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STRONGLY π -REGULAR RINGS

By

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ARENS-KAPLANSKY [1] and KAPLANSKY [3] investigated, as generalizations of algebraic algebras and rings with minimum condition, following two types of rings: one is a π -regular ring, that is, a ring in which for every element a there exists an element x and a positive integer n such that $a^n x a^n = a^n$, and the other is a ring in which for every a there exists an x and an n such that $a^{n+1} x = a^n$ — this we shall call a right π -regular ring. The present note is devoted mainly to study the latter more precisely. Apparently, the two notions of π -regularity and right π -regularity are different ones in general. However we can prove, among others, that under the assumption that a ring is of bounded index (of nilpotency) it is π -regular if and only if it is right π -regular. Moreover, we shall show, in this case, that we may find, for every a , an element z such that $az = za$ and $a^{n+1} z = a^n$, where n is the least upper bound of all indices of nilpotency in the ring. This is obviously a stronger result than a theorem of KAPLANSKY (2) as well as that of GERTSCHIKOFF (3), both of which are stated in section 8 of KAPLANSKY [3].

1. **Strong regularity.** Let A be a ring. Let a be an element of A . a is called *regular* (in A) if there exists an element x of A such that $axa = a$, while a is said to be *right* (or *left*) *regular* if there exists x such that $a^2 x = a$ (or $x a^2 = a$). Further, we call a *strongly regular* if it is both right regular and left regular.

Lemma 1. *Let a be a strongly regular element of A . Then there exists one and only one element z such that $az = za$, $a^2 z (= z a^2) = a$ and $az^2 (= z^2 a) = z$, and in particular a is regular. For any element x such that $a^2 x = a$, z coincides with ax^2 . Moreover, z commutes with every element which is commutative with a .*

Proof. Let x, y be two elements such that $a^2 x = a$, $ya^2 = a$. Then

$$(1) \quad ax = ya^2 x = ya,$$

so that

$$(2) \quad ax^2 = yax = y^2a.$$

From (1) we have also

$$(3) \quad axa = ya^2 = a = a^2x = aya.$$

Now put $z = ax^2$. It follows then from (1), (2), (3) that $az = ayax = ax = ya = yaxa = za$, $a^2z = aza = axa = a$, $az^2 = yaz = yax = z$, as desired.

Suppose next z' be any element which satisfies the same equalities as z : $az' = z'a$, $a^2z' = a$, $az'^2 = z'$. Then, by replacing x, y in (2) by z, z' respectively, we get $z = az^2 = z'^2a = z'$, showing the uniqueness of z .

For the proof of the last assertion, let c be any element such that $ac = ca$. Then we have first $zac = zca = zca^2z = za^2cz = acz = caz$, i.e., c commutes with $za = az$. It follows from this now $zc = z^2ac = zcza = zac = czaz = cz$, and this completes our proof.

Lemma 2. *Let a be a right regular element of A and let $a^2x = a$. Then, for any positive integer n , we have*

$$(a - ax^n a^n)^r = \begin{cases} a^r - ax^{n-r+1} a^n, & r = 1, 2, \dots, n, \\ 0, & r = n+1. \end{cases}$$

Proof. Since the assertion is valid for $r=1$, we may proceed by induction on r (for fixed n). Suppose $r \leq n$ and our lemma holds for r :

$$(a - ax^n a^n)^r = a^r - ax^{n-r+1} a^n.$$

Right-multiplying by $a - ax^n a^n$ and using the relation $a^{n+1} x^n = a$, which follows immediately from $a^2 x = a$, we have $(a - ax^n a^n)^{r+1} = a^{r+1} - a^{r+1} x^n a^n - ax^{n-r+1} a^{n+1} + ax^{n-r+1} a^{n+1} x^n a^n = a^{r+1} - a^{r+1} x^n a^n$. But when $r < n$ $a^{r+1} x^n = a^{r+1} x^r x^{n-r} = a^{r-n}$, while when $r = n$ $a^{r+1} x^n = a^{n+1} x^n = a$. This completes our induction.

