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CONSTRUCTION OF 2^m S_n-FIELDS CONTAINING A C_{2^m}-FIELD

by

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1. Introduction

In the present paper, we find explicit solutions to embedding problems given by central extensions of symmetric groups with kernel a cyclic 2-group, different from those considered in [4].

We recall that $H^2(A_n, C_{2^m}) \simeq \mathbf{Z}/2\mathbf{Z}$ and $H^2(S_n, C_{2^m}) \simeq \mathbf{Z}/2\mathbf{Z} \times \mathbf{Z}/2\mathbf{Z}$ and so we have two central extensions of S_n by C_{2^m} reducing to the non trivial central extension $2^m A_n$ of A_n by C_{2^m}.

We denote by $2S_n^-$ the double cover of S_n in which transpositions lift to elements of order 4, by s_n^- the corresponding element in $H^2(S_n, C_2)$; by $2^m S_n^-$ the central extension corresponding to $j_* s_n^-$, for $j_* : H^2(S_n, C_2) \to H^2(S_n, C_{2^m})$ the map induced by the embedding $j : C_2 \to C_{2^m}$; by $2^m S_n^+$ the second central extension of S_n by C_{2^m} reducing to $2^m A_n$, for $m \geq 1$. For s_n^+ the element in $H^2(S_n, C_2)$ corresponding to $2S_n^+$, we note that $j_* s_n^+ = j_* s_n^-$. By a result of Sonn [10], we know that all central extensions of S_n appear as Galois groups over $\mathbf{Q}$.

In this paper, K will always denote a field of characteristic different from 2, L a Galois S_n-extension of K. In [1], we obtained an explicit resolution of embedding problems

$$2S_n^{\pm} \to S_n \simeq \mathrm{Gal}(L|K)$$

and in [3],[4],[5], of embedding problems

$$2^m S_n^- \to S_n \simeq \mathrm{Gal}(L|K).$$

Here we deal with embedding problems

$$2^m S_n^+ \to S_n \simeq \mathrm{Gal}(L|K).$$

Comparing [4] Proposition 1 and Proposition 1 below, we see that a $2^m S_n^+$-field contains a C_{2^r}-extension whereas a $2^m S_n^-$-field does not.

If $e : G_K \to S_n$ denotes the epimorphism corresponding to the Galois extension $L|K$, the obstruction to the solvability of the embedding problem $2S_n^+ \to S_n \simeq \mathrm{Gal}(L|K)$ is given by the element $e^* s_n^+ \in H^2(G_K, C_2)$, which can be computed effectively by means of a formula of Serre [9, Théorème 1]. Following Serre, for a Galois S_n-extension $L|K$, we denote by E the subfield of L fixed by the isotropy group of one letter, by d_E the discriminant of the extension $E|K$, by Q_E its trace form. For a quadratic form Q, we denote by $\mathrm{w}(Q)$ its Hasse-Witt invariant. Serre's formula reads:

$$e^*(s_n^+) = \mathrm{w}(Q_E)(2, d_E).$$

Let us note that the formula of Serre has been generalized by Fröhlich to compute the obstruction to the solvability of an embedding problem $\widehat{G} \to G \simeq \mathrm{Gal}(L|K)$ with kernel C_2, such that the element in $H^2(G, C_2)$ corresponding to $\widehat{G}$ is the second Stiefel-Whitney class $\mathrm{sw}(\rho)$ of an orthogonal representation ρ of the group G in the orthogonal group of a quadratic form defined over the field K [6, Theorem 3].

For embedding problems of the type considered by Fröhlich, we gave in [2] a method of explicit resolution.

When dealing with embedding problems $2^m S_n^+ \to S_n \simeq \mathrm{Gal}(L|K)$, for $m \geq 2$, we obtain a criterion for the solvability and a method of computation of the solutions by reducing to an embedding problem with a kernel of order 2.

