Some remarks concerning van der Waerden ideal

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An arithmetic progression of length $l$ is the finite sequence
\[
\{a + id : i = 0, 1, \ldots, l - 1\}
\] where $a, d \in \mathbb{N}$.

Van der Waerden Theorem (finite version).
For any given natural numbers $k$ and $l$, there is some natural number $W(k, l)$ such that if the integers $\{1, 2, \ldots, W(k, l)\}$ are colored, each with one of $k$ different colors, then there exists an arithmetic progression of length at least $l$, all of which elements are of the same color.
Van der Waerden theorem and AP-sets

Definition.
A set $A \subseteq \mathbb{N}$ is called an AP-set if it contains arbitrary long arithmetic progressions.

Van der Waerden Theorem (infinite version).
If an AP-set is partitioned into finitely many pieces then at least one of them is again an AP-set.

Sets which are not AP-sets form a proper ideal on $\mathbb{N}$ — van der Waerden ideal denoted by $\mathcal{W}$
Van der Waerden ideal and other ideals

Szemerédi Theorem.

\[ \mathcal{W} \subseteq \mathcal{Z} \quad \text{where} \quad \mathcal{Z} = \{ A \subseteq \mathbb{N} : \limsup_{n \to \infty} \frac{|A \cap n|}{n} = 0 \} \]

Erdős Conjecture.

\[ \mathcal{W} \subseteq \mathcal{I}_{1/n} \quad \text{where} \quad \mathcal{I}_{1/n} = \{ A \subseteq \mathbb{N} : \sum_{a \in A} \frac{1}{a} < \infty \} \]
What sets belong to $\mathcal{W}$?

Example A. $\{n! : n \in \omega\}$ or $\{2^n : n \in \omega\}$ do not contain arithmetic progressions of length 3.
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Example B. $\{n^2 : n \in \omega\}$ contains infinitely many arithmetic progressions of length 3 (known by Pythagoras), but no arithmetic progression of length 4 (proved by Euler).
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Example B. $\{n^2 : n \in \omega\}$ contains infinitely many arithmetic progressions of length 3 (known by Pythagoras), but no arithmetic progression of length 4 (proved by Euler).

Example C. The set of the prime numbers does not belong to the van der Waerden ideal (Green-Tao).
Van der Waerden ideal $\mathcal{W}$

The van der Waerden ideal $\mathcal{W}$ is

- **a tall ideal** — because every infinite $A \subseteq \mathbb{N}$ contains an infinite subset with no arithmetic progressions of length 3

- **not a $P$-ideal** — consider for example the sets
  
  $$A_k = \{2^n + k : n \in \omega\} \text{ for } k \in \omega$$
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- $F_\sigma$-ideal — because $\mathcal{W} = \bigcup_{n \in \mathbb{N}} \mathcal{W}_n$ where

$$\mathcal{W}_n = \{ A \subseteq \mathbb{N} : A \text{ contains no a. p. of length } n \}$$
The van der Waerden ideal $\mathcal{W}$ is

- $F_\sigma$-ideal — because $\mathcal{W} = \bigcup_{n \in \mathbb{N}} \mathcal{W}_n$ where
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  \]

The family $\mathcal{W}_n$

- is not an ideal for every $n \in \mathbb{N}$
- generates a proper ideal $\langle \mathcal{W}_n \rangle$
Strictly increasing sequence of ideals

The ideal \( \langle \mathcal{W}_n \rangle \) is a tall \( F_\sigma \)-ideal for every \( n \geq 3 \).

Fact.

\[
\mathcal{W} = \bigcup_{n \geq 3} \langle \mathcal{W}_n \rangle
\]

and \( \langle \mathcal{W}_n \rangle \subseteq \langle \mathcal{W}_{n+1} \rangle \) for every \( n \in \mathbb{N} \).
Proposition 1.

For every $n \geq 3$ there exists $A \subset \mathbb{N}$ such that

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Proof. Consider

$$A = \left\{ \sum_{i=0}^{k} c_i \cdot n^{2i} : k \in \omega, c_i = 0, \ldots, n - 1, c_k \neq 0 \right\}$$
Strictly increasing sequence of ideals

Claim 1. Show $A \in \mathcal{W}_{n+1}$ (straightforward calculation)

Claim 2. Show $A \notin \langle \mathcal{W}_n \rangle$ (use Hales-Jewett theorem)
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Let $L(n) \ldots$ be the set of finite words in the alphabet $\{0, 1, \ldots, n-1\}$.

A variable word $w(x)$ is a finite word in the alphabet $\{0, 1, \ldots, n-1, x\}$ in which the variable $x$ occurs at least once.
Hales-Jewett theorem.

For every $n, r \in \mathbb{N}$ there exists a number $HJ(n, r)$ such that if words in $L(n)$ of length $HJ(n, r)$ are colored by $r$ colors then there exists a variable word $w(x)$ such that $w(0), w(1), \ldots, w(n-1)$ have the same color.

The symbol $w(i)$ denotes the word in $L(n)$ which is produced from $w(x)$ by replacing all the occurrences of the variable $x$ by the letter of the alphabet in brackets.
Some questions

Conjecture. $A \in \langle \mathcal{W}_n \rangle$ if and only if there exists $k \in \mathbb{N}$ such that $A$ does not contain a copy of $n^k$. 
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Question 1. Is it true that whenever a set \( A \) does not contain a copy of \( 3^2 \) then \( A \in \langle \mathcal{W}_3 \rangle \)?
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**Question 1.** Is it true that whenever a set \( A \) does not contain a copy of \( 3^2 \) then \( A \in \langle \mathcal{W}_3 \rangle \)?

**Question 2.** Does the set \( \{n^2 : n \in \omega \} \) belong to the ideal \( \langle \mathcal{W}_3 \rangle \)?
Cofinality number of $\mathcal{W}$

$$\text{cof}^*(I) = \min\{|A| : A \subseteq I \land (\forall I \in \mathcal{I})(\exists A \in \mathcal{A})(I \subseteq^* A)\}$$

**Proposition 2.** \[\text{cof}^*(\mathcal{W}) = 2^{\aleph_0}\]
Cofinality number of $\mathcal{W}$

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Proposition 2. \hspace{1cm} $\text{cof}^*(\mathcal{W}) = 2^{\aleph_0}$

Sketch of the proof:

1. Show that there exists a perfect set $P \subseteq \omega \omega$ such that every $f \in P$ satisfies $f(n + 1) > 2f(n)$ for every $n \in \omega$ and whenever $f_0, f_1, \ldots, f_k \in P$ are distinct, there exist infinitely many $n \in \omega$ such that $\{f_0(n), f_1(n), \ldots, f_k(n)\}$ is a set of $k + 1$ successive integers.
Cofinality number of \( \mathcal{W} \)

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2. \( A_f = \{f(n) : n \in \omega\} \in \mathcal{W} \) for every \( f \in P \)
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2. $A_f = \{f(n) : n \in \omega\} \in \mathcal{W}$ for every $f \in P$

3. $\{f \in P : A_f \subseteq^* B\}$ is finite for every $B \in \mathcal{W}$