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► **To cite this version:**

Jean Goubault-Larrecq. Infinitary Noetherian Constructions I. Infinite Words. Colloquium Mathematicum, In press. hal-03414552v1

HAL Id: hal-03414552

<https://hal.science/hal-03414552v1>

Submitted on 4 Nov 2021 (v1), last revised 17 Dec 2021 (v2)

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INFINITARY NOETHERIAN CONSTRUCTIONS I. INFINITE WORDS

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ABSTRACT. We define and study Noetherian topologies for spaces of infinite sets and for spaces of infinite words. In each case, we also obtain S-representations, namely, computable presentations of the sobrifications of those spaces.

1. INTRODUCTION

A quasi-ordering, a.k.a. a preordering, is a reflexive and transitive relation. A *well-quasi-order* (*wqo*) is a quasi-ordered set in which every infinite sequence $(x_n)_{n \in \mathbb{N}}$ must contain two elements $x_m \leq x_n$ with $m < n$. Well-quasi-orders are a fundamental tool in mathematics and computer science, however they are not closed under several infinitary constructions; e.g., the set of all subsets of a wqo is not in general wqo [12], and a similar problem plagues sets of infinite words, and of infinite trees, over a well-quasi-ordered alphabet. Nash-Williams discovered that a strengthening of the notion of wqo, the notion of *better quasi-orders* (*bqo*), was closed under the usual finitary constructions that preserved being wqo (finite words, finite trees, etc.), and also under their infinitary variants [11].

A *Noetherian space* is a topological space in which every open set is compact, i.e., in which every open cover of an open set contains a finite subcover—we do not assume any separation axiom here. It was observed in [3] that Noetherian spaces formed a natural topological generalization of the order-theoretic notion of wqo. Noetherian spaces are closed under the same finitary constructions as wqos (finite words under embedding, finite trees under homeomorphic embedding, etc., see [4, Section 9.7]), but also under some infinitary constructions. In [3], notably, we remarked that the so-called

2020 *Mathematics Subject Classification*. Primary 54G99; Secondary 06A07.

Key words and phrases. Noetherian spaces, well-quasi-orders, infinite words.

The author was supported by grant ANR-17-CE40-0028 of the French National Research Agency ANR (project BRAVAS).

Hoare powerdomain of a Noetherian space—equivalently, its powerset under the so-called lower Vietoris topology—is Noetherian.

The main purpose of this paper is to show that Noetherianness is preserved under some of the usual infinitary constructions that spurred the invention of bqos.

A secondary purpose is to design those infinitary constructions in such a way that the closed subsets have finite representations suitable for an implementation on a computer. We do not mean to develop this here, but one should note that infinite words are pervasive in verification, mostly as infinite runs in various forms of automata, such as Büchi automata, see [14] for a survey. Downwards-closed subsets of runs, a very closely related notion, were instrumental in the pioneering paper by Leroux and Schmitz on the complexity of VASS reachability [9], too.

Let us illustrate our goal by an example of a finitary construction, taken from [4, Section 9.7] and [2, Section 7]. Let X^* denote the set of finite words over an alphabet X (not necessarily finite). For every quasi-ordering \leq on X , the (scattered) word embedding quasi-ordering \leq^* on X^* is defined by $w \leq^* w'$ if and only if w' can be obtained from w by increasing some letters from w and by inserting arbitrarily many new letters at arbitrary positions. Higman's Lemma [6] states that \leq^* is a well-quasi-ordering if and only if \leq is. Similarly, the *word topology* on X^* , where X is now a topological space, is generated by basic open sets of the form $\langle U_1; U_2; \dots; U_n \rangle \stackrel{\text{def}}{=} X^*U_1X^*U_2 \dots X^*U_nX^*$, where $n \in \mathbb{N}$ and each U_i is open in X —those are the sets of words that contain a letter in U_1 , then a letter in U_2 to the right of the previous one, and so on, until we find a letter in U_n . (Note that they form a base, not just a subbase.) Then the following hold (all required notions will be introduced in Section 2):

- (A) X is Noetherian if and only if X^* (with the word topology) is Noetherian.
- (B) The specialization preordering of X^* is \leq^* , where \leq denotes the specialization preordering of X .
- (C) If X is wqo, then so is X^* .
- (D) If X has an S-representation (a certain, computable, way of representing the irreducible closed subsets of X , and therefore all closed subsets of X), then X^* has an S-representation, too.

We wish to obtain similar results for infinitary constructions, e.g., spaces of infinite words. Our proposals will allow us to obtain equivalents of (A) and (D). (B) will only hold if X is wqo, and (C) will hold if and only if

X is essentially finite (see below); however negative the latter result seems, one should note that we define a topological space as *wqo* if and only if its specialization preordering is a wqo *and* its topology is Alexandroff—that is a pretty strong requirement.

Outline. After some preliminaries in Section 2, we examine the case of the powerset $\mathbb{P}(X)$ for Noetherian X . That $\mathbb{P}(X)$ is Noetherian in that case is not new [3, 4, 2], but it seems important to understand why. This will occupy Section 3.1, in which we will deal with properties (A) and (D) in that case. In Section 3.2, we examine properties (B) and (C). That is new. As promised, property (B) will hold only when X is wqo, and (C) only when X is essentially finite. We then make a small detour and introduce a few useful results pertaining to so-called initial maps in Section 4. With all that in our hands, we will proceed to show that the space X^ω of all infinite words over X , with a natural topology, enjoys properties (A) through (D)—in the case of (B) and (C), exactly with the same restrictions on X as above.

2. PRELIMINARIES

We have already defined well-quasi-orders. They can be defined in many equivalent ways. Notably, as already observed by Higman [6, Theorem 2.1], it is equivalent to require any of the following properties, for a quasi-ordered set X : (i) every upwards-closed subset of X is the upward-closure of a finite set; (ii) the lattice of upwards-closed subsets of X has the ascending chain condition, namely: every ascending sequence $(U_n)_{n \in \mathbb{N}}$ of upwards-closed subsets is stationary, in other words, there is a rank n_0 such that $U_n = U_{n_0}$ for every $n \geq n_0$ (in general, we say that a quasi-ordering \leq has the *ascending chain condition* if and only if it has no strictly ascending infinite sequence $x_0 < x_1 < \dots < x_n < \dots$, where $x < y$ means $x \leq y$ and $y \not\leq x$); (iv) every infinite sequence of elements of X has an infinite ascending subsequence; (v) X is wqo. (We omit characterizations (iii) and (vi), which we will not require.)

Let us turn to topology, for which we refer the reader to [4]. Noetherian spaces are specifically covered in Section 9.7 there. Note that none of the topologies we will consider are Hausdorff. In fact, a Hausdorff topological space is Noetherian if and only if it is finite.

A *subbase* of a topology is any family of open sets that generates the family. A *base* of a topology is a family of open sets such that every open set can be written as a union of basic open sets. We write $cl(A)$ for the

closure of a subset A of a topological space. We will often use the fact that $cl(A)$ intersects an open set U if and only if A intersects U .

Noetherian spaces have many equivalent characterizations (compare with the equivalent characterizations (i)–(vi) of wqos mentioned earlier). Those are also the spaces in which every ascending sequence $(U_n)_{n \in \mathbb{N}}$ of open subsets is stationary; or also the spaces in which every descending sequence $(C_n)_{n \in \mathbb{N}}$ of closed subsets is stationary. The first of those characterizations shows that Noetherianness is a property that depends only on the lattice of open subsets of the space, not on its point.

Noetherian spaces are closed under finite products, finite coproducts, subspaces, under the process of replacing the topology by a coarser one, under images by continuous maps, and various other constructions, such as the X^* construction.