We note that the symmetric group S_4 is a subgroup of the projective linear group $\mathrm{PGL}(2, \mathbb{C})$ and the groups $2^m S_4^+$ and $2^m S_4^-$ fit in a commutative diagram

$$\begin{tikzcd} 2^m S_4^{\pm} \arrow[r] \arrow[d] & S_4 \arrow[d] \\ \mathrm{GL}(2, \mathbb{C}) \arrow[r] & \mathrm{PGL}(2, \mathbb{C}). \end{tikzcd}$$

Embedding problems given by $2^m S_4^{\pm}$ over a field K correspond then to liftings of projective to linear representations of the absolute Galois group G_K of the field K. Using this correspondence, Quer obtains, in the case $K = \mathbb{Q}$, a criterion for the solvability of the embedding problem

$$2^m S_4^{\pm} \to S_4 \simeq \mathrm{Gal}(L|\mathbb{Q})$$

in terms of local conditions (cf. [7]).

2. Existence of solutions

The next proposition shows that the resolution of the embedding problem considered can be reduced to the resolution of an embedding problem with kernel C_2.

Proposition 1. *Given a Galois S_n-extension $L|K$, the embedding problem*

$$(1) \qquad 2^m S_n^+ \to S_n \simeq \mathrm{Gal}(L|K)$$

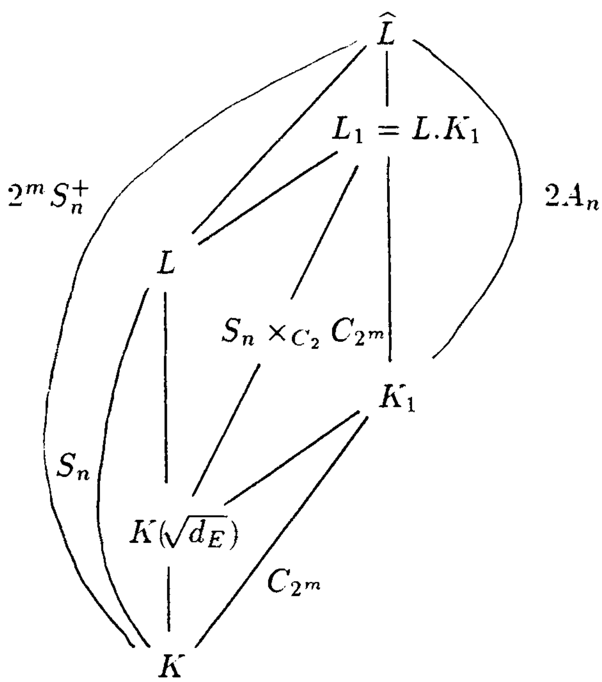
is solvable if and only if there exists a Galois extension $K_1|K$ with Galois group C_{2^m} such that $K_1 \cap L = K(\sqrt{d_E})$ and the central embedding problem (with kernel C_2)

$$(2) \qquad 2^m S_n^+ \to S_n \times_{C_2} C_{2^r} \simeq \mathrm{Gal}(L.K_1|K)$$

is solvable.

In this case, the set of solutions to (1) is equal to the union of the sets of solutions to the embedding problems (2) for $K_1|K$ running over the extensions satisfying the above conditions.

Proof. By taking into account that $2A_n$ is contained in $2^m S_n^+$, we obtain the following picture of subextensions of a solution field $\widehat{L}$ for the embedding problem (1).



From here, it is easy to see that $\widehat{L}$ solution to (1) is equivalent to $\widehat{L}$ solution to (2) for some K_1 satisfying the conditions in the proposition.

Now we obtain easily the following result on the obstruction to solvability of the embedding problem (2).

Proposition 2. *Given a Galois S_n-extension $L|K$, and a Galois C_{2^m}-extension $K_1|K$ such that $K_1 \cap L = K(\sqrt{d_E})$, $m \geq 2$, the element in $H^2(G_K, C_2)$ giving the obstruction to solvability of the embedding problem (2) is equal to the product of the elements giving the obstructions to solvability of the embedding problems $2S_n \to S_n \simeq \mathrm{Gal}(L|K)$, where $2S_n$ can be both $2S_n^+$ or $2S_n^-$, and $C_{2^{m+1}} \to C_{2^m} \simeq \mathrm{Gal}(K_1|K)$.*

Let us note that the elements in $H^2(S_n, C_2)$ corresponding to $2S_n^+$ and $2S_n^-$ differ in $(d_E) \cup (d_E)$, which is trivial in $H^2(S_n \times_{C_2} C_{2^m}, C_2)$.

