
Peer reviewed version
License (if available): CC BY-NC-ND
Link to publication record in Explore Bristol Research
PDF-document

This is the accepted author manuscript (AAM). The final published version (version of record) is available online via Elsevier at http://dx.doi.org/10.1016/j.jcta.2014.10.002. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research
General rights
This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available: http://www.bristol.ac.uk/pure/about/ebr-terms
Distinguishing subgroups of the rationals by their Ramsey properties

Ben Barber
School of Mathematics
University of Birmingham
Edgbaston
Birmingham B15 2TT
UK

Neil Hindman
Department of Mathematics
Howard University
Washington, DC 20059
USA

Imre Leader
Department of Pure Mathematics and Mathematical Statistics
Centre for Mathematical Sciences
Wilberforce Road
Cambridge CB3 0WB
UK

Dona Strauss
Department of Pure Mathematics
University of Leeds
Leeds LS2 9J2
UK

Email addresses: b.a.barber@bham.ac.uk (Ben Barber), nhindman@aol.com (Neil Hindman), leader@dpmms.cam.ac.uk (Imre Leader), d.strauss@hull.ac.uk (Dona Strauss)

URL: http://nhindman.us (Neil Hindman)

¹This author acknowledges support received from the National Science Foundation via Grant DMS-1160566.
Abstract

A system of linear equations with integer coefficients is partition regular over a subset $S$ of the reals if, whenever $S \setminus \{0\}$ is finitely coloured, there is a solution to the system contained in one colour class. It has been known for some time that there is an infinite system of linear equations that is partition regular over $\mathbb{R}$ but not over $\mathbb{Q}$, and it was recently shown (answering a long-standing open question) that one can also distinguish $\mathbb{Q}$ from $\mathbb{Z}$ in this way.

Our aim is to show that the transition from $\mathbb{Z}$ to $\mathbb{Q}$ is not sharp: there is an infinite chain of subgroups of $\mathbb{Q}$, each of which has a system that is partition regular over it but not over its predecessors. We actually prove something stronger: our main result is that if $R$ and $S$ are subrings of $\mathbb{Q}$ with $R$ not contained in $S$, then there is a system that is partition regular over $R$ but not over $S$. This implies, for example, that the chain above may be taken to be uncountable.

**Key words:** partition regular, rationals, subgroups, central sets

**2010 MSC:** 05D10, 22A15, 54D35

1. Introduction

Consider the following system of $u$ linear equations in $v$ unknowns:

\[
\begin{align*}
& a_{1,1}x_1 + a_{1,2}x_2 + \cdots + a_{1,v}x_v = 0 \\
& a_{2,1}x_1 + a_{2,2}x_2 + \cdots + a_{2,v}x_v = 0 \\
& \vdots \quad \vdots \quad \ddots \quad \vdots \quad \vdots \\
& a_{u,1}x_1 + a_{u,2}x_2 + \cdots + a_{u,v}x_v = 0
\end{align*}
\]

If the coefficients are rational numbers and the set $\mathbb{N}$ of positive integers is finitely coloured, is one guaranteed to be able to find monochromatic $x_1, x_2, \ldots, x_v$ solving the given system? That is, is the system of equations partition regular? In [8], Rado answered this question, showing that the
system is partition regular if and only if the matrix of coefficients
\[
A = \begin{pmatrix}
a_{1,1} & a_{1,2} & \cdots & a_{1,v} \\
a_{2,1} & a_{2,2} & \cdots & a_{2,v} \\
\vdots & \vdots & \ddots & \vdots \\
a_{u,1} & a_{u,2} & \cdots & a_{u,v}
\end{pmatrix}
\]
satisfies the columns condition:

**Definition 1.1.** Let \( u, v \in \mathbb{N} \) and let \( A \) be a \( u \times v \) matrix with entries from \( \mathbb{Z} \). Denote column \( i \) of \( A \) by \( \vec{c}_i \). The matrix \( A \) satisfies the columns condition if there exist \( m \in \{1, 2, \ldots, v\} \) and a partition \( \{I_1, I_2, \ldots, I_m\} \) of \( \{1, 2, \ldots, v\} \) such that

1. \( \sum_{i \in I_1} \vec{c}_i = \vec{0} \);
2. for each \( t \in \{2, 3, \ldots, m\} \), if any, \( \sum_{i \in I_t} \vec{c}_i \) is a linear combination with coefficients from \( \mathbb{Q} \) of \( \{\vec{c}_i : i \in \bigcup_{j=1}^{t-1} I_j\} \).

If one considers the same equations over \( \mathbb{R} \), an easy compactness argument shows that a finite system of equations is partition regular over the reals if and only if it is partition regular over the integers.

