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RING-LOGICS AND CERTAIN CLASSES OF RINGS

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Introduction. Boolean rings $(B, \times, +)$ and Boolean logics $(=$ Boolean algebras) $(B, \cap, {}^*)$ though historically and conceptionally different, are equationally interdefinable in a familiar way [7]. With this equational interdefinability as motivation, Foster [1; 2] introduced and studied the theory of ring-logics. Indeed, let $(R, \times, +)$ be a commutative ring with unit 1, and let $K = \{\varrho_1, \varrho_2, \ldots\}$ be a transformation group in R. The *K-logic* of the ring $(R, \times, +)$ is the (operationally closed) system $(R, \times, \varrho_1, \varrho_2, \ldots)$ whose class R is identical with the class of ring elements, and whose operations are the ring product « $\times$ » together with the unary operations $\varrho_1, \varrho_2, \ldots$ of K. The ring $(R, \times, +)$ is called a *ring-logic*, mod K if (1) the « $+$ » of ring is *equationally* definable in terms of its K-logic $(R, \times, \varrho_1, \varrho_2, \ldots)$, and (2) the « $+$ » of the ring is *fixed* by its K-logic. The Boolean theory results from the special choice, for K, of the « Boolean group », C, generated by $x^* = 1 - x$ (order 2, $x^{**} = x$). Furthermore, by choosing K to be the « natural group », N, generated by $x^\wedge = 1 + x$, Foster showed [1] that a p-ring with unit is a ring-logic, mod N. Again, by choosing K to be the « normal group », D, where the generator $x^\cap$ of D is now no longer linear, Foster [2] was able to show that a p^k-ring with unit is a ring-logic, mod D. These results naturally suggest the following question: are the groups C, N, D, in any way related, and are they the only possible transformation groups with respect to which the corresponding rings are ring-logics? It turns out that for the class of all p^k-rings (and hence, in particular, for p-rings and Boolean rings) *any* transitive $0 \to 1$ permutation of $GF(p^k)$ induces a transformation group in the corresponding p^k-ring R with respect to which R is a ring-logic.

Indeed, x^*, $x^\wedge$, $x^\cap$ above are merely examples of some transitive $0 \to 1$ permutations of $GF(2)$, $GF(p)$, $GF(p^k)$, respectively, and these in turn induce the above transformation groups C, N, D, with respect to which the corresponding rings are ring-logics.

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1. **The Finite Field Case.** Let $(F_{p^k}, \times, +)$ be a (finite) Galois field with exactly p^k elements (p prime). Then, as is well known, $F_{p^k} = \{0, \zeta, \zeta^2, \ldots, \zeta^{p^k-1} (= 1)\}$ for some ζ in F_{p^k}. We now have the following

THEOREM 1. *Let F_{p^k} be a Galois field, and let ζ be a generator of F_{p^k}. Let $^{\cap} : x \rightarrow x^{\cap}$ be any permutation of F_{p^k}. Then $^{\cap}$ is expressible as a polynomial in x over F_{p^k}.*

PROOF. Denote the elements of F_{p^k} by $x_1, \ldots, x_n$ $(n = p^k)$, and denote $x_i^{\cap}$ by x_i' $(i = 1, \ldots, n)$. We shall show that $x^{\cap}$ can be written as

$$(1.1) \qquad x^{\cap} = a_0 + a_1 x + \ldots + a_{n-1} x^{n-1} \, (n = p^k)$$

for some $a_0, a_1, \ldots, a_{n-1}$ in F_{p^k}. Since $x_i^{\cap} = x_i'$ $(i = 1, \ldots, n)$, therefore, (1.1) gives n linear equations in the n unknowns $a_0, a_1, \ldots, a_{n-1}$. Now, the determinant of the coefficients of the a_i is the familiar VanderMonde determinant which, except possibly for sign, is equal to $\mathop{\Pi}\limits_{i,j=1,\, i>j}^{n} (x_i - x_j)$, and hence does not vanish since the x_i are *distinct* elements of F_{p^k}. Hence the above equations are solvable, and the theorem is proved.