3. Solvability in terms of Hilbert symbols

The condition for solvability can be made more explicit if we know a parametrization of the C_{2^m}-extensions of the field K and an explicit expression in terms of Hilbert symbols of the obstruction to solvability of $C_{2^{m+1}} \to C_{2^m} \simeq \mathrm{Gal}(K_1|K)$.

In the case of $C_{16} \to C_8$, the obstruction to solvability has been computed by Swallow [11], for C_8-extensions belonging to a parametric family given by Schneps [8]. Following Swallow, we refer to C_8-extensions included in this parametric family as *admissible extensions* and we shall call a field *admissible* when all its C_8-extensions are admissible. We note that the class of admissible fields contains $\mathbb{Q}$ and $\mathbb{Q}(T)$ (cf. [8]).

Proposition 3. *a) Assume K contains a primitive 2^m-root of unity ζ. Then for a Galois S_n-extension $L|K$, the embedding problem $2^m S_n^+ \to S_n \simeq \mathrm{Gal}(L|K)$, $m \geq 1$, is solvable if and only if $\mathrm{w}(Q_E) = (-2\zeta, d_E)$.*
b) Let K be any field of characteristic different from 2, $L|K$ a Galois S_n-extension. Then the embedding problem $4S_n^+ \to S_n \simeq \mathrm{Gal}(L|K)$ is solvable if and only if $(-1, d_E) = 1$ and $\mathrm{w}(Q_E) = (-1, r)$ for some r in K.
c) Let K be any field of characteristic different from 2 (resp. an admissible field), $L|K$ a Galois S_n-extension. Then the embedding problem $8S_n^+ \to S_n \simeq \mathrm{Gal}(L|K)$ is solvable if (resp. if and only if) $(-1, d_E) = (2, d_E) = 1$ and there exist elements r, s in K such that $(-1, r) = 1$ and $\mathrm{w}(Q_E) = (s(z-w), -1)(rz(z-y), -2)(z(z-w), d_E)$ for $d_E = x^2 + y^2 = z^2 - 2w^2$.

Proof. a) In this case, we take $K_1 = K(\sqrt[2^r]{d_E})$ and apply [6](7.10).
b) Here the condition $(-1, d_E) = 1$ is equivalent to the existence of a Galois C_4-extension $K_1|K$ containing $K(\sqrt{d_E})$ and all such K_1 are of the form

$$K_1 = K\left(\sqrt{r(d_E + y\sqrt{d_E}}\right) \quad \text{for } d_E = x^2 + y^2, r \in K.$$

The obstruction to solvability of $C_8 \to C_4 \simeq \mathrm{Gal}(K_1|K)$ is equal to $(2, d_E)(-1, r)$ (see e.g.[8]).
c) The existence of an admissible C_8-extension of K containing $K(\sqrt{d_E})$ is equivalent to $(-1, d_E) = (2, d_E) = 1$ and $(-1, r) = 1$ for some r [8]. Then all such C_8-extensions are:

$$K_1 = K\left(\sqrt{s(z + \sqrt{d_E})\left(2rd_E + v\sqrt{rd_E + ry\sqrt{d_E}} + u\sqrt{rd_E - ry\sqrt{d_E}}\right)}\right)$$

for $r = t_1^2 + t_2^2$, $u = t_1 x - t_2 y - t_1 y - t_2 x$, $v = t_1 x - t_2 y + t_1 y + t_2 x$, and we use the explicit expression for the obstruction to solvability of $C_{16} \to C_8 \simeq \mathrm{Gal}(K_1|K)$ obtained by Swallow [11].

4. Construction of the solutions

We can apply to the embedding problem

$$2^m S_n^+ \to S_n \times_{C_2} C_{2^m} \simeq \mathrm{Gal}(L_1|K)\ ,\ m \geq 2,$$

where $L_1 = L.K_1$, the method of construction of the solutions obtained in [2] whenever we have an orthogonal representation ρ of the group $S_n \times_{C_2} C_{2^m}$ such that its second Stiefel-Withney class $\mathrm{sw}(\rho)$ corresponds to the extension