Note that the restriction to integer coefficients might as well be to rational coefficients, as we are always free to multiply each equation by a constant. We remark in passing that if one were to allow coefficients that are not rational, then the situation for finite systems is again understood: in [9], Rado extended his result by showing that if \( R \) is any subring of the set \( \mathbb{C} \) of complex numbers and the entries of \( A \) are from \( R \), then the system of equations is partition regular over \( R \) if and only if the matrix \( A \) satisfies the columns condition over the field \( F \) generated by \( R \) (which means that we replace ‘linear combination with coefficients from \( \mathbb{Q} \)’ by ‘linear combination with coefficients from \( F \)’).

So the partition regularity of finite systems is quite settled. The case with infinite systems of linear equations, however, is much harder, and in general is still poorly understood. There is by now a large literature on the subject (see the survey [5]), but there is nothing resembling a characterisation of those infinite systems that are partition regular over \( \mathbb{Z}, \mathbb{Q}, \) or any other interesting subset of \( \mathbb{C} \).

One difference between finite and infinite systems is the main focus of this paper. As stated above, if a finite system of linear equations has rational
coefficients, it is a consequence of Rado’s original theorems that the system is partition regular over \( \mathbb{N} \) if and only if it is partition regular over \( \mathbb{R} \) (and thus if and only if it is partition regular over \( \mathbb{Z} \) or over \( \mathbb{Q} \)).

It was shown in [6] that the infinite system of equations \( y_n = x_n - x_{n+1} \) \((n = 0, 1, 2, \ldots)\) is partition regular over \( \mathbb{R} \) but not over \( \mathbb{Q} \). It was an open problem for some time whether every system of linear equations with rational coefficients that is partition regular over \( \mathbb{Q} \) must also be partition regular over \( \mathbb{N} \). (We remark in passing that there is no difference between \( \mathbb{N} \) and \( \mathbb{Z} \) in this regard, because if a system has a bad \( k \)-colouring over \( \mathbb{N} \) then it also has a bad \( 2k \)-colouring over \( \mathbb{Z} \), obtained by copying the colouring of \( \mathbb{N} \) to the negative integers but using \( k \) new colours—so we switch freely between \( \mathbb{N} \) and \( \mathbb{Z} \) in this paper.)

This question was answered in the negative in [1, Theorem 12] by showing that the following system of equations is partition regular over \( \mathbb{D} \), the set of dyadic rationals. (It is not partition regular over \( \mathbb{N} \) because it has no solutions in \( \mathbb{N} \) at all.)

\[
\begin{align*}
x_{1,1} + 2^{-1}y &= z_{1,1} \\
x_{2,1} + x_{2,2} + 2^{-2}y &= z_{2,1} + z_{2,2} \\
&\quad\vdots \\
x_{n,1} + \cdots + x_{n,n} + 2^{-n}y &= z_{n,1} + \cdots + z_{n,n} \\
&\quad\vdots
\end{align*}
\]

In this paper we extend this result by considering the following system of equations, which is a generalisation of another system introduced in [1]. Let \( \alpha \in \mathbb{N} \) and, for \( n \geq 2 \) and \( 1 \leq i \leq \alpha \), let \( d_{n,i} \) be an element of some infinite ring \( R \). (We take rings to have identities.)

**System \((*)\):**

\[
\begin{align*}
x_{2,1} + x_{2,2} + d_{2,1}y_1 + d_{2,2}y_2 + \cdots + d_{2,\alpha}y_\alpha &= z_2 \\
x_{3,1} + x_{3,2} + x_{3,3} + d_{3,1}y_1 + d_{3,2}y_2 + \cdots + d_{3,\alpha}y_\alpha &= z_3 \\
&\quad\vdots \\
x_{n,1} + \cdots + x_{n,n} + d_{n,1}y_1 + d_{n,2}y_2 + \cdots + d_{n,\alpha}y_\alpha &= z_n \\
&\quad\vdots
\end{align*}
\]
In Section 3 we prove (Theorem 3.6) that, if \( R \) satisfies a certain technical condition, then System (\( \ast \)) is partition regular over \( R \). (This technical condition is satisfied by all subrings of \( \mathbb{Q} \).) We actually show that System (\( \ast \)) satisfies a slightly stronger condition: it is strongly partition regular over \( R \).

**Definition 1.2.** Let \( R \) be a ring. A system of linear equations (with coefficients in \( R \)) is strongly partition regular over \( R \) if, whenever \( R \) is finitely coloured, there exists a monochromatic solution to the system with distinct variables taking on different values.

This is the reason for starting System (\( \ast \)) at \( n = 2 \). If we include the equation for \( n = 1 \), then the system remains partition regular, but we cannot ensure that \( x_{1,1} \) and \( z_1 \) receive different colours: consider the case where \( d_{1,1} = d_{1,2} = \cdots d_{1,\alpha} = 0 \).