Every topological space has a *specialization* preordering \leq , defined by $x \leq y$ if and only if every open neighborhood of x contains y . We then say that x is less than or equal to y , or *below* y , or that y is larger than or equal to x , or *above* x . The closure of $\{x\}$ is the *principal ideal* $\downarrow x$, namely the set of all points below x in that quasi-ordering. (Symmetrically, we write $\uparrow x$ for the set of all points above x .) An *Alexandroff topology* is a topology in which every intersection of open subsets is open, or equivalently, in which the open subsets are exactly the upwards-closed subsets in the specialization preordering \leq . The Alexandroff topology of a given quasi-ordering \leq is, correspondingly, the collection of all its upwards-closed sets. Among the topologies with a given specialization preordering \leq , the Alexandroff topology is the finest, and the coarsest is the *upper topology*, whose closed sets are intersections of sets of the form $\downarrow E$, E finite; the notation $\downarrow E$ denotes $\bigcup_{x \in E} \downarrow x$.

There is some degree of ambiguity in a notation such as $\downarrow E$, which will be particularly apparent when we work in spaces of subsets. For $E \in \mathbb{P}(X)$, where $\mathbb{P}(X)$ is equipped with the inclusion ordering, say, $\downarrow E$ might denote $\{E' \in \mathbb{P}(X) \mid E' \subseteq E\}$ or $\{x \in X \mid \exists y \in E, x \leq y\}$. In such cases, we will disambiguate by writing $\downarrow_{\mathbb{P}(X)} E$ for the first set, and $\downarrow_X E$ for the second one.

It turns out that a quasi-ordering \leq is a well-quasi-ordering if and only if its Alexandroff topology is Noetherian [4, Proposition 9.7.17]. For short, we will say that a topological space is a *wqo* if and only if it is Noetherian and its topology is the Alexandroff topology, equivalently if and only if its topology is the Alexandroff topology of a well-quasi-ordering.

A subset C of a topological space X is *irreducible* if and only if it is non-empty, and for all closed subsets C_1, C_2 of X such that $C \subseteq C_1 \cup C_2$, we have $C \subseteq C_1$ or $C \subseteq C_2$. Equivalently: C is non-empty, and for all open subsets U_1, U_2 of X that intersect C , $U_1 \cap U_2$ also intersects C .

A *sober space* is a topological space in which every irreducible closed subset is the closure $cl(\{x\}) = \downarrow x$ of a unique point x . (Chapter 8 of [4] is all about sober spaces.) The (standard) *sobrification* $\mathcal{S}X$ of a topological space X is its set of irreducible closed subsets, with the *hull-kernel topology*, whose open subsets are (exactly) the sets of the form $\diamond U \stackrel{\text{def}}{=} \{C \in \mathcal{S}X \mid C \cap U \neq \emptyset\}$, where U ranges over the open subsets of X . The specialization (quasi-)ordering of $\mathcal{S}X$ is inclusion. $\mathcal{S}X$ is always sober, there is a continuous map $\eta_X: X \rightarrow \mathcal{S}X: x \mapsto \downarrow x$, and for every continuous map $f: X \rightarrow Y$ where Y is sober, there is a unique continuous map $\hat{f}: \mathcal{S}X \rightarrow Y$ such that $\hat{f} \circ \eta_X = f$.

\mathcal{S} defines an endofunctor on the category of topological spaces, and its action on morphisms is defined by $\mathcal{S}(f)(C) \stackrel{\text{def}}{=} cl(f[C])$, where $f[C]$ denotes the image of C under f . In particular, $cl(f[C])$ is irreducible closed for every irreducible closed set C and every continuous map f .

Sober spaces are closed under arbitrary topological products. Furthermore, the sobrification of any product of spaces is homeomorphic to the product of the sobrifications. Explicitly, and in the binary case, given any two irreducible closed subsets C of X and C' of Y , $C \times C'$ is irreducible closed in $X \times Y$. Moreover, all irreducible closed subsets of $X \times Y$ are of this form: $(C, C') \mapsto C \times C'$ is the indicated homeomorphism from $\mathcal{S}(X) \times \mathcal{S}(Y)$ to $\mathcal{S}(X \times Y)$.

A space is Noetherian if and only if its sobrification is Noetherian. Indeed, the map $U \mapsto \diamond U$ is an order-isomorphism, hence the lattice of open sets of X has the ascending chain condition if and only if the lattice of open sets of $\mathcal{S}X$ has it as well.

We say that a quasi-ordered set (resp., a topological space) is *essentially finite* if and only if it has only finitely many upwards-closed subsets (resp., open subsets). Note that the topology of an essentially finite topological space is Alexandroff, and trivially Noetherian. A topological space X is essentially finite if and only if its T_0 quotient, namely the quotient X/\equiv where $\equiv \stackrel{\text{def}}{=} \leq \cap \geq$, is finite.

The sober Noetherian spaces are particularly interesting, as they can be characterized entirely in terms of their specialization preordering. Explicitly, the sober Noetherian spaces are exactly the sets X with a well-founded quasi-ordering \leq such that every finite intersection of principal ideals can

be expressed as a finite union of principal ideals (a quasi-ordering \leq is *well-founded* if and only if every strictly descending chain is finite); furthermore, the topology of X is uniquely determined as the upper topology of \leq . In that case, the closed subsets are exactly the sets of the form $\downarrow E$ with E *finite*, which makes them suitable for a representation on a computer—provided all the elements of E are themselves representable.

As a corollary, the closed subsets C of a Noetherian space X are exactly the finite unions of irreducible closed subsets C_1, \dots, C_n of X . Indeed, given any closed subset C of X , the set $\downarrow_{\mathcal{S}X} C$ of all irreducible closed subsets of X below (included in) C is equal to $\mathcal{S}X \setminus \diamond(X \setminus C)$, hence is closed in $\mathcal{S}X$. Also, $\eta_X^{-1}(\downarrow\{C\}) = C$. Since $\mathcal{S}X$ is Noetherian, one can write $\downarrow\{C\}$ as $\downarrow\{C_1, \dots, C_n\}$ for finitely many points C_1, \dots, C_n of $\mathcal{S}X$, and then $C = \eta_X^{-1}(\downarrow\{C\})$ is the union of the finitely many irreducible closed subsets $\eta_X^{-1}(\downarrow\{C_i\}) = C_i$, $1 \leq i \leq n$.

We will be interested in computer representations of irreducible closed subsets of X (i.e., of elements of $\mathcal{S}(X)$), and this will immediately allow us to represent all closed subsets C as finite sets $\{C_1, \dots, C_n\}$, where each C_i is in $\mathcal{S}(X)$. If we can decide inclusion of irreducible closed subsets, one can also decide the inclusion of arbitrary closed subsets: if C is represented by the finite set $\{C_1, \dots, C_m\}$ and C' is represented by the finite set $\{C'_1, \dots, C'_n\}$, then $C \subseteq C'$ if and only if for every i , there is a j such that $C_i \subseteq C'_j$. This is a simple consequence of the fact that each C_i is irreducible. We will also require to be able to compute the intersection $C \cap C'$ of any two irreducible closed subsets of X as a finite union $C_1 \cup \dots \cup C_n$ of irreducible closed subsets.

Those computability requirements are formalized by the notion of an *S-representation* [2, Definition 5.1]. An S-representation of a Noetherian space X is a 5-tuple $(S, \llbracket _ \rrbracket, \preceq, \tau, \wedge)$ where:

- (1) S is a recursively enumerable set of so-called *codes* (of irreducible closed subsets);
- (2) $\llbracket _ \rrbracket$ is a surjective map from S to $\mathcal{S}X$;
- (3) \preceq is a decidable relation such that, for all codes $a, b \in S$, $a \preceq b$ iff $\llbracket a \rrbracket \leq \llbracket b \rrbracket$;
- (4) τ is a finite subset of S , such that $X = \bigcup_{a \in \tau} \llbracket a \rrbracket$;
- (5) \wedge is a computable map (the *intersection map*) from $S \times S$ to the collection $\mathbb{P}_{fin}(S)$ of finite subsets of S (and we write $a \wedge b$ for $\wedge(a, b)$) such that $\llbracket a \rrbracket \cap \llbracket b \rrbracket = \bigcup_{c \in a \wedge b} \llbracket c \rrbracket$.