Now A is called a ring of *bounded index* if indices of nilpotency of all nilpotent elements of A are bounded; and, in this case, the least upper bound of all indices of nilpotency is called the *index* of A . (Cf. JACOBSON [2], KAPLANSKY [3].) We can now prove the fundamental

Theorem 1. *Let A be a ring of bounded index. Then every right regular element of A is (left whence) strongly regular.*

Proof. Let n be the index of A . Let A be any right regular element of A : $a^2 x = a$. Then, since $(a - ax^n a^n)^{n+1} = 0$ by Lemma 2, we must have $(a - ax^n a^n)^n = 0$. On the other hand, $(a - ax^n a^n)^n = a^n - axa^n$ by the same lemma, and we obtain $a^n - axa^n = 0$. Apply furthermore Lemma 2 to $n+1$ instead of n . Then $(a - ax^{n+1} a^{n+1})^{n+1} = a^{n+1} - axa^{n+1} = a(a^n - axa^n)$

$=0$, and so $(a-ax^{n+1}a^{n+1})^n=0$. But $(a-ax^{n+1}a^{n+1})^n=a^n-ax^2a^{n+1}$ again by Lemma 2. Hence it follows $a^n=ax^2a^{n+1}$. Right-multiply now by ax^n and make use of the relation $a^{n+1}x^n=a$. Then we find finally $a=ax^2a^2$, which shows the left regularity of a .

In connection with the preceding theorem, we want to add the following theorem, although we shall not need it later:

Theorem 2. *Let a be a right regular element of A . Then a is strongly regular if and only if $r(a^2)=r(a)$, where $r(\cdot)$ denotes the set of all right annihilators.*

Proof. The "only if" part is easy to see. So we have only to prove the "if" part. The right regularity of a implies $a^2A=aA$. The mapping $u \rightarrow au$ ($u \in aA$) gives therefore an operator-homomorphism of the right ideal aA onto itself. Moreover, this is an isomorphism because the kernel is zero by the assumption $r(a^2)=r(a)$. Let φ be the inverse mapping of it; φ is also an operator-isomorphism of aA onto itself. Since $a \in (a^2A=a)A$ we have in particular $\varphi a^2=a$. From this it follows $(\varphi^2 a)a^2 = \varphi(\varphi a^2)a = \varphi a^2 = a$, showing the left regularity of a .

Remark. VON NEUMANN called A a *regular ring* if every element of A is regular, while ARENS-KAPLANSKY [1] defined A to be a *strongly regular ring* when every element is right regular. However, it was shown in above paper that if A is strongly regular then every element of A is indeed strongly regular; this follows also from our Theorem 1 directly, since a strongly regular ring A has evidently no non-zero nilpotent element. This fact justifies our definition of strong regularity for elements.

2. Strong π -regularity. Let us call an element a of A *π -regular*, *right π -regular*, or *left π -regular* if a suitable power of a is regular, right regular, or left regular respectively. Furthermore we call a *strongly π -regular* if it is both right π -regular and left π -regular. Now it can readily be seen that a power a^n of a is right (or left) regular if and only if there exists an element x such that $a^{n+1}x=a^n$ (or $xa^{n+1}=a^n$). On the other hand, we have

Lemma 3. *Let x, y satisfy $a^{n+1}x=a^n, ya^{m+1}=a^m$ for some n, m . Then they satisfy $a^{m+1}x=a^m, ya^{n+1}=a^n$ too.*

Proof. When $m \geq n$ $a^{m+1}x=a^m$ follows immediately from $a^{n+1}x=a^n$. Suppose now $m < n$. Then $a^m=ya^{m+1}$ implies $a^m(=y^2a^{m+2}=\dots)=y^{n-m}a^n$, and so we obtain $a^{m+1}x=y^{n-m}a^{n+1}x=y^{n-m}a^n=a^m$. Similarly, we can verify the validity of $ya^{n+1}=a^n$.