In Section 4 we apply the results of Section 3 to show that there is an infinite increasing sequence \( \langle G_n \rangle_{n=1}^{\infty} \) of subgroups of \( \mathbb{Q} \) with the property that, for each \( n \), there is a choice of the coefficients \( \langle d_{n,i} \rangle_{n=1}^{\infty} \) making System (\( \ast \)) strongly partition regular over \( G_{n+1} \) while it is not partition regular over \( G_n \). We actually prove rather more (Theorem 4.3): this separation property holds for any two subrings of the rationals. This means that, for example, there is even an uncountable chain with this property. We close with some open problems.

The results of Section 3 make substantial use of the algebraic structure of the Stone–Čech compactification of a discrete semigroup, which we briefly introduce in Section 2.

**2. The Stone–Čech compactification**

Let \( S \) be a semigroup. We shall be concerned here exclusively with commutative semigroups, so we will denote the operation of \( S \) by \(+\). For proofs of the assertions made here, see the first five chapters of [7].

The **Stone–Čech compactification** of \( S \) is denoted by \( \beta S \). The points of \( \beta S \) are the ultrafilters on \( S \). We identify the principal ultrafilters with the points of \( S \), whereby we pretend that \( S \subseteq \beta S \). The operation on \( S \) extends to an operation on \( \beta S \), also denoted by \(+\), with the property that, for \( x \in S \) and \( q \in \beta S \), the functions

\[
p \mapsto x + p \quad \text{and} \quad q \mapsto p + q
\]

are continuous functions of the ultrafilter \( p \).
are continuous. (The reader should be cautioned that \((\beta S, +)\) is almost certain to be non-commutative: the centre of \((\beta N, +)\) is \(N\).) Given \(A \subseteq S\) and \(p, q \in \beta S\), \(A \in p + q\) if and only if \(\{x \in S : -x + A \in q\} \in p\), where \(-x + A = \{y \in S : x + y \in A\}\).

With the operation described above, \((\beta S, +)\) is a compact Hausdorff right topological semigroup. Any such object contains idempotents, points \(p\) such that \(p = p + p\). The semigroup \(\beta S\) has a smallest two-sided ideal, \(K(\beta S)\), which is the union of all of the minimal right ideals of \(\beta S\) as well as the union of all of the minimal left ideals of \(\beta S\). The intersection of any minimal right ideal with any minimal left ideal is a group (and any two such groups are isomorphic). In particular, there are idempotents in \(K(\beta S)\)—such idempotents are called minimal.

A subset \(A\) of \(S\) is
- an \(IP\)-set if it is a member of some idempotent;
- central if it is a member of some minimal idempotent;
- central* if it is a member of every minimal idempotent;
- an \(IP^*\)-set if it is a member of every idempotent.

Equivalently, \(A\) is an \(IP^*\)-set if, whenever \(\langle x_n \rangle_{n=1}^{\infty}\) is a sequence in \(S\), there exists \(F \in \mathcal{P}_f(\mathbb{N})\), the set of finite nonempty subsets of \(\mathbb{N}\), such that \(\sum_{n \in F} x_n \in A\). We will use this to show that certain sets are central*.

We will also require the following more specialised results from [7].

**Lemma 2.1.** (a) Let \(G\) be a commutative group. Then every minimal idempotent in \(\beta G\) is non-principal.

(b) Let \(S\) be a semigroup, let \(p\) be an idempotent in \(\beta S\) and, for \(C \in p\), let \(C^* = \{s \in S : -s + C \in p\}\). Then \(C^* \in p\) and, for each \(s \in C^*\), we have \(-s + C^* \in p\).

**Proof.** (a) Let \(p\) be a principal ultrafilter. Then \(p\) is idempotent if and only if \(p + p = p\) in \(G\), that is, if and only if \(p = 0\). Suppose that \(0\) were a minimal idempotent. Then by Theorem 1.48 of [7], \(\beta S + 0 = \beta S\) is a minimal left ideal. But by Corollary 4.33 of [7], \(\beta S \setminus S\) is a left ideal, contradicting the minimality of \(\beta S\).

(b) This follows from Lemma 4.14 (and the preceding discussion) of [7].
3. General results

In this section we will show that System (\(\ast\)), with coefficients \(d_{n,i}\) in some infinite ring \(R\), is strongly partition regular over \(R\). In fact, we shall establish a stronger conclusion.

**Definition 3.1.** Let \((S, +)\) be a semigroup.

- A system of linear equations is *centrally partition regular over* \(S\) if, whenever \(A\) is a central subset of \(S\), there exists a solution to the system contained in \(A\).
- A system of linear equations is *strongly centrally partition regular over* \(S\) if, whenever \(A\) is a central subset of \(S\), there exists a solution to the system contained in \(A\) with distinct variables taking on different values.