Let us take X^* , with the word topology, as an example. We use standard notations for certain regular languages on X : for every $C \subseteq X$, $C^?$ denotes the set of words of at most one letter, and that letter is in C ; for every $F \subseteq X$, F^* is the set of words whose letters are all in F ; for all $A, B \subseteq X^*$, AB denotes the set of all concatenations of one word from A and one from B ; ϵ denotes both the empty word and the language $\{\epsilon\}$. A *word product* is a language of the form $P \stackrel{\text{def}}{=} A_1 A_2 \cdots A_N$, where each A_i is an *atom*, i.e., a language of the form $C^?$ with $C \in \mathcal{S}X$ or F^* where F is a closed subset of X . When X is Noetherian, the irreducible closed subsets of X^* are exactly the word products [2, Proposition 7.14]. One can also decide inclusion of word products in polynomial time with an oracle deciding inclusion in $\mathcal{S}X$ [2, Lemma 7.10, Corollary 7.11], and compute intersections of word products as finite unions of word products in polynomial time with an oracle computing binary intersections in $\mathcal{S}X$ as finite unions of irreducible closed subsets [2, Lemma 7.13]. Formally:

Proposition 2.1 (Theorem 7.15 of [2]). *Given an S -representation $(S, \llbracket - \rrbracket, \trianglelefteq, \tau, \wedge)$ of a Noetherian space X , the following tuple $(S', \llbracket - \rrbracket', \trianglelefteq', \tau', \wedge')$ is an S -representation of X^* :*

- (1) S' is the collection of all (syntactic) word products over the alphabet S , namely all regular expressions $A_1 A_2 \cdots A_N$ where each A_i is either an expression of the form $a^?$ with $a \in S$, or u^* where u is a finite subset of S (we write ϵ when $N = 0$).
- (2) $\llbracket A_1 A_2 \cdots A_N \rrbracket' \stackrel{\text{def}}{=} \llbracket A_1 \rrbracket' \llbracket A_2 \rrbracket' \cdots \llbracket A_N \rrbracket'$, where we let $\llbracket a^? \rrbracket' \stackrel{\text{def}}{=} \llbracket a \rrbracket'?$ and $\llbracket \{a_1, \dots, a_n\}^* \rrbracket' \stackrel{\text{def}}{=} (\llbracket a_1 \rrbracket' \cup \cdots \cup \llbracket a_n \rrbracket')^*$.
- (3) \trianglelefteq' is defined inductively by:

$\epsilon \trianglelefteq' Q$ is always true

$P \trianglelefteq' \epsilon$ is false, if $P \neq \epsilon$

$$a^? P \trianglelefteq' b^? Q \text{ iff } \begin{cases} P \trianglelefteq' Q & \text{if } a \trianglelefteq b \\ a^? P \trianglelefteq' Q & \text{otherwise} \end{cases}$$

$$a^? P \trianglelefteq' v^* Q \text{ iff } \begin{cases} P \trianglelefteq' v^* Q & \text{if } \exists b \in v, a \trianglelefteq b \\ a^? P \trianglelefteq' Q & \text{otherwise} \end{cases}$$

$$u^* P \trianglelefteq' b^? Q \text{ iff } \begin{cases} P \trianglelefteq' b^? Q & \text{if } u = \emptyset \\ u^* P \trianglelefteq' Q & \text{otherwise} \end{cases}$$

$$u^* P \trianglelefteq' v^* Q \text{ iff } \begin{cases} P \trianglelefteq' v^* Q & \text{if } \forall a \in u, \exists b \in v, a \trianglelefteq b \\ u^* P \trianglelefteq' Q & \text{otherwise} \end{cases}$$

- (4) τ' is $\{\tau^*\}$.

(5) \wedge' is implemented by the following clauses (together with the obvious symmetric clauses):

$$\varepsilon \wedge' Q \stackrel{\text{def}}{=} \{\varepsilon\} \quad (2.1)$$

$$\begin{aligned} a^? P \wedge' b^? Q &\stackrel{\text{def}}{=} (a^? P \wedge' Q) \cup (P \wedge' b^? Q) \\ &\cup \{c^? R \mid c \in a \wedge b, R \in P \wedge' Q\} \end{aligned} \quad (2.2)$$

$$a^? P \wedge' v^* Q \stackrel{\text{def}}{=} \begin{cases} \{c^? R \mid c \in \bigcup_{b \in v} (a \wedge b), R \in P \wedge' v^* Q\} \cup (a^? P \wedge' Q) \\ \quad \text{if } a \wedge b \neq \emptyset \text{ for some } b \in v, \\ (P \wedge' v^* Q) \cup (a^? P \wedge' Q) & \text{otherwise} \end{cases} \quad (2.3)$$

$$u^* P \wedge' v^* Q \stackrel{\text{def}}{=} \left\{ \left(\bigcup_{a \in u, b \in v} a \wedge b \right)^* R \mid R \in (P \wedge' v^* Q) \cup (u^* P \wedge' Q) \right\}. \quad (2.4)$$

Remark 2.2. One can optimize the procedures above in a number of ways. In the definition of \wedge' , one can remove any subsumed word product in the result. A word product P is *subsumed* by another one, Q , in a given set, if and only if $P \leq' Q$, or equivalently $\llbracket P \rrbracket' \subseteq \llbracket Q \rrbracket'$. As a special case, in (2.3), if $Q = \varepsilon$, then we can remove $a^? P \wedge' Q (= \{\varepsilon\})$, which is subsumed by some other word product, since $\llbracket \varepsilon \rrbracket' = \{\varepsilon\}$ is included in the denotation of the remaining word products (the union of the sets $\llbracket c^? R \rrbracket'$ where $c \in \bigcup_{b \in v} (a \wedge b)$ and $R \in P \wedge' v^* Q$ if $a \wedge b \neq \emptyset$ for some $b \in v$, the union of the sets $\llbracket R \rrbracket'$ where $R \in P \wedge' v^* Q$ otherwise).

3. POWERSSETS

3.1. Properties (A) and (D). Let $\mathbb{P}(X)$ denote the powerset of a space X , with the *lower Vietoris topology*, generated by subbasic open sets of the form $\diamond U \stackrel{\text{def}}{=} \{A \in \mathbb{P}(X) \mid A \cap U \neq \emptyset\}$. By that, we mean that the open subsets of $\mathbb{P}(X)$ are the unions of finite intersections $\bigcap_{i=1}^n \diamond U_i$. (Note the similarity of that notation with the open subsets $\diamond U$ of $\mathcal{S}X$. They are defined the same way, but the sets $\diamond U$ only form a subbase of the lower Vietoris topology, whereas the sets $\diamond U$ range over all the open sets in the hull-kernel topology on $\mathcal{S}X$. Also, \diamond and \diamond commute with arbitrary unions, but \diamond additionally commutes with finite intersections.)

The subset of $\mathbb{P}(X)$ consisting of all closed subsets of X is called the *Hoare powerspace* of X , and will be written as $\mathcal{H}(X)$. We again write $\diamond U$ for the open set $\{C \in \mathcal{H}(X) \mid C \cap U \neq \emptyset\}$. Those sets generate the subspace topology on $\mathcal{H}(X)$, and we will also call it the lower Vietoris topology. For any set A , A intersects an open set U if and only if $cl(A)$ intersects U , and this implies that the function that maps every open subset of $\mathbb{P}(X)$ to its intersection with $\mathcal{H}(X)$ is an order-isomorphism. The following lemma,

which is of independent interest, shows that $\mathcal{H}(X)$ is homeomorphic to $\mathcal{S}(\mathbb{P}(X))$. We also deal with $\mathbb{P}^*(X)$, the subspace of *non-empty* subsets of X , and with $\mathcal{H}^*(X)$, the subspace of non-empty closed subsets of X .

