

3. Van der Waerden's Theorem

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To see that A is in fact a minimal left ideal, assume we have a left ideal $B \subseteq A$ and pick $x \in B$. Then as above $S + x \in \mathcal{A}$ while $S + x \subseteq S + B \subseteq B \subseteq A$ so $S + x = A$ so $B = A$ \square

2.3 Definition. Let S be a semigroup. Then $M(S) = \cup \{L : L \text{ is a minimal left ideal of } S\}$.

It is a fact (which we will not need) that if S is a compact Hausdorff right topological semigroup, then $M(S)$ is a two-sided ideal of S .

2.4 LEMMA. Let S be a compact Hausdorff right topological semigroup and let I be a two-sided ideal of S . Then $M(S) \neq \emptyset$ and $M(S) \subseteq I$.

Proof. Since S is a left ideal of S it contains by Lemma 2.2 a minimal left ideal so $M(S) \neq \emptyset$. So see that $M(S) \subseteq I$, let $x \in M(S)$. There is a minimal left ideal L of S with $x \in L$. Also choose some $y \in I$. Then $y + x \in L \cap I$ (since I is a right ideal) so $L \cap I \neq \emptyset$. Thus $L \cap I$ is a left ideal contained in L so that $L \cap I = L$. \square

The proof of the following lemma is an easy exercise and we omit it.

2.5 LEMMA. Let S_1 and S_2 be compact right topological semigroups and let $S_1 \times S_2$ have the product topology and coordinatewise operations. Then $S_1 \times S_2$ is a compact right topological semigroup. Given $x \in S_1$ and $y \in S_2$, λ_x and λ_y may or may not be continuous (where $\lambda_x(t) = x + t$). If $\lambda_x : S_1 \rightarrow S_1$ and $\lambda_y : S_2 \rightarrow S_2$ are continuous, then $\lambda_{(x,y)} : S_1 \times S_2 \rightarrow S_1 \times S_2$ is continuous.

3. VAN DER WAERDEN'S THEOREM

We let $l \in \mathbf{N}$ be fixed throughout and show that given any finite partition of \mathbf{N} some one cell contains a length l arithmetic progression.

3.1 Definition. (a) Let $Y = (\beta\mathbf{N})^l$ with the product topology and coordinatewise operations.

$$(b) \quad E^* = \{(a, a + d, a + 2d, \dots, a + (l-1)d) : a \in \mathbf{N} \text{ and } d \in \mathbf{N} \cup \{0\}\}.$$

$$(c) \quad I^* = \{(a, a + d, a + 2d, \dots, a + (l-1)d) : a, d \in \mathbf{N}\}.$$

$$(d) \quad E = cl_Y E^*$$

$$(e) \quad I = cl_Y I^*.$$

Note that by Lemmas 1.1 and 2.5, Y is a compact Hausdorff right topological semigroup and whenever $\mathbf{x} = (x_1, x_2, \dots, x_l) \in \mathbf{N}^l$, $\lambda_{\mathbf{x}}$ is continuous.

3.2 LEMMA. E is a compact Hausdorff right topological semigroup and I is a two sided ideal of E .

Proof. Compactness is immediate and the Hausdorff property and right continuity are inherited from Y . We let $\mathbf{p} = (p_1, p_2, \dots, p_l)$ and $\mathbf{q} = (q_1, q_2, \dots, q_l)$ be members of E and show that $\mathbf{p} + \mathbf{q} \in E$. We show further that if either \mathbf{p} or \mathbf{q} is in I , then $\mathbf{p} + \mathbf{q} \in I$.

To see that $\mathbf{p} + \mathbf{q} \in E$, let U be a neighborhood of $\mathbf{p} + \mathbf{q}$. By the continuity of $\rho_{\mathbf{q}}$, pick a neighborhood V of \mathbf{p} with $V + \mathbf{q} = \rho_{\mathbf{q}}[V] \subseteq U$. Since $\mathbf{p} \in cl E^*$ we may pick $a \in \mathbf{N}$ and $d \in \mathbf{N} \cup \{0\}$ with

$$(a, a+d, a+2d, \dots, a+(l-1)d) \in V.$$

If $\mathbf{p} \in I$ we may presume $d \neq 0$. Let $\mathbf{x} = (a, a+d, a+2d, \dots, a+(l-1)d)$. Then $\mathbf{x} \in V$ so $\mathbf{x} + \mathbf{q} \in U$. By the continuity of $\lambda_{\mathbf{x}}$, pick a neighborhood W of \mathbf{q} with $\mathbf{x} + W = \lambda_{\mathbf{x}}[W] \subseteq U$. Since $\mathbf{q} \in cl E^*$, pick $b \in \mathbf{N}$ and $c \in \mathbf{N} \cup \{0\}$ (with $c \neq 0$ if $\mathbf{q} \in I$) such that $(b, b+c, b+2c, \dots, b+(l-1)c) \in W$. Let $\mathbf{y} = (b, b+c, b+2c, \dots, b+(l-1)c)$. Then $\mathbf{x} + \mathbf{y} \in U \cap E^*$. If either $d \neq 0$ or $c \neq 0$, then $c + d \neq 0$ so $\mathbf{x} + \mathbf{y} \in U \cap I^*$. \square

3.3 THEOREM. Let $p \in M(\beta\mathbf{N})$ and let $\mathbf{p} = (p, p, \dots, p)$. Then $\mathbf{p} \in I$.

Proof. We first show that $\mathbf{p} \in E$. Let $U_1 \times U_2 \times \dots \times U_l$ be a basic neighborhood of \mathbf{p} . Then $U_1 \cap U_2 \cap \dots \cap U_l$ is a neighborhood of p in $\beta\mathbf{N}$. Since \mathbf{N} is dense, pick $a \in \mathbf{N} \cap (U_1 \cap U_2 \cap \dots \cap U_l)$. Then $(a, a, \dots, a) \in E^* \cap (U_1 \times U_2 \times \dots \times U_l)$. Thus $\mathbf{p} \in cl E^* = E$.

