ON A PROBLEM OF CHEVALLEY

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Recently Prof. Chevalley in Nagoya suggested to the author the following problem: Let k be a field, $K_5 = k(x_1, x_2, x_3, x_4, x_5)$ be a purely transcendental extension field (of transcendental degree 5) of k, s_5 be the cyclic permutation of x: $s_5x_1 = x_2 s_5x_2 = x_3 s_5 x_3 = x_4 s_5 x_4 = x_5 s_5 x_5 = x_1$, and let L_5 be the field of invariants of s_5 in K_5. Is L_5 then purely transcendental over k or not? When the characteristic p of k is not equal to 5, it is answered in the following positively. When the characteristic p of k is equal to 5, it is answered also positively by Mr. Kuniyoshi's result in [2].

Now let $K_n = k(x_1, x_2, x_3, \ldots, x_n)$ be a purely transcendental extension field (of transcendental degree n) of k, s_n be the cyclic permutation of x: $s_n x_1 = x_2$ $s_n x_2 = x_3 \ldots s_n x_n = x_1$, and let L_n be the field of invariants of s_n in K_n. We suppose from now on throghout the present article that n is not divisible by the characteristic p of k. If the ground field k involves a primitive n-th root ζ_n of 1, we can see easily that L_n is purely transcendental over k. From this fact we obtain in the following that existence of certain sets of primitive generators of $L_n(\zeta_n)$ over $k(\zeta_n)$ (the definition is shown in the following) is a necessary and sufficient condition for L_n to be purely transcendental over k, and the existence of such sets of primitive generators are shown for every case of $n \leqq 7$ through calculations on factor sets[1]. It looks that a more arithmetical approach will be necessary to solve the problem with reference to general n.

1. Let $k'_n = k(\zeta_n)$, $K'_n = K_n(\zeta_n)$ and $\mathfrak{G}$ be the Galois group of k' over k. We omit all n as subscripts throughout in the following, unless indispensable. Let L' denote the field of invariants of s in K'. K and K' are clearly Galois extension fields over L and L' of the same rank n respectively. Their Galois groups are generated by the automorphism induced by s. We do not distin-

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[1] Cf. [1] and [3]. Hasse factor sets defined in [3] without the supposition that the absolutely irreducible representations of Galois groups are obtained in the ground field has close relations to the problem of the pure transcendency of L_n over k.

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guish these two Galois groups and the cyclic permutation group of x generated by s and denote them by same $\mathfrak{G}$. As K is purely transcendental over k, K and k' are linearly disjoint over k[2] and $[K' : K] = [L(\zeta) : L] = [k' : k]$. The restrictions of the Galois group of K' over K into $L(\zeta)$ and k' are the Galois group of $L(\zeta)$ over L and the Galois group of k' over k respectively. We do not distinguish these three Galois groups and denote them by same $\mathfrak{G}$. Then we can see easily from the Galois theory that $\mathrm{L}(\zeta) \cap K = L$ and $[K : L] = [K' : L(\zeta)] = [K' : L']$. As $L(\zeta) \subset L'$, we obtain now the following Lemma.

LEMMA 1. *$L' = L(\zeta)$, $L' \cap K = L$ and $[L' : L] = [k' : k]$.*

Let $y_j = \sum_{i=1}^{n} \zeta^{-ij} x_i$ and $c_{j,k} = y_j y_k / y_{\overline{j+k}}$ for $j, k = 1, 2, \ldots, n$, where we denote by $\overline{j+k}$ the integer determined uniquely by $\overline{j+k} \equiv j+k \bmod n$ and $1 \leqq \overline{j+k} \leqq n$. $c_{j,k}$ belongs clearly to L'. Let M' denote the field generated over k' by all $c_{j,k}$ for $j, k = 1, 2, \ldots, n$. From $c_{i,j} = c_{1,j} c_{1,\overline{j+1}} \ldots c_{1,\overline{j+i}} / c_{1,1} c_{1,2} \ldots c_{1,i-1}$ it follows easily that $M' = k'(c_{1,1} c_{1,2}, \ldots, c_{1,n})$ and $y^n \in M'$. As y_1 gives an isomorphic irreducible representation of $\mathfrak{G}$, $[M'(y_1) : M'] = n$. As $y_2, y_3, \ldots, y_n$ can be written as rational combinations of y_1 and $c_{j,k}$ over M' with coefficients in k', $M'(y_1) = M'(y_1, y_2, \ldots, y_n) = K'$. So $[K' : M'] = n$, $M' = L'$ and $L' = k'(c_{1,1}, c_{1,2}, c_{1,3}, \ldots, c_{1,n})$. As the transcendental degree of L' is n, we obtain

