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ADJOINING A UNIVERSAL INNER INVERSE TO A RING ELEMENT

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Abstract. Let R be an associative unital algebra over a field k, let p be an element of R, and let $R' = R\langle q \mid pqp = p\rangle$. We obtain normal forms for elements of R', and for elements of R'-modules arising by extension of scalars from R-modules. The details depend on where in the chain $pR \cap Rp \subseteq pR \cup Rp \subseteq pR + Rp \subseteq R$ the unit 1 of R first appears.

This investigation is motivated by a hoped-for application to the study of the possible forms of the monoid of isomorphism classes of finitely generated projective modules over a von Neumann regular ring; but that goal remains distant.

We end with a normal form result for the algebra obtained by tying together a k-algebra R given with a nonzero element p satisfying $1 \notin pR+Rp$ and a k-algebra S given with a nonzero q satisfying $1 \notin qS+Sq$, via the pair of relations $p = pqp$, $q = qpq$.

1. Motivation: monoids of projective modules

It is known that the abelian monoid of isomorphism classes of finitely generated projective modules over a general ring is subject to no nonobvious restrictions – the obvious restrictions being

(1) no two nonzero elements of the monoid have sum zero,

and

(2) the monoid has an element u such that every element is a summand in nu for some positive integer n.

(Namely, u is the isomorphism class of the free module of rank 1.)

Indeed, every abelian monoid M satisfying (1) and (2) is known to be the monoid of finitely generated projective modules of some hereditary k-algebra, for any field k. (This was proved for finitely generated M in [9, Theorem 6.2], while Theorem 6.4 of that paper claimed to show that if one weakened 'hereditary' to 'semihereditary', the assumption that M was finitely generated could be dropped. The argument indeed gave a k-algebra R having M as its monoid of finitely generated projectives, but the proof that R was semihereditary was incorrect. However, in [11, Theorem 3.4] it is shown that the R so constructed is not merely semihereditary, but hereditary. For a similar result, see [3, Corollary 4.5].)

Recall that a ring R is called *von Neumann regular* if every element $p \in R$ has an *inner inverse*, that is, an element $q \in R$ satisfying $pqp = p$. The monoid of isomorphism classes of finitely generated projective modules over a von Neumann regular ring is known to satisfy not only (1) and (2), but a strong additional restriction, the *Riesz refinement property* [6]:

(3) If $A_0 \oplus A_1 \cong B_0 \oplus B_1$, then there exist C_{ij} $(i, j \in \{0,1\})$ such that $A_i \cong C_{i0} \oplus C_{i1}$ and $B_i \cong C_{0i} \oplus C_{1i}$;

that is, any such isomorphism $A_0 \oplus A_1 \cong B_0 \oplus B_1$ can be written in the trivial form

$$(4) \qquad (C_{00} \oplus C_{01}) \oplus (C_{10} \oplus C_{11}) \cong (C_{00} \oplus C_{10}) \oplus (C_{01} \oplus C_{11}).$$

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Until a couple of decades ago, it was an open question whether (1)-(3) completely characterized the monoids of finitely generated projectives of von Neumann regular rings. Then F. Wehrung [17] constructed a monoid of cardinality $\aleph_2$ satisfying (1)-(3) which cannot occur as such a monoid of projectives. More recently, he has given an example of a *countable* monoid satisfying (1)-(3) which does not occur in this way for any von Neumann regular algebra over an *uncountable* field [1, §4]. It remains open whether every *countable* monoid satisfying (1)-(3) is the monoid of finitely generated projectives of *some* von Neumann regular ring.

But there is in fact a strong condition, not implied by (1)-(3), which is not known to fail in any von Neumann regular ring:

(5) $\quad A \oplus A \cong A \oplus B \cong B \oplus B \implies A \cong B.$

An abelian monoid satisfying (5). is called *separative*. A positive answer to the question of whether the monoid of finitely generated projectives of every von Neumann regular ring is separative would solve several other questions about such rings [6]. We remark that it is known [18], [2, §4] that every monoid satisfying (1) and (2) can be embedded in one that also satisfies (3) (which can be taken countable if the original monoid was). Hence, applying this to monoids for which (5) fails, one sees that there do exist abelian monoids satisfying (1)-(3) but not (5). For more on these questions, see [1], [2], [4], [5], [6].

Now it is known that many universal constructions on k-algebras make only "obvious" changes in the structure of the monoid of finitely generated projectives [8], [9], [11]. This suggests that to investigate the possible structures of those monoids for von Neumann regular k-algebras, we could start with a general k-algebra, recursively adjoin universal inner inverses to its elements till it becomes von Neumann regular, and see what conditions this process forces on the monoid of projectives.

That plan has not proved as easy as I hoped. We obtain below normal forms for elements of the k-algebra $R' = R\langle q \mid pqp = p\rangle$ and for elements of modules $M \otimes_R R'$; but it is not clear whether these can be used to get useful results on isomorphism classes of modules.

The descriptions of the algebra R' will show surprising differences, depending on how near to invertible the element $p \in R$ to which we adjoin a universal inner inverse is. Below, we begin with a case that is challenging enough to illustrate our method without being excessively difficult, the case where p is farthest from invertible, namely, where $1 \notin pR + Rp$ (§3). We then quickly cover the easy cases where $1 \in pR$ and/or $1 \in Rp$, i.e., where p is left or right invertible, or both (§7). Finally, we treat the surprisingly difficult intermediate case where $1 \in pR + Rp$, but $1 \notin pR \cup Rp$ (§9). We also examine the particular instance of this construction where R is the Weyl algebra (§11). The last main results of the paper (§12) concern a variant of the above constructions, in which the pair of relations $pqp = p$, $qpq = q$, is used to join together two given k-algebras.

For reasons to be noted in §6, the difficult results of §9 (and the easy results of §7) may be less useful than the results of §3; so some readers may wish to skip or skim them. A list of the sections of this note containing the most important material, in this light, along with some others, noted in curly brackets, that are less essential but not very difficult, is: §§2 3 {4} 5 {6 7} 12 {13}.

Incidentally, though, as noted above, there exist monoids satisfying conditions (1)-(3) but not condition (5), no "concrete" examples of such monoids appear to be known, but only constructions which obtain them by starting with a monoid satisfying neither (3) nor (5), universally adjoining elements C_{ij} as required by (3), and repeating this construction transfinitely – i.e., the analog of the way non-separative von Neumann regular rings might be constructed if the plan suggested above is successful. It would, of course, be of interest to have concrete examples in both the monoid and the algebra situations.

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2. Generalities

All rings will here be associative with unit; and the rings for which we will study the construction of universal inner inverses will be algebras over a fixed field k. If R is a nonzero k-algebra, we will identify the k-subspace of R spanned by 1 with k.

I am using the term "inner inverse" (at the advice of T. Y. Lam) for what I had previously known as a "quasi-inverse", since the latter term also has a different, better-established sense. (Elements x and y of a not necessarily unital ring R are called quasi-inverses in that sense if $xy = yx = -x - y$; in other words, if on adjoining a unit to R, one gets mutually inverse elements $1+x$ and $1+y$. We will not consider that concept here. On the other hand, the choice of the letter q for universal inner inverses below is based on my having used "quasi-inverse" in early drafts of this note, while the element whose inner inverse we are adjoining will be denoted p because of the visual matching of the shapes of these two letters.)

Note that if R is a ring of endomorphisms of an abelian group A, then an inner inverse of an element $p \in R$ is an endomorphism q that takes every member of the image of p to some inverse image under p of that element, with no restriction on what it does to elements not in the image of p. From this it is easy to show that in the algebra of endomorphisms of any k-vector space, every element has an inner inverse; so such algebras are examples of von Neumann regular rings.

The relation "is an inner inverse of" is not symmetric: if q is an inner inverse of p, p need not be an inner inverse of q. For example, any element of any ring is an inner inverse of 0, but 0 is not an inner inverse of any nonzero element. However, if an element p has an inner inverse q, we find that $q' = qpq$ is an inner inverse of p such that p *is* an inner inverse of q'. Thus, the condition that an element of a ring have an inner inverse is equivalent to the condition that it have a "mutual inner inverse". Even when both relations $pqp = p$ and $qpq = q$ hold, however, p does not uniquely determine q. For instance, in the ring $M_2(R)$ of 2×2 matrices over any ring R, any two members of $\{e_{11} + re_{12} \mid r \in R\}$ are inner inverses of one another.

Our normal form results for algebras constructed by adjoining universal inner inverses will be proved using the ring-theoretic version of the Diamond Lemma, as developed in [10, §1]. However, where in [10] I formalized reduction rules as ordered pairs (W, f), with W a word in our given generators, and f a linear combination of words, to be substituted for occurrences of W as subwords of other words, I here use the more informal notation "$W \mapsto f$". (Another formulation of the Diamond Lemma appears as [12, Proposition 1]. Bokut' [13], [14] refers to it as "the method of Gröbner-Shirshov bases".)

Given a k-algebra R and an element $p \in R$, our construction of a normal form for elements of $R\langle q \mid pqp = p\rangle$ will start with a k-basis for R, which we shall want to choose in a way that allows us to see which elements of R are left and/or right multiples of p. In describing such a basis, it will be convenient to use

Definition 1. *If $U \subseteq V$ are k-vector-spaces, then a k-*basis of V relative to U *will mean a subset $B \subseteq V$ with the property that every element of V can be written uniquely as the sum of an element of U and a k-linear combination of elements of B.*

Thus, the general basis of V relative to U can be obtained by choosing a basis B' of V/U, and selecting one inverse image in V of each element of B'; or, alternatively, by choosing any direct-sum complement to U in V, and taking a basis of that complement. Clearly, the union of any k-basis of U and any k-basis of V relative to U is a k-basis of V.

Lemma 2. *Suppose V_1, V_2 are subspaces of a vector space W, and let B_0 be a basis of $V_1 \cap V_2$, B_1 a basis of V_1 relative to $V_1 \cap V_2$, and B_2 a basis of V_2 relative to $V_1 \cap V_2$.*

Then B_0, B_1, and B_2 are disjoint, and their union is a basis of $V_1 + V_2$. (Hence B_1 is also a basis of $V_1 + V_2$ relative to V_2, and B_2 a basis of $V_1 + V_2$ relative to V_1.)

Hence if, further, B_3 is a basis of W relative to $V_1 + V_2$, then $B_0 \cup B_1 \cup B_2 \cup B_3$ is a basis of W.

Proof. The disjointness of B_0, B_1, and B_2 is immediate. The fact that B_2 is a basis of V_2 relative to $V_1 \cap V_2$ means that its image in $V_2/(V_1 \cap V_2)$ is a basis thereof. But $V_2/(V_1 \cap V_2) \cong (V_1 + V_2)/V_1$, so B_2 is also a basis of $V_1 + V_2$ relative to V_1, hence its union with the basis $B_0 \cup B_1$ of V_1 is a basis of $V_1 + V_2$, giving the first assertion, and, in the process, the parenthetical note that follows it. The final assertion is then immediate. □

3. A normal form for $R\langle q \mid pqp = p\rangle$ when $1 \notin pR + Rp$.

Here is the situation we will consider first:

(6) In this section, R will be a k-algebra, and p a fixed element of R such that $1 \notin pR + Rp$. (So in particular, R is nonzero.)

Under this assumption, I claim we can take a k-basis of R of the form

(7) $$B \cup \{1\} \;=\; B_{++} \cup B_{+-} \cup B_{-+} \cup B_{--} \cup \{1\},$$

where

(8)
B_{++} is any k-basis of $pR \cap Rp$ which, if $p \neq 0$, contains p,
B_{+-} is any k-basis of pR relative to $pR \cap Rp$,
B_{-+} is any k-basis of Rp relative to $pR \cap Rp$,
B_{--} is any k-basis of R relative to $pR + Rp + k$.

(Mnemonic: a $+$ on the left signals left divisibility by p, a $+$ on the right, right divisibility.)

Indeed, let B_{++}, B_{+-}, B_{-+}, B_{--} be sets as in (8). By Lemma 2, $B_{++} \cup B_{+-} \cup B_{-+}$ will be a k-basis of $pR + Rp$. By assumption, $1 \notin pR + Rp$, so $B_{++} \cup B_{+-} \cup B_{-+} \cup \{1\}$ is a k-basis of $pR + Rp + k$. Hence bringing in the k-basis B_{--} of R relative to that subspace gives us a k-basis of R.

Below, we will typically denote an element of B by a letter such as x. However, when such an element is specified as belonging to $B_{++} \cup B_{+-}$ (respectively, to $B_{++} \cup B_{-+}$), we shall often find it useful to write it in a form such as px (respectively, xp). Note that if p is a zero-divisor in R, the x in such an expression will not be uniquely determined. We could assume one such representation fixed for each member of $B_{++} \cup B_{+-}$, but we shall not find this necessary; rather, the uses to which we shall put such expressions will not depend on the choice of x. In particular, note that given elements $xp \in Rp$ and $py \in pR$, the value of xpy depends only on the elements xp and py, not on the choices of x and y. For if $xp = x'p$ and $py = py'$, then $xpy = x'py = x'py'$.

In the case of elements specified as belonging to B_{++}, we will often use three representations, $x = x'p = px''$.

The construction of a normal form for $R\langle q \mid pqp = p\rangle$ in this section, and of similar normal forms in subsequent sections, involves considerations both of *elements* of k-algebras, and of *expressions* for such elements. We shall tread the thin line between ambiguity and cumbersome notation by making

Convention 3. *Throughout this note, when we consider a k-algebra S generated by a set G, an* expression *for an element $s \in S$ will mean an element of the free k-algebra $k\langle G\rangle$ which maps to s under the natural homomorphism $k\langle G\rangle \to S$. A* word *or* monomial *will mean a member of the free monoid generated by G in $k\langle G\rangle$. Thus, in descriptions of reductions $W \mapsto f$, the word W and the expression f are understood to lie in $k\langle G\rangle$.*

A family of words will be said to give a k-basis for S *if the k-subspace of $k\langle G\rangle$ spanned by that family maps bijectively to S under the above natural homomorphism; in other words, if the family is mapped one-to-one into S, and its image is a k-basis of S.*

We shall use the same symbols for elements of $k\langle G\rangle$ and their images in S, distinguishing these by context: in descriptions of normal forms and reductions, our symbols will denote elements of $k\langle G\rangle$, while in statements that a relation *holds in S, they will denote elements of S.*

In the situation at hand, the outputs of our reductions for $R\langle q \mid pqp = p\rangle$ will often have to be expressed in terms of the operations of R. For this purpose, we make the notational convention that for any k-algebra expression f for an element of R, we shall write f_R for the unique k-linear combination of elements of $B \cup \{1\}$ which gives the value of f in R. (Thus, when we come to reductions (12) and (13) below, the inputs will be words of lengths 2 and 3 respectively, while the outputs, by this notational convention, are k-linear combinations of words of lengths ≤ 1.)

Note also that since the monomials that span the free algebra $k\langle B \cup \{q\}\rangle$ include the empty word 1, and none of the reductions we will give has 1 as its input, 1 will belong to the k-basis described in the theorem.

We can now state and prove our normal form.

Theorem 4. *Let R be a k-algebra, p an element of R such that $1 \notin pR + Rp$, $B \cup \{1\}$ a k-basis of R as in* (7) *and* (8) *above, and*

(9) $\quad R' \;=\; R\langle q \mid pqp = p\rangle,$

the k-algebra gotten by adjoining to R a universal inner inverse q to p.