We shall from now on be primarily concerned only with *transitive* $0 \rightarrow 1$ permutations of F_{p^k}. This simply means a permutation, $^{\cap}$, of F_{p^k} such that (i) $0^{\cap} = 1$, and (ii) for any given elements α, β in F_{p^k}, there exists an integer r such that $\alpha^{\cap^r} = \beta$, where $\alpha^{\cap^r} = (\ldots((\alpha^{\cap})^{\cap})\ldots)^{\cap}$ (r-iterations). We now have the following

THEOREM 2. *Let, $^{\cap}$, be any transitive $0 \rightarrow 1$ permutation of the Galois field F_{p^k}, and let K be the transformation group in F_{p^k} generated by, $^{\cap}$. Then the elements of F_{p^k} are equationally definable in terms of the K-logic $(F_{p^k}, \times, ^{\cap})$.*

PROOF. Since, $^{\cap}$, is a transitive permutation of F_{p^k}, therefore, $F_{p^k} = \{0, 0^{\cap}, 0^{\cap^2}, \ldots, 0^{\cap^{p^k-1}}\}$. A similar argument shows that, for any x in F_{p^k}, $x x^{\cap} x^{\cap^2} \ldots x^{\cap^{p^k-1}} = 0$. Hence 0 (and with it $0^{\cap}, 0^{\cap^2}, \ldots, 0^{\cap^{p^k-1}}$) is expressible in terms of the K-logic, and the theorem is proved.

We recall from [4] the *characteristic function* $\delta_\mu(x)$, defined as follows: for any given $\mu \in F_{p^k}$, $\delta_\mu(x) = 1$ if $x = \mu$, and 0 if $x \neq \mu$.

We now have the following

THEOREM 3. *Let F_{p^k}, K, $^{\cap}$, be as in Theorem 2. Then the characteristic functions $\delta_\mu(x)$, $\mu \in F_{p^k}$, are equationally definable in terms of the K-logic $(F_{p^k}, \times, ^{\cap})$.*

Proof. Since, $^\cap$, is a *transitive* $0 \longrightarrow 1$ permutation of F_{p^k}, therefore, $\mu^{\cap r} = 0$ for some integer r. Now, one readily verifies that, since $y^{p^k-1} = 1$, $y \neq 0$, $y \in F_{p^k}$, $\delta_\mu(x) = (((x^{\cap r})^{p^k-1})^{\cap p^k-1})^{p^k-1}$, and the theorem is proved.

Now, let, $^\cup$, denote the inverse of the $0 \longrightarrow 1$ transitive permutation, $^\cap$, and as in [2], define $a \times_\cap b = (a^\cap \times b^\cap)^\cup$. Then, $a \times_\cap 0 = a = 0 \times_\cap a$. Hence, we have the following « normal expansion formula » [4]

$$(1.2) \qquad f(x, y, \dots) = \sum_{\alpha, \beta, \dots, \in F_{p^k}}^{\times_\cap} f(\alpha, \beta, \dots)(\delta_\alpha(x)\,\delta_\beta(y) \dots).$$

In (1.2), $\alpha, \beta, \dots$ range independently over all the elements of F_{p^k} while $x, y, \dots$ are indeterminates over $F_{p^k} \cdot \sum\limits_{\alpha_i \in F}^{\times_\cap} \alpha_i$ denotes $\alpha_1 \times_\cap \alpha_2 \times_\cap \dots$, where $\alpha_1, \alpha_2, \dots$ are all the elements of F.

Theorem 4. *Let,* $^\cap$, *be any transitive* $0 \longrightarrow 1$ *permutation of the Galois field* F_{p^k}, *and let* K *be the transformation group in* F_{p^k} *generated by,* $^\cap$. *Then* $(F_{p^k}, \times, +)$ *is a ring-logic, mod* K.

Proof. By (1.2),

$$x + y = \sum_{\alpha, \beta \in F_{p^k}}^{x_\cap} (\alpha + \beta)(\delta_\alpha(x)\,\delta_\beta(y)).$$

Now, by Theorem 2 and Theorem 3, the right-side of the above equation equationally definable in terms of the K-logic $(F_{p^k}, \times, ^\cap)$. Hence the « - of F_{p^k} is *equationally* definable in terms of the K-logic. Next, we show th $(F_{p^k}, \times, +)$ is *fixed* by ist K-logic. Suppose that $(F_{p^k}, \times, +')$ is another ring with the same class of elements F_{p^k} and the same « $\times$ » as $(F_{p^k}, \times, +)$ and which has the *same logic* as $(F_{p^k}, \times, +)$. To prove that $+' = +$. But this follows since, up to isomorphism, there is *only one* Galois field with exactly p^k elements.