Notice that, since whenever a semigroup is finitely coloured, one colour class must be central, it follows that, if a system of equations is strongly centrally partition regular, then it is strongly partition regular.

We use the usual additive notation

\[
A + B = \{a + b : a \in A, b \in B\}
\]

\[
A - B = \{a - b : a \in A, b \in B\}
\]

\[
kA = A + \cdots + A \quad (k \text{ times})
\]

and write \(k \cdot A = \{k \cdot a : a \in A\}\).

We shall need the following result from [2, Lemma 3.7].

**Lemma 3.2.** Let \((G, +)\) be a commutative group and assume that \(c \cdot G\) is a central\(^*\) set for each \(c \in \mathbb{N}\). Let \(C\) be a central subset of \(G\). Then there is an \(m \in \mathbb{N}\) and a \(k\) such that, if \(n \geq k\), then \(m \cdot G \subseteq C - nC\).

**Definition 3.3.** Let \(A\) be a \(u \times v\) matrix with entries from a ring \(R\). An element \(a_{i,j}\) of \(A\) is a *first entry* of \(A\) if \(a_{i,k} = 0\) for \(k < j\) and \(a_{i,j} \neq 0\). We say that \(A\) satisfies the *weak first entries condition* if no row of \(A\) is \(\vec{0}\) and if \(a_{i,k}\) and \(a_{j,k}\) are first entries of \(A\), then \(a_{i,k} = a_{j,k}\).

We call this the *weak* first entries condition because, as usually defined with \(R = \mathbb{Q}\), one assumes that first entries are positive—which of course does not make sense for general rings.
Lemma 3.4. Let $R$ be an infinite ring. Let $u, v \in \mathbb{N}$, let $A$ be a $u \times v$ matrix with entries from $R$ that satisfies the weak first entries condition, and suppose that $c \cdot R$ is central* in $R$ for each first entry $c$ of $A$. Let $C$ be central in $R$. Then there is an $\vec{x}$ in $(R \setminus \{0\})^v$ such that $A\vec{x} \in C^u$.

Proof. This is a special case of [7, Theorem 15.5]. That theorem was stated only for coefficients which were natural numbers so that it made sense in an arbitrary semigroup, but the proof in the case of rings is nearly identical. □

Theorem 3.5. Let $R$ be an infinite ring and assume that, for each $m \in \mathbb{N}$, $m \cdot R$ is central* in $R$. Let $\alpha \in \mathbb{N}$ and, for each $n \geq 2$ and $1 \leq i \leq \alpha$, let $d_{n,i}$ be in $R$. Then for each central subset $C$ of $R$ there is a solution $y_1, y_2, \ldots, y_\alpha, x_2, 1, x_2, 2, x_3, 1, x_3, 2, x_3, 3, z_3, \ldots$ of System (\ast) contained in $C$; that is, System (\ast) is centrally partition regular over $R$. Moreover, the solution can be chosen so that $y_1, y_2, \ldots, y_\alpha$ are distinct.

Proof. Let $C$ be central in $R$. There is an idempotent $p \in \beta S$ such that $C \in p$, and by Lemma 2.1(a), $p \neq 0$. Hence $C \setminus \{0\} \in p$, so $C \setminus \{0\}$ is also central and we may assume that $0 \notin C$.

By Lemma 3.2, there is an $m \in \mathbb{N}$ and a $k$ such that, if $n \geq k$, then $m \cdot G \subseteq C - nC$. Since $m \cdot G$ is central*, $C \cap m \cdot G$ is central.

Let $b_i = 0$ and, for $2 \leq j \leq k$, let $b_j = b_{j-1} + j$. Let $v = b_k + \alpha$ and let $A$ be the $(k - 1) \times v$ matrix with entries given by

$$a_{i,j} = \begin{cases} 1 & \text{if } b_i < j \leq b_{i+1}; \\ d_{i+1,t} & \text{if } j = b_k + t; \\ 0 & \text{otherwise.} \end{cases}$$

Let $B$ be an $\binom{\alpha}{2} \times v$ matrix such that for every $b_k < i < j \leq b_k + \alpha$, some row of $B$ has a 1 in position $i$ and a $-1$ in position $j$, with all other entries equal to 0. (If $\alpha = 1$, let $B$ be empty.) Thus, for example, if $k = 4$ and $\alpha = 3$, then

$$A = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & d_{2,1} & d_{2,2} & d_{3,3} \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & d_{3,1} & d_{3,2} & d_{3,3} \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & d_{4,1} & d_{4,2} & d_{4,3} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{pmatrix},$$