Then R' has a k-basis given by the set of those words in the generating set $B \cup \{q\}$ that contain no subwords of the form

(10) $\quad xy \quad$ *with* $x, y \in B$

nor

(11) $\quad (xp)\,q\,(py) \quad$ *with* $xp \in B_{++} \cup B_{-+}$ *and* $py \in B_{++} \cup B_{+-}$.

The reduction to the above normal form may be accomplished by the systems of reductions

(12) $\quad xy \ \mapsto\ (xy)_R \quad$ *for all* $x, y \in B$,

and

(13) $\quad (xp)\,q\,(py) \ \mapsto\ (xpy)_R \quad$ *for all* $xp \in B_{++} \cup B_{-+},\ py \in B_{++} \cup B_{+-}$.

Proof. Clearly, R' is generated as a k-algebra by $B \cup \{q\}$, and we see that the relations

(14) $\quad xy \ =\ (xy)_R \quad$ for x, y as in (12)

and

(15) $\quad (xp)\,q\,(py) \ =\ (xpy)_R \quad$ for $xp,\ py$ as in (13)

do hold in R'. Moreover, these relations are sufficient to define R' in terms of our generators. Indeed the relations (14) constitute a presentation of R; to get the additional relation $pqp = p$ of (9), note that if $p = 0$ this is vacuous, while if $p \neq 0$, it is the case of (15) where $xp = p = py$.

Since (14) and (15) give a presentation of R', the statement of the Diamond Lemma in [10, Theorem 1.2] tells us that the reductions (12) and (13) will yield a normal form for R' if, first of all, they satisfy an appropriate condition guaranteeing that repeated applications of these reductions to any expression eventually terminate, and if, moreover, every "ambiguity", in the sense of [10], is "resolvable".

The first of these conditions is immediate, since each of our reductions replaces a word by a linear combination of shorter words; so the partial ordering on the set of all words which makes shorter words "$<$" longer words, and distinct words of equal length incomparable, is, in the language of [10], a semigroup partial ordering that is compatible with our reduction system, and has descending chain condition.

To show that all ambiguities are resolvable, we note that there are four sorts of ambiguously reducible words (notation explained below):

(16) $\quad x \cdot y \cdot z, \quad$ where $x, y, z \in B$,

(17) $\quad (xp)\,q \cdot (py) \cdot z, \quad$ where $xp \in B_{++} \cup B_{-+},\ py \in B_{++} \cup B_{+-},\ z \in B$,

(18) $\quad x \cdot (yp) \cdot q\,(pz), \quad$ where $x \in B,\ yp \in B_{++} \cup B_{-+},\ pz \in B_{++} \cup B_{+-}, \quad$ and

(19) $\quad (xp)\,q \cdot y \cdot q\,(pz), \quad$ where $xp \in B_{++} \cup B_{-+},\ y = py' = y''p \in B_{++},\ pz \in B_{++} \cup B_{+-}$.

In each of these words, I have placed dots so as to indicate the two competing reductions applicable to the word in question, namely, the application of one of the reductions (12) or (13) to the product of the two strings of generators surrounding the first dot, and the application of another such reduction to the product of the two strings surrounding the second dot. For example, in (17) we can either reduce $(xp)\,q\,(py)$ using (13), or reduce $(py)z$ using (12).

In each case, each of our two competing reductions will, as noted, turn the indicated expression into a k-linear combination of shorter words. Most of these new words are in turn subject to a second reduction. (The exceptions are those that arise from an occurrence of the empty word, 1, in the output of the first reduction.) I claim that for each of (16)-(19), after these reductions are complete, the two resulting expressions are equal; namely, that we get $(xyz)_R$, $(xpyz)_R$, $(xypz)_R$ and $(xyz)_R$, respectively.

I will show this first, in detail, for the simplest case, (16), then in outline for the most complicated case, (19), then note briefly what happens in the intermediate cases (17) and (18).

In the case of (16), let

(20) $\quad (xy)_R \ =\ \sum_{u \in B \cup \{1\}} \alpha_u u \ \ (\alpha_u \in k)$.

Thus, the result of the "left-hand" reduction of $x \cdot y \cdot z$ is $\sum_{u \in B \cup \{1\}} \alpha_u u\, z$. Now for $u = 1$, the empty string, we have $uz = z$, which we can write $(uz)_R$, while for all other u, the string uz can be reduced to $(uz)_R$ by an application of (12). Hence the expression $\sum \alpha_u u\, z$ can be reduced using (12) to $\sum \alpha_u (uz)_R = (\sum \alpha_u uz)_R$, which by (20) equals $(xyz)_R$, as claimed. By symmetry, the calculation beginning with the right-hand reduction of $x \cdot y \cdot z$ likewise yields $(xyz)_R$, showing that, in the language of [10], the ambiguity corresponding to (16) is resolvable.

Let us now look at the case of (19), but without explicitly writing expressions f_R as linear combinations of basis elements, merely understanding that they represent such linear combinations, and that the analogs of the reductions (12) and (13) for such linear combinations can be achieved by applying (12) or (13) respectively to each word in the linear expression.

Writing y in (19) as py', we see that the result of applying (13) to $(xp)\,q\,(py')$ is $(xpy')_R$, so the left-hand reduction of $(xp)\,q\,y\,q\,(pz)$ gives $(xpy')_R\,q\,(pz)$. Using now the fact that in (19), $py' = y''p$, we can rewrite this as $(xy''p)_R\,q\,(pz)$. Since $xy''p$ is right-divisible by p, $(xy''p)_R$ is a k-linear combination of elements of $B_{++} \cup B_{-+}$, so we can apply (13) to each term of this expression, and get $(xy''pz)_R$, in other words, $(xyz)_R$. Again, by symmetry the calculation beginning with the right-hand reduction gives the same result.

The cases (17) and (18) combine features of the above two. In the former, for instance, the reader is invited to verify that whether we begin with the reduction of $(xp)\,q\,(py)$ or of $(py)\,z$, a following application of reductions of the other sort brings us to the common answer $(xpyz)_R$. In this case, the two parts of the verification are not left-right dual to each other; rather, the verification of (17) is left-right dual to that of (18).

Since all our ambiguities are resolvable, [10, Theorem 1.2] tell us that the words in B which do not have as subwords any words appearing as inputs of reductions (12) or (13) form a k-basis of R', as claimed. □

4. A digression on algebras over non-fields.

An immediate consequence of the above theorem is that R can be embedded in a k-algebra in which p has an inner inverse. However, this can be more easily seen from the fact that R embeds in the algebra of all endomorphisms of its underlying k-vector-space, which is von Neumann regular.

On the other hand, letting K be a general commutative ring (so as not to violate our convention that k denotes a field), a K-algebra R with a specified element p need not be embeddable in a K-algebra in which p has an inner inverse. For instance, if K is an integral domain, p a nonzero nonunit of K, and $R = K/(p^2)$, we see that in R, the image of p is nonzero, but if an inner inverse q to p is adjoined, then since $p \in K$ must remain central, we get $p = p\,q\,p = p^2 q = 0$ in R'. The following result (which will not be used in the sequel) shows, inter alia, that for K a general commutative ring, such problems occur if and only if K is not itself von Neumann regular.

Proposition 5. *For K a commutative ring, the following conditions are equivalent.*

(a) *K is von Neumann regular.*

(b) *Every K-algebra R can be embedded in a von Neumann regular K-algebra.*

(c) *For every ideal I of K and element $p \in K/I$, the K-algebra K/I can be embedded in a K-algebra in which p has an inner inverse.*

(d) *For every K-module M and nonzero $x \in M$, one has $x \notin PM$ for some maximal ideal P of K.*

Proof. We shall show that (a) $\Longrightarrow$ (d) $\Longrightarrow$ (b) $\Longrightarrow$ (c) $\Longrightarrow$ (a).

(a) $\Longrightarrow$ (d): Given M and x as in (d), let P be maximal among proper ideals of K containing the annihilator of x, and suppose by way of contradiction that $x \in PM$, so that $x = \sum_1^n a_i x_i$ with $a_i \in P$, $x_i \in M$. The ideal of K generated by the a_i will be generated by an idempotent e, since K is von Neumann regular [15, Theorem 1.1(a)$\Longrightarrow$(b)], so $e \in P$, and since each a_i lies in eK, we have $ex = x$. This says that $(1-e)x = 0$, so $1 - e \in P$ (since P contains the annihilator of x), so $1 = e + (1-e) \in P$, contradicting the assumption that P is proper.

(d) $\Longrightarrow$ (b): Assuming (d), we shall show that for every nonzero $x \in R$, there is a homomorphism from R to a von Neumann regular K-algebra which does not annihilate x. Hence R embeds in a direct product of such algebras, which will itself be von Neumann regular.

Given $x \in R - \{0\}$, if we regard R as a K-module, (d) says that $x \notin PR$ for some maximal ideal P of K. Regarding K/P as a field, this tells us that x has nonzero image in the K/P-algebra R/PR. And as noted at the beginning of this section, every algebra over a field k embeds in a von Neumann regular k-algebra.

(b) $\Longrightarrow$ (c): Apply (b) with $R = K/I$.

(c) $\Longrightarrow$ (a): Take any $p \in K$, and apply (c) with $I = p^2 K$, and with the image $\overline{p}$ of p in K/I in the role of p. This gives us a K-algebra containing K/I in which $\overline{p}$ has an inner inverse $\overline{q}$, and we compute $\overline{p} = \overline{p}\,\overline{q}\,\overline{p} = \overline{p}^2\,\overline{q} = 0\,\overline{q} = 0$. Thus $p \in I = p^2K$, i.e., in K we can write $p = p^2q$, and since K is commutative, this equals pqp. Thus every $p \in K$ has an inner inverse, so K is von Neumann regular. $\square$

5. R'-modules

Returning to the situation of R a k-algebra, and $p \in R$ with $1 \notin pR + Rp$, for which we have described the extension $R' = R\langle q \mid p = pqp\rangle$, we now want to describe the R'-module $M \otimes_R R'$ for an arbitrary right R-module M, and examine such questions as whether an inclusion of R-modules $M \subseteq N$ induces an embedding of $M \otimes_R R'$ in $N \otimes_R R'$.

Our normal form for R' will generalize easily to a normal form for $M \otimes_R R'$, but we shall find that an inclusion of R-modules does not necessarily induce an embedding of R'-modules. The reason is that the relation $p = pqp$ in R' makes $1 - qp$ right annihilate p, hence $1 - qp$ also annihilates all elements of the form xp in any right R'-module. We shall in fact see that in $M \otimes_R R'$, the set of elements of M annihilated by $1 - qp$ is precisely Mp. Hence if M is a submodule of an R-module N, and there is an element $y \in M$ which is not a multiple of p in M, but becomes one in N, then the map of R'-modules induced by the inclusion $M \subseteq N$ will kill the nonzero element $y(1 - qp)$.

However, we shall find that we can describe the structure of the R'-submodule of $N \otimes_R R'$ generated by M wholly in terms of the R-module structure of M, and the set of elements of M which become multiples of p in N. Let us set up language and notation to handle this. In the next definition, we do not assume $1 \notin pR + Rp$, since we will be calling on it again in sections where that assumption does not apply.

Definition 6. *Let k be a field, R a k-algebra, and p an element of R.*

By a p-tempered *right R-module, we shall mean a pair (M, M_+) where M is a right R-module, and M_+ is any k-vector-subspace of M which contains the subspace Mp, is annihilated by the right annihilator of p in R, and is closed under multiplication by the subring $\{x \in R \mid px \in Rp\} \subseteq R$.*

A morphism *of p-tempered right R-modules $h : (M, M_+) \to (N, N_+)$ will mean an R-module homomorphism $h : M \to N$ such that $h(M_+) \subseteq N_+$. Such a morphism will be called an* embedding *of p-tempered right R-modules if it is one-to-one, and satisfies $M_+ = h^{-1}(N_+)$.*

Finally, let $R' = R\langle q \mid p = pqp\rangle$. Then for any p-tempered R-module (M, M_+), we shall denote by $(M, M_+) \otimes_{(R,p)} R'$ the quotient of $M \otimes_R R'$ by the submodule generated by all elements

$$(21) \qquad xqp - x \qquad \text{for } x \in M_+.$$

Observe that if $M_+ = Mp$, then $(M, M_+) \otimes_{(R,p)} R'$ is simply $M \otimes_R R'$.

For $B \cup \{1\}$ a k-basis of R, and f an expression representing an element of R, we shall continue to write f_R for the k-linear expression in elements of $B \cup \{1\}$ that gives the value of f. Likewise, if we are given a k-basis C of M, then for any expression f representing an element of M (for example, any k-linear combination of words each given by an element of C followed by a (possibly empty) string of elements of B), we shall write f_M for the k-linear expression in elements of C giving the value of f in M.

Using the version of the Diamond Lemma for modules in [10, §9.5], let us now prove

Proposition 7. *Let k, R, p, B, and $R' = R\langle q \mid p = pqp\rangle$ be as in Theorem 4. Let (M, M_+) be a p-tempered right R-module, let C_+ be a k-basis of M_+, and let C_- be a k-basis of M relative to M_+, so that $C = C_+ \cup C_-$ is a k-basis of M.*

Then $(M, M_+) \otimes_{(R,p)} R'$ has k-basis given by all words w that are composed of an element of C followed by a (possibly empty) string of elements of $B \cup \{q\}$, such that w contains no subwords (10) *or* (11) *as in Theorem 4, nor any subwords*

$$(22) \qquad xy \qquad \text{with } x \in C \text{ and } y \in B$$

or

$$(23) \qquad x\,q\,(py) \qquad \text{with } x \in C_+ \text{ and } py \in B_{++} \cup B_{+-}\,.$$

The reduction to the above normal form may be accomplished by the system of reductions (12) *and* (13) *given in Theorem 4, together with*

$$(24) \qquad xy \;\mapsto\; (xy)_M \qquad \text{for } x \in C,\ y \in B$$

and

$$(25) \qquad x\,q\,(py) \;\mapsto\; (xy)_M \qquad \text{for } x \in C_+,\ py \in B_{++} \cup B_{+-}\,.$$

Sketch of proof. Let us first observe that in (25), though the basis-element py may not uniquely determine y, the element $(xy)_M$ is nonetheless well-defined, since if py can also be written py', then y and y' differ by a member of the right annihilator of p, so by the definition of p-tempered R-module, their difference annihilates $x \in M_+$.

The relations corresponding to the reductions (12), (13), (24) and (25) all hold in $(M, M_+) \otimes_{(R,p)} R'$. Indeed, those corresponding to applications of (12) and (13) hold by the structure of R'; those corresponding to (24) by the R-module structure of M, and those corresponding to (25) because in defining $(M, M_+)\otimes_{(R,p)} R'$, we have divided out by the submodule generated by all elements (21). And in fact, we see that the relations corresponding to these reductions constitute a presentation of the R'-module $(M, M_+) \otimes_{(R,p)} R'$. As before, our reductions decrease the lengths of words, so if all ambiguities of our reduction system are resolvable, it will yield a normal form for the R'-module $(M, M_+) \otimes_{(R,p)} R'$.