$$2^m S_n^+ \to S_n \times_{C_2} C_{2^m}. \tag{3}$$

Such a representation ρ can be obtained as $\rho_1 \perp \rho_2$ for ρ_1 an orthogonal representation of S_n such that $\mathrm{sw}(\rho_1)$ corresponds to $2S_n^+ \to S_n$ (e.g. the embedding of S_n in the orthogonal group $O_n(K)$ of the identity quadratic form in n variables) or to $2S_n^- \to S_n$ (e.g. the inclusion $S_n \hookrightarrow A_n \times C_2 \hookrightarrow A_{n+2}$ given by $s \mapsto (s, \mathrm{sg}\, s)$ followed by the embedding of A_{n+2} in the special orthogonal group $SO_{n+2}(K)$ of the identity quadratic form in $n+2$ variables) and ρ_2 an orthogonal representation of C_{2^m} such that $\mathrm{sw}(\rho_2)$ corresponds to $C_{2^{m+1}} \to C_{2^m}$. Such a representation ρ_2 is known in the cases included in Proposition 3. Namely, it is given in [6] for case a), in [11] for case c) and is obtained by restricting to C_4 the embedding of S_4 in $O_4(K)$ in case b).

Now, given a representation $\rho : S_n \times_{C_2} C_{2^m} \to O(Q)$, as above, we can assume that it is special (i.e. that its image is contained in the special orthogonal group) and satisfies $\mathrm{sp} \circ \rho = 1$ for sp the spinor norm in the orthogonal group $O(Q)$ (cf. [2] Proposition 3). Under these conditions, the embedding problem considered is solvable if and only if the Hasse-Witt invariants of the quadratic form Q and its twist Q_ρ by ρ are equal. By applying [2] Theorem 1, we obtain that the set of solutions to the embedding problem considered are the fields $L_1(\sqrt{r\gamma})$, for $r \in K^*$ and γ a nonzero coordinate of the spinor norm of an adequate element z in the Clifford algebra over L_1 of the quadratic form Q_ρ, which can be given explicitly.

Further, [2] Theorem 2 gives when this element γ can be given in terms of matrices. In particular, if the two quadratic forms Q and Q_ρ are equivalent, γ is given by a single determinant.

5. The case $4S_n^+$

We examine now more closely the embedding problem

$$4S_n^+ \to S_n \simeq \mathrm{Gal}(L|K).$$

It is solvable if and only if $(-1, d_E) = 1$, i.e there exist elements x and y in K such that $d_E = x^2 + y^2$, and $\mathrm{w}(Q_E) = (-1, r)$, for some $r \in K$. If this is the case, its resolution is reduced to the resolution of the embedding problems

$$4S_n^+ \to S_n \times_{C_2} C_4 \simeq \mathrm{Gal}(K_1.L|K), \tag{4}$$

where $K_1 := K(\sqrt{r(d_E + y\sqrt{d_E})}$, for r and y as above. We consider the special representation $\rho = \rho_1 \perp \rho_2$ for ρ_1 the orthogonal representation of S_n obtained by embedding S_n in the orthogonal group $O_n(K)$ of the identity quadratic form in n variables and ρ_2 the orthogonal representation of C_4 obtained by restriction of the embedding of S_4 in $O_4(K)$.

The quadratic form Q_ρ is then $\mathrm{Tr}_{E|K}(x^2) \perp \mathrm{Tr}_{K_1|K}(y^2)$. If the two quadratic forms Q and Q_ρ are equivalent, let P be a matrix in $\mathrm{GL}(n+4, K)$ such that $P^t[Q_\rho]P = [Q]$ and M the matrix in $\mathrm{GL}(n+4, L_1)$ given by

$$M = \begin{pmatrix} (x_i^j)_{\substack{1 \le i \le n \\ 0 \le j \le n-1}} & 0 \\ 0 & (y_i^j)_{\substack{1 \le i \le 4 \\ 0 \le j \le 3}} \end{pmatrix}$$

for x_i the roots of a polynomial in $K[X]$ of degree n, with decomposition field L, and y_i the elements $\pm\sqrt{r(d_E \pm y\sqrt{d_E})}$. We obtain then a solution to the embedding problem (4) as $\widehat{L} = L_1(\sqrt{\gamma})$, for $\gamma = \det(MP + I)$.

In the case $K = \mathbb{Q}$, we can determine under which conditions the two quadratic forms Q and Q_ρ are equivalent. By considering Q and Q_ρ at ∞, we obtain that, if the embedding problem considered is solvable, the elements d_E and r must have the same sign and, if they are both positive, then the two quadratic forms Q and Q_ρ are equivalent.