8
Let $I$ be the $v \times v$ identity matrix. Then \[
\begin{pmatrix}
I \\
A \\
B
\end{pmatrix}
\] satisfies the first entries condition with each first entry equal to 1, so by Theorem 3.4 there exist
\[x_{2,1}, x_{2,2}, x_{3,1}, x_{3,2}, x_{3,3}, \ldots, x_{k,1}, x_{k,2}, \ldots, x_{k,k}, y_1, y_2, \ldots, y_\alpha\]
such that all entries of
\[
\begin{pmatrix}
I \\
A \\
B
\end{pmatrix}
\begin{pmatrix}
x_{2,1} \\
\vdots \\
x_{k,k} \\
y_1 \\
\vdots \\
y_\alpha
\end{pmatrix}
\]
are in $C \cap m \cdot G$.

For $2 \leq n \leq k$, let $z_n = x_{n,1} + \cdots + x_{n,n} + d_{n,1} y_1 + \cdots + d_{n,\alpha} y_\alpha$. The submatrix $I$ ensures that the $x_{n,j}$ ($2 \leq n \leq k$ and $1 \leq j \leq n$) and $y_i$ ($1 \leq i \leq \alpha$) are in $C$, the submatrix $A$ ensures that the $z_n$ ($2 \leq n \leq k$) are in $C$, and the submatrix $B$ ensures that $y_i \neq y_j$ ($1 \leq i < j \leq \alpha$) as $y_i - y_j \in C \subseteq R \setminus \{0\}$.

For $n > k$, $d_{n,1} y_1 + \cdots + d_{n,\alpha} y_\alpha \in m \cdot G \subseteq C - nC$, so choose $z_n$ and $x_{n,1} \ldots x_{n,n}$ in $C$ such that $d_{n,1} y_1 + \cdots + d_{n,\alpha} y_\alpha = z_n - x_{n,1} - \cdots - x_{n,n}$.  

We are now ready for the main result of this section.

**Theorem 3.6.** Let $R$ be an infinite ring and assume that, for each $m \in \mathbb{N}$, $m \cdot R$ is central* in $R$. Let $\alpha \in \mathbb{N}$ and, for each $n \geq 2$ and $1 \leq i \leq \alpha$, let $d_{n,i}$ be in $R$. Then System (*) is strongly centrally partition regular over $R$.

**Proof.** We already know that System (*) is centrally partition regular, by Theorem 3.5. We will apply Theorem 3.5 to a different central set ($C^*$, defined below), then use that solution to build a solution in $C$ with all values of the variables distinct. This will be possible because at each stage we will only have finitely many previously used values to avoid: since the minimal idempotent $p$ witnessing the fact that various sets $X$ are central is non-principal, sets obtained from $X$ by deleting finitely many elements remain in $p$.

So let $C$ be a central subset of $G$ and pick a minimal idempotent $p \in \beta G$ such that $C \in p$. As in the proof of Theorem 3.5, $p$ is non-principal and we
can assume that \( 0 \notin C \). For each \( B \in p \), let \( B^* = \{ x \in B : B - x \in p \} \). If \( B \in p \) and \( x \in B^* \), then by Lemma 2.1(b), \( B^* - x \in p \).

Again by Lemma 2.1(b), we have that \( C^* \) is central, so pick by Theorem 3.5 a solution

\[
y_1, y_2, \ldots, y_\alpha, x_{2,1}, x_{2,2}, z_2, x_{3,1}, x_{3,2}, x_{3,3}, z_3, \ldots
\]

of System \((*)\) contained in \( C^* \) such that the values of the \( y_i \) are distinct. We will use this solution to build a new solution in variables \( y_i, u_{i,j} \) and \( v_i \) for which the values taken by the variables are all distinct.

Suppose that, for \( 2 \leq i < n \) and \( 1 \leq j \leq i \), we have already chosen \( u_{i,j} \) and \( v_i \) distinct from each other and from \( y_1, y_2, \ldots, y_\alpha \) such that

\[
u_{i,1} + \cdots + u_{i,i} + d_{i,1}y_1 + \cdots + d_{i,\alpha}y_\alpha = v_i.
\]

We will choose \( w_1, \ldots, w_n \) in such a way that, setting \( u_{n,i} = x_{n,i} + w_i \) and \( v_n = z_n + w_1 + \cdots + w_n \), the same is true with \( n \) replaced by \( n + 1 \).