The ambiguities are of two sorts: the four given by (16)-(19), which are resolvable by Theorem 4, and the four analogous ones in which the leftmost factor comes from C rather than B :

(26) $\quad x \cdot y \cdot z,$ where $x \in C,\ \ y, z \in B,$

(27) $\quad x\,q \cdot (py) \cdot z,$ where $x \in C_+,\ \ py \in B_{++} \cup B_{+-},\ \ z \in B,$

(28) $\quad x \cdot (yp) \cdot q\,(pz),$ where $x \in C,\ \ yp \in B_{++} \cup B_{-+},\ \ pz \in B_{++} \cup B_{+-},$

(29) $\quad x\,q \cdot y \cdot q\,(pz),$ where $x \in C_+,\ \ y = py' = y''p \in B_{++},\ \ pz \in B_{++} \cup B_{+-}\,.$

I claim (26)-(29) are resolvable by computations analogous to those we used for (16)-(19), the common forms to which the results of the two possible reductions lead now being $(xyz)_M$ for (26) and (27), $(xypz)_M$ for (28), and $(xy'z)_M$ for (29). Let us sketch the verifications.

The resolvability of (26) follows from the fact that M is an R-module.

The case of (27) is like that of (17), the one difference being that where there we wrote the leftmost basis element as xp, here it is a general element $x \in M_+$; but in either case, our reduction (25) allows us (roughly speaking) to drop a following "qp".

In (28), if we begin by reducing $x \cdot (yp)$ using (24), that product becomes $(xyp)_M$, the representation of a member of $Mp \subseteq M_+$, hence its expression in terms of C involves only members of C_+. Hence by (25), when we multiply it by $q\,(pz)$, each of the resulting products reduces to the value we would have gotten if we had simply multiplied by z, so the result is indeed $(xypz)_M$. If instead we first reduce $(yp)\,q \cdot (pz)$ to $(ypz)_R$ using (13), then multiply x by this, applying (24) to each term occurring, we get the same result $(xypz)_M$.

The calculation for (29) combines the features of the two preceding cases. The reduction of $xq \cdot y$ works as in the case of (27) once we rewrite y as py', and gives $(xy')_M$. Moreover, because $py' = y''p$, the subspace $M_+ \subseteq M$ is carried into itself by multiplication by y' (see end of second paragraph of Definition 6), so $xy' \in M_+$; hence multiplication of $(xy')_M$ by $q\,(pz)$ is the same as multiplication by z, and gives $(xy'z)_M$. On the other hand, if we begin by reducing $y \cdot q\,(pz) = (y''p)\,q\,(pz)$ to $(y''pz)_R = (py'z)_R$, then the result of multiplying $x\,q$ by this is again $(xy'z)_M$, by application of (25) to each term occurring. $\square$

Here are some easy consequences.

Corollary 8. *For R, p, R' and (M, M_+) as in Proposition 7, the canonical R-module homomorphism $M \to (M, M_+) \otimes_{(R,p)} R'$ is an embedding; and identifying M with its image under this map, we have*

(30) $\quad M_+ \ = \ M \ \cap \ ((M, M_+) \otimes_{(R,p)} R')\,p \ = \ \{x \in M \mid x(qp - 1) = 0 \ \textit{in} \ (M, M_+) \otimes_{(R,p)} R'\}.$

In particular, for any p-tempered R-module (M, M_+), the module M can be embedded in an R-module N so that $M_+ = M \cap Np$.

Proof. The map $M \to (M, M_+) \otimes_{(R,p)} R'$ takes elements of the k-basis C of M to themselves as elements of the k-basis of $(M, M_+) \otimes_{(R,p)} R'$ described in Proposition 7; hence it is one-to-one.

In (30), it is easy to see that the leftmost and rightmost subspaces are equal, since for a k-linear combination x of the elements of C, the reduction rules reduce xqp to x if and only if all the basis elements occurring in x belong to C_+, i.e., if and only if $x \in M_+$. To see the equality of the middle and rightmost subspaces, note that in any right R'-module, and so in particular, in $(M, M_+) \otimes_{(R,p)} R'$, every right multiple of p is annihilated by $qp-1$, and conversely, any element x satisfying $x(qp-1)=0$ satisfies $x=xqp$, and so is a right multiple of p.

The final statement is seen on taking $N=(M,M_+)\otimes_{(R,p)}R'$, regarded as an R-module. $\square$

Corollary 9. *Let R, p and R' be as in Proposition 7, and let $h:(M,M_+)\to(N,N_+)$ be a morphism of p-tempered R-modules. Then the induced homomorphism of R'-modules $h\otimes_{(R,p)}R':(M,M_+)\otimes_{(R,p)}R'\to(N,N_+)\otimes_{(R,p)}R'$ is one-to-one if and only if h is an embedding of p-tempered R-modules in the sense of Definition 6.*

Proof. Suppose h is an embedding of p-tempered R-modules. Then without loss of generality, we can assume that M is a submodule of N, and $M_+=M\cap N_+$. Let us take a k-basis $C_+^{(0)}\cup C_-^{(0)}$ of M as in the statement of Proposition 7, and extend $C_+^{(0)}$ to a k-basis $C_+^{(0)}\cup C_+^{(1)}$ of N_+. By Lemma 2, $C_+^{(0)}\cup C_-^{(0)}\cup C_+^{(1)}$ is a k-basis of $M+N_+$, and we can extend this to a k-basis $C_+^{(0)}\cup C_-^{(0)}\cup C_+^{(1)}\cup C_-^{(1)}$ of N. If we now write this basis as $(C_+^{(0)}\cup C_+^{(1)})\cup(C_-^{(0)}\cup C_-^{(1)})$ and use it to define a normal form in $(N,N_+)\otimes_{(R,p)}R'$, we see that $(M,M_+)\otimes_{(R,p)}R'$ forms a submodule thereof; so the induced homomorphism is one-to-one.

Conversely, if that induced homomorphism is one-to-one, then restricting it to the embedded copies of M and N in those modules, we see that h is one-to-one. Moreover, the elements of M that are annihilated by $qp-1$ in $(M,M_+)\otimes_{(R,p)}R'$ will be those whose images are annihilated by that element in $(N,N_+)\otimes_{(R,p)}R'$, i.e., $M_+=h^{-1}(N_+)$. Thus the homomorphism is indeed an embedding of p-tempered R-modules. $\square$

6. Do we need to go beyond the case $1\notin pR+Rp$?

Above, we have studied the properties of $R'=R\langle q\mid p=pqp\rangle$ when $1\notin pR+Rp$. In the next five sections we examine cases where $1\in pR+Rp$. But it may well be that for attacking the problem of whether the monoid of finitely generated projectives of a von Neumann regular k-algebra is always separative, the case considered above is all that matters.

Indeed, Pere Ara (personal communication) notes that the separativity question for unital von Neumann regular algebras is equivalent to the same question for nonunital von Neumann regular algebras. For if R were a unital example with non-separative monoid, then regarding it as a nonunital algebra, its (slightly larger) monoid of projectives would still have that property; while conversely, if we had a nonunital example R, then the algebra R^1 gotten by adjoining a unit to R would be a unital example. Note, moreover, that if R is any nonunital k-algebra, then the process of adjoining a universal inner inverse to an element $p\in R$ can be carried out by passing to R^1, universally adjoining an inner inverse to p in R^1 as a unital algebra, then dropping the adjoined unit (i.e., passing to the nonunital subalgebra generated by $R\cup\{q\}$). In this construction, $1\notin pR^1+R^1p$, since $pR^1+R^1p\subseteq R$; hence the construction of universally adjoining an inner inverse to p in R^1 falls under the case considered in the preceding sections.

Kevin O'Meara (personal communication) has likewise suggested that the study of the separativity question can be reduced to the case $1\notin pR+Rp$.

So the reader mainly interested in tackling that question using our normal form may wish to skip or skim §§7-§11.

However, the cases considered in those sections seem interesting; especially the case $1\in pR+Rp-(pR\cup Rp)$, where the elaborate complexity of the normal form we shall discover suggests some strange territory to be explored; so we include them.

Let us first get the easy case out of the way.

7. Normal forms when $1\in pR$ and/or $1\in Rp$.

Since the two cases $1\in pR$ and $1\in Rp$ are left-right dual, let us assume without loss of generality that $1\in pR$. This says p has a right inverse; let us fix such a right inverse $q_0\in R$. It will clearly be an inner inverse to p, so our motivation for adjoining a universal inner inverse (to move our ring a step toward being von Neumann regular) is not relevant here; but for the sake of our general understanding of the adjunction of inner inverses, we are including this case.

If q is any other inner inverse to p, then right multiplying the relation $pqp=p$ by q_0, we get $pq=1$; in other words, once p has a right inverse, every inner inverse to p is a right inverse. Moreover, subtracting the equations $pq_0=1$ and $pq=1$, we get $p(q_0-q)=0$; so all right inverses to p are obtained by adding to q_0 arbitrary elements that right annihilate p.

Note that if both $1 \in pR$ and $1 \in Rp$ hold, then p will be invertible, and if we adjoin a universal inner inverse, it will have to be an inverse to p, hence will fall together with the existing inverse; so in that case, the adjunction of a universal inner inverse to p leaves R unchanged. Hence we will assume below that $1 \in pR$ but $1 \notin Rp$. (In particular, $1 \neq 0$, equivalently, $R \neq \{0\}$.)

Since $1 \in pR$, we have $pR = R$, so the analog of the sort of basis of R that we used in the preceding sections becomes simpler. Namely, we take a basis

(31) $\quad B \cup \{1\} \ = \ B_{++} \cup B_{+-} \cup \{1\},$

where

(32) $\quad \begin{array}{l} B_{++} \text{ is any } k\text{-basis of } Rp = pRp \text{ containing } p, \\ B_{+-} \text{ is any } k\text{-basis of } R = pR \text{ relative to } Rp + k. \end{array}$

Our extension

(33) $\quad R' \ = \ R\langle q \mid pqp = p \rangle \ = \ R\langle q \mid pq = 1 \rangle$

is clearly spanned by words in $B \cup \{q\}$ which contain no subwords either of the form

(34) $\quad xy \quad$ with $x, y \in B$

or of the form

(35) $\quad (xp)\, q \quad$ with $xp \in B_{++}$,

and any expression in our generators can be reduced to a linear combination of such words via the system of reductions

(36) $\quad xy \ \mapsto \ (xy)_R \quad$ for all $x, y \in B$

and

(37) $\quad (xp)\, q \ \mapsto \ x_R \quad$ for all $xp \in B_{++}$.

In contrast to the situation of the preceding sections, the element xp of (37) *does* determine x : if $q_0 \in R$ is a right inverse to p, we see that $x = (xp)\, q_0$; so the expression x_R in (37) is well-defined.

We find that the only ambiguities of this reduction system are

(38) $\quad x \cdot y \cdot z,$ where $x, y, z \in B$,

(39) $\quad x \cdot (yp) \cdot q,$ where $x \in B,\ yp \in B_{++}$,

and it is straightforward to verify, by the approach used in §3, that these are both resolvable.

Note that in the resulting normal form, elements of B_{++} can appear nowhere but in the last position in a reduced word.

(We would get the same ring R' if we adjoined to R an element u subject to the relation $pu = 0$; that extension is isomorphic to the one constructed above via the identification of q with $q_0 + u$. The construction using u would be simpler to study on its own, but the construction using q lends itself better to comparison with the other cases.)

We can likewise look at extension of scalars from R-modules to R'-modules. Since our assumption that p has a right inverse is not left-right symmetric, right and left modules need to be considered separately.

If M is a right R-module, we take, as in the preceding section, a k-basis $C_+ \cup C_-$ for M, where C_+ is a k-basis for Mp. In this situation, we do not have to think about a more general k-subspace M_+, consisting of elements that might become the multiples of p in an overmodule, because the upper and lower bounds for such an M_+ given in Definition 6 coincide: x is a multiple of p in M if and only if $x = xq_0p$, i.e., if and only if x is annihilated by the element $1 - q_0 p$ of the right annihilator of p in R.

It is straightforward to verify that $M \otimes_R R'$ is spanned by words in $C \cup B \cup \{q\}$ in which elements of C occur in the leftmost position and only there, and which are irreducible under the reductions (36) and (37), and also the corresponding reductions in which the leftmost element of B, respectively B_{++}, is replaced by an element of C, respectively C_+. In this case, we see that if the leftmost factor of a reduced word is in C_+, then that factor is the whole word.

Turning to left R-modules M, we find that we do not have to distinguish a subspace pM or M_+ at all, since $pM = M$. Again, we get reduced words having the same formal descriptions as for reduced words of R'. In this case, the analog of the fact that elements of B_{++} and C_+ can only appear in final position is that elements of B_{++} never appear. (Whatever such an element might be followed by – a member of B, a q, or a member of C – leads to a reducible word.)

Returning to our development of the structure of $R' = R\langle q \mid pqp = p\rangle$, we remark that the uninteresting case that we referred to briefly at the start of this section and then put aside, where p is invertible in R, so that $R' = R$, is the one case where the subalgebra of R' generated by q may fail to be a polynomial ring $k[q]$. Rather, it will, necessarily, fall together with $k[p^{-1}] \subseteq R$, which, if p is algebraic over k, is the finite-dimensional subalgebra of R generated by p.

8. The case where $1 \in pR + Rp - (pR \cup Rp)$: groping toward a normal form.

We now consider the most difficult case, that in which $1 \in pR + Rp$, but where 1 does not lie in pR or Rp. In this section we illustrate the process of trying to find a normal form, discovering more and more reductions as we go. In the next section, we shall make precise the pattern that these show, and prove that the resulting set of reductions does lead to a normal form for R'.

Let us begin with a general observation, and a slight digression.

In any ring R with an element p that has an inner inverse q, so that

(40) $\quad pqp \ = \ p,$

note that p is left-annihilated by $pq - 1$ and right-annihilated by $qp - 1$. Consequently,

(41) $\quad (pq - 1)(pR + Rp)(qp - 1) \ = \ \{0\}.$

Hence in the situation we are now interested in, where $1 \in pR + Rp$, we get $(pq - 1)1(qp - 1) \ = \ 0$, i.e.,

(42) $\quad pqqp \ = \ pq + qp - 1.$

In the k-algebra R presented simply by two generators p and q and the relations (40) and (42), we find that the reduction system

(43) $\quad pqp \ \mapsto \ p,$

(44) $\quad pqqp \ \mapsto \ pq + qp - 1$

satisfies the conditions of the Diamond Lemma: there are just four ambiguities, corresponding to the words

(45) $\quad pq \cdot p \cdot qp, \quad pq \cdot p \cdot qqp, \quad pqq \cdot p \cdot qp, \quad pqq \cdot p \cdot qqp,$

and straightforward computations show that these are all resolvable. So this algebra has a normal form with basis the set of all strings of p's and q's that contain no substrings pqp or $pqqp$. Curiously, this algebra itself satisfies $1 \in pR + Rp$, by (42). Consequently, it is universal among k-algebras R given with elements p and q satisfying (40) and such that $1 \in pR + Rp$. (It is not, however, universal among k-algebras given with elements p and q satisfying (40) together with specified elements s and t such that $1 = ps + tp$, i.e., it is not $k\langle p, q, s, t \mid p = pqp,\, 1 = ps + tp\rangle$, the universal example one would first think of.)

The above algebra might be worthy of study, but it is not one of the algebras we are preparing to investigate here. Those are the algebras R' gotten by starting with a k-algebra R given with an element p such that

(46) $\quad 1 \in pR + Rp$ but $1 \notin pR,\ 1 \notin Rp,$

and adjoining a universal inner inverse q to p.