Lemma 3.1 (Lemma 5.10 of [2]). *The map $F \mapsto \downarrow F$ is a homeomorphism from $\mathcal{H}(X)$ onto $\mathcal{S}(\mathbb{P}(X))$, resp. from $\mathcal{H}^*(X)$ onto $\mathcal{S}(\mathbb{P}^*(X))$. \square*

It follows that for every space X , $\mathbb{P}(X)$ is Noetherian if and only if $\mathcal{H}(X)$ is Noetherian, and similarly for $\mathbb{P}^*(X)$ and $\mathcal{H}^*(X)$. It is easy to see that every subspace and every homeomorph of a Noetherian space is Noetherian, so any of those properties implies that X , which is homeomorphic to the subspace of points $\{x\}$ in $\mathbb{P}(X)$ (resp., $\mathbb{P}^*(X)$), is Noetherian. Conversely, if X is Noetherian, then \subseteq is well-founded on $\mathcal{H}(X)$. Any finite intersection of principal ideals $\downarrow_{\mathcal{H}(X)} F_i$, $1 \leq i \leq n$, in $\mathcal{H}(X)$ can be expressed as a finite union of principal ideals, in fact just as $\downarrow_{\mathcal{H}(X)} (F_1 \cap \dots \cap F_n)$. It follows that $\mathcal{H}(X)$ is Noetherian, and sober, with the upper topology of inclusion. Since the complement of $\downarrow_{\mathcal{H}(X)} \{F_1, \dots, F_n\}$ is equal to $\diamond U_1 \cap \dots \cap \diamond U_n$, where each U_i is the complement of F_i in X , that upper topology is none other than the lower Vietoris topology.

The next proposition follows easily, and is a reformulation of Theorem 5.11, (A)–(C), of [2]; that theorem actually gives a full description of an S-representation for $\mathbb{P}(X)$ and for $\mathbb{P}^*(X)$, while Theorem 5.8 of [2] gives the analogous S-representation for $\mathcal{H}(X)$ and for $\mathcal{H}^*(X)$.

Proposition 3.2. *For every topological space X , X is Noetherian if and only if $\mathbb{P}(X)$ (resp., $\mathcal{H}(X)$, $\mathbb{P}^*(X)$, $\mathcal{H}^*(X)$) is.*

Letting $Y \stackrel{\text{def}}{=} \mathbb{P}(X)$ (resp., $\mathbb{P}^(X)$), the irreducible closed subsets of Y are exactly the sets of the form $\downarrow_Y F = \{A \in Y \mid A \subseteq F\}$, where $F \in \mathcal{H}(X)$ (resp., $\mathcal{H}^*(X)$).*

In particular, if X is Noetherian, then the irreducible closed subsets of Y can be represented as finite sets $\{C_1, \dots, C_n\}$ (resp., with $n \geq 1$), denoting $\downarrow_Y (C_1 \cup \dots \cup C_n)$, where each $C_i \in \mathcal{S}X$; if inclusion is decidable on $\mathcal{S}X$, then inclusion is decidable on $\mathcal{S}Y$: if F is represented by the finite set $\{C_1, \dots, C_m\}$ and F' is represented by the finite set $\{C'_1, \dots, C'_n\}$, then $F \subseteq F'$ if and only if for every i , there is a j such that $C_i \subseteq C'_j$. \square

Those match properties (A) and (D) mentioned in the introduction, as promised.

3.2. Properties (B) and (C). As for property (B), the specialization preordering on $\mathbb{P}(X)$ (resp., $\mathbb{P}^*(X)$) is given by $A \leq^b B$ if and only if $cl(A) \subseteq$

$cl(B)$. When X is a wqo, $cl(A) = \downarrow_X A$, so $A \leq^b B$ if and only if for every $a \in A$, there is a $b \in B$ such that $a \leq b$, and we retrieve the usual *domination* (a.k.a., *Hoare*) quasi-ordering.

We now inquire about property (C). One may wonder when $\mathbb{P}(X)$ is wqo, in the sense that its topology is both Alexandroff and Noetherian. One might think that this would be the case if and only if X is ω^2 -wqo (see [8, 10] or [7] for example). This is wrong, as we will see in Proposition 3.4 below. If X is ω^2 -wqo, what we obtain is that the domination quasi-ordering on $\mathbb{P}(X)$ is a well-quasi-ordering (this can be taken as a definition of an ω^2 -wqo), *not* that the lower Vietoris topology is Alexandroff. We will use the following lemma.

Lemma 3.3. (1) *A topological space whose lattice of open subsets is well-founded under inclusion has the Alexandroff topology of its specialization preordering, and that quasi-ordering has the ascending chain condition.*

(2) *A well-quasi-ordering with the ascending chain condition is essentially finite.*

(3) *A Noetherian space whose lattice of open subsets is well-founded is essentially finite.*

Proof. (1) Let us assume that the lattice of open subsets of X is well-founded. Given any $x \in X$, there is a minimal open neighborhood U_x of x . By definition of the specialization preordering \leq , for every point $y \in X$ such that $x \not\leq y$, there is an open subset U of X that contains x but not y . Since $U \cap U_x$ is an open neighborhood of x , the minimality of U_x entails that $U \cap U_x = U_x$, that is, $U_x \subseteq U$. It follows that y is not in U_x . We have shown the implication $x \not\leq y \Rightarrow y \notin U_x$, from which we deduce $U_x \subseteq \uparrow x$. Every open set is upwards-closed in the specialization preordering, so $U_x = \uparrow x$.

From this, we deduce that $\uparrow x$ is open for every $x \in X$. Every upwards-closed subset A is equal to $\bigcup_{x \in A} \uparrow x$, hence is open. Hence the topology of X is the Alexandroff topology of \leq .

We now consider any strictly increasing sequence $x_0 < x_1 < \dots < x_n < \dots$. Then the sets $\uparrow x_n$ form a strictly descending sequence of open subsets, contradicting our well-foundedness assumption. Hence \leq has the ascending chain condition.

(2) By contradiction, let us assume that there is an infinite set A whose elements are pairwise inequivalent with respect to $\equiv \stackrel{\text{def}}{=} \leq \cap \geq$. We extract a countable infinite subset $(x_n)_{n \in \mathbb{N}}$ of A . In a well-quasi-ordering, every infinite sequence has an infinite ascending subsequence, so we may assume

without loss of generality that $x_0 \leq x_1 \leq \dots \leq x_n \leq \dots$. By the ascending chain condition, only finitely many of those inequalities can be strict, hence $x_n \equiv x_{n+1}$ for at least one n . That is absurd.

(3) If X is Noetherian with a well-founded lattice of open subsets, by (1) it is Alexandroff, hence wqo, and satisfies the ascending chain condition. We conclude by (2). \square

Proposition 3.4. *Let X be a Noetherian space. The lower Vietoris topology on $\mathbb{P}(X)$ (resp., $\mathcal{H}(X)$, $\mathbb{P}^*(X)$, $\mathcal{H}^*(X)$) is Alexandroff if and only if X is essentially finite.*

Proof. The if direction is clear. Let Y be $\mathbb{P}(X)$ (resp., $\mathcal{H}(X)$, $\mathbb{P}^*(X)$, $\mathcal{H}^*(X)$), and let us assume that Y is Alexandroff. We use Lemma 3.3 (3), first showing that the lattice of open subsets of X is well-founded, or equivalently that there is no infinite strictly ascending sequence of closed subsets of X .