THEOREM 1. *L' is purely transcendental over k'.*

We call a set $(a_1, a_2, \ldots, a_t)$ of elements in L' a primitive generating set of L' over $k(\zeta)$, if $\sum_{i=1}^{t} \iota(a_i) = n$ and $L' = k'(a_1, a_1', a_1'', \ldots a_1^{(\iota(a_1)-1)}, a_2, a_2', a_2'', \ldots, a_2^{(\iota(a_2)-1)}, \ldots, a_t, a_t', a_t'', \ldots, a_t^{(\iota(a_t)-1)})$, where we denote by $\iota(a_i)$ the number of (different) conjugate elements of a_i over L. So the number t of elements in such a set is not greater than n, $\iota(a_i) = [L(a_i) : L]$ and $a_i^{(j)} \neq a_{i'}^{(j')}$ except only when $i = i'$, $j = j'$. As $\mathfrak{G}$ is an abelian group, $L(a_i)$ is a Galois extension field of L and $L(a_i, a_i', a_i'', \ldots, a_i^{(\iota(a_i)-1)}) = L(a_i)$. Now we prove the following theorem.

THEOREM 2. *L is purely transcendental over k, if and only if there exists a primitive generating set of $L(\zeta)$ over $k(\zeta)$.*

Proof. (i) Sufficiency. Let $(a_1, a_2, \ldots, a_t)$ be a primitive generating set

[2] Cf. Chap. I. §7 in [4].

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of L' over k. Let $k'_i = L(a_i) \cap k'$ for $i=1, 2, \dots, t$. Then $L(a_i) = Lk'_i$ and the Galois group of $L(a_i)$ over L is equal to the Galois group of k'_i over k. Let $\omega_{i,1}, \omega_{i,2}, \dots, \omega_{i,\iota(a_i)}$ be a normal basis of k' over k (accordingly also such one of $L(a_i)$ over L). a_i can be written as $a_i = \sum_{j=1}^{\iota(a_i)} \omega_{i,j} m_{j,i}$ with $m_{j,i}$ in L for $i=1, 2, \dots, t$. $a_i, a'_i, a''_i, \dots, a_i^{\iota(a_i)-1}$ are clearly written as bilinear combinations of $\omega_{i,1}, \omega_{i,2}, \dots, \omega_{i,\iota(a_i)}$ and $m_{1,i}, m_{2,i}, \dots, m_{\iota(a_i),i}$. As $a_i, a'_i, a''_i, \dots, a_i^{(\iota(a_i)-1)}$ are algebraically independent over k', these forms are as linear combinations of $m_{1,i}, m_{2,i}, \dots, m_{\iota(a_i),i}$ with coefficients in k' linearly independent. So $m_{1,i}, m_{2,i}, \dots, m_{\iota(a_i),i}$ can be written as linear combinations of $a_i, a'_i, a''_i, \dots, a_i^{(\iota(a_i)-1)}$ with coefficients in k'_i and so $k'(a, a'_i, a''_i, \dots, a_i^{(\iota(a_i)-1)}) = k'(m_{1,i}, m_{2,i}, \dots, m_{\iota(a_i),i})$. Thus we obtain $L' = k'(a_1, a'_1, a''_1, \dots, a_1^{(\iota(a_1)-1)}, a_2, a'_2, a''_2, \dots, a_2^{(\iota(a_2)-1)}, \dots, a_t, a'_t, a''_t, \dots, a_t^{(\iota(a_t)-1)}) = k'(m_{1,1}, m_{2,1}, \dots, m_{\iota(a_1),1}, m_{1,2}, m_{2,2}, \dots, m_{\iota(a_2),2}, \dots, m_{1,t}, m_{2,t}, \dots, m_{\iota(a_t),t})$. Let $M = k(m_{1,1}, m_{2,1}, \dots, m_{\iota(a_1),1}, m_{1,2}, m_{2,2}, \dots, m_{\iota(a_2),2}, \dots, m_{1,t}, m_{2,t}, \dots, m_{\iota(a_t)t})$. Then $M \subseteqq L$. As $Mk' = L'$, L' is algebraic over M and $[L' : M] \leqq [k' : k]$, so $M = L$. As the transcendental degree of $L(=M)$ is n, m's are algebraically independent generators of L and L is purely transcendental over k.