As in the preceding sections, we shall start by taking an appropriate k-basis of R. A problem is that since $1 \in pR + Rp$, we can't take a k-basis containing sets B_{++}, B_{+-} and B_{-+} as in (7) and (8), and *also* the unit 1 (which we want to represent by the empty word in our normal form for R'). What we shall do instead is choose a spanning set for R rather like that of (7) and (8), but which is not quite k-linearly independent, then handle the one linear relation it satisfies as an extra reduction, (51) below.

(Naively we might, instead, think of using a normal form for R' in which 1 is not represented by the empty monomial, but by the sum of a basis element from pR and a basis element from Rp. However, the version of the Diamond Lemma we are using requires that we regard 1 as the empty monomial in our generators, so that won't work. It *would* work if we use the version of the Diamond Lemma for nonunital rings. But then, to restore unitality, we would have to throw in reductions that force our new generator q to be fixed under left and right multiplication by the sum-of-generators that gives the 1 of R, and this seems messier than the path we shall follow.)

So given R satisfying (46), let us fix elements $s,\ t \in R$ such that

(47) $\quad 1 \ = \ ps + tp \ \text{ in } \ R,$

and choose a spanning set for R as a k-vector-space, of the form

(48) $\quad B \cup \{1\} \ = \ B_{++} \cup B_{+-} \cup B_{-+} \cup B_{--} \cup \{1\},$

where

(49)
B_{++} is any k-basis of $pR \cap Rp$ containing the element p,
B_{+-} is any k-basis of pR relative to $pR \cap Rp$ containing the element ps,
B_{-+} is any k-basis of Rp relative to $pR \cap Rp$ containing the element tp,
B_{--} is any k-basis of R relative to $pR + Rp$.

Note that the condition above that B_{+-} contain ps can be achieved because ps does not lie in $pR \cap Rp$; if it did, (47) would imply $1 \in Rp$, contrary to our assumptions. By the dual observation, the condition that B_{-+} contain tp can also be achieved. Since $pR + Rp$ contains 1, we don't have to throw a "$+k$" onto the $pR + Rp$ in the description of B_{--} as in (8). Thus the above B will be a k-basis of R by Lemma 2. But this means that $B \cup \{1\}$ will not. Rather, by (47), $B \cup \{1\} - \{ps\}$ will be a k-basis of R.

For any k-algebra expression f in the elements of B, let f_R denote the unique k-linear combination of elements of $B \cup \{1\} - \{ps\}$ representing the value of f in R. Then we see that R can be presented using the generating set B, the relations corresponding to the reductions

(50) $\quad xy \ \mapsto \ (xy)_R \qquad \text{for all } \ x, y \in B,$

and the relation corresponding to the single additional reduction

(51) $\quad (ps) \ \mapsto \ 1 - (tp).$

We now construct R' by adjoining an additional generator q, and imposing the relation $pqp = p$. As in §3, this leads to the further reductions

(52) $\quad (xp)\, q\, (py) \ \mapsto \ (xpy)_R \qquad \text{for all } \ xp \in B_{++} \cup B_{-+}, \ \ py \in B_{++} \cup B_{+-}\,.$

But in view of (42), these reductions cannot be sufficient to give a normal form for R', so they must have non-resolvable ambiguities.

And indeed, note that for any $xp \in B_{++} \cup B_{-+}$, the word $(xp)\, q\, (ps)$ is ambiguously reducible, using (52) on the one hand or (51) on the other. Equating the results gives the relation $(xps)_R = (xp)\, q - (xp)\, q\, (tp)$. Regarding this as a formula for reducing the longest monomial that it involves, $(xp)\, q\, (tp)$, we get a new family of reductions,

(53) $\quad (xp)\, q\, (tp) \ \mapsto \ (xp)\, q - (xps)_R \qquad \text{for all } \ xp \in B_{++} \cup B_{-+}\,.$

These, in turn, lead to an ambiguity in the reduction of any word $(xp)\, q \cdot (tp) \cdot q\, (py)$: we can apply (53), getting $(xp)\, qq\, (py) - (xps)_R\, q\, (py)$, or (52), getting $(xp)\, q\, (tpy)_R$. So let us again make the relation equating these expressions into a reduction affecting the longest word occurring, which is now $(xp)\, qq\, (py)$. With a view to what is to come, I will number this

(52_2) $\quad (xp)\, qq\, (py) \ \mapsto \ (xps)_R\, q\, (py) + (xp)\, q\, (tpy)_R \qquad \text{for all } \ xp \in B_{++} \cap B_{-+} \ \text{ and } \ py \in B_{++} \cap B_{+-}\,.$

(Digression: If we rewrite the factor $(xps)_R$ in the first term of the output of the above reduction as $(x(1-tp))_R = x_R - (xtp)_R$, and inversely, rewrite the factor $(tpy)_R$ at the end of the last term as $((1-ps)y)_R = y_R - (psy)_R$, then the resulting terms of (52_2) include $(xtp)_R\, q\, (py)$ and $(xp)\, q\, (psy)_R$, which by (52) reduce to $(xtpy)_R$ and $(xpsy)_R$, which then sum to $(x(ps+tp)y)_R = (xy)_R$. This turns (52_2) into

(54) $\quad (xp)\, qq\, (py) \ \mapsto \ x_R\, q\, (py) + (xp)\, q\, y_R - (xy)_R.$

This can be seen as embodying (42); it represents the result of multiplying that equation on the left by x and on the right by y. The form (54) has the nice feature of not depending on the choice of s and t in (47), but it has the downside that it involves expressions x_R, y_R and $(xy)_R$ which are not uniquely determined by the given basis elements xp and py, in contrast to the situation we had in §3, where expressions occurring in our reductions, such as $(xpy)_R$, were shown to depend only on the basis elements xp and py. For this reason we will use (52_2) rather than (54).)

The five families of reductions (50), (51), (52), (53), (52_2) that we have accumulated at this point admit 20 families of ambiguities! Namely, the *final* factor in B of the input-monomials of each of these sorts of reductions can coincide with the *initial* factor in B of the input-monomials of most of these sorts of reduction, the exceptions being that the lone factor (ps) of the input of (51) cannot coincide with the initial factors of the inputs of (52), (53) or (52_2), nor with the final factor of the input of (53) (thus eliminating four of the 25 potential pairings); nor does one get an ambiguity by overlapping (51) with itself.

Many of these 20 sorts of ambiguities are already resolvable, either because of the way they incorporate the structure of the associative ring R, or because some of the later reductions were introduced precisely to make earlier ambiguities resolvable. Summarizing long and tedious hand computations (which we will be able to circumvent in the next section), one finds that of those 20 sorts of ambiguities, 17 are resolvable, the three exceptions being

$$(55)\qquad (xp)\,q\cdot(tp)\cdot q\,(tp),\qquad (xp)\,q\cdot(tp)\cdot qq\,(py),\qquad (xp)\,qq\cdot(ps).$$

Of these, the first and third turn out to yield a common relation. Selecting, as usual, the longest monomial in that relation, and writing the result as a formula reducing that monomial to a combination of the others, this takes the form

$$(53_2)\qquad (xp)\,qq\,(tp)\ \mapsto\ (xp)\,qq-(xps)_R\,q+(xps)_R\,q\,(tp)-(xp)\,q\,(tps)_R.$$

The middle ambiguity shown in (55) yields a different reduction:

$$(52_3)\qquad (xp)\,qqq\,(py)\ \mapsto\ (xps)_R\,qq\,(py)+(xp)\,q\,(tps)_R\,q\,(py)+(xp)\,qq\,(tpy)_R-(xps)_R\,q\,(tpy)_R.$$

Examining the reductions we have been getting (after (50) and (51), which describe R itself), they appear to fall into two series (as indicated in numbering I have given them), one starting with (52), (52_2), (52_3), the other with (53), (53_2). Examining which ambiguities turned out to yield which new reductions, one can guess which should yield the next term in each series. In this way one finds, for instance, the next reduction in the (52)-series:

$$(52_4)\qquad \begin{aligned}(xp)\,qqqq\,(py)\ \mapsto\ &(xps)_R\,qqq\,(py)+(xp)\,q\,(tps)_R\,qq\,(py)+(xp)\,qq\,(tps)_R\,q\,(py)+(xp)\,qqq\,(tpy)_R\\ &-(xps)_R\,q\,(tps)_R\,q\,(py)-(xps)_R\,qq\,(tpy)_R-(xp)\,q\,(tps)_R\,q\,(tpy)_R.\end{aligned}$$

The pattern of the inputs of (52), (52_2), (52_3), (52_4) is clear; but what about the outputs? It appears that (ignoring signs, for the moment), each term in the output of a reduction "(52_n)" is obtained from the input monomial $(xp)\,q^n\,(py)$ by replacing or not replacing the initial $(xp)\,q$ with $(xps)_R$, replacing or not replacing the final $q\,(py)$ with $(tpy)_R$, and replacing or not replacing some of the remaining q's with $(tps)_R$. But not every possible combination of such changes and non-changes shows up in our reductions; only those where no two successive q's are changed.

Can we make sense of this?

9. The normal form, described and proved.

The relations in R' that yield the reductions (52_n) can in fact be derived from scratch in roughly the way we obtained the relation (42); namely, by inserting terms $1=ps+tp$ between certain factors of the input monomial, partly expanding the result, and then simplifying using (47) and (52). For example, the relation corresponding to (52_2) can be gotten as follows:

$$(56)\qquad \begin{aligned}(xp)\,qq\,(py)\ &=\ (xp)\,q\,(ps+tp)\,q\,(py)\\ &=\ (xp)\,q\,(ps)\,q\,(py)+(xp)\,q\,(tp)\,q\,(py)\\ &=\ (xps)_R\,q\,(py)+(xp)\,q\,(tpy)_R.\end{aligned}$$

However, not every string of insertions of terms (ps) and (tp) between q's in a word $(xp)\,q\dots q\,(py)$ admits a simplification of the sort used above. We could not, for instance, simplify a string $\dots(tp)\,q\,(tp)\dots$ using (52), because the second (tp) does not begin with a p, and so does not give us a "pqp" to reduce.

So the equations on which we should perform the simplifications that will yield the reductions (52_n) for general n are not obvious. For instance, the next case, (52_3), can be obtained similarly by writing $(xp)\,qqq\,(yp)$ as $(xp)\,q\,(ps+tp)\,q\,(ps+tp)\,q\,(py)$, then using the expansion

$$(57)\qquad \begin{aligned}(xp)\,q\,(ps+tp)\,q\,(ps+tp)\,q\,(py)\ &=\ (xp)\,q\,(ps)\,q\,(ps+tp)\,q\,(py)\\ &+(xp)\,q\,(tp)\,q\,(ps)\,q\,(py)+(xp)\,q\,(ps+tp)\,q\,(tp)\,q\,(py)-(xp)\,q\,(ps)\,q\,(tp)\,q\,(py),\end{aligned}$$

and reducing these terms. That (57) is an identity of associative rings is easy to check. (Clearly, before checking it we can drop the initial (xp) and final (py) of each term.) But it is not obvious how we would have come up with that identity to use. In the next lemma we shall describe and prove a sequence of identities to which the result of deleting the initial (xp) and final (py) from each term of (57) belongs, and the n-th step of which will similarly allow us to obtain (52_n).

(Though I believe in the principle of stating results in their abstractly most natural form, since they may prove useful in contexts very different from the ones for which they were devised, the lemma below is unabashedly rigged to be used in the specific context we will apply it in, for the sake of smoothing that application. I will re-state it in a more general form as Corollary 16, when we are through with the work of this section.)

Lemma 10. *Let $n \geq 2$ be an integer, F the free associative k-algebra on generators p, s, t, q, and $S(n)$ the set of elements of F which can be obtained by the following procedure:*

(58) *Starting with the monomial q^n, insert between each pair of successive q's either $(ps+tp)$, or (ps) alone, or (tp) alone, in such a way that every q that is immediately preceded by (tp) is either immediately followed by (ps) or is the final q, and every q that is followed immediately by (ps) is either immediately preceded by (tp) or is the initial q.*

Then multiply the resulting element by $(-1)^d$, where d is the number of q's in its expression which are preceded by (tp) and/or followed by (ps). (I.e., which are initial and followed by (ps), or are simultaneously preceded by (tp) and followed by (ps), or are final and preceded by (tp)).

Then the sum in F of the set $S(n)$ is 0.

Proof. Let us multiply out each element of the set $S(n)$ described above to get a sum of monomials; i.e., wherever a factor $(ps+tp)$ occurs in such a product, write the product as the sum of a product having (ps) and a product having (tp) in that position. Thus, each of the resulting monomials will contain n q's, with every pair of successive q's having either a (tp) or a (ps) between them. Let $W(n)$ be the set of all monomials of this form. We must prove that for every $w \in W(n)$, the sum of the coefficients with which it occurs in members of $S(n)$ is 0.

Within a monomial $w \in W(n)$, let us call an occurrence of q "marked" if it is initial and followed by (ps), or preceded by (tp) and followed by (ps), or final and preceded by (tp). Every $w \in W(n)$ has at least one marked q; for if there is at least one factor (ps), then the q preceding the first such factor (whether it is initial or preceded by a (tp)) will be marked, while if there are no factors (ps), then the final q will be preceded by a (tp), and hence marked. On the other hand, two successive q's can never both be marked, since if they have a (tp) between them, the left-hand q won't be marked, while if they have a (ps) between them, the right-hand q won't be marked.

Let $e \geq 1$ be the number of marked q's in w. I claim that there are exactly 2^e elements $v \in S(n)$ which contain a $\pm w$ in their expansion, half of them with a plus sign and half with a minus sign. Indeed, given w, all such elements $v \in S(n)$ can be found by a construction that makes the following binary choice at each marked q of w: If the marked q in question is neither initial nor final, so that it is preceded by a (tp) and followed by a (ps), the choice is between keeping these factors (tp) and (ps) unchanged in v, or replacing both with $(ps+tp)$. (The definition of $S(n)$ doesn't allow any other possibilities.) If the q in question is initial, the choice is simply between keeping the following (ps) unchanged or replacing it with $(ps+tp)$, while if it is final, the choice is between keeping the preceding (tp) unchanged or replacing it with $(ps+tp)$. (Since successive q's cannot be marked, the effects of choices at different marked q's will not conflict with each other.) Finally, for factors (tp) of w that do not precede marked q's, and factors (ps) that do not follow marked q's, there is no choice: we replace these with $(ps+tp)$.