For the sake of contradiction, we assume that there is such an infinite strictly ascending sequence $F_0 \subsetneq F_1 \subsetneq \dots \subsetneq F_n \subsetneq \dots$. Up to the removal of F_0 , we may assume that every F_n is non-empty: this is needed for the cases where Y is $\mathbb{P}^*(X)$ or $\mathcal{H}^*(X)$. For each $n \in \mathbb{N}$, $\downarrow_Y F_n = Y \setminus \diamond(X \setminus F_n)$ is closed. Since Y is Alexandroff, any union of closed subsets of Y is closed, so $\mathcal{F} \stackrel{\text{def}}{=} \bigcup_{n \in \mathbb{N}} \downarrow_Y F_n$ is closed.

Let F_∞ be the closure of $\bigcup_{n \in \mathbb{N}} F_n$ in X . We claim that F_∞ is in \mathcal{F} . Otherwise, by the definition of the lower Vietoris topology, F_∞ would be in some finite intersection $\bigcap_{i=1}^m \diamond U_i$, disjoint from \mathcal{F} , where each U_i is open in X . For each i , U_i would then intersect F_∞ , hence $\bigcup_{n \in \mathbb{N}} F_n$, hence F_{n_i} for some $n_i \in \mathbb{N}$. Let $n \in \mathbb{N}$ be larger than every n_i , $1 \leq i \leq m$. Then F_n intersects every U_i , $1 \leq i \leq m$, as well, so $F_n \in \bigcap_{i=1}^m \diamond U_i$. However, F_n is in \mathcal{F} , by definition of \mathcal{F} , which is impossible since \mathcal{F} is disjoint from $\bigcap_{i=1}^m \diamond U_i$ by assumption.

Since F_∞ is in \mathcal{F} , it is in some $\downarrow_Y F_n$. In particular, $F_{n+1} \subseteq F_\infty \subseteq F_n$, which is impossible. Hence there is no strictly ascending sequence of closed subsets of X , and we conclude by Lemma 3.3 (3). \square

4. INITIAL MAPS

We will use the following additional facts about Noetherian spaces. An *initial* map $f: Y \rightarrow Z$ between topological spaces is one such that the open subsets of Y are exactly the sets of the form $f^{-1}(W)$, W open in Z . All initial maps are continuous.

Remark 4.1. Given a subbase of the topology of Y , a practical way of checking that $f: Y \rightarrow Z$ is initial consists in verifying that f is continuous, and that every subbasic open subset V of Y can be written as $f^{-1}(W)$ for some open subset W of Z . In other words, we do not need to check the latter for every open subset of Y , just for subbasic open sets. Indeed, every open subset V of Y can be written as $\bigcup_{i \in I} \bigcap_{j=1}^{n_i} V_{ij}$ where each V_{ij} is subbasic, and if we can write each V_{ij} as $f^{-1}(W_{ij})$ with W_{ij} open in Z , then V is equal to $f^{-1}(\bigcup_{i \in I} \bigcap_{j=1}^{n_i} W_{ij})$.

A general way of finding initial maps is as follows. Let Z be a topological space and f be a map from a set Y to Z . With the coarsest topology on Y that makes f continuous, f is initial. This is notably the case of topological embeddings, which are those initial maps that are injective.

Lemma 4.2. *Let $f: Y \rightarrow Z$ be an initial map between topological spaces. If Z is Noetherian, then Y is Noetherian.*

Proof. The open subsets of Y are the sets $f^{-1}(W)$, W open in Z . Let $(f^{-1}(W_n))_{n \in \mathbb{N}}$ be a monotonic sequence of open subsets in Y . Replacing W_n by $W_0 \cup W_1 \cup \dots \cup W_n$, we may assume that $(W_n)_{n \in \mathbb{N}}$ is also a monotonic sequence. Since Z is Noetherian, all sets W_n are equal for n large enough. Hence all sets $f^{-1}(W_n)$ are equal for n large enough. \square

Lemma 4.3. *Let $f: Y \rightarrow Z$ be an initial map. The irreducible closed subsets D of Y are all of the form $f^{-1}(C)$ where C is some irreducible closed in Z . More precisely, one can always choose $C \stackrel{\text{def}}{=} cl(f[D])$.*

Proof. Let D be irreducible closed in Y , and consider $C \stackrel{\text{def}}{=} cl(f[D])$. Recall that $C = \mathcal{S}(f)(D)$ is irreducible closed.

Since f is initial, $D = f^{-1}(C')$ for some closed subset C' of Z . Then $f[f^{-1}(C')]$ is included in C' , so its closure $C \stackrel{\text{def}}{=} cl(f[D])$ is also included in C' . In particular, $f^{-1}(C)$ is included in $f^{-1}(C') = D$. Conversely, for every $y \in D$, $f(y)$ is in $f[D]$ hence in C , so D is included in $f^{-1}(C)$. Therefore $D = f^{-1}(C)$, where C is irreducible closed. \square

Note that Lemma 4.3 does not say that every set $f^{-1}(C)$, $C \in \mathcal{S}Z$, is irreducible closed in Y , just that every irreducible closed subset of Y must be of that form. We have a complete characterization when the image of f is open or closed:

Lemma 4.4. *Let $f: Y \rightarrow Z$ be an initial map.*

- (1) *If the image of f is open, then the irreducible closed subsets of Y are exactly those sets of the form $f^{-1}(C)$ where C ranges over the irreducible closed subsets of Z that intersect the image of f .*
- (2) *If the image of f is closed, then the irreducible closed subsets of Y are exactly those sets of the form $f^{-1}(C)$ where C ranges over the irreducible closed subsets of Z that are included in the image of f .*

Proof. 1. Let us assume that the image $\text{Im } f$ of f is open. By Lemma 4.3, every irreducible closed subset of Y must be of the form $f^{-1}(C)$, with C irreducible closed in Z . Necessarily, $f^{-1}(C)$ must be non-empty, and that implies that C intersects the image $\text{Im } f$ of f .

In the converse direction, let C be irreducible closed in Z , and let us assume that C intersects $\text{Im } f$. Then $f^{-1}(C)$ is non-empty. Let us now consider two open subsets of Y that intersect $f^{-1}(C)$. Since f is initial, they must be of the form $f^{-1}(U)$ and $f^{-1}(V)$, where U and V are open in Z . Since $f^{-1}(C)$ intersects $f^{-1}(U)$, there is a point $y \in Y$ such that $f(y)$ is in C and in U , and therefore $\text{Im } f \cap U \cap C$ is non-empty. In other words, C intersects $\text{Im } f \cap U$. Similarly, C also intersects $\text{Im } f \cap V$. Both $\text{Im } f \cap U$ and $\text{Im } f \cap V$ are open in Z . Since C is irreducible, it must intersect their intersection, which is $\text{Im } f \cap U \cap V$. Hence there is a point $f(y)$ (with $y \in Y$) in $\text{Im } f$ which is also in C , U , and V . Then y is in $f^{-1}(C)$, $f^{-1}(U)$ and $f^{-1}(V)$, so $f^{-1}(C)$ intersects $f^{-1}(U) \cap f^{-1}(V)$. We conclude that $f^{-1}(C)$ is irreducible.

2. We now assume that $\text{Im } f$ is closed. By Lemma 4.3, every irreducible closed subset D of Y must be of the form $f^{-1}(C)$, where $C \stackrel{\text{def}}{=} cl(f[D])$ is irreducible closed in Z . Since $f[D] \subseteq \text{Im } f$ and $\text{Im } f$ is closed, $cl(f[D])$ is also included in $\text{Im } f$, so C is included in the image of f .