Now we prove

Theorem 3. *Let a be a strongly π -regular element of A . Suppose that a^n is right regular. Then a^n is in fact strongly regular, and moreover there exists an element z such that $az=za$ and $a^{n+1}z=a^n$.*

Proof. That a^n is strongly regular is an immediate consequence of Lemma 3. Now from Lemma 1 it follows that there exists an element z such that $a^{2n}z=a^n$ and z commutes with every element which is commutative with a^n ; however the latter condition implies, since a is commutative with a^n , that $az=za$. Denoting $a^{n-1}z$ again by z , z is evidently the desired element.

Corollary. *Strongly π -regular element is π -regular.*

Now we define the *index* of a strongly π -regular element a as the least integer n such that a^n is right regular. By Lemma 3, the index n is characterized also as the least integer such that a^n is left regular. It is to be noted further that every nilpotent element is strongly π -regular and its index of nilpotency coincides with the index in the sense defined above, as can be seen quite easily. Furthermore we have

Lemma 4. *Let a be a strongly π -regular element of index n , and z an element such that $az=za$ and $a^{n+1}z=a^n$ (as in Theorem 3). Then $a-a^2z$ is a nilpotent element of index n .*

Proof. Since $az=za$ we have the following binomial expansion:

$$(a-a^2z)^n = a^n - \binom{n}{1}a^{n+1}z + \binom{n}{2}a^{n+2}z^2 - \dots + (-1)^na^{2n}z^n.$$

But $a^n=a^{n+1}z$ implies $a^n=a^{n+2}z^2=\dots=a^{2n}z^n$. Hence we get

$$(a-a^2z)^n = a^n - \binom{n}{1}a^n + \binom{n}{2}a^n - \dots + (-1)^na^n = (a-a)^n = 0.$$

On the other hand, $(a-a^2z)^{n-1}$ is, again by a binomial expansion, say, expressible in a form $a^{n-1}-a^nx$ with some x ; but this is certainly not zero because a is of index n . Thus, the index of $a-a^2z$ is exactly n .

We now obtain from Theorems 1, 3 and Lemma 4 immediately the following

Theorem 4. *Let A be a ring of bounded index (of nilpotency). Then every right π -regular element of A is strongly π -regular and its index does not exceed the index of A .*

Above results show us in fact the appropriateness of our definition of index for strongly π -regular elements. This is strengthened further by the following

Remark. Suppose that A is (not necessarily finite dimensional) algebra over a field K . Let a be an algebraic element of A , and $\mu(\lambda)$ the minimum polynomial of a (without constant term). JACOBSON [2] defined the index of a as the largest integer r such that λ^r divides $\mu(\lambda)$. Now we want to show that a is then strongly π -regular and (the Jacobson index) r coincides with the index in our sense. For the proof, we may assume, since λ^r divides exactly $\mu(\lambda)$, that $\mu(\lambda)$ is of the form $\lambda^r + \alpha_1 \lambda^{r+1} + \alpha_2 \lambda^{r+2} + \dots$ (with $\alpha_1, \alpha_2, \dots$ in K). It follows then $\alpha_1 \lambda \mu(\lambda) = \alpha_1 \lambda^{r+1} + \alpha_1^2 \lambda^{r+2} + \dots$, and so we have $\mu(\lambda) - \alpha_1 \lambda \mu(\lambda) = \lambda^r + (\alpha_2 - \alpha_1^2) \lambda^{r+2} + \dots = \lambda^r - \lambda^{r+1} \nu(\lambda)$, where $\nu(\lambda) = (\alpha_1^2 - \alpha_2) \lambda + \dots$ is also a polynomial. Since now $\mu(\lambda)$ has a for a root, so does $\mu(\lambda) - \alpha_1 \lambda \mu(\lambda)$ too, i.e., we have $a^r = a^{r+1} \nu(a)$, which shows the strong π -regularity of a . Let n be the index of a (as strongly π -regular element). Then $n \leq r$, and moreover we have from Lemma 3 that $a^n = a^{n+1} \nu(a)$, that is, a is a root of the polynomial $\lambda^n - \lambda^{n+1} \nu(\lambda)$. Since $\mu(\lambda)$ is the minimum polynomial of a , the latter must be divisible by $\mu(\lambda)$, and this implies in particular that $n \geq r$, proving our assertion.