It is not hard to see from the definition of $S(n)$ that these 2^e ways of modifying w indeed give precisely the elements $v \in S(n)$ that have w in their expansion. Moreover, by the second paragraph of (58), such an element of $S(n)$ will bear a plus sign if the number of marked q's around which we did not choose to change the adjacent factor(s) of w to $(ps+tp)$ is even, a minus sign if that number is odd. Hence half of the resulting occurrences of w have a plus sign and half have a minus sign, so they sum to zero; and since this is true for each w, we get $\sum_{v \in S(n)} v = 0$, as claimed. $\square$

Now returning to the k-algebra $R' = R\langle q \mid p = pqp\rangle$, where $1 = ps+tp$ in R, let us map the free algebra of the above lemma into R' by sending each indeterminate to the element of R' denoted by the same letter. The lemma then tells us that in R', a certain sum of signed products is zero. Hence if we choose any $(xp) \in B_{++} \cup B_{-+}$ and $(py) \in B_{++} \cup B_{+-}$, and multiply that sum of products on the left by (xp) and on the right by (py), the resulting sum of products is still zero. In the expressions for these products, we now can cross out each factor $(ps+tp)$, since it equals 1, and replace occurrences of $(xp)\,q\,(ps)$, $(tp)\,q\,(ps)$, and $(tp)\,q\,(py)$ by $(xps)_R$, $(tps)_R$, and $(tpy)_R$ respectively. The one element of $(xp)\,S(n)\,(py)$ in which no reduction of these three sorts is made is the one that had $(ps+tp)$ in all $n{-}1$ positions, and is now simply $(xp)\,q^n\,(py)$. Using the relation we have obtained to express that product as a linear combination of products with fewer remaining q's, we get,

Corollary 11. *For R, p, B as in the preceding section, any $(xp)\in B_{++}\cup B_{-+}$ and $(py)\in B_{++}\cup B_{+-}$, and any $n\geq 2$, let $T((xp),n,(py))$ be the set of k-linear combinations of words in B formed by modifying the word $(xp)\,q^n\,(py)$ as follows:*

Choose any nonempty *subset of the string of n q's in that word, to be called "marked" q's, such that no two adjacent q's are both marked. If the first q in the string is marked, replace the initial term $(xp)\,q$ with $(xps)_R$. If the last q is marked, replace the final term $q\,(py)$ with $(tpy)_R$. Replace every marked q that is neither initial nor final with $(tps)_R$. Finally, multiply the result by -1 if the number of marked q's was* even.

Then the reduction

$$(52_n)\qquad (xp)\,q^n\,(py)\ \mapsto\ \textstyle\sum_{v\in T((xp),n,(py))}\ v$$

corresponds to a relation holding in R'. (I.e., the elements of R' represented by the input and the output of (52_n) are equal.) ☐

Some remarks before we go further:

The number of terms in the set $S(n)$ of Lemma 10 (and hence in the reduction (52_n)), counting the input term as well as the terms in $T((xp),n,(py)))$, is the $n{+}2$'nd Fibonacci number, F_{n+2}, since this is known to be the number of subsets of a sequence of n elements containing no two successive elements [16, p. 14, Problem 1(b)].

The reduction (52) clearly deserves to be called (52_1); but we assumed $n\geq 2$ in the preceding lemma and corollary because the $n=1$ case differs from the general case in a couple of ways. On the one hand, when $n=1$, the initial q is also the final q, so we get an output term $(xpy)_R$, which is not one of the three sorts that occur when $n\geq 2$. More important, the two sides of (52) do not differ as a result of where factors $(ps+tp)$, (ps) or (tp) appeared in a term v, but simply as to whether or not one reduces the product $(xp)\,q\,(py)$ in the tautology $(xp)\,q\,(py)=(xp)\,q\,(py)$. Nevertheless, (52) has precisely the right form to be described as reduction (52_1), and we will so consider it when we describe our normal form for R'. (We might consider the lone q "unmarked" in the input of (52) and "marked" in the output.)

Let us note, finally, that monomials occurring in the output of (52_n) may admit further reductions. For instance, in the output term $(xps)_R\,q\,(py)$ of (52_2), some of the elements of B appearing in $(xps)_R$ may be of the form $(x'p)$, allowing reductions $(x'p)\,q\,(py)\mapsto(x'py)_R$. (Indeed, all of them will have this form if x is a right multiple of p in R, since then $xps=x(1-tp)$ will be a right multiple of p.) However, this does not interfere with our application of the Diamond Lemma. The formulation of that lemma does not require that the output of each reduction not admit further reductions, but simply that it be a linear combination of words smaller than the word one started with, under an appropriate partial ordering.

We now turn to the other family of reductions we encountered, beginning with (53). Since, as just noted, it is not essential that all the terms of the outputs of our reductions be, themselves, reduced, we can make a slight simplification in the form of (53_2), replacing the final (tp) in the third output term by $(1-ps)$, to which it is equal in R. Two terms then cancel, after which (53_2) takes the form

$$(53'_2)\qquad (xp)\,qq\,(tp)\ \mapsto\ (xp)\,qq-(xps)_R\,q\,(ps)-(xp)\,q\,(tps)_R.$$

This leads to a version of the (53)-series of reductions that is easily deduced from Corollary 11.

Corollary 12. *For every $n\geq 2$ and $(xp)\in B_{++}\cup B_{-+}$, the reduction*

$$(53'_n)\qquad (xp)\,q^n\,(tp)\ \mapsto\ (xp)\,q^n-\textstyle\sum_{v\in T((xp),n,(ps))}v,$$

where $\sum_{v\in T((xp),n,(ps))}v$ is defined as in Corollary 11, corresponds to a relation holding in R'.

Proof. Applying Corollary 11 with $py=ps$ (which is allowable, since $ps\in B_{+-}$), we get $(xp)\,q^n\,(ps)=\sum_{v\in T((xp),n,(ps))}v$ in R'. Rewriting the factor (ps) on the left-hand side as $1-(tp)$, multiplying out, moving the shorter of the two resulting terms to the right-hand side, and changing all signs, we get $(xp)\,q^n\,(tp) = (xp)\,q^n - \sum_{v\in T((xp),n,(ps))} v$, the desired relation. $\square$

We now have four families of reductions, (50), (51), (52_n) and ($53'_n$), where in the last two, we from now on allow all $n \geq 1$, counting (52) as (52_1), and (53) as ($53'_1$); and we wish to show that these together determine a normal form for elements of R'. We have established that they correspond to relations holding in R'. Moreover, they imply the defining relations for that k-algebra in terms of our generating set $B \cup \{q\}$, since (50) and (51) determine the structure of R, while the imposed relation $pqp = p$ is the case of (52_1) where both xp and py are p. It remains to find a partial ordering on words in $B \cup \{q\}$ respecting multiplication and having descending chain condition, with respect to which all of these reductions are strictly decreasing, and to prove that the ambiguities of the resulting reduction system are resolvable.

The required partial ordering can be obtained by associating to every word w in $B \cup \{q\}$ the 3-tuple with first entry the number of q's in w, second entry the number of occurrences of members of B in w, and third entry the number of occurrences of the particular element $(ps) \in B$ in w, and considering one word greater than another if the corresponding 3-tuples are so related under lexicographic order, while considering distinct words which correspond to the same 3-tuple incomparable. It is easy to see that this ordering has descending chain condition and respects formal multiplication of words (juxtaposition), and that in each of our reductions, all words of the output are strictly less than the input word. (The first coordinate of the 3-tuple is enough to show this last property for the reductions (52_n); the second coordinate is needed for the reductions (50), and for the first term of the output of ($53'_n$), while the third coordinate is only needed for (51).)

Proving resolvability of ambiguities will, of course, be the hard task.

The ambiguities among the cases of (50) and (51) are, as usual, resolvable because they describe the structure of the associative k-algebra R.

I claim that ambiguities based on the fact that a word can be reduced either by (52_n) or by (50), i.e., those involving words of the forms $(xp)\,q^n\,\cdot(py)\cdot z$ and $x\cdot(yp)\cdot q^n\,(pz)$, are also easily shown to be resolvable. As in the case of the ambiguities (17) and (18) considered in §3, the reason will be, in the former case, that right multiplication by z carries pR left R-linearly into itself, and in the latter, that left multiplication by x carries Rp into itself right R-linearly; so that whether we apply the reduction (52_n) before or after that operation, we get the same result. For more detail, let us, in the case of $(xp)\,q^n\,\cdot(py)\cdot z$, subdivide the summands in $\sum_{v\in T((xp),n,(py))} v$ in (52_n) according to whether they end with (py) or $(tpy)_R$, writing that reduction as

(59) $$(xp)\,q^n\,(py) \;\mapsto\; \sum_{v\in T((xp),n,(py))} v \;=\; A((xp),n)\,(py) + B((xp),n)\,(tpy)_R.$$

The reader can now easily verify that whichever of the two competing reductions we perform first on $(xp)\,q^n\cdot(py)\cdot z$, the output can be reduced to $A((xp),n)(pyz)_R + B((xp),n)(tpyz)_R$.

The case of $x\cdot(yp)\cdot q^n\,(pz)$ is handled similarly, using a decomposition of the elements of $T((xp),n,(py))$ by initial rather than final factors, which we write down for later reference as

(60) $$(xp)\,q^n\,(py) \;\mapsto\; \sum_{v\in T((xp),n,(py))} v \;=\; (xp)\,C(n,(py)) + (xps)_R\,D(n,(py)),$$

(though in the present application, the roles of the (xp) and (py) in the above formula are played by the elements (yp) and (pz)).

The resolution of ambiguities arising from words $x\cdot(yp)\cdot q^n\,(tp)$, which can be reduced using either (50) on the left or ($53'_n$) on the right, is verified similarly.

A little more complicated is the case of $(xp)\,q^n\cdot(tp)\cdot y$, which can be reduced either by applying ($53'_n$) on the left, or (50) on the right. We recall that the result of reducing $(xp)\,q^n(tp)$ by ($53'_n$) is $(xp)\,q^n$ minus the result of reducing $(xp)\,q^n(ps)$ by (52_n); so applying this reduction in $(xp)\,q^n(tp)\,y$, and then making appropriate applications of (50), we get $(xp)\,q^n y$ minus the result of reducing $(xp)\,q^n(psy)_R$ by (52_n). On the other hand, if we begin by applying (50), we get $(xp)\,q^n(tpy)_R$. Since $tp = 1 - ps$ in R, we have $(tpy)_R = y - (psy)_R$, and this leads to a decomposition of $(xp)\,q^n(tpy)_R$ as the difference of two terms, one of which is $(xp)\,q^n y$, while the other, $(xp)\,q^n(psy)_R$, can be reduced as just mentioned. So both reductions lead to $(xp)\,q^n y$ minus the result of reducing $(xp)\,q^n(psy)_R$ using (52_n), showing that this ambiguity is also resolvable.

And the ambiguities coming from words $(xp)\,q^n\cdot(ps)$, which can be reduced either by applying (52_n) to the whole expression, or (51) to the final factor, are resolvable because of the reductions ($53'_n$), which were introduced precisely to handle them. (These ambiguities are, incidentally, what are called in [10] "inclusion ambiguities", where the input-word of one reduction is a subword of the input-word of another reduction. All other ambiguities occurring in this note are "overlap ambiguities".)

We are left with the ambiguities resulting from the overlap of two words both of which admit reductions in our (52)-series and/or our (53)-series.

Again, some of these are fairly straightforward to show resolvable. Consider first a word $(xp)\,q^m\cdot y\cdot q^n(pz)$ where $y=py'=y''p\in B_{++}$, with $m,n\geq 2$, to which we can apply either (52_m) on the left, or (52_n) on the right. It is not hard to verify that whichever of those operations we apply first, the other will then be applicable to all the words in the resulting expression. (For instance, though the result of first applying (52_m) will include some terms in which the factor $y=py'$ has been absorbed into a product $(tpy')_R$, the relation $py'=y''p$ allows us to rewrite this as $(ty''p)_R$, so it lies in Rp, hence is a k-linear combination of generators in $B_{++}\cup B_{-+}$, allowing a subsequent application of (52_n) to each term.) One finds that the result of either order of reductions is the sum of a set of terms which can be constructed as follows: Starting with the word $(xp)\,q^m\cdot y\cdot q^n(pz)$, "mark" an arbitrary subset of the q's, subject to the condition that the marked subset of the first m q's be nonempty and contain no pair of adjacent q's, and that the marked subset of the last n q's likewise be nonempty and contain no adjacent pair. Now, as before, we make appropriate replacements involving the marked q's. What most of these should be are clear from the statement of Corollary 11. For instance, if the first q is marked, replace $(xp)\,q$ by $(xps)_R$; if the last q is marked, replace $q\,(pz)$ by $(tpz)_R$; if a q that is neither initial nor final in the string q^m or q^n is marked, replace it with $(tps)_R$. Likewise, if the last q before the factor y is marked, but the q following the y is not, then we replace $q\,y=q\,py'$ by $(tpy')_R$, while if the q following the y is marked but not the one that precedes it, we replace $y\,q=(y''p)\,q$ by $(y''ps)_R$. But what if both of those q's are marked? Then we find that the results of performing either of those two replacements, followed by the reductions corresponding to the other, give the same result. Indeed, the replacements correspond to two ways of reducing $(tp)\,q\,y\,q\,(ps)$, which is an instance of (19), the resolvability of which was verified in §3; both reductions of that factor give $(tys)_R$. So this ambiguity is also resolvable.

The corresponding ambiguities with m and/or n equal to 1 are resolved in the same way, with the obvious adjustments; e.g., if $m=1$, then instead of $q(py')$ being replaced by $(tpy')_R$ in some terms of (59), we will have $(xp)\,q\,(py')$ replaced by $(xpy')_R$. (The case $m=n=1$ is precisely (19).)

And the ambiguities $(xp)\,q^m\cdot y\cdot q^n(tp)$, which can be reduced by applying (52_m) on the left, or $(53'_n)$ on the right, are handled like the above, *mutatis mutandis*.

There remain two sorts of ambiguities, which get a bit more interesting. These will be given as (61) and (68) below, but let us prepare for them with the following observation. Up to this point, ambiguities involving reductions (52_n) and/or $(53'_n)$ for certain values of n were resolved using only reductions indexed by the same value(s) of n and the value 1. Now if this were the case for the remaining sorts of ambiguities as well, then for any set N of positive integers containing 1, the system of reductions given by (50), (51), and the (52_n) and $(53'_n)$ for $n\in N$ would have all ambiguities resolvable, and so would determine a basis of monomials for the k-algebra presented by the generating set $B\cup\{q\}$ and the relations corresponding to those reductions. But we have seen that the relations corresponding to (50), (51), and (52_1) are sufficient to present R', in which all of the (52_n) and $(53'_n)$ are satisfied; so all such subsystems of our system of reductions would yield k-bases for R'. Yet some of these bases of R' (those arising from larger sets N) would be properly contained in others (arising from smaller sets N), since a larger set of reductions would make more words reducible.

Since a proper inclusion among bases of R' is impossible, it *must* be true that in resolving some of the ambiguities we have not yet considered, reductions with larger subscripts than those involved in the ambiguities themselves must be used. And indeed, we saw in the preceding section that trying to resolve the ambiguity $(xp)\,q\cdot(tp)\cdot q\,(py)$, arising from the reductions $(53'_1)$ and (52_1), required us to introduce the new reduction (52_2). So with the expectation that this will happen, let us look at the two remaining families of ambiguities.