Let

\[
A = (C - x_{n,1}) \cap (C - x_{n,2}) \cap \cdots \cap (C - x_{n,n}) \cap (C - z_n),
\]

\[
B = \{ y_1, \ldots, y_\alpha \} \cup \{ u_{i,j} : 2 \leq i < n, 1 \leq j \leq i \}
\]

\[
\cup \{ v_i : 2 \leq i < n \} \cup \{ x_{n,i} - z_n : 1 \leq i \leq n \}, \text{ and}
\]

\[
D = A \setminus (B \cup (B - x_{n,1}) \cup \cdots \cup (B - x_{n,n}) \cup (B - z_n)).
\]

Since the \( x_{i,j} \) and \( z_i \) are in \( C^* \), \( A \in p \). Since \( B \) is finite, \( D \in p \). Choose \( w_1 \in D^* \).

Let \( 2 \leq k \leq n \) and suppose that we have already chosen \( w_1, \ldots, w_{k-1} \) such that

(i) if \( \emptyset \neq F \subseteq \{1, 2, \ldots, k-1\} \), then \( \sum_{j \in F} w_j \in D^* \), and

(ii) if \( 1 \leq i < j \leq k - 1 \), then \( x_{n,i} + w_i \neq x_{n,j} + w_j \).

Choose

\[
w_k \in D^* \cap \bigcap_{\emptyset \neq F \subseteq \{1, 2, \ldots, k-1\}} (D^* - \sum_{j \in F} w_j) \setminus \{ x_{n,j} + w_j - x_{n,k} : 1 \leq j < k \}.
\]

Then (i) and (ii) hold with \( k \) replaced by \( k + 1 \).
Having chosen \( w_1, \ldots, w_n \), let \( u_{n,i} = x_{n,i} + w_i \) and let \( v_n = z_n + w_1 + \cdots + w_n \).

By (i), \( w_1, \ldots, w_n \) and \( w_1 + \cdots + w_n \) are each in \( D^* \subseteq D \). Hence by the definition of \( A \), \( u_{n,1}, \ldots, u_{n,n} \) and \( v_n \) are all in \( C \), and by the definitions of \( B \) and \( D \), \( u_{n,1}, \ldots, u_{n,n} \) and \( v_n \) are all distinct from the \( y_i \) (\( 1 \leq i \leq \alpha \)), \( u_{i,j} \) (\( 2 \leq i < n \) and \( 1 \leq j \leq i \)) and \( v_i \) (\( 2 \leq i < n \)). By (ii), the \( u_{n,j} \) are all distinct.

Finally, suppose that \( v_n = u_{n,j} \) for some \( j \). Then \( w_1 + \cdots + w_{j-1} + w_{j+1} + \cdots + w_n = x_{n,j} - z_n \in B \), but by (i) \( w_1 + \cdots + w_{j-1} + w_{j+1} + \cdots + w_n \in D^* \subseteq D \), which is a contradiction. \( \square \)

4. Applications

In this section we show that for any two subrings \( R \) and \( S \) of \( \mathbb{Q} \) such that \( R \) is not contained in \( S \), there is a system that is partition regular over \( R \) but not over \( S \). In fact, we shall obtain this for a choice of the sequence \( \langle d_n \rangle_{n=1}^\infty \), making System (*) strongly centrally partition regular over \( R \) while it has no solutions in \( S \).

In particular, this will give us a chain of \( \epsilon \) subgroups of \( \mathbb{Q} \) (where \( \epsilon \) is the cardinality of the continuum), any two of which have different partition regular systems, as stated in the introduction. (To see that any countable set has a chain of subsets ordered by \( \mathbb{R} \), simply consider \( \{ \{ x \in \mathbb{Q} : x < y \} : y \in \mathbb{R} \} \).)

**Definition 4.1.** Let \( P \) be the set of primes and let \( F \subseteq P \). Then

\[
G_F = \{ a/b : a \in \mathbb{Z}, b \in \mathbb{N} \text{ and all prime factors of } b \text{ are in } F \}.
\]

Thus \( G_\emptyset = \mathbb{Z} \), \( G_{\{2\}} = \mathbb{D} \) and \( G_P = \mathbb{Q} \). It is easy to check that the \( G_F \) are precisely the subrings of \( \mathbb{Q} \). (Given a subring \( R \) of \( \mathbb{Q} \), let \( F = \{ p \in P : \frac{1}{p} \in R \} \) and use the fact that \( 1 \in R \).)

We will invoke Theorem 3.6, so we need to know that for any subset \( F \) of \( P \) and any \( m \in \mathbb{N} \), \( m \cdot G_F \) is central* in \( G_F \). We will in fact show that it is IP*. Recall that this means that, given any sequence \( \langle x_n \rangle_{n=1}^\infty \) in \( G_F \), there is some \( H \in \mathcal{P}(\mathbb{N}) \) such that \( \sum_{n \in H} x_n \in m \cdot G_F \) or, equivalently, that \( m \cdot G_F \) is a member of every idempotent in \( \beta G_F \).

