \neq b$ then (ab) is a transposition in G and its conjugate $g(ab)g^{-1}$ is also in G. It's a general fact that the conjugate of a cyclic permutation is a cycle of the same length. More precisely, for every cyclic permutation $(a_1\ a_2\ \ldots\ a_k)$ in S_n and π in S_n,

$$\pi(a_1\ a_2\ \ldots\ a_k)\pi^{-1} = (\pi a_1\ \pi a_2\ \ldots\ \pi a_k).$$

Therefore $g(ab)g^{-1} = (ga\ gb)$, so the transposition $(ga\ gb)$ is also in G.

Break up G into equivalence relations for $\sim$. Let $[a]$ be the equivalence class of a. The group G acts on equivalence classes by $g[a] = [ga]$; we already showed this is well-defined. Since G acts transitively on $\{1, 2, \ldots, n\}$, it acts transitively on the equivalence classes: for all a and b, there is some $g \in G$ such that $ga = b$, so $g[a] = [b]$. Moreover, the action of g provides a function $[a] \to [b]$ given by $x \mapsto gx$ (if $x \sim a$ then $gx \sim ga = b$) and the action of g^{-1} provides a function $[b] \to [a]$ given by $x \mapsto g^{-1}x$ that is inverse to the action of g sending $[a]$ to $[b]$. Therefore all equivalence classes have the same size.

Let M be the common size of the equivalence classes and let N be the number of equivalence classes, so $n = MN$. Since G contains a transposition and the two numbers in a transposition in G are equivalent, $M \geq 2$. We want to show $N = 1$. By hypothesis there is a p-cycle in G. Call it g. The group $\langle g \rangle$ has order p, so the orbits of $\langle g \rangle$ on the equivalence classes each have size 1 or p. (When a finite group acts on a set, all orbits have order dividing the order of the group, by the orbit–stabilizer formula.) If some orbit has size p, say $[a], [ga], \ldots, [g^{p-1}a]$, then $N \geq p$ so

$$n = MN \geq Mp \geq 2p > 2\frac{n}{2} = n,$$

a contradiction. Therefore all $\langle g\rangle$-orbits have size 1, so for every $a \in \{1, 2, \ldots, n\}$ we have $[ga] = [a]$, which means $a \sim ga$ for all a. Since g is a p-cycle, by relabeling (which amounts to replacing G with a conjugate subgroup in S_n) we can assume $g = (12 \ldots p)$. That means $2 = g(1), 3 = g(2), \ldots, p = g(p-1)$, so because $a \sim ga$ for all a we have

$$1 \sim 2 \sim 3 \sim \cdots \sim p,$$

so the equivalence class [1] has size at least p. Therefore $M \geq p$ so

$$n = MN \geq pN > \frac{n}{2}N,$$

hence $N < 2$, so $N = 1$. □

Proof. (of Theorem 2.2) Let G be a transitive subgroup of S_n containing a 3-cycle and a p-cycle for some prime $p > n/2$. Since a transitive subgroup of S_3 has to be A_3 or S_3, we can assume $n \geq 4$. Then $p > n/2 \geq 2$, so p is odd. A cycle with an odd number of terms has even sign (think about 3-cycles, or the more simple 1-cycles!), so p-cycles are even. We will show G contains a set of 3-cycles that generates A_n, so G is A_n or S_n.

For a and b in $\{1, 2, \ldots, n\}$, set $a \sim b$ if $a = b$ or if there is a 3-cycle (abc) in G. We will check this is an equivalence relation on $\{1, 2, \ldots, n\}$

Reflexive: Clear.

Symmetric: If $a \neq b$ and $a \sim b$ then some 3-cycle (abc) is in G, so its inverse $(abc)^{-1} = (bac)$ is in G, so $b \sim a$.

Transitive: This will be trickier than the transitivity proof in Theorem 2.1 because we will have 5 parameters to keep track of and need to worry about the possibility that some of them may be equal.