Consider first an ambiguously reducible word of the form

(61) $\qquad (xp)\,q^m\cdot(tp)\cdot q^n\,(py).$

In analyzing the effects of our reductions on this expression, we shall use both of the notations introduced in (59) and (60). Observe that in (59), the term $A((xp),n)(py)$ arises from those ways of marking q^n such that at least one q is marked, but the last q is *not* marked (since (py) has not been absorbed in a term $(tpy)_R$), while $B((xp),n)(tpy)_R$ arises from those ways of marking q^n under which a set of q's *including* the last q is marked. Similarly, the two terms of (60) arise from ways of marking q^n so that the *first* q is not, respectively, is, marked. Note, finally that in the notation of (59), the output of the reduction $(53'_m)$ is

$$(xp)\,q^m - A((xp),m)(ps) - B((xp),m)(tps)_R. \tag{62}$$

Now starting with the monomial (61), if we apply, on the one hand, $(53'_m)$ with its output written as (62) to the terms surrounding the first dot, and, on the other hand, (52_n) with output written as in (60) to the terms surrounding the second dot, then the equation equating the results, which we hope to show can be established by further reductions in our system, is

$$\begin{aligned}(xp)\,q^{m+n}\,(py) \;-\; A((xp),m)\,(ps)\,q^n\,(py) \;-\; B((xp),m)\,(tps)_R\,q^n\,(py)&\\ =\; (xp)\,q^m(tp)\,C(n,(py)) \;+\; (xp)\,q^m(tps)_R\,D(n,(py)).&\end{aligned} \tag{63}$$

The very first term above is the input of the reduction (52_{m+n}), so our ambiguity will be resolvable if, on moving the other terms of (63) to the right-hand side, the value we end up with there, namely

$$\begin{aligned}&A((xp),m)\,(ps)\,q^n\,(py) \;+\; B((xp),m)\,(tps)_R\,q^n\,(py) \;+\\ &\qquad (xp)\,q^m(tp)\,C(n,(py)) \;+\; (xp)\,q^m(tps)_R\,D(n,(py))\end{aligned} \tag{64}$$

can be reduced to the output of (52_{m+n}). We can, in fact, recognize two of the terms of (64) as parts of that output. Namely, $B((xp),m)\,(tps)_R\,q^n\,(py)$ can be seen to be the sum of all terms gotten from $(xp)\,q^{m+n}\,(py)$ by marking some subset of the first m q's which includes the m-th, and then making the replacements described in Corollary 11. Likewise, $(xp)\,q^m(tps)_R\,D(n,(py))$ is the sum of the terms we get on marking some subset of the last n q's which includes the first of these, and making the appropriate replacements. So it suffices to show that the first and third terms of (64) can be reduced to the sum of the other terms in the output of (52_{m+n}). (As they stand, the do not consist of such terms, since terms in the outputs of our (52)-series reductions have no internal factors (ps) or (tp).)

The term $A((xp),m)\,(ps)\,q^n\,(py)$ can be reduced by applying (51) to the factor (ps), while the term $(xp)\,q^m\,(tp)\,C(n,(py))$ can be reduced by applying $(53'_m)$ to its initial factors. Then these two remaining terms of (64) become

$$\begin{aligned}&A((xp),m)\,q^n\,(py) \;-\; A((xp),m)\,(tp)\,q^n\,(py) \;+\\ &\quad (xp)\,q^m\,C(n,(py)) - \;A((xp),m)\,(ps)\,C(n,(py)) \;-\; B((xp),m)\,(tps)_R\,C(n,(py)).\end{aligned} \tag{65}$$

Of these terms, the first can be seen to consist of those summands in the output of (52_{m+n}) in which, again, only a subset of the first m q's have been marked, this time a subset which does *not* include the m-th q; and the third term likewise consists of those summands in which a subset of the last n q's have been marked, but that subset does not include the first of these. Dropping these two terms from our calculation, the first of the remaining terms can be reduced using (52_n). After performing that reduction, and again using (60) to describe the output, the terms that remain to be considered take the form

$$\begin{aligned}&-A((xp),m)\,(tp)\,C(n,(py)) - A((xp),m)\,(tps)_R\,D(n,(py))\\ &\quad - A((xp),m)\,(ps)\,C(n,(py)) - B((xp),m)\,(tps)_R\,C(n,(py)).\end{aligned} \tag{66}$$

The first and third of these can be combined using the relation $ps+tp=1$ (or, formally, by applying the reduction (51) to the latter, and adding the result to the former), giving

$$-A((xp),m)\,C(n,(py)) - A((xp),m)\,(tps)_R\,D(n,(py)) - B((xp),m)\,(tps)_R\,C(n,(py)). \tag{67}$$

I claim that this expression gives precisely the remaining terms of the output of (52_{m+n}), i.e., those in which there are marked q's among both the first m and the last n. Indeed, the first summand in (67) contains the terms of this sort in which neither the m-th nor the $(m{+}1)$-st q is marked; the next gives those in which the m-th q is again not marked, but the $(m{+}1)$-st is, and the last gives those in which the m-th is marked, but not the $(m{+}1)$-st. Since adjacent q's cannot both be marked, these are all the possibilities.

But are the negative signs in (67) what we want? I agonized over this till I finally saw that they are. In the description of the output of our reductions in the (52)-series, a term is assigned a minus sign if it involves an *even* number of marked q's, a plus sign if it involves an *odd* number. (This is the result of moving these terms of the expression proved to sum to zero in Lemma 10 to the opposite side of the equation from $(xp)\,q^n(py)$.) Hence when we form a product such as $A((xp),m)\,C(n,(py))$ in (67), the terms involving an even total number of marked q's will end up with a plus sign and those with an odd total number will have a minus sign. So this and the other terms of (67) indeed need negative signs to give the corresponding summands in the output of (52_{m+n}).

Once again, the verifications of the cases where m and/or n is 1 differ only in minor formal details from the above.

And the resolvability of the one remaining sort of ambiguity,

$$(68) \qquad (xp)\, q^m \cdot (tp) \cdot q^n\, (tp)$$

reduces to the resolvability of the case of (61) where (py) is (ps), via Corollary 12. These computations establish

Theorem 13. *Let R be a k-algebra, let p be an element of R such that $1 \in pR + Rp$ but $1 \notin pR$ and $1 \notin Rp$, choose $s, t \in R$ such that $1 = ps + tp$ as in* (47)*, let $B \cup \{1\}$ be a spanning set for R satisfying* (48) *and* (49)*, and let*

$$(69) \qquad R' \;=\; R\langle q \mid pqp = p\rangle.$$

Then R' has a k-basis given by all words in the generating set $B \cup \{q\}$ that contain no subwords of any of the following forms:

$$(70) \qquad xy \qquad \text{with } x, y \in B,$$

$$(71) \qquad (ps),$$

$$(72) \qquad (xp)\, q^n\, (py) \qquad \text{with } xp \in B_{++} \cup B_{-+},\ \ py \in B_{++} \cup B_{+-},\ \text{and } n \geq 1,$$

$$(73) \qquad (xp)\, q^n\, (tp) \qquad \text{with } xp \in B_{++} \cup B_{-+} \text{ and } n \geq 1.$$

The reduction to the above normal form may be accomplished by the systems of reductions (50), (51), (52_n) (*as shown in Corollary 11, but with* (52) *also included as* (52_1)) *and* $(53'_n)$ (*as shown in Corollary 12, but with* (53) *also included as* $(53'_1)$)*.* □

Combining this with the results of §3 and §7, we see that we have determined the structure of $R\langle q \mid pqp = p\rangle$ for all cases of a k-algebra R and an element $p \in R$.

10. Some consequences, and a couple of loose ends

The proof of Theorem 13 extends without difficulty to give the analog of Proposition 7, with "p-tempered R-module" still defined as in Definition 6. As in that proposition, we take a k-basis $C = C_+ \cup C_-$ for M, and supplement the reductions we have used in the normal form for R' with corresponding reductions in which the leftmost factor, x or (xp), is replaced with an element of C; an arbitrary element in the case of the x of (70), a member of C_+ in the case of the (xp) of (72) and (73).

We will not write the result out in detail; but let us note a common feature of this and our other results on the extension of p-tempered R-modules to R'-modules.

Corollary 14. *If R is a k-algebra, p any element of R, and (M, M_+) a p-tempered R-module, as defined in Definition 6, then the canonical map $M \to (M, M_+) \otimes_{(R,p)} R'$ is an embedding such that* (*identifying M with its image under that map*) *we have $M_+ = M \cap (M \otimes_{(R,p)} R')\, p$.* □

We can also ask when an inclusion of k-algebras leads to an embedding of extensions of these algebras by universal inner inverses. This is answered by

Proposition 15. *Let $R^{(0)} \subseteq R^{(1)}$ be an inclusion of k-algebras, and p an element of $R^{(0)}$. Then the following conditions are equivalent.*

(a) *The induced map $R^{(0)}\langle q \mid pqp = p\rangle \;\to\; R^{(1)}\langle q \mid pqp = p\rangle$ is an embedding.*

(b) $R^{(0)} \cap (R^{(1)}p) = R^{(0)}p$, *and* $R^{(0)} \cap (pR^{(1)}) = pR^{(0)}$, *and* $R^{(0)} \cap (pR^{(1)} + R^{(1)}p) = pR^{(0)} + R^{(0)}p$.

Proof. The direction (a) $\implies$ (b) will not use our normal form results, and, indeed, holds without the assumption that k is a field. Observe that in any ring, if an element p has an inner inverse q, then an element x is right divisible by p if and only if $x(1-qp)=0$: "only if" is clear, while "if" holds because the indicated equation makes $x = xqp$. (We used the same idea in the proof of Corollary 8.) Under the assumption (a), this immediately gives the first equality of (b); the second is seen dually. The third holds by the similar criterion saying that $x \in pR+Rp$ if and only if $(1-pq)\,x\,(1-qp)=0$, where "if" holds because that equation can be written $x = pqx + xqp - pqxqp$.

The proof that (b) $\implies$ (a) will use our normal form results. Under the assumptions of (b), note that whichever of the cases "$1 \notin pR+Rp$", "$1 \in pR+Rp-(pR \cup Rp)$", "$1 \in pR$", "$1 \in Rp$" apply to $R^{(1)}$ will also apply to $R^{(0)}$.

Let us now take a generating set $B^{(0)} = B^{(0)}_{++} \cup B^{(0)}_{+-} \cup B^{(0)}_{-+} \cup B^{(0)}_{--}$ for $R^{(0)}$ as in our development of the case under which $R^{(0)}$ and $R^{(1)}$ both fall. (Some of these sets will be empty if we are in a case where p is right and/or left invertible.) It follows from (b) that we can extend each of $B^{(0)}_{++}$, $B^{(0)}_{-+}$, $B^{(0)}_{+-}$, $B^{(0)}_{--}$ to a subset $B^{(1)}_{++}$, $B^{(1)}_{-+}$, $B^{(1)}_{+-}$, $B^{(1)}_{--}$ of $R^{(1)}$ satisfying the corresponding conditions, so as to yield a generating set $B^{(1)}$ for $R^{(1)}$ with each component containing the corresponding component of the generating set $B^{(0)}$ for $R^{(0)}$. Using these generating sets, the normal form expression for each element of $R^{(0)}\langle q \mid pqp=p\rangle$ is also the normal form of its image in $R^{(1)}\langle q \mid pqp=p\rangle$. Hence, if an element is nonzero in the former ring, so is its image in the latter, establishing (a). $\square$

(Incidentally, the first two equalities of (b) above do not imply the third. For a counterexample, let $R^{(1)}$ be the Weyl algebra, written as in (78) below, and $R^{(0)}$ its subalgebra $k[p]$. Then $1 \notin pR^{(0)}+R^{(0)}p$ but $1 \in pR^{(1)}+R^{(1)}p$, so the third condition of (b) fails, though the first two clearly hold. More on the algebra gotten by adjoining an inner inverse to p in the Weyl algebra in the next section.)

Is there a generalization of the above proposition based on a concept of a "p-tempered k-algebra" R, in which certain k-subspaces of R are specified whose elements are to be treated like right and/or left multiples of p? A difficulty is that although, when we are dealing with genuine left and right multiples of p, reductions $(xp)\,q\,(py) \mapsto (xpy)_R$ turn out to be well-defined, there is no evident reduction of xqy when x and y are elements "to be regarded as" a right and a left multiple of p respectively. But I have not looked closely at the question.

Let's clear up a couple of loose ends. I mentioned in the preceding section that the formulation of Lemma 10 used there was rigged for quick application. Here is the promised more abstract version. Note that the n of the result below corresponds to $n-1$ in Lemma 10, since there are $n-1$ places in which to insert factors between n q's. The proof is essentially as before.

Corollary 16 (to proof of Lemma 10)**.** *Let $n \geq 1$, let A and A' be abelian groups, let $\mu: A^n \to A'$ be an n-linear map, and let x and y be elements of A. Let $S(n)$ be the family of elements $\pm\,\mu(a_1,\dots,a_n) \in A'$ which arise from all ways of choosing each a_i from the* 3*-element set $\{x, y, x{+}y\}$, and also choosing the sign plus or minus, so as to satisfy the following conditions.*

If $(a_1,\dots,a_n)$ has an x in a nonfinal position, it has a y in the next position.
If $(a_1,\dots,a_n)$ has a y in a noninitial position, it has an x in the preceding position.
(74) *If the number of occurrences in $(a_1,\dots,a_n)$ of the substring "x, y", plus the number of occurrences of initial y and/or final x, is odd, then the sign appended to $\mu(a_1,\dots,a_n)$ is $-$; otherwise it is $+$.*

Then the sum of the resulting set $S(n)$ of elements $\pm\,\mu(a_1,\dots,a_n) \in A'$ is 0.
(*Above, if two of x, y, $x{+}y \in A$ happen to be equal, we treat them as formally distinct in interpreting* (74).) $\square$

Is the above the nicest version of the result? A "cleaner" form would be the special case where A is the free abelian group on $\{x, y\}$, and A' the n-fold tensor power of A, since the form given above can be obtained from that case by composing with maps into general A and A'; and that case would avoid distractions when studying the combinatorics of the result. On the other hand, the form given above simplifies applications such as we are making here.

Turning back to the proof of resolvability of the ambiguities (61) and (68), it might be possible to make this cleaner by first obtaining identities involving the families $S(n) \subseteq k\langle p, s, t, q\rangle$. If we let $S'(n)$ denote the subset of $S(n)$ consisting of those elements, in the construction of which the final q was *not* marked (and, for convenience, define $S'(1)=\{q\}$), then we can express the $S(n)$ in terms of these sets:

(75) $$S(n) \;=\; S'(n) \,\cup\, -S'(n{-}1)\,(tp)\,q \quad (n\geq 2),$$

and give a recursive construction of the $S'(n)$:

(76) $$S'(1)=\{q\}, \qquad S'(2)=\{q\,(ps{+}tp)\,q,\ q\,(ps)\,q\},$$

(77) $$S'(n) \;=\; S'(n{-}1)\,(ps{+}tp)\,q \,\cup\, -S'(n{-}2)\,(tp)\,q\,(ps)\,q \quad (n\geq 3).$$

We would likewise let $S''(n)\subseteq S(n)$ be the subset determined by the condition the that *initial* q not be marked, and give the corresponding formulas for these sets; and we could probably develop formulas which, mapped to our ring R', would be equivalent to the resolvability of our ambiguities. If the method of the preceding section should prove useful beyond the particular results we obtain there, this approach might be worth pursuing.

11. What if R is the Weyl algebra? Don't ask!

A well-known example of a ring with an element p that is neither left nor right invertible, but which satisfies $1\in pR+Rp$, is the Weyl algebra. This is usually denoted $A=k\langle x,y\mid yx=xy+1\rangle$ or $A=k\langle x,\,d/dx\rangle$; but for consistency with the notation in the rest of this note, let us write it

(78) $$R \;=\; k\langle p,s\mid ps+(-s)p=1\rangle.$$

It is natural to ask whether we can get a nice normal form for the extension

(79) $$R' \;=\; k\langle p,s,q\mid ps+(-s)p=1,\ pqp=p\rangle.$$

If we want to apply the construction of Theorem 13, we first need to determine the k-subspaces pR and Rp of R, and their intersection. It is a standard result that a k-basis of the Weyl algebra is given by

(80) $$\{s^m p^n\mid m,n\geq 0\}.$$

Indeed, every element of R can be reduced to a linear combination of members of this basis by repeated application of the reduction

(81) $$ps \;\mapsto\; sp+1,$$

which has no ambiguities.