(ii) Necessity. Suppose that L is purely transcendental over k and $L = k(a_1, a_2, \dots, a_n)$. $(a_1, a_2, \dots, a_n)$ is clearly a primitive generating set of L' over $k(\zeta)$. q.e.d.

2. Now we prove the following theorem.

Theorem 3. *Let $n \leqq 7$ and suppose that the characteristic p of k does not divide n. Then L is purely transcendental over k.*

Proof. (i) When $n=1$, the theorem is trivial.

(ii) When $n=2$, it holds $[k' : k]=1$ from $p \nmid n$ and the theorem follows from Theorem 1.

(iii) When $n=3$, $[k' : k]=1$ or 2. If $[k' : k]=1$, the theorem follows from Theorem 1. If $[k' : k]=2$, let $a_1 = c_{1,3} = x_1+x_2+x_3$ and $a_2 = c_{1,1} = (\zeta_3 x_1 + \zeta_3^2 x_2 + x_3)^2/\zeta_3^2 x_1 + \zeta_3 x_2 + x_3$. Then $\iota(a_1)+\iota(a_2) = 1+2 = 3$ and since $a_2 = c_{2,2} = c_{1,2}c_{1,3}/c_{1,1}$ it follows $k'(a_1, a_2, a'_2) = k'(c_{1,1}, c_{1,2}, c_{1,3}) = L'_3$. So (a_1, a_2) is a primitive generating set of L'_3 over $k(\zeta_3)$ and the theorem follows from Theorem 2.

(iv) When $n=4$, $[k' : k]=1$ or 2. If $[k' : k]=1$, the theorem fol-

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lows from Theorem 1. When $[k' : k] = 2$, let $a_1 = c_{1,4}$, $a_2 = c_{1,2}$, $a_3 = c_{1,3}$. Then $\iota(a_1) + \iota(a_2) + \iota(a_3) = 1 + 2 + 1$ and since $a_2' = c_{3,2} = c_{1,3}c_{1,4}/c_{1,1}$ it follows $k'(a_1, a_2, a_2', a_3) = k'(c_{1,1}, c_{1,2}, c_{1,3}, c_{1,4}) = L_4'$. So (a_1, a_2, a_3) is a primitive generating set of L_4' over $k(\zeta_4)$ and the theorem follows from Theorem 2.

(v) When $n = 5$, $[k' : k] = 1$ or 2 or 4. If $[k' : k] = 1$, the theorem follows from Theorem 1. When $[k' : k] = 4$, let $a_1 = c_{1,5}$, $a_2 = c_{1,2}$. Then $\iota(a_1) + \iota(a_2) = 1 + 4 = 5$ and it follows from $a_2' = c_{2,4} = c_{1,4}c_{1,5}/c_{1,1}$, $a_2'' = c_{1,3}$, $a_2''' = c_{3,4} = c_{1,4}c_{1,5}/c_{1,2}$ that $k'(a_1, a_2, a_2', a_2'', a_2''') = k'(c_{1,1}, c_{1,2}, c_{1,3}, c_{1,4}, c_{1,5}) = L_5'$. So (a_1, a_2) is a primitive generating set of L_5' over $k(\zeta_5)$, and the theorem follows from Theorem 2. If $[k' : k] = 2$ it is easily seen that one of the following three sets $(c_{1,5}, c_{1,2}, c_{2,1})$, $(c_{1,5}, c_{1,2}, c_{1,3})$, $(c_{1,5}, c_{1,2}, c_{3,4})$ becomes a primitive generating set of $L(\zeta_5)$ over $k(\zeta_5)$.