In the converse direction, let C be irreducible closed in Z , and let us assume that $C \subseteq \text{Im } f$. Since C is non-empty, $f^{-1}(C)$ is non-empty. Let us now consider two closed subsets of Y whose union contains $f^{-1}(C)$. Since f is initial, they must be of the form $f^{-1}(C_1)$ and $f^{-1}(C_2)$, where C_1 and C_2 are closed in Z . For every $z \in C$, we can write z as $f(y)$ for some $y \in Y$ since $C \subseteq \text{Im } f$. Then y is in $f^{-1}(C)$, hence in $f^{-1}(C_1)$ or in $f^{-1}(C_2)$. It follows that z is in C_1 or in C_2 . This shows that C is included in $C_1 \cup C_2$, hence in C_1 or in C_2 , using irreducibility. In the first case, $f^{-1}(C)$ is included in $f^{-1}(C_1)$, otherwise in $f^{-1}(C_2)$. We conclude that $f^{-1}(C)$ is irreducible. \square

5. INFINITE WORDS

Let X be an alphabet, by which we simply mean a topological space, not necessarily finite. An *infinite word* on X is an infinite sequence of elements of X , i.e., a function from \mathbb{N} to X . We let X^ω denote the set of all infinite words on X . We write every $w \in X^\omega$ as $w_0w_1 \cdots w_n \cdots$, where $w_n \in X$. We also write $w_{<n}$ for the length n prefix $w_0w_1 \cdots w_{n-1}$ of w , and $w_{\geq n}$ for the remainder $w_nw_{n+1} \cdots$.

We will also consider the set of *finite-or-infinite words* $X^{\leq\omega} \stackrel{\text{def}}{=} X^\omega \cup X^*$. Those can be defined as the functions w from an initial segment $\text{dom } w$ of \mathbb{N} to X .

There is a standard quasi-ordering \leq^ω on $X^{\leq\omega}$, defined by $w \leq^\omega w'$ if and only if w is a *subword* of w' , namely if there is a monotonic, injective map $f: \text{dom } w \rightarrow \text{dom } w'$ such that $w_n \leq w'_{f(n)}$ for every $n \in \text{dom } w$. (As usual, \leq is the specialization preordering of X .)

The topology we will be interested in is the following. We reuse the notation $\langle U_1; U_2; \cdots; U_n \rangle$ to denote the set of finite *or infinite* words that have a (finite) subword in $U_1U_2 \cdots U_n$. The context should make clear whether we reason in X^* or in $X^{\leq\omega}$. The notation $\langle U_1; U_2; \cdots; U_n; (\infty)U \rangle$ denotes the set of (necessarily infinite) words that can be written as a concatenation uw where u is a finite word in $\langle U_1; U_2; \cdots; U_n \rangle$ and w contains infinitely many letters from U .

Definition 5.1. The *asymptotic subword topology* on $X^{\leq\omega}$ is generated by the subbasic open sets $\langle U_1; U_2; \cdots; U_n \rangle$ and $\langle U_1; U_2; \cdots; U_n; (\infty)U \rangle$, where $n \in \mathbb{N}$, and U_1, \dots, U_n, U are open in X .

Note that X^ω is an open subset of $X^{\leq\omega}$, since $X^\omega = \langle (\infty)X \rangle$. It follows that X^* occurs as a closed subset of $X^{\leq\omega}$.

We equip each subspace of $X^{\leq\omega}$ with the subspace topology. In particular, we will call *asymptotic subword topology* on X^ω the subspace topology. The subspace topology on X^* happens to coincide with the word topology.

Fact 5.2. *Every open (resp., closed) subset of $X^{\leq\omega}$ in the asymptotic subword topology is upwards-closed (resp., downwards-closed) with respect to \leq^ω .* \square

We will now show that, if X is Noetherian, then the asymptotic subword topology is the join of two simpler topologies, the prefix and the suffix topology. (The *join* of two topologies is the coarsest topology that is finer than both. It has a base of open sets of the form $U_1 \cap U_2$, where U_1 is open in the first topology and U_2 is open in the other one.)

5.1. The prefix topology. For every $w \in X^{\leq \omega}$, the set $\text{pref}(w) \stackrel{\text{def}}{=} cl(\{w_{<n} \mid n \in \text{dom } w\})$ is irreducible in X^* : if \mathcal{U}_1 and \mathcal{U}_2 are two open subsets of X^* that intersect $\text{pref}(w)$, then $w_{<m} \in \mathcal{U}_1$ and $w_{<n} \in \mathcal{U}_2$ for some $m, n \in \text{dom } w$; since all open subsets of X^* are upwards-closed in \leq^* , $w_{<\max(m,n)}$ is both in \mathcal{U}_1 and in \mathcal{U}_2 , showing that $\text{pref}(w)$ intersects $\mathcal{U}_1 \cap \mathcal{U}_2$.

Definition 5.3. The *prefix map* $\text{pref}: X^{\leq \omega} \rightarrow \mathcal{S}(X^*)$ is defined by $\text{pref}(w) \stackrel{\text{def}}{=} cl(\{w_{<n} \mid n \in \text{dom } w\})$ for every $w \in X^{\leq \omega}$.

The *prefix topology* on $X^{\leq \omega}$ is the coarsest that makes pref continuous.

In other words, a subbase of the prefix topology is given by sets of the form $\text{pref}^{-1}(\diamond U)$, where U is open in X^* .

Remark 5.4. Let us take X Noetherian. Since $\text{pref}(w)$ is in $\mathcal{S}(X^*)$, one must be able to write it as a word product. The closed subsets $F_n \stackrel{\text{def}}{=} cl(\{w_m \mid m \in \text{dom } w, m \geq n\})$, $n \in \mathbb{N}$, form a descending sequence, so there is an index n_0 such that for every $n \geq n_0$, $F_n = F_{n_0}$. Although we will not use it, one can show that $\text{pref}(w) = (\downarrow w_0)^? (\downarrow w_1)^? \cdots (\downarrow w_{n-1})^? F_n^*$ for every $n \geq n_0$. We leave this as an exercise to the reader. As a hint, first, show that the right-hand side $\mathcal{C} \stackrel{\text{def}}{=} (\downarrow w_0)^? (\downarrow w_1)^? \cdots (\downarrow w_{n-1})^? F_n^*$ does not depend on $n \geq n_0$. Second, show that $w_{<n} \in \mathcal{C}$ for every $n \in \mathbb{N}$, and deduce that $\text{pref}(w) \subseteq \mathcal{C}$. In the reverse direction, consider any basic open set $\mathcal{U} \stackrel{\text{def}}{=} \langle U_1; U_2; \cdots; U_k \rangle$ that intersects \mathcal{C} , say at $u \stackrel{\text{def}}{=} u_0 a_1 u_1 a_2 u_2 \cdots u_{k-1} a_k u_k$, where each u_i is in X^* , each a_i is in U_i . By picking n larger than the length of u in the definition of \mathcal{C} , observe that $a_1 a_2 \cdots a_k$ is a subword of $w_{<n}$, and conclude that \mathcal{U} intersects $\text{pref}(w)$ at $w_{<n}$.

For the next lemma, we recall that the sets of the form $\langle U_1; U_2; \cdots; U_n \rangle$, where each U_i is open in X , form a base, not just a subbase of the asymptotic subword topology on X^* .

Lemma 5.5. *The prefix map pref is continuous from $X^{\leq \omega}$ with its asymptotic subword topology to $\mathcal{S}(X^*)$. A base of the prefix topology is given by the sets $\langle U_1; U_2; \cdots; U_n \rangle$, where U_1, \dots, U_n are open in X .*

The prefix topology is coarser than the asymptotic subword topology.