Since $p \in M(\beta\mathbf{N})$, there is a minimal left ideal L of $\beta\mathbf{N}$ with $p \in L$. Since $E + \mathbf{p}$ is a left ideal of E , pick by Lemma 2.2 a minimal left ideal L^* of E with $L^* \subset E + \mathbf{p}$. Since L^* is closed, hence compact, pick by Lemma 2.1 an idempotent $\mathbf{q} = (q_1, q_2, \dots, q_l)$ in L^* . Now $\mathbf{q} \in L^* \subseteq E + \mathbf{p}$ so pick some $\mathbf{s} = (s_1, s_2, \dots, s_l)$ in E with $\mathbf{q} = \mathbf{s} + \mathbf{p}$.

We show that $\mathbf{p} + \mathbf{q} = \mathbf{p}$. To this end let $i \in \{1, 2, \dots, l\}$. Now $q_i = s_i + p \in L$ so $\beta\mathbf{N} + q_i \subseteq \beta\mathbf{N} + L \subseteq L$. Thus $\beta\mathbf{N} + q_i$ is a left ideal contained in the minimal left ideal L so that $\beta\mathbf{N} + q_i = L$. Thus since $p \in L$ there exists $t_i \in \beta\mathbf{N}$ with $t_i + q_i = p$. But then $p + q_i = t_i + q_i + q_i = t_i + q_i = p$ as required.

Since $\mathbf{p} \in E$ and $\mathbf{q} \in L^*$, a left ideal of E , we have $\mathbf{p} = \mathbf{p} + \mathbf{q} \in L^*$ so that $\mathbf{p} \in M(E)$. Thus by Lemma 2.4, $\mathbf{p} \in I$.

3.4 COROLLARY (van der Waerden). Let $m \in \mathbf{N}$ and let $\{A_1, A_2, \dots, A_m\}$ be a partition of \mathbf{N} . There exist $i \in \{1, 2, \dots, m\}$ and $a, d \in \mathbf{N}$ with $\{a, a+d, a+2d, \dots, a+(l-1)d\} \subseteq A_i$.

Proof. By Lemma 2.4 $M(\beta\mathbf{N}) \neq \emptyset$ so pick $p \in M(\beta\mathbf{N})$ and let $\mathbf{p} = (p, p, \dots, p)$. By Lemma 1.2 pick $i \in \{1, 2, \dots, m\}$ such that $cl A_i$ is a neighborhood of p and let $U = cl A_i$. Then $U \times U \times \dots \times U$ is a neighborhood of \mathbf{p} while, by Theorem 2.3, $\mathbf{p} \in I = cl I^*$. Pick $a, d \in \mathbf{N}$ with $(a, a+d, a+2d, \dots, a+(l-1)d) \in U \times U \times \dots \times U$. Then

$$\{a, a+d, a+2d, \dots, a+(l-1)d\} \subseteq U \cap \mathbf{N} = (cl A_i) \cap \mathbf{N} = A_i. \quad \square$$

We remark that if one starts with the free semigroup on l letters in place of \mathbf{N} , essentially the same proof yields the Hales-Jewett Theorem. See [3] for the details.

REFERENCES

- [1] BERGLUND, J., H. JUNGHEHN and P. MILNES. *Compact right topological semigroups and generalizations of almost periodicity*. Lecture Notes in Math. 663, Springer-Verlag, Berlin (1978).
- [2] ELLIS, R. *Lectures on Topological Dynamics*. Benjamin, New York, 1969.
- [3] FURSTENBERG, H. and Y. KATZNELSON. Idempotents and coloring theorems. *To appear*.
- [4] FURSTENBERG, H. and B. WEISS. Topological dynamics and combinatorial number theory. *J. d'Analyse Math.* 34 (1978), 61-85.
- [5] GRAHAM, R. and B. ROTHCHILD. A short proof of van der Waerden's Theorem. *Proc. Amer. Math. Soc.* 42 (1974), 385-386.
- [6] HINDMAN, N. Ultrafilters and Ramsey Theory — an update. *Proceedings of "Set Theory and its Applications – Conference at York"*. To appear.
- [7] SHELAH, S. Primitive recursive bounds for van der Waerden numbers. *J. Amer. Math. Soc.* 1 (1989), 683-697.
- [8] TAYLOR, A. A note on van der Waerden's Theorem. *J. Comb. Theory (Series A)* 33 (1982), 215-219.
- [9] VAN DER WAERDEN, B. Beweis einer Baudetschen Vermutung. *Nieuw Arch. Wisk* (3) 19 (1927), 212-216.

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