6. Examples

In each example we consider a polynomial $F(X)$ realizing S_4 over $\mathbb{Q}$ and let L denote its decomposition field, E the field obtained by adjoining to $\mathbb{Q}$ one root of F. We consider the embedding problems

$$2^m S_4^+ \to S_4 \simeq \mathrm{Gal}(L|\mathbb{Q}) \tag{5}$$

for $m \geq 1$. We recover the results of Quer concerning solvability (cf. [7]) and exhibit an element γ generating the set of solutions in our last example.

Example 1.

For $F(X) = X^4 + X^3 - 6X^2 + X + 2$ we have $d_E = 15529 = 53 \times 293 = 115^2 + 48^2$, $\mathrm{w}(Q_E) = 1$, $(2, d_E) = -1$ in exactly 53 and 293.

By applying [9] Théorème 1 and Proposition 3, we obtain that the embedding problem (5) is not solvable for $m = 1$ and $m = 3$ and solvable for $m = 2$. Moreover, $(2, d_E) \neq 1$ implies that $\mathbb{Q}(\sqrt{d_E})|\mathbb{Q}$ cannot be included in a C_8-extension and so neither in a C_{2^m}-extension for $m \geq 3$ and we obtain then that (5) is not solvable for any $m \geq 3$.

We obtain the set of solutions to

$$4S_4^+ \to S_4 \simeq \mathrm{Gal}(L|\mathbb{Q})$$

as the union of the sets of solutions to

$$4S_4^+ \to S_4 \times_{C_2} C_4 \simeq \mathrm{Gal}\left(L\left(\sqrt{r(15529 + 48\sqrt{15529}}\right)|\mathbb{Q}\right)$$

for r running over the square-free integers which are a sum of 2 squares.

Example 2.

For $F(X) = X^4 + X^3 - 11X^2 + 12$ we have $d_E = 2^5 \times 3^2 \times 2969$, $\mathrm{w}(Q_E) = -1$ in exactly 2 and 3, $(-1, d_E) = (2, d_E) = 1$.

We have then that (5) is not solvable for $m = 1$. Further, $(-1, d_E) = 1$ and $\mathrm{w}(Q_E) = (-1, 3)$ imply that (5) is solvable for $m = 2$.

Now $(-1, d_E) = (2, d_E) = 1$ imply that $\mathbb{Q}(\sqrt{d_E})$ is embeddable in a C_8-extension and the condition for (5) being solvable for $m = 3$ is that there exist $r, s \in \mathbb{Q}$ with $(-1, r) = 1$

such that $(s(z-w),-1)(rz(z-y),-2)(z(z-w),d_E) = -1$ exactly in 2 and 3, where $x = 36, y = 924, z = 1800, w = 1092$. This is equivalent to $(s,-1)(r,2) = -1$ exactly in 2,59,2969 which fails in 2969. So (5) is not solvable for $m = 3$.

The condition for $\mathbb{Q}(\sqrt{d_E})$ embeddable in a C_{16}-extension is that there exist $r, s \in \mathbb{Q}$ with $(-1,r) = 1$ such that $(s(z-w),-1)(rz(z-y),-2)(z(z-w),d_E) = 1$, which is equivalent to $(s,-1)(r,2) = 1$, which fails in 2969. So (5) is not solvable for $m \geq 3$.

We obtain the set of solutions to

$$4S_4^+ \to S_4 \simeq \mathrm{Gal}(L|\mathbb{Q})$$

as the union of the sets of solutions to

$$4S_4^+ \to S_4 \times_{C_2} C_4 \simeq \mathrm{Gal}\left(L\left(\sqrt{r(2.2969 + 77\sqrt{2.2969}}\right)|\mathbb{Q}\right)$$

for r running over the square-free integers such that $3r$ is a sum of 2 squares.

Example 3.

For $F(X) = X^4 + X^3 - 4X^2 - X + 2$ we have $d_E = 2777$, $\mathrm{w}(Q_E) = (-1, d_E) = (2, d_E) = 1$.