Proof. Every open subset of X^* is a union of basic open subsets of the form $\langle U_1; U_2; \cdots; U_n \rangle$ where each U_i is open in X . In order to show that pref is continuous, since \diamond commutes with arbitrary unions, it is enough to show that $\text{pref}^{-1}(\diamond(\langle U_1; U_2; \cdots; U_n \rangle))$ is open in the asymptotic subword topology. That is the set of finite or infinite words w such that $cl(\{w_{<m} \mid m \in \text{dom } w\})$ intersects the open set $\langle U_1; U_2; \cdots; U_n \rangle$; equivalently, such that

some prefix $w_{<m}$ belongs to $\langle U_1; U_2; \dots; U_n \rangle$. The set $\text{pref}^{-1}(\diamond(\langle U_1; U_2; \dots; U_n \rangle))$ is therefore equal to the open subset $\langle U_1; U_2; \dots; U_n \rangle$ of $X^{\leq \omega}$.

This also shows that the sets $\langle U_1; U_2; \dots; U_n \rangle = \text{pref}^{-1}(\diamond(\langle U_1; U_2; \dots; U_n \rangle))$ form a subbase of the prefix topology.

Since pref^{-1} and \diamond commute with finite intersections, since the sets $\langle U_1; U_2; \dots; U_n \rangle$ form a base of the topology on X^* , every finite intersection U of sets of the form $\text{pref}^{-1}(\diamond(\langle U_1; U_2; \dots; U_n \rangle))$ can be written as $\text{pref}^{-1}(\diamond \mathcal{U})$ where \mathcal{U} is a union of basic open sets of X^* . Since pref^{-1} and \diamond commute with all unions, \mathcal{U} is also a union of subbasic open sets of the form $\langle U_1; U_2; \dots; U_n \rangle$. This shows that the given subbase is a base.

The final claim is an immediate consequence of the first one. \square

5.2. The suffix topology. In any complete lattice L , the *limit superior* of a sequence $(u_n)_{n \in \mathbb{N}}$ is $\limsup_{n \in \mathbb{N}} u_n = \bigwedge_{n \in \mathbb{N}} \bigvee_{m \geq n} u_m$. We will use that notion in lattices of closed sets. Then $\limsup_{n \in \mathbb{N}} C_n = \bigcap_{n \in \mathbb{N}} \text{cl}(\bigcup_{m \geq n} C_m)$, where cl is closure. On a Noetherian space, descending families of closed sets are stationary, so $\limsup_{n \in \mathbb{N}} C_n = \text{cl}(\bigcup_{m \geq n} C_m)$ for large enough n . (The quantifier “for large enough n ” means “for some n_0 , for every $n \geq n_0$ ”.)

Let the *suffix map* $\text{suf}: X^{\leq \omega} \rightarrow \mathcal{H}(X)$ be defined by:

$$\begin{aligned} \text{suf}(w) &\stackrel{\text{def}}{=} \limsup_{n \in \mathbb{N}} \downarrow \{w_m \mid m \in \text{dom } w, m \geq n\} \\ &= \bigcap_{n \in \mathbb{N}} \text{cl}(\{w_m \mid m \in \text{dom } w, m \geq n\}). \end{aligned}$$

Note that $\text{suf}(w)$ is empty for every finite word w . When X is Noetherian (or more generally, compact), this is an equivalence: $\text{suf}(w) = \emptyset$ if and only if $w \in X^*$.

The *suffix topology* on $X^{\leq \omega}$ is the coarsest that makes suf continuous.

Lemma 5.6. *Let X be a Noetherian space. The suffix map suf is continuous from $X^{\leq \omega}$ with its asymptotic subword topology to $\mathcal{H}(X)$. A subbase of the suffix topology is given by the sets $\langle (\infty)U \rangle$, U open in X .*

The suffix topology is coarser than the asymptotic subword topology.

Proof. A subbase of the suffix topology is given by the sets $\text{suf}^{-1}(\diamond U)$, U open in X . We claim that $\text{suf}^{-1}(\diamond U) = \langle (\infty)U \rangle$. This readily implies the first and the second claim, and the third one will be an immediate consequence.

Let $w \in X^{\leq \omega}$, and let n_0 be such that $\limsup_{n \in \mathbb{N}} \downarrow \{w_m \mid m \in \text{dom } w, m \geq n\} = \text{cl}(\{w_m \mid m \in \text{dom } w, m \geq n\})$ for every $n \geq n_0$. If $w \in \text{suf}^{-1}(\diamond U)$, then for every $n \geq n_0$, $\text{cl}(\{w_m \mid m \in \text{dom } w, m \geq n\})$ intersects U , so $w_m \in$

U for some $m \in \text{dom } w$ such that $m \geq n$. Hence $w \in \langle(\infty)U\rangle$. Conversely, if $w \in \langle(\infty)U\rangle$, then $\text{dom } w = \mathbb{N}$ and there are infinitely many positions $n \geq n_0$ where w_n is in U . Take one. Then $\text{cl}(\{w_m \mid m \in \text{dom } w, m \geq n_0\})$ intersects U at w_n , showing that w is in $\text{suf}^{-1}(\diamond U)$. \square

Proposition 5.7. *Let X be a Noetherian space. The asymptotic subword topology on X is the join of the prefix and the suffix topologies. The function $\langle \text{pref}, \text{suf} \rangle: X^{\leq \omega} \rightarrow \mathcal{S}(X^*) \times \mathcal{H}(X)$ that maps w to $(\text{pref}(w), \text{suf}(w))$ is initial.*

Proof. The asymptotic subword topology is finer than both the prefix and the suffix topologies, by Lemma 5.5 and Lemma 5.6. Conversely, every subbasic open set $\langle U_1; U_2; \dots; U_k \rangle$ is prefix-open, and every subbasic open set $\langle U_1; U_2; \dots; U_k; (\infty)U \rangle$ is the intersection of the prefix-open set $\langle U_1; U_2; \dots; U_k \rangle$ with the suffix-open set $\langle(\infty)U\rangle$.

By the first part of the lemma, the asymptotic subword topology on $X^{\leq \omega}$ is the coarsest that makes both pref and suf continuous, hence the coarsest that makes $\langle \text{pref}, \text{suf} \rangle$ continuous. It follows that $\langle \text{pref}, \text{suf} \rangle$ is initial. \square

Property (A) follows:

Theorem 5.8. *For every space X , $X^{\leq \omega}$ (with the asymptotic subword topology) is Noetherian if and only if X is Noetherian. Similarly with X^ω .*

Proof. If X is Noetherian, then so are X^* , $\mathcal{S}(X^*)$, $\mathcal{H}(X)$ and their product $\mathcal{S}(X^*) \times \mathcal{H}(X)$, as we have already seen in Section 2 and Section 3. Since $f \stackrel{\text{def}}{=} \langle \text{pref}, \text{suf} \rangle$ is initial (Proposition 5.7), Lemma 4.2 ensures that $X^{\leq \omega}$ and its subspace X^ω are Noetherian in the asymptotic subword topology.

In the converse direction, we use the following argument, which works in both the $X^{\leq \omega}$ and X^ω cases. Let g be the function that maps every $x \in X$ to the infinite word $x^\omega \stackrel{\text{def}}{=} xx \cdots x \cdots$ (in $X^{\leq \omega}$, resp., X^ω). This is continuous since $g^{-1}(\langle U_1; U_2; \dots; U_k \rangle) = U_1 \cap U_2 \cap \dots \cap U_k$ and $g^{-1}(\langle U_1; U_2; \dots; U_k; (\infty)U \rangle) = U_1 \cap U_2 \cap \dots \cap U_k \cap U$. With $k \stackrel{\text{def}}{=} 0$, we also obtain that every open subset U of X is obtained as $g^{-1}(\langle(\infty)U\rangle)$, so g is initial. By Lemma 4.2, if $X^{\leq \omega}$ (resp., X^ω) is Noetherian, then so is X . \square

From now on, and unless noted otherwise, we understand $X^{\leq \omega}$ (and X^ω) with the asymptotic subword topology.