**Proposition 4.2.** Let \( m \in \mathbb{N} \), \( F \subseteq P \) and \( \langle x_n \rangle_{n=1}^{(m-1)^2+1} \) be a sequence of elements of \( G_F \). Then there exists \( \emptyset \neq H \subseteq \{1, 2, \ldots, (m-1)^2 + 1\} \) such that \( \sum_{n \in H} x_n \in m \cdot G_F \).
Proof. Write the \( x_n \) over a common denominator: choose \( s \in \mathbb{N} \) with all prime factors in \( F \) such that \( x_n = y_n/s \) with \( y_n \in \mathbb{Z} \). At least \( m \) of the \( y_n \) must have the same residue modulo \( m \); let \( H \) be a set of size \( m \) such that \( y_n \equiv h \pmod{m} \) for \( n \in H \). Then \( \sum_{n \in H} y_n = km \) for some \( k \), hence \( \sum_{n \in H} x_n = km/s \in m \cdot \mathbb{G}_F \). \qed

**Theorem 4.3.** Let \( F \) and \( H \) be subsets of \( P \) with \( H \setminus F \neq \emptyset \) and pick \( q \in H \setminus F \). Let \( \alpha = 1 \) and for \( k \in \mathbb{N} \), let \( d_{n,1} = \frac{1}{q^n} \). Then System (*) is strongly centrally partition regular over \( \mathbb{G}_H \) but is not partition regular over \( \mathbb{G}_F \).

**Proof.** It is immediate that System (*) has no solutions in \( \mathbb{G}_F \). By Theorem 3.6 with \( R = \mathbb{G}_H \), System (*) is strongly centrally partition regular over \( \mathbb{G}_H \). \qed

By applying this to a chain of size \( \epsilon \) of subsets of the primes, we immediately obtain a chain of \( \epsilon \) subrings of \( \mathbb{Q} \), no two of which have the same partition regular systems.

If we want to separate \( \mathbb{Q} \) from all proper subrings simultaneously then we have the following, whose proof is identical. Let \( p_1, p_2, \ldots \) be an enumeration of the primes.

**Theorem 4.4.** Let \( \alpha = 1 \) and for \( n \in \mathbb{N} \), let \( d_{n,1} = \prod_{t=1}^n \frac{1}{p_t} \). Then System (*) is strongly centrally partition regular over \( \mathbb{G}_F \) for any proper subset \( F \) of \( P \).

One might raise the objection that it almost seems like cheating to show that a system is not partition regular over \( G \) by showing that it has no solutions there at all. We see now that by taking \( \alpha = 2 \), we can get examples where System (*) has solutions in \( \mathbb{N} \), but the conclusions of Theorems 4.3 and 4.4 still hold.

**Theorem 4.5.** Let \( F \) and \( H \) be subsets of \( P \) with \( H \setminus F \neq \emptyset \) and pick \( q \in H \setminus F \). Let \( \alpha = 2 \) and, for \( n \in \mathbb{N} \), let \( d_{n,1} = \frac{1}{q^n} \) and \( d_{n,2} = \frac{2}{q^n} \). Then System (*) has solutions in \( \mathbb{N} \) and is strongly centrally partition regular over \( \mathbb{G}_H \), but is not partition regular over \( \mathbb{G}_F \).

**Proof.** By Theorem 3.6 with \( R = \mathbb{G}_H \), System (*) is strongly centrally partition regular over \( \mathbb{G}_H \). Let \( y_1 = 2 \) and \( y_2 = 1 \). Then for every \( n \in \mathbb{N} \), \( d_{n,1}y_1 + d_{n,2}y_2 = 0 \) so it is easy to find a solution to System (*) in \( \mathbb{N} \).
To see that System (∗) is not partition regular over $\mathbb{G}_F$, two-colour $\mathbb{G}_F \setminus \{0\}$ so that for all $x \in \mathbb{G}_F \setminus \{0\}$, $x$ and $2x$ do not have the same colour. (For example colour by the parity of $\lfloor \log_2(|x|) \rfloor$.) Suppose we have a monochromatic solution to System (∗) in $\mathbb{G}_F$. We have that $y_1 \neq 2y_2$ and, for each $n \in \mathbb{N}$, $(2y_2 - y_1)/q^n = z_n - x_{n,1} - \cdots - x_{n,n} \in \mathbb{G}_F$, which is a contradiction for $n$ sufficiently large.

Similarly, we have an analogue of Theorem 4.4.

**Theorem 4.6.** Let $\alpha = 2$ and for $n \in \mathbb{N}$, let $d_{n,1} = \prod_{t=1}^{n} \frac{1}{p_t}$ and $d_{n,2} = \prod_{t=1}^{n} \frac{2}{p_t}$. Then System (∗) is strongly partition regular over $\mathbb{Q}$ and has solutions in $\mathbb{N}$, but is not partition regular over $\mathbb{G}_F$ for any proper nonempty subset $F$ of $P$.