Suppose $a \sim b$ and $b \sim c$. We want to show $a \sim c$. It is easy if two of these three numbers are equal, so we may assume a, b, and c are distinct. Then (abd) and (bce) are in G for some d and e with $d \neq a$ or b and $e \neq b$ or c. It might happen that $d = e$ or $d = c$ or $e = a$. To show G contains a 3-cycle $(ac*)$, we need to take separate cases to deal with these possibile equalities.

Case 1: a, b, c, d, e are distinct. The conjugate

$$(bce)(abd)(bce)^{-1} = (bce)(abd)(bec) = (acd)$$

is in G, so $a \sim c$.

Case 2: $d = e$, so a, b, c, d are distinct. Here (abd) and (bcd) are in G, so G contains

$$(bcd)(abd)(bcd)^{-1} = (bcd)(abd)(bdc) = (acb).$$

Case 3: $d = c$ and $e \neq a$, so a, b, c, e are distinct. Here (abc) and (bce) are in G, so G contains

$$(bce)(abc)(bce)^{-1} = (bce)(abc)(bec) = (ace).$$

Case 4: $d \neq c$ and $e = a$, so a, b, c, d are distinct. Here (abd) and (bca) are in G, so G contains

$$(abd)(bca)^{-1} = (abd)(bac) = (acd).$$

Case 5: $d = c$ and $e = a$, so we only have three numbers a, b, and c with (abc) and (bca) in G. Of course $(bca) = (abc)$, so all we have to work with here is (abc). Invert it: G contains

$$(abc)^{-1} = (acb).$$

Thus $a \sim c$, so $\sim$ is transitive.

The equivalence relation $\sim$ is preserved by G: if $g \in G$ and $a \sim b$ then $ga \sim gb$. This is obvious if $a = b$. If $a \neq b$ then some 3-cycle (abc) is in G, so the conjugate

$$g(abc)g^{-1} = (ga\ gb\ gc)$$

is in G. Therefore $ga \sim gb$.

For $a \in \{1, 2, \ldots, n\}$, write $[a]$ for the equivalence class of a. The group G acts on equivalence classes by $g[a] = [ga]$ and all equivalence classes have the same size. Let M be the common size of the equivalence classes and N be the number of equivalence classes, so $n = MN$. Since G contains a 3-cycle and the numbers in a 3-cycle in G are equivalent, $M \geq 3$.

Let $g \in G$ be a p-cycle, so the orbits of $\langle g \rangle$ on the equivalence classes have size 1 or p. We will show all the sizes are 1. If there is an orbit of size p then $N \geq p$, so

$$n = MN \geq Mp \geq 3p > 3\frac{n}{2} > n,$$

a contradiction. Thus $\langle g \rangle$ fixes all the equivalence classes, so $a \sim ga$ for all $a \in \{1, 2, \ldots, n\}$. Therefore, as in the proof of Theorem 2.1, $M \geq p$ so

$$n = MN \geq pN > \frac{n}{2}N,$$

so $N < 2$, which means $N = 1$. That all a and b in $\{1, 2, \ldots, n\}$ are equivalent for the relation $\sim$ means for all distinct a and b in $\{1, 2, \ldots, n\}$, there is some 3-cycle (abc) in G.

We have *not* (yet) shown all 3-cycles are in G, but only that for all distinct a and b in $\{1, 2, \ldots, n\}$ there is a 3-cycle $(abc) \in G$ for some $c \neq a$ or b. We will use this to show G contains all 3-cycles of the form $(12j)$, meaning

$$(123), (124), \ldots, (12n). \tag{1}$$

It turns out that the set of 3-cycles $(12j)$ in (1) generates A_n: that's clear when $n = 3$, so we can take $n \geq 4$. In that case,

- every 3-cycle (abc) not containing 1 is $(1ab)(1bc)$,
- every 3-cycle of the form $(1ij)$ that doesn't contain 2 is $(12j)(12j)(12i)(12j)$,
- every 3-cycle $(1i2)$ is $(12i)^{-1}$.