(vi) When $n = 6$, $[k' : k] = 1$ or 2. When $[k' : k] = 1$, the theorem follows from Theorem 1. When $[k' : k] = 2$, let $a_1 = c_{1,6}$, $a_2 = c_{1,2}$, $a_3 = c_{1,4}$, $a_4 = c_{1,5}$, then $\iota(a_1) + \iota(a_2) + \iota(a_3) + \iota(a_4) = 1 + 2 + 2 + 1 = 6$, and it follows from $a_2' = c_{5,4} = c_{1,5}$, $c_{1,6}/c_{1,3}$, $a_3' = c_{5,2} = c_{1,5}$, $c_{1,6}/c_{1,1}$ that $k'(a_1, a_2, a_2', a_3, a_3', a_4) = k'(c_{1,1}, c_{1,2}, c_{1,3}, c_{1,4}, c_{1,5}, c_{1,6}) = L_6'$. So (a_1, a_2, a_3, a_4) is a primitive generating set of L_6' over $k(\zeta_6)(= k'(\zeta_3))$ and the theorem follows from Theorem 2.

(vii) When $n = 7$, $[k' ; k] = 1$ or 2 or 3 or 6. If $[k' : k] = 1$, the theorem follows from Theorem 1. In the case of $[k' : k] = 6$, let $a_1 = c_{1,7}$, $a_2 = c_{1,3}$. Then $\iota(a_1) + \iota(a_2) = 1 + 6 = 7$, and $a_2' = c_{2,3}$, $a_2'' = c_{2,6}$, $a_2''' = c_{4,6}$, $a_2'''' = c_{4,5}$, $a_2''''' = c_{1,5}$. It follows from $c_{1,2} = c_{4,6}$, $c_{1,5}/c_{4,5}$, $c_{1,4} = c_{2,3}$, $c_{4,6}/c_{2,6}$, $c_{1,1} = c_{2,6}/c_{4,6}$, $c_{1,3}$ that $k'(a_1, a_2, a_2', a_2'', a_2''', a_2'''', a_2''''') = k'(c_{1,1}, c_{1,2}, c_{1,3}, c_{1,4}, c_{1,5}, c_{1,6}, c_{1,7}) = L'$, and (a_1, a_2) is a primitive generating set of L_7' over $k(\zeta_7)$ and the theorem follows from Theorem 2. If $[k' : k] = 3$ or 2, we can find easily a primitive generating set in $(c_{1,7}, c_{1,3}, c_{2,3}, c_{2,6}, c_{4,6}, c_{4,5}, c_{1,5})$ and the theorem follows from Theorem 2.

In the following we give polynomials of x which are algebraically independent generators of L_n over k for $n \leqq 4$ obtained easily from the above primitive generators.

When $n = 1$; x_1.

$n = 2$; $x_1 + x_2$, $x_1 x_2$.

$n = 3$; $x_1 + x_2 + x_3$, $\left(\sum_{i=1}^{3} x_i x^2_{\overline{i+1}} - x_1 x_2 x_3\right) / \left(\sum_{i=1}^{3} x_i^2 - \sum_{i=1}^{3} x_i x_{\overline{i+1}}\right)$,

$\left(\sum_{i=1}^{3} x_i x^2_{\overline{i+1}} - x_1 x_2 x_3\right) / \left(\sum_{i=1}^{3} x_i^2 - \sum_{i=1}^{3} x_i x_{\overline{i+1}}\right)$.

$$n=4;\quad x_1+x_2+x_3+x_4,\ \sum_{i=1}^{4} x_i^2-2(x_1x_3+x_2x_4)$$

$$\sum_{i=1}^{4} x_i^3-\sum_{i\neq j} x_i^2 x_j+2\,x_1x_2x_3x_4,\ -\sum_{i=1}^{4} x_i^2 x_{\overline{i+1}}+\sum_{i=1}^{4} x_i^2 x_{i+3}.$$

This shows that $L_n \cap k[x_1, x_2, \ldots, x_n]$ is purely transcendental integral domain over k, when $n=1, 2, 4$.

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