Let us end by remarking that it would be interesting to understand what happens beyond $\mathbb{Q}$—in other words, for subrings (or subgroups) that lie between $\mathbb{Q}$ and $\mathbb{R}$. Of course, if one allows non-rational coefficients then it is easy to separate sets, so the interest would be for systems of equations whose coefficients are integers (or, equivalently, rationals).

We see now that the system mentioned in the Introduction that distinguishes $\mathbb{R}$ from $\mathbb{Q}$ in fact distinguishes any uncountable subgroup $G$ of $\mathbb{R}$ from $\mathbb{Q}$.

In the following result we use, as in [6], the Baumgartner–Hajnal theorem [3, Theorem 1]. This theorem states that if $A$ is a linearly ordered set with the property that whenever $\phi : A \to \mathbb{N}$, there is an infinite increasing sequence in $A$ on which $\phi$ is constant, then for any countable ordinal $\alpha$, and any finite colouring $\psi$ of the two-element subsets of $A$ there is a subset $B$ of $A$ which has order type $\alpha$ such that $\psi$ is constant on the two-element subsets of $B$. (The theorem was proved in [3] using Martin’s axiom followed by an absoluteness argument to show that it is a theorem of ZFC. A direct combinatorial proof was obtained by Galvin in [4, Theorem 4].)

**Theorem 4.7.** Let $G$ be an uncountable subgroup of $\mathbb{R}$. Then the system of equations $y_n = x_n - x_{n+1}$ ($n = 0, 1, 2, \ldots$) is partition regular over $G$ but not over $\mathbb{Q}$.

**Proof.** It was shown in [6] (immediately before Question 6) that the system is not partition regular over $\mathbb{Q}$. To show that the system is partition regular over $G$, we use the Baumgartner–Hajnal theorem. For this we need to observe
that given any countable colouring of $G$, there is a monochromatic increasing sequence. To see this, let $\varphi : G \to \mathbb{N}$ and define $\psi : G \to \mathbb{N} \times \mathbb{N}$ by $\psi(x) = (\varphi(x), \varphi(-x))$. Pick $(n, m) \in \mathbb{N} \times \mathbb{N}$ such that $A = \psi^{-1}\{(n, m)\}$ is infinite. Then $A$ contains a sequence $\langle x_i \rangle_{i=1}^\infty$ which is either increasing or decreasing. If $\langle x_i \rangle_{i=1}^\infty$ is increasing, then it is an increasing sequence in $\varphi^{-1}\{n\}$. If $\langle x_i \rangle_{i=1}^\infty$ is decreasing, then $\langle -x_i \rangle_{i=1}^\infty$ is an increasing sequence in $\varphi^{-1}\{m\}$.

Now let $G$ be finitely coloured by $\varphi$ and, given a two-element subset $\{x, y\}$ of $G$, define $\psi(\{x, y\}) = \varphi(\|x - y\|)$. By the Baumgartner–Hajnal theorem, pick an increasing sequence $\langle z_\sigma \rangle_{\sigma < \omega+1}$ such that $\psi$ is constant on $\{\{z_\sigma, z_\tau\} : \sigma < \tau\}$. Given $n \in \mathbb{N}$, let $x_n = z_\omega - z_n$ and let $y_n = z_{n+1} - z_n$. \qed

Perhaps even more interesting would be to understand what happens for subgroups of $\mathbb{Q}$. The following is the obvious question to ask.

**Question 4.8.** If $G$ and $H$ are subgroups of $\mathbb{Q}$ such that $G$ does not contain a subgroup isomorphic to $H$, must there exist a system (of linear equations with integer coefficients) that is partition regular over $H$ but not over $G$?

It is easy to check that every subgroup of $\mathbb{Q}$ that contains 1 is the set of rationals $a/b$ such that the multiplicity of $p_i$ in the prime factorisation of $b$ is at most $k_i$, where each $k_i$ is either a non-negative integer or $\infty$. Given two such sequences $k$ and $k'$, if there is some $i$ for which $k_i = \infty$ while $k'_i$ is finite, then the corresponding groups can be separated by the methods of this section. But if for every $i$, either both $k_i$ and $k'_i$ are infinite, or both are finite, then we are unable to say anything.

The most attractive special case is surely the following.

**Question 4.9.** Does there exist a system (of linear equations with integer coefficients) that is partition regular over the set of rationals with squarefree denominators but is not partition regular over the integers?

**References**


\(^2\)Currently available at [http://nhindman.us/preprint.html](http://nhindman.us/preprint.html).