So if G contains the 3-cycles in (1) then it contains *all* 3-cycles, and it's a standard theorem in group theory that the set of all 3-cycles in S_n generates A_n. Thus G is A_n or S_n.

To show G contains the 3-cycles in (1), we can suppose $n \geq 4$ since when $n = 3$, the hypothesis that G contains a 3-cycle means G contains (123): the only other 3-cycle (132) and that is $(123)^{-1}$.

Since $1 \sim 2$ there is some 3-cycle $(12c)$ in G where c is not 1 or 2. For every $d \neq c$, 1, or 2 (there are such d since $n \geq 4$), we want to show $(12d) \in G$. Since $c \sim d$, some 3-cycle (cde) is in G, where e is not c or d. The numbers 1, 2, c, and d are distinct by hypothesis, as are c, d, and e, but e might equal 1 or 2. To show $(12d)$ is in G we take cases.

Case 1: $e \neq 1$ or 2, so 1, 2, c, d, e are distinct. The conjugate

$$(cde)(12c)(cde)^{-1} = (cde)(12c)(ced) = (12d)$$

is in G.

Case 2: $e = 1$. Here $(12c)$ and $(cd1)$ are in G, so G contains

$$(cd1)(12c) = (12d).$$

Case 3: $e = 2$. Here $(12c)$ and $(cd2)$ are in G, so G contains

$$(12c)(cd2)^{-1} = (12c)(c2d) = (12d). \qquad \square$$

Here are some other theorems in group theory in the spirit of Theorem 2.1.

Theorem 3.1. *For $n \geq 2$, a transitive subgroup of S_n that contains a transposition and an $(n-1)$-cycle is S_n.*

Proof. Let G be a transitive subgroup of S_n containing an $(n-1)$-cycle. By suitable labeling, G contains the particular $(n-1)$-cycle $\sigma = (12 \dots n-1)$. This cycle fixes n and moves all the other numbers around. We can't say for sure which transpositions are in G, only that some transposition is in it. Say (ab) is a transposition in G. For each $g \in G$, G contains the conjugate transposition $g(ab)g^{-1} = (ga\ gb)$. Since G is a transitive subgroup, there is a $g \in G$ such that $gb = n$. Necessarily $ga \neq gb$, so G contains a transposition $\tau = (in)$ where $i = ga \in \{1, 2, \dots, n-1\}$.

For $j = 1, 2, \dots, n$, G contains the transposition

$$\sigma^j \tau \sigma^{-j} = (\sigma^j(i)\ \sigma^j(n)) = (i + j\ n).$$

Therefore G contains $(1n)$, $(2n), \dots, (n-1\ n)$. For distinct i and j in $\{1, \dots, n-1\}$, G contains

$$(in)(jn)(in) = (ij).$$

Therefore G contains all transpositions, so $G = S_n$. □

It's left to the reader to return to Examples 2.3 and 2.4 and solve them using Theorem 3.1 in place of Theorem 2.1. For large n, Theorem 2.1 is more flexible than Theorem 3.1 since it only requires you find a p-cycle with some prime $p > n/2$ rather than specifically an $(n-1)$-cycle.

Theorem 3.2. *For $n \geq 2$, a transitive subgroup of S_n that contains a transposition and has a generating set of cycles of prime order is S_n.*

Proof. See [4, pp. 139–140]. □

Theorem 3.2 appears to be less simple to apply to specific examples than the other theorems, because it requires knowing a generating set of cycles of prime order in the Galois group. It's one thing to know a few cycle types in G_f, by Dedekind's theorem, but how could we know generating cycle types in G_f before we know G_f? Using a lot more mathematics, there really are situations where Theorem 3.2 can be applied to compute Galois groups over $\mathbf{Q}$. For instance, Osada [3] showed the Galois group of $X^n - X - 1$ over $\mathbf{Q}$ is S_n using the special case of Theorem 3.2 for cycles of prime order 2: a transitive subgroup of S_n generated by transpositions must be S_n. An account of Osada's proof is in `https://kconrad.math.uconn.edu/blurbs/gradnumthy/galoisselmerpoly.pdf`.

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