Now we say that a ring A is π -regular, right π -regular, left π -regular, or strongly π -regular if so is every element of A respectively. (Cf. KAPLANSKY [3].) Evidently A is strongly π -regular if and only if it is both right π -regular and left π -regular. Moreover, strong π -regularity of A implies π -regularity of A , according to Corollary of Theorem 3. However, the converse is also true provided A is assumed to be of bounded index. Namely, we have

Theorem 5. Under the assumption that A is of bounded index, the following four conditions are equivalent to each other:

- i) A is π -regular,
- ii) A is right π -regular,
- iii) A is left π -regular,
- iv) A is strongly π -regular.

Proof. That ii) implies iv) is a direct consequence of Theorem 4. By right-left symmetry, iii) implies also iv). Therefore we have only to prove that ii) follows from i).

Suppose that A is a π -regular ring of index n . Let a be an element of A . Then a^n is π -regular, that is, there exists an integer $n' (\geq 1)$ such that $a^{nn'}$ is regular. Put $r = nn'$. Then $r \geq n$ and there exists an element x such that $a^r x a^r = a^r$. Write $e = a^r x$. Then e is an idempotent and satisfies $eA = a^r A$. Similarly, the π -regularity of, say, a^{r+1} implies the existence of an integer s and an idempotent f such that $s > r$ and fA

$=\alpha^s A$. Since then $\alpha^r A \supset \alpha^s A$, fA is necessarily a direct summand right subideal of eA . Hence we can construct, as is well-known, two orthogonal idempotents f_1 and g such that $e=f_1+g$ and $f_1 A=fA(=\alpha^s A)$. Now take any primitive ideal P of A . By KAPLANSKY [3, Theorem 2.3] the residue class ring $\bar{A}=A/P$ is a (full) matrix ring over a division ring of degree at most n . Denote by \bar{a} the residue class of a modulo P , and consider the chain of right ideals $\bar{A} \supset \bar{a}\bar{A} \supset \bar{a}^2\bar{A} \supset \dots$. It follows then, since the degree of the simple ring \bar{A} is equal to the composition length for right ideals of \bar{A} , that $\bar{a}^n\bar{A}=\bar{a}^{n+1}\bar{A}=\dots$, and we have in particular $\bar{a}^r\bar{A}=\bar{a}^s\bar{A}$. Write further by \bar{e} , \bar{f}_1 , \bar{g} the residue classes of e , f_1 , g modulo P respectively. Then $\bar{e}\bar{A}=\bar{a}^r\bar{A}$, $\bar{f}_1\bar{A}=\bar{a}^s\bar{A}$ whence $\bar{e}\bar{A}=\bar{f}_1\bar{A}$. On the other hand, $\bar{e}=\bar{f}_1+\bar{g}$ and \bar{f}_1 , \bar{g} are orthogonal demp- tentents; hence $\bar{e}\bar{A}$ is the direct sum of $\bar{f}_1\bar{A}$ and $\bar{g}\bar{A}$: $\bar{e}\bar{A}=\bar{f}_1\bar{A} \oplus \bar{g}\bar{A}$. This implies evidently that $\bar{g}\bar{A}=0$, i.e., $\bar{g}=0$ or $g \in P$. This is the case for every primitive ideal P , and so g must lie in the intersection of all P 's i.e. the (Jacobson) radical of A . If we observe however that 0 is the only quasi-regular idempotent, it follows indeed $g=0$, and this shows that $\alpha^r A(=eA=f_1 A)=\alpha^s A$ whence $\alpha^r A=\alpha^{r+1} A$. The latter equality implies, since $\alpha^r=\alpha^r \alpha \alpha^r$ is in $\alpha^r A$, the right π -regularity of α . Thus, the proof of our theorem is concluded.

Remark. The radical of a π -regular ring as well as that of a right π -regular ring is always a nil-ideal, as was shown in KAPLANSKY [3, section 2] and ARENS-KAPLANSKY [1, Theorem 3.1]; the assumption in the latter that (the right π -regular ring) A is of bounded index being superfluous for proving our assertion.

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