2. The General Case. In this section we shall extend the results of Theorem 4 to p-rings and p^k-rings by use of the familiar subdirect structure of these rings [6 ; 5]. Thus, suppose R is a commutative ring with unit 1, and suppose that p is a *prime* integer. R is called a *p-ring* [6] if $a^p = a$, $pa = 0$ for all a in R. Furthermore, R is called a *p^k-ring* [2] if $(i)\, a^{p^k} = a$, $pa = 0$ for all a in R, and (ii) R has a subring ($=$ field) F which is isomorphic to the Galois field F_{p^k} and where $1 \in F$. (Under a somewhat broader definition, p^k-rings were first introduced by McCoy [5]). Clearly, every

p-ring R with unit is a p^k-ring ($k = 1$) (in this case (i) implies (ii) in the above definition, since F can be chosen as the prime field of R). From [5], we now recall the following fundamental subdirect structure

THEOREM 5. *A p^k-ring is isomorphic to a subdirect power of the Galois field F_{p^k}.*

We are now in a position to prove the following

THEOREM 6. *Any p^k-ring R with unit is a ring-logic, mod K, where K is the transformation group in R induced by any transitive $0 \longrightarrow 1$ permutation, $^{\cap}$, of F_{p^k}.*

PROOF. By Theorem 5, R is isomorphic to a (not necessarily finite) subdirect power $F^m_{p^k}$ of F_{p^k}. Now, suppose $x = (x_1, x_2, \ldots)$ is any element in $R\,(= F^m_{p^k})$. Define $(x_1, x_2, \ldots)^{\cap} = (x_1^{\cap}, x_2^{\cap}, \ldots)$, and let K be the transformation group generated by, $^{\cap}$. We shall now show that $F^m_{p^k}$ is a ring-logic, mod K. Indeed, by Theorem 4, there exists a «logical expression» $\varphi(a, b; \times, ^{\cap})$ such that $a + b = \varphi(a, b; \times, ^{\cap})$ for all a, b in F_{p^k}. Since the operations are *component-wise* in $F^m_{p^k}$, therefore, for all x, y in $F^m_{p^k}\,(= R)$, we have $x + y = \varphi(x, y; \times, ^{\cap})$. Hence the « $+$ » of $F^m_{p^k}$ is equationally definable in terms of the K-logic. Next, we show that $F^m_{p^k}$ is fixed by its K-logic. Suppose that $(F^m_{p^k}, \times, +')$ is another ring with the same class of elements and the same « $\times$ » as $(F^m_{p^k}, \times, +)$ and which has the same logic as $(F^m_{p^k}, \times, +)$. To prove $+ = +'$. Now, a new « $+'$ » in $F^m_{p^k}$ defines and is defined by a new « $+'_i$ » in F_{p^k} ($= i$ — th component in $F^m_{p^k}$) such that $(F_{p^k}, \times, +'_i)$ is a ring, for each i. Furthermore, the assumption that $(F^m_{p^k}, \times, +')$ has the same logic as $(F^m_{p^k}, \times, +)$ is equivalent to the assumption that each $(F_{p^k}, \times, +'_i)$ has the same logic as $(F_{p^k}, \times, +)$. Since, by Theorem 4, $(F_{p^k}, \times, +)$ is a ring-logic, and hence with its « $+$ » fixed, therefore, $+'_i = +$ for each i. Hence $+' = +$, and the theorem is proved.

COROLLARY 7. *Any p-ring R with unit is a ring-logic, mod K, wehere K is the transformation group in R induced by any transitive $0 \longrightarrow 1$ permutation of F_p.*

This is the case $k = 1$ of Theorem 6.

It is noteworthy to observe that, since there is *only one* $0 \longrightarrow 1$ (transitive) permutation of F_2, the level of generality given in Theorem 6 and Corollary 7 is not apparent in the Boolean case.

Now, by choosing $a_0, a_1, \ldots, a_{p^k-1}$, in (1.1), in all of the $(p^k - 2)!$ available ways tho get *transitive* $0 \longrightarrow 1$ permutations of F_{p^k}, we obtain the corresponding transformation groups with respect to which a p^k-ring is a ring-logic. Thus, if in (1.1) we choose, $x^{\cap} = 1 - x \, (p^k = 2^1)$, we recover the generator x^* of the Boolean group C (see introduction). Similarly, if we set $x^{\cap} = 1 + x \, (p^k = p)$ in (1.1), we obtain the generator $x^{\wedge}$ of the natural group N. Finally, by selecting the a_i in (1.1) so that $0^{\cap} = 1, 1^{\cap} = \zeta$, $\zeta^{\cap} = \zeta^2, \ldots, (\zeta^{p^k-3})^{\cap} = \zeta^{p^k-2}, (\zeta^{p^k-2})^{\cap} = 0$, where ζ is a generator of F_{p^k}, we obtain the generator $x^{\cap}$ of the normal group D (see [2]). Hence, we have proved, as a further corollary of Theorem 6, the following theorem which contains Foster's results [1 ; 2] (see also [8]):

COROLLARY 8. (i) *Any Boolean ring with unit is a ring-logic, mod C;* (ii) *any p-ring with unit is a ring-logic, mod N;* (iii) *any p^k-ring with unit is a ring-logic, mod D; where C, N, D, are the Boolean group, natural group, and normal group, respectively.*

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