Since right multiplying a k-linear combination of elements of (80) by p gives a k-linear combination of such elements having $n>0$, it follows that Rp is precisely the k-subspace of R spanned by the elements $s^m\,p^n$ with $n>0$.

One can characterize pR similarly using the basis $\{p^n s^m\mid m,n\geq 0\}$, but this does not help if we want to study both subspaces at the same time. So let us, for now, represent elements of R using the basis (80), and investigate what linear combinations of these basis elements lie in pR.

If we apply (81) repeatedly starting with $p\,s^m$, we get

(82) $$p\,s^m \;=\; s^m\,p \;+\; m\,s^{m-1}.$$

Thus, $s^m p\equiv -\,m s^{m-1}\pmod{pR}$, and right multiplying this congruence by p^{n-1}, we get

(83) $$s^m p^n \;\equiv\; -m\,s^{m-1}p^{n-1}\pmod{pR}\quad \text{for } m,n\geq 1.$$

We can iterate (83), decreasing the exponents of s and p until one of them goes to zero. So if $n>m$, we conclude that $s^m p^n$ is congruent modulo pR to an integer multiple of a positive power of p; hence it lies in pR; and since it also lies in Rp, we get

(84) $$s^m p^n\in pR\cap Rp \quad \text{if } n>m.$$

On the other hand, if $m\geq n>1$, it is convenient to iterate (83) only to the point of bringing the exponent of p down to 1. That gives us $s^m p^n\equiv(-1)^{n-1}\,m(m-1)\dots(m-n+2)\,s^{m-n+1}\,p\pmod{pR}$, so again, since both expressions lie in Rp, we get

(85) $$s^m p^n \;\equiv\; (-1)^{n-1}\,m(m{-}1)\dots(m{-}n{+}2)\,s^{m-n+1}\,p \pmod{pR\cap Rp}\quad \text{if } m\geq n>1.$$

Combining (84), (85), and the vacuous relation $s^m\;\equiv\;s^m\pmod{pR\cap Rp}$, we get

(86) Every element of R is congruent modulo $pR{\cap}Rp$ to a linear combination of words s^m and $s^m p$.

Since the family of words $\{s^m,\, s^m p \mid m \geq 0\}$ is "small" compared with the full k-basis (80), we see that when we form our desired spanning set B, "most of" that set can be expected to lie in the component B_{++}.

Further details depend on the characteristic of k. We shall consider the case where $\mathrm{char}(k) = 0$.

In this case, solving (82) for s^{m-1}, we see that every power of s lies in $pR + Rp$. Hence,

(87) If $\mathrm{char}(k) = 0$, then $R = pR + Rp$.

It is now easy to verify that

(88) If $\mathrm{char}(k) = 0$, then a spanning set B for R with the properties of (48), (49) is given by

$$\begin{aligned} B_{++} &= \{s^m p^n \mid n > m \geq 0\} \;\cup\; \{s^m p^n + m s^{m-1} p^{n-1} \mid m \geq n > 1\} \quad \text{(cf. (84) and (83))},\\ B_{-+} &= \{-s^m\, p \mid m > 0\},\\ B_{+-} &= \{p\, s^m \mid m > 0\} \;=\; \{s^m\, p + m\, s^{m-1} \mid m > 0\} \quad \text{(cf. (82))},\\ B_{--} &= \emptyset. \end{aligned}$$

(I have put a minus sign into the entries of B_{-+} to conform with the convention made in (48), that B_{-+} contain tp, which, in writing (78), we have taken to be $(-s)p$.)

Using the above basis, we can obtain by Theorem 13 a normal form for $R' = k\langle p, s, q \mid ps + (-s)p = 1,\; pqp = p\rangle$.

But what we would really like is a normal form in terms of the generators p, s and q. When first exploring the case $1 \in pR + Rp - (pR \cup Rp)$ of the subject of this note, I took the Weyl algebra as a sample case, and tried to find such a normal form; but the ambiguities among reductions I obtained kept spawning new reductions, without apparent pattern. This, along with calculations showing that the forms of these reductions must depend on the characteristic of k, led me to doubt for a long time that any reasonable normal form could be found when $1 \in pR + Rp - (pR \cup Rp)$. It was only when I dropped the case of the Weyl algebra, and returned to consideration of a general k-algebra, that I was able to get anywhere.

However, with the results of §9 now at hand, we can develop a normal form for this algebra R' in terms of p, s and q, and shall do so below (still assuming $\mathrm{char}(k) = 0$).

(Let me here moderate the semi-facetious title of this section, to merely say that if, at some point the reader chooses not to slog further through the lengthy argument for the sake of a normal form whose value is not evident, I will not argue with his or her choice.)

In preparation for the result, let us note that the normal form that we would get by simply applying Theorem 13 to the basis (88) for R is somewhat atypical among applications of that theorem. In the general situation of Theorem 13, if we take from our spanning set B three elements $xp \in B_{++} \cup B_{-+}$, $y \in B_{--}$, $pz \in B_{++} \cup B_{+-}$ (note the choice of y here, the opposite of what we considered when looking for ambiguities!), then products $(xp)\, q^m\, y\, q^n\, (pz)$ are irreducible: the presence of $y \in B_{--}$ between (xp) and (pz) blocks any reductions. However, with a basis like (88), where B_{--} is empty, no such blockage is possible; and we find that in any string of elements of $B \cup \{q\}$ that is reduced with respect to the normal form of Theorem 13, no element of $B_{++} \cup B_{-+}$ can occur anywhere to the left of an element of $B_{++} \cup B_{+-}$. So the elements of B (if any) occurring interspersed among the q's in our word will begin with a sequence (possibly empty) of members of B_{+-}, and end with a sequence (possibly empty) of members of B_{-+}, with at most a single member of B_{++} between these.

This will prepare us for the fact that words in the normal form based on p, s and q that we shall obtain will typically have a sort of singularity in the middle. To prepare us in a more detailed way for the form they will have, let us note that where in §9, a key tool was to apply, between various pairs of q's in a string $q \ldots q$, the relation $1 = ps + tp$, in the present situation we can, more generally, whenever an s^m $(m \geq 0)$ appears between q's, apply the result of putting $m{+}1$ for m in (82) and solving for s^m :

(89) $$s^m \;=\; (m+1)^{-1}(ps^{m+1} - s^{m+1}p).$$

Using these ideas, we shall now prove

Theorem 17. *Let k be a field of characteristic 0. Then the algebra*

(90) $$R' \;=\; k\langle p, s, q \mid ps = sp + 1,\; pqp = p\rangle$$

has a k-basis consisting of all words in p, s and q in which no p is immediately followed by an s, and the p's that occur (if any) form a single consecutive string. In other words, every such word has the form

(91) $\quad s^{a_0}\,q\,s^{a_1}\,q\,\ldots\,q\,s^{a_{m-1}}\,q\,s^{a_m}\,p^b\,q\,s^{a_{m+1}}\,q\,\ldots\,q\,s^{a_n},$

where $0\leq m\leq n$, $b\geq 0$, and all $a_i\geq 0$. (Remark: If $b=0$, then m is, of course, not uniquely defined.)

Proof. We shall first show that every monomial in our generators can be reduced to a linear combination of monomials (91), so that these span R', then that the set of such monomials is k-linearly independent. We will not follow the formalism of the Diamond Lemma, though some of the ideas will be similar. In particular, in the first part of our proof, we shall associate to every monomial a 4-tuple of natural numbers, and show that every monomial not of the form (91) is equal in R' to a k-linear combination of monomials each of which has smaller associated 4-tuple, under lexicographic ordering. This is enough to show that every monomial is a k-linear combination of monomials (91). (If not every monomial were so expressible, there would be a least 4-tuple associated with a counterexample monomial w, and applying a reduction of the indicated sort to w would give a contradiction.)

The 4-tuple we shall associate with a word w is

(92) $\quad h(w)\ =\ (a_q(w),\,a_p(w),\,a_s(w),\,b_{p,s}(w)),$

where the first three coordinates are the numbers of q's, p's and s's in w, and the last is the number of occurrences of a p anywhere before an s, i.e., the number of ordered pairs (i,j) with $i<j$ such that the i-th factor of w is a p and the j-th is an s. This refinement of the coordinate "number of occurrences of the element (ps)" that we used in §9 is needed here: if we simply counted occurrences of the string ps, calling this number $a_{ps}(w)$, then inequalities involving this function would not respect formal multiplication of monomials: clearly, $a_{ps}(sp)<a_{ps}(ps)$, yet multiplying these monomials on the left by p we find that $a_{ps}(psp)\not< a_{ps}(pps)$. However, I claim that for h defined by (92), if $h(u)\leq h(u')$ and $h(v)\leq h(v')$, with at least one of these inequalities strict, then $h(uv)<h(u'v')$. Indeed, this is obvious except in the case where the first three coordinates of $h(u)$ agree with those of $h(u')$ and the first three coordinates of $h(v)$ agree with those of $h(v')$, so that the comparison depends on the 4-th coordinate, $b_{p,s}$. Now it is easy to see that in general, $b_{p,s}(uv)=b_{p,s}(u)+b_{p,s}(v)+a_p(u)\,a_s(v)$, so when the a-coordinates are the same for u and u', and likewise for v and v', the $b_{p,s}$-coordinate of our product depends additively on the $b_{p,s}$-coordinates of the factors, from which the desired inequality follows.

So let us assume w is a monomial not of the form (91), and prove that it is a linear combination of monomials with smaller values of h.

If w contains a sequence ps, then applying the relation $ps=sp+1$, we get a sum of two monomials on each of which h clearly has value $<h(w)$.

If w has no subsequence ps, then to fail to have the form (91), it must have two p's with a nonempty string of non-p terms between them. Writing u and v for the (possibly empty) segments before and after these two p's, we can write

(93) $\quad w\ =\ u\,p\,q\,s^{m_1}\,q\,\ldots\,q\,s^{m_{n-1}}\,q\,s^{m_n}\,p\ v,\qquad \text{where }\ n\geq 1\ \text{ and }\ s_{m_1},\ldots,s_{m_n}\geq 0.$

It will now suffice to show that the string between u and v,

(94) $\quad p\,q\,s^{m_1}\,q\,\ldots\,q\,s^{m_n}\,q\,s^{m_n}\,p$

is equal in R' to a k-linear combination of words on which h has lower values.

As a first step, let us use the relation (82) in reverse, to replace the final $s^{m_n}p$ of (94) with $p\,s^{m_n}-m_ns^{m_n-1}$ if $m_n>0$, turning (94) into a linear combination of two monomials. One of these, the one arising from the s^{m_n-1} term, has a strictly lower value of h, so we can ignore it. The other,

(95) $\quad p\,q\,s^{m_1}\,q\,\ldots\,q\,s^{m_{n-1}}\,q\,p\,s^{m_n}$

has value of h that is higher than (94), but only in its $b_{p,s}$ coordinate. I claim now that we can further rewrite (95) so as to turn it into a k-linear combination of monomials all involving fewer q's, and hence all having lower values of h than (94) has. If $m_n=0$ (the case we temporarily excluded at the start of this paragraph), (95) is the same as (94); so in either case we have the latter expression to consider.

If $n=1$, then (95) has the form $p\,q\,p\,s^{m_1}$, which clearly equals $p\,s^{m_1}$, giving a decreased value of a_q, as desired. For $n>1$, the idea will be, as indicated, to apply (89) to each of the factors s^{m_i} nestled between the q's, and then treat these as we treated the factors $1=ps+tp$ in §9. Now replacing s_i^m by

$(m_i+1)^{-1}(ps^{m_i+1}-s^{m_i+1}p)$ gives terms with larger values of a_p, a_s and (usually) $b_{p,s}$ than (95) had; but it does not affect the value of a_q, so we will still be safe if the result can be reduced to a linear combination of terms all having lower values of a_q.

To formalize this process, we shall apply Corollary 16, with $n{-}1$ for the n of that corollary, taking for A a 2-dimensional k-vector-space with basis written $\{x,y\}$, and for A' the underlying k-vector-space of R'. Let us define k-linear maps $\mu_1,\dots,\mu_{n-1}: A\to R'$ by letting μ_i carry x to $(m_i+1)^{-1}s^{m_i+1}p$, and y to $(m_i+1)^{-1}p\,s^{m_i+1}$, so that it carries $x{+}y$ to s^{m_i}. Define $\mu: A^{n-1}\to A'$ by

$$(96)\qquad \mu(a_1,\dots,a_{n-1}) \;=\; p\,q\,\mu_1(a_1)\,q\,\dots\,q\,\mu_{n-1}(a_{n-1})\,q\,p\,s^{m_n}.$$

By Corollary 16, the sum of the set $S(n{-}1)$ defined in that corollary using the map (96) equals zero. We find that the term of that sum in which all of $a_1,\dots,a_{n-1}$ are $x{+}y$ is exactly (95), while in every other term, at least one of the n q's has a p before it and a p after it, so that an application of the relation $pqp=p$ allows us to reduce the number of q's. So (95) is equal to a linear combination of monomials each involving fewer q's, as claimed. This completes our proof that the elements (91) span R'.

How shall we now show these elements k-linearly independent? One approach would be to formalize the above argument as giving a reduction system in the sense of the Diamond Lemma, and verify that all its ambiguities are reducible. But that verification was already tedious in the simpler context of Theorem 13.

Rather, let us apply Theorem 13 to the generating set (88) of R', and then show that when the monomials (91) are expressed in terms of the basis given by that theorem, they have distinct leading terms, proving them k-linearly independent.

Of course, to define "leading term", we need a total ordering on the basis of R' in question. To describe the ordering we will use, let the "weight" of a member of the basis B of (88) be the highest exponent of s appearing in its expression. (E.g., the weight of $s^m p + m s^{m-1}\in B_{+-}$ is m.) We now define a word w in the elements of $B\cup\{q\}$ to be larger than a word w' if it involves more q's; or if it involves the same number of q's but the total weight of the factors from B is higher, or if we have equality of both of these, but it has more terms from B_{+-}; while when all of these are equal, let the total ordering be chosen in an arbitrary fashion.

We now consider a word w of the form (91), and the operation of expressing it in the normal form of Theorem 13 determined by the basis (88) of our Weyl algebra; and ask what its leading term with respect to the above ordering will be.

First, suppose that b, the exponent of p in (91), is zero. Then to write w as an expression (not reduced, to start with) in the elements of in $B\cup\{q\}$, we may replace every term s^{a_i} with $a_i>0$ by $(a_i+1)^{-1}((ps^{a_i+1})-(s^{a_i+1}p))$, while writing any factors s^{a_i} with $a_i=0$ as 1, the empty word. When we multiply this expression out, every pair of successive q's are either adjacent, or have between them a generator $(ps^{a_i+1})\in B_{+-}$ or $(s^{a_i+1}p)\in B_{-+}$. Those of the resulting words that have a member of B_{-+} anywhere to the left of a member of B_{+-} can be reduced by one of the reductions in our (52)-series to a linear combination of words involving smaller numbers of q's. Of those that remain, we see that the one that will be largest under our ordering will be (by the stipulation regarding elements of B_{+-} in our description of that ordering), the one with the greatest number of factors from B_{+-}; i.e., the one in which $(ps^{a_i+1})\in B_{+-}$ has been used in each position where $a_i>0$. Clearly this leading reduced word determines the sequence of exponents a_i, hence it uniquely determines w.