We have then that (5) is solvable for $m = 1$ and $m = 2$. Now, $(-1, d_E) = (2, d_E) = 1$ imply that $\mathbb{Q}(\sqrt{d_E})$ is embeddable in a C_8-extension. The conditions for (5) solvable for $m = 3$ and $\mathbb{Q}(\sqrt{d_E})$ embeddable in a C_{16}-extension are both equivalent to the existence of $r, s \in \mathbb{Q}$ with $(-1,r) = 1$ such that $(s(z-w),-1)(rz(z-y),-2)(z(z-w),d_E) = 1$, for $x = 29, y = 44, z = 53, w = 4$, which is equivalent to $(s,-1)(r,2) = -1$ exactly in 2 and 2777, which fails in 2777. So (5) is not solvable for $m \geq 3$.

We obtain the set of solutions to

$$4S_4^+ \to S_4 \simeq \mathrm{Gal}(L|\mathbb{Q})$$

as the union of the sets of solutions to

$$4S_4^+ \to S_4 \times_{C_2} C_4 \simeq \mathrm{Gal}\left(L\left(\sqrt{r(2777 + 44\sqrt{2777}}\right)|\mathbb{Q}\right)$$

for r running over the square-free integers which are a sum of 2 squares.

For $r = d_E = 2777$, an element γ generating the set of solutions is

$$\begin{aligned}
\gamma = \;& 3272981289064523539933868006 + 5562840786788949523164832441\, x_1 \\
& -7857424647479352840038038361\, x_1^2 - 5183506568458279697365246 53\, x_1^3 \\
& +7600643699302539469685190834\, x_2 + 2280324081956182768636706459\, x_1 x_2 \\
& -8844713788527631409805787463\, x_1^2 x_2 + 3941469499008338311921460 99\, x_1^3 x_2 \\
& +1940685159241524676959527572\, x_2^2 - 2210403079523052949625817486\, x_1 x_2^2 \\
& -6622780224635788135820644 10\, x_1^2 x_2^2 + 2994070627466094130216928 31\, x_1^3 x_2^2 \\
& +9846407664804530113585990756\, x_3 - 8010122436987691214034628162\, x_1 x_3 \\
& -1199944498013714305372776380 4\, x_1^2 x_3 + 8730375993903968171520578231\, x_1^3 x_3 \\
& +7712880420702604369208311568\, x_2 x_3 + 4928896021004161858583085 6\, x_1 x_2 x_3
\end{aligned}$$

$$
\begin{aligned}
&-7516185875908586411439042817\ x_1^2x_2x_3 + 6012292488309441399071087 40\ x_1^3x_2x_3 \\
&-7107698002435360464530660820\ x_2^2x_3 + 1191801140151465382970128941 0\ x_1x_2^2x_3 \\
&+1108569996544199260092735551 4\ x_1^2x_2^2x_3 - 1144293817614091840320597580 2\ x_1^3x_2^2x_3 \\
+y\ (&877020547103738725470 + 1486993746036323616141\ x_1 \\
&-2101389180427447237485\ x_1^2 - 1388590642629665734 65\ x_1^3 \\
&+2033449398120606798906\ x_2 + 6115178937332804421 51\ x_1x_2 \\
&-2365767832053607527243\ x_1^2x_2 + 1045444016736342773 67\ x_1^3x_2 \\
&+519408508832688336084\ x_2^2 - 5906342659813138317 42\ x_1x_2^2 \\
&-1778194165837926959 70\ x_1^2x_2^2 + 8020179704372142830 7\ x_1^3x_2^2 \\
&+2634313987410770530740\ x_3 - 2143427459163936044586\ x_1x_3 \\
&-3209464706321712842820\ x_1^2x_3 + 2335301399751945044571\ x_1^3x_3 \\
&+2063293554270949305264\ x_2x_3 + 1395409407720707512 8\ x_1x_2x_3 \\
&-2011038940649902656693\ x_1^2x_2x_3 + 1607282172067388708 76\ x_1^3x_2x_3 \\
&-1901083573458202228740\ x_2^2x_3 + 3188278642452195718170\ x_1x_2^2x_3 \\
&+2964881256785137801458\ x_1^2x_2^2x_3 - 3060877901617363446594\ x_1^3x_2^2x_3\ )
\end{aligned}
$$

for x_1, x_2, x_3 three distinct roots of the polynomial $F(X)$ and y a root of the polynomial $X^4 - 2X^2 + \dfrac{29^2}{2777}$.

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