Next, suppose $b=1$. The first step in expressing w in terms of the generators (88) is the same as before, except that the factor $s^{a_m}p$, unlike the factors s^{a_i}, is not modified, since it is, as it stands, a member of B_{-+}. In this case, all the words we get that have a member of B_{+-} *after* that term again have a member of B_{-+} to the left of a member of B_{+-}, and so can be reduced to terms with fewer q's, so the terms that cannot be so reduced must have factors $(s^{a_i+1}p)\in B_{-+}$ in those positions. On the other hand, of the terms before $s^{a_m}\,p$, the largest one under our ordering will again have all factors from B of the form $(ps^{a_i+1})\in B_{+-}$. So the largest term occurring determines both the sequence of a_i and the position where the p occurs in w (namely, the position where the first element of B_{-+} appears). Moreover, that leading term is not equal to the leading term of an expression with $b=0$, since as we have seen, the latter have no factors in B_{-+}.

Finally, if $b>1$, we have behavior similar to the case $b=1$, except that the factor $s^{a_m}\,p^b$ now reduces to the sum of an element of B_{++} and possibly an expression lower under our ordering. (By the description of B_{++} in (88), such a lower summand will appear if $b\le a_m$.) Only the former summand need be looked at;

and we see again that the unique term having members of B_{+-} before that element of B_{++}, and members of B_{-+} after it, will be irreducible under the normal form of Theorem 13, and will give the leading term of our reduced expression. This leading term now determines both the value of b and, as before, the values of m and of the a_i, and so again determines w.

This completes the proof of the Theorem. ☐

When $\mathrm{char}(k) = e > 0$, things are somewhat different. On the one hand, (85) simplifies pleasantly whenever $e \mid m(m-1)\dots(m-n+2)$. On the other hand, I claim that the elements s^m with $m \equiv -1 \pmod{e}$ are k-linearly independent modulo $pR+Rp$. Indeed, since R is spanned over k by elements $s^m p^n$, the space pR is spanned by elements $p\,s^m p^n$, and using (82) we see that in the expansions of these elements in terms of the basis (80), basis elements s^m with $m \equiv -1 \pmod{e}$ never appear with nonzero coefficients. Since they also certainly do not appear with nonzero coefficients in the expressions in that basis for elements of Rp, they do not appear in the expressions for elements of $pR+Rp$. One finds that $\{s^m \mid m \equiv -1 \pmod{e}\}$ can be taken as a basis of B_{--}. Probably one can get a normal form for R' somewhat like the above; but with multiple clusters of p's allowed, separated by strings $q\,s^m\,q$ with $m \equiv -1 \pmod{e}$. However, I have not looked into this.

12. Late addendum: mutual inner inverses

At about the time this paper was accepted for publication, I received a preprint of [7], in which P. Ara and K. O'Meara used results in the preprint version of this note to answer an open question on nilpotent regular elements in rings. Their method required them to extend the result of Theorem 4, for a certain R, to get a description of the k-algebra generated over that R by a universal *mutual* inner inverse of p, $R'' = R\langle q \mid pqp = p,\, qpq = q\rangle$. This led me to wonder whether I could save them that awkwardness, and get some useful general results, by extending some of the material of this paper to mutual inner inverses. (Incidentally, what I am calling "mutual inner inverses" are more often called "generalized inverses", and are so called in [7]. But I prefer to use here a term that highlights their relation with inner inverses.)

The symmetry of the property of being mutually inner inverse suggests that, just as p is taken in Theorem 4 to be an element of a fairly general k-algebra R, so q might be taken from another such k-algebra S. And, indeed, it turns out that if such p and q are *nonzero* and satisfy $1 \notin pR+Rp$, $1 \notin qS+Sq$, then we can build on Theorem 4 to get a very similar normal form for this construction. In this normal form, we will, on the one hand, use a k-basis B for R as in Theorem 4 (but note that in the present situation, the qualifying phrase "if $p \neq 0$" can be removed from the condition that B_{++} contain p, in the first line of (8), since, as noted above, p is here assumed nonzero). Likewise, we will use a k-basis for S of the analogous form,

$$C \cup \{1\} \;=\; C_{++} \cup C_{+-} \cup C_{-+} \cup C_{--} \cup \{1\}, \tag{97}$$

where

$$\begin{array}{ll} C_{++} & \text{is any } k\text{-basis of } qS \cap Sq \text{ which contains } q,\\ C_{+-} & \text{is any } k\text{-basis of } qS \text{ relative to } qS \cap Sq,\\ C_{-+} & \text{is any } k\text{-basis of } Sq \text{ relative to } qS \cap Sq,\\ C_{--} & \text{is any } k\text{-basis of } S \text{ relative to } qS+Sq+k. \end{array} \tag{98}$$

We can now state and prove

Theorem 18. *Suppose R and S are k-algebras* (*which for notational simplicity we will assume are disjoint except for the common subfield k*), *and let $p \in R-\{0\}$, $q \in S-\{0\}$ satisfy*

$$1 \notin pR+Rp, \qquad 1 \notin qS+Sq. \tag{99}$$

Let $B \cup \{1\}$ be a k-basis for B as in (7) *and* (8), *and $C \cup \{1\}$ a k-basis for S as in* (97) *and* (98).

Then the k-algebra T freely generated by the two k-algebras R and S, subject to the two additional relations

$$pqp \;=\; p, \quad qpq \;=\; q, \tag{100}$$

has a k-basis given by all words in $B \cup C$ which contain no subwords as in (10) *or* (11) (*that is, no subwords of the form xy with $x, y \in B$, or $(xp)\,q\,(py)$ with $xp \in B_{++} \cup B_{-+}$, $py \in B_{++} \cup B_{+-}$*), *nor any subwords* *of the analogous forms*

(101) $\quad xy \quad$ *with* $x, y \in C$,

or

(102) $\quad (xq)\,p\,(qy) \quad$ *with* $xq \in C_{++} \cup C_{-+}$ *and* $qy \in C_{++} \cup C_{+-}$.

The reduction to the above normal form may be accomplished by the reductions (12) *and* (13) *of Theorem 4, together with the analogous reductions,*

(103) $\quad xy \;\mapsto\; (xy)_S \quad$ *for all* $x, y \in C$,

and

(104) $\quad (xq)\,p\,(qy) \;\mapsto\; (xqy)_S \quad$ *for all* $xq \in C_{++} \cup C_{-+}$, $qy \in C_{++} \cup C_{+-}$.

Proof. It is clear that the reductions (12), (13), (103) and (104) correspond to relations holding in T, and include enough relations to present that algebra, and that they all reduce the lengths of their input-words. So it suffices to check that all ambiguities of the resulting reduction system are resolvable.

Note that the input-word of each of the reductions (12), (13) begins and ends with generators from B, while the input-words of (103) and (104) begin and end with generators from C. Hence, if an ambiguity in our reduction system involves an overlap of only one letter, the two words must either both come from (12) and/or (13), or both come from (103) and/or (104). In the former case, that ambiguity will be resolvable by Theorem 4, and in the latter case, by that same theorem applied with S, q and p in the roles of R, p and q.

It remains to consider two-letter overlaps. We implicitly noted in the proof of Theorem 4 that there were no such overlaps involving only reductions (12) and/or (13); so there are likewise none involving only (103) and/or (104). Hence two-letter overlaps must involve one reduction from the former family and one from the latter. However, the only generators appearing in both families of reductions are p and q. From this it is easy to check that the remaining ambiguously reducible monomials are precisely

(105) $\quad (xp)\cdot q\,p\cdot (qy), \quad$ where $\quad xp \in B_{++} \cup B_{-+}$, $qy \in C_{++} \cup C_{+-}$,

and

(106) $\quad (xq)\cdot p\,q\cdot (py), \quad$ where $\quad xq \in C_{++} \cup C_{-+}$, $py \in B_{++} \cup B_{+-}$.

I claim that the two competing reductions applicable to (105) each reduce it to $(xp)(qy)$. Indeed, to reduce the initial string $(xp)\,q\,p$ in (105), we write the factor p as $(p1) \in B_{++}$ and apply (13), getting $(xp)\,q\,(p1) \mapsto (xp1)_R = (xp)$; which reduces the product (105) to $(xp)(qy)$. The other reduction similarly applies (104) to the final string $q\,p\,(qy)$, and gives the same result.

Likewise, the two reductions applicable to (106) both reduce it to $(xq)(py)$.

Hence all the ambiguities of our reduction system are resolvable, so T has a normal form given by the words irreducible under that system; that is, those having no subwords (10), (11), (101) or (102), as required. $\square$

The construction needed for [7] can now be gotten as a special case.

Corollary 19. *As in Theorem 4, let* R *be a* k*-algebra,* p *an element of* R *such that* $1 \notin pR + Rp$, *and* $B \cup \{1\}$ *a basis of* R *as in* (7) *and* (8)*; and let us also assume* $p \neq 0$. *Let*

(107) $\quad R'' \;=\; R\,\langle q \mid pqp = p,\, qpq = q\rangle$,

i.e., the k*-algebra gotten by adjoining to* R *a universal mutual inner inverse* q *to* p.

Then R'' *has a* k*-basis given by all words in the generating set* $B \cup \{q\}$ *which contain no subwords as in* (10) *or* (11) (*that is, no subwords of the form* xy *with* $x, y \in B$ *or* $(xp)\,q\,(py)$ *with* $xp \in B_{++} \cup B_{-+}$, $py \in B_{++} \cup B_{+-}$), *nor any subwords*

(108) $\quad q\,p\,q$.

The reduction to the above normal form may be accomplished by the reductions (12) *and* (13) *of Theorem 4, together with the reduction*

(109) $\quad q\,p\,q \;\mapsto\; q$.

Proof. The normal form described is essentially that of the case of Theorem 18 where S is the polynomial ring $k[q]$, and $C = C_{++} = \{q^n \mid n > 0\}$. There is the formal difference that words in the basis described in this corollary may contain strings of the generator q, while each such string is represented in the basis gotten from Theorem 18 as a single generator (q^n); however, the systems of elements of R'' described by the resulting words are clearly the same. Likewise, in the indicated case of Theorem 18, the reduction (109) is supplemented by the reductions $(q^m)\,p\,(q^n) \mapsto (q^{m+n-1})$ for all $m, n > 0$; but the reduction (109) applied to the subword qpq of the length-$m{+}n{+}1$ string $q^m p\, q^n$ clearly has the corresponding effect.

We remark that it would have been no harder – but also not significantly easier – to verify directly that adding (109) to the reductions of Theorem 4 yields a reduction system for R'' with all ambiguities resolvable. □

It is easy to supplement Theorem 18 with a normal form result paralleling Proposition 7 for the T-module induced by a p-tempered right R-module, or by a q-tempered right S-module, defined analogously.

13. Further questions and observations

Do results paralleling Theorem 18 and Corollary 19 hold without the hypotheses $1 \notin pR + Rp$ and $1 \notin qS + Sq$?

For the analog of Corollary 19, where we are only free to modify R, we can say "yes" in the situation of §7, and "probably" in that of §9. In former situation, taking p right invertible in R, we saw in §7 that in $R' = R\langle q \mid pqp = p\rangle$ our adjoined element q also became a right inverse to p. But this makes p and q mutually inner inverse; so $R'' = R'$; so the additional relation $qpq = q$ and the reduction $qpq \mapsto q$ have no additional effect, nor does exclusion of the string qpq from words in our basis. Thus, for this case the analog of Corollary 19 is trivially true.

For R and p as in §9, hand calculations I have made suggest that the analog of Corollary 19 also holds: All the ambiguities arising from overlaps between (109) and the reductions (52), (52_2), (52_3), (53) and (53_2) appear to be resolvable, so it is likely that computations like those of §9 can prove the same for ambiguities involving (109) and any of the reductions (52_n) and (53_n).

On the other hand, for Theorem 18, the obvious generalization with R no longer assumed to satisfy $1 \notin pR + Rp$, while S is still assumed to satisfy $1 \notin qS + Sq$, but not restricted to be $k[q]$, definitely does not hold. For an extreme example, if $p \in R$ is a nonzero element generating within R a finite-dimensional field extension F of k, then F will also be generated by p^{-1}, hence if an element $q \in S$ is to become an inner inverse of p in an algebra containing (embedded copies of) both R and S, the subalgebra of S generated by q must have the same structure F; which cannot be true if $1 \notin qS \cap Sq$ (and is very restrictive even if this is not assumed). To see that there are also obstructions to the analog of Theorem 18 when $1 \in pR + Rp - (pR \cup Rp)$, take $S = k[q \mid q^2 = 0]$ (which clearly satisfies $1 \notin qS + Sq$). We saw in §8 that the relations $pqp = p$ and $1 \in pR + Rp$ together imply $pqqp = pq + qp - 1$ (42). Combining this with the relation $q^2 = 0$ holding in S, we get $pq + qp = 1$. But pq, qp and 1 are distinct words not containing any subwords (70)-(73), (101) or (102); so if the analog of Theorem 18 held, they would be k-linearly independent. Nor does it help to assume, instead, that S and q satisfy $1 \in qS + Sq - (qS \cup Sq)$; for if we take for S the 2×2 matrix ring over k, and for q the square-zero matrix e_{12}, we get the same problem just described.

But perhaps others will be able to find useful normal form results for some cases of this construction.

We end this note by recording an alternative way to construct the algebra $R'' = R\,\langle q \mid pqp = p,\, qpq = q\rangle$ from $R' = R\,\langle q \mid pqp = p\rangle$, implicitly noted in the original version of [7]. This does not require that our algebras be over a field, so we assume an arbitrary commutative base ring K.

Lemma 20 (after P. Ara and K. O'Meara, original version of [7])**.** *Let R be an algebra over a commutative ring K, let p be any element of R, and let R' be the K-algebra $R\,\langle q \mid pqp = p\rangle$.*

Then R' admits a retraction (idempotent K-algebra endomorphism) φ that fixes the image of R, and takes q to qpq. The retract $\varphi(R')$ is naturally isomorphic to $R'' = R\,\langle q \mid pqp = p, qpq = q\rangle$, via an isomorphism ψ that carries $q \in R''$ to $\varphi(q) = qpq \in \varphi(R')$.

Proof. The defining relation $pqp = p$ of R' clearly implies the two relations

(110) $\quad p \cdot qpq \cdot p = p \quad$ and $\quad qpq \cdot p \cdot qpq = qpq.$

The first shows that qpq satisfies the relation over R that is imposed on q in R'; hence R' admits an endomorphism φ over R taking q to qpq, and by the second relation, φ is idempotent. Moreover, the relations of (110) together show that the image of q in $\varphi(R')$ satisfies the relations imposed on q in the definition of R''; so we get a homomorphism $\psi : R'' \to \varphi(R')$ taking q to $\varphi(q) = qpq$. On the other hand, the factor-map $\theta : R' \to R''$ takes $qpq \in R'$ to $qpq = q \in R''$, from which it is easily seen that the restriction of θ to $\varphi(R')$ is a 2-sided inverse to ψ, establishing the asserted isomorphism. □

So if we know the structure of R', the above lemma gives us a way of studying R''. However, I have not found it easy to apply this to the description of R' that we obtained in §9 for the case $1 \in pR+Rp-(pR \cup Rp)$, because substituting qpq for q in normal-form expressions for elements of R' gives expressions that are in general not in normal form. E.g., for $n > 1$ the image $\varphi(q^n)$ can be reduced repeatedly using (42), and it is hard to see just what relations such reductions lead to.

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