5.3. A few useful auxiliary results. We pause for a moment, and establish two useful results.

Proposition 5.9. *The concatenation map $\text{cat}: X^* \times X^{\leq \omega} \rightarrow X^{\leq \omega}$ is continuous.*

Proof. Let (u, w) be any point in $\text{cat}^{-1}(W)$, where $W = \langle U_1; U_2; \dots; U_k \rangle$ (resp., $W = \langle U_1; U_2; \dots; U_k; (\infty)U \rangle$), where U_1, \dots, U_k , and U are open in X . There is an index j , $0 \leq j \leq k$ such that u is in $\langle U_1; U_2; \dots; U_j \rangle$, and w is in $\langle U_{j+1}; \dots; U_k \rangle$ (resp., $\langle U_{j+1}; \dots; U_k; (\infty)U \rangle$). Then $\langle U_1; U_2; \dots; U_j \rangle \times \langle U_{j+1}; \dots; U_k \rangle$ (resp., $\langle U_1; U_2; \dots; U_j \rangle \times \langle U_{j+1}; \dots; U_k; (\infty)U \rangle$) is an open neighborhood of (u, w) that is included in $\text{cat}^{-1}(W)$. \square

The sets $\langle U_1; U_2; \dots; U_k \rangle$ and $\langle U_1; U_2; \dots; U_k; (\infty)U \rangle$ only form a sub-base of X^ω . We obtain a base as follows. $\langle U_1; U_2; \dots; U_k; (\infty)V_1 \cap \dots \cap \dots (\infty)V_\ell \rangle$ denotes the set of finite-or-infinite words that contain letters from U_1, U_2, \dots, U_k in that order, followed by a suffix that contains infinitely many letters from V_1 , and also infinitely many from V_2, \dots , and infinitely many from V_ℓ . We allow ℓ to be equal to 0; if $\ell \neq 0$, then that set only contains infinite words.

Lemma 5.10. *Let X be a Noetherian space. A base of the asymptotic sub-word topology on $X^{\leq \omega}$ is given by the subsets $\langle U_1; U_2; \dots; U_k; (\infty)V_1 \cap \dots \cap \dots (\infty)V_\ell \rangle$ where $U_1, \dots, U_n, V_1, \dots, V_\ell$ are open in X .*

Proof. As a consequence of Proposition 5.7, a base is given by intersections of one element $\langle U_1; U_2; \dots; U_k \rangle$ of the base of the prefix topology given in Lemma 5.5, and of one element of a base of the suffix topology. For the latter, one can take finite intersections $\langle (\infty)V_1 \rangle \cap \dots \cap \langle (\infty)V_\ell \rangle = \langle (\infty)V_1 \cap \dots \cap (\infty)V_\ell \rangle$. \square

5.4. The sobrification of $X^{\leq \omega}$. We extend the notion of word product to *finite-or-infinite word products*: ω -regular expressions of the form $PF^{\leq \omega}$, where P is a word product and F is a closed subset of X . $PF^{\leq \omega}$ denotes the sets of finite or infinite words that are obtained as the concatenation of a finite word in P with a finite-or-infinite word whose letters are all in F . We also write PF^ω for $PF^{\leq \omega} \cap X^\omega$: this is the set of infinite words obtained as the concatenation of a finite word in P with an infinite word whose letters are all in F . This is empty if F is empty. We call *infinite word products* the expressions PF^ω where P is a word product and F is a *non-empty* closed subset of X .

Proposition 5.11. *Let X be a Noetherian space. Every irreducible closed subset of $X^{\leq \omega}$ is an finite-or-infinite word product.*

Proof. Let D be an irreducible closed subset of $X^{\leq \omega}$. The map $f \stackrel{\text{def}}{=} \langle \text{pref}, \text{suf} \rangle$ is initial by Proposition 5.7. We can therefore apply Lemma 4.3 to f , and we obtain that D is the inverse image of some irreducible closed subset of

$\mathcal{S}(X^*) \times \mathcal{H}(X)$ by f . Since the latter space is already sober ($\mathcal{H}(X)$ is sober by Lemma 3.1, or by [13, Proposition 1.7]), an irreducible subset is just the downward closure of a point (P, F) of $\mathcal{S}(X^*) \times \mathcal{H}(X)$. Here P must be a word product $A_1A_2 \cdots A_N$, and F must be a closed subset of X .

Hence D is the set of words $w \in X^{\leq\omega}$ such that $\text{pref}(w) \subseteq P$ and $\text{suf}(w) \subseteq F$, that is, such that all the finite prefixes of w are in P and the letters w_n are in F for $n \in \text{dom } w$ large enough. There may be different choices of the pair (P, F) , and we choose one such that the number N of atoms in P is minimal, and such that given that N , F is minimal with respect to inclusion. This is possible since X is Noetherian.

If F is empty, then D is the set of finite words w such that $\text{pref}(w) \subseteq P$, or equivalently such that every prefix of w is in P . Therefore $D = P$, and that can also be written as $PF^{\leq\omega}$, since $F = \emptyset$. Henceforth let us assume that F is non-empty.

We note that: (*) D is not included in X^* . Indeed, otherwise, for every $w \in D$, w would be finite, so $\text{suf}(w)$ would be empty. It would follow that D would be included in $f^{-1}(\downarrow(P, \emptyset))$, and that would contradict the minimality of F .

Let us write P as a product $A_1A_2 \cdots A_N$ of atoms, with N minimal. Since $\emptyset^* = \{\epsilon\}$, we may simply erase all atoms of the form A^* with A empty: since N is minimal, no A_i is of the form \emptyset^* . We claim that $N \geq 1$ and that A_N is of the form F'^* for some (necessarily non-empty) closed set F' . We cannot have $N = 0$, since that would imply that for every $w \in D$, $\text{pref}(w) = \{\epsilon\}$, hence that $D = \{\epsilon\}$; this is impossible since $\text{suf}(\{\epsilon\}) = \emptyset$, contradicting the fact that F is non-empty. Hence let us write P as $P'A_N$. We now assume that A_N is of the form $C^?$ with C irreducible closed, and we aim for a contradiction. For every infinite word $w \in D$, we note that $\text{pref}(w)$ is included in P' : for every finite prefix $w_{<n}$ of w , the finite prefix $w_{<n+1} = w_{<n}w_n$ is in $\text{pref}(w)$, hence in $P = P'C^?$, and that implies that $w_{<n}$ is in P' ; since n is arbitrary, $\{w_{<n} \mid n \in \text{dom } w\}$ is included in P' , and therefore $\text{pref}(w) \subseteq P'$, since P' is closed. Hence every infinite word in D is included in $\text{pref}^{-1}(P')$. Alternatively, D is included in the union of the set X^* of finite words and of $\text{pref}^{-1}(P')$. Since D is irreducible, and both X^* and $\text{pref}^{-1}(P')$ are closed (the latter by Lemma 5.5), D must be included in one of them. By (*), D is not included in X^* , so D is included in $\text{pref}^{-1}(P')$. It follows that D is the set of words $w \in X^{\leq\omega}$ such that $\text{pref}(w) \subseteq P'$ (not just P) and $\text{suf}(w) \subseteq F$, and this contradicts the minimality of N .

We have shown that P is of the form $P'F'^*$ for some non-empty closed subset F' of X . We now claim that F must be included in F' . For every infinite word w in D , $\text{pref}(w) \subseteq P$, so every finite prefix of w is in P . Then, either every finite prefix of w is in P' —in which case $\text{pref}(w) \subseteq P'$ —or there is a largest $n_0 \in \mathbb{N}$ such that $w_{<n_0}$ is in P' . In the latter case, every letter w_n with $n \geq n_0$ must be in F' . For n_1 large enough, $\text{suf}(w) = \text{cl}(\{w_m \mid m \geq n_1\})$. By picking n_1 larger than n_0 , every letter w_n with $n \geq n_1$ is also in F . Hence w_n is in $F \cap F'$ for every $n \geq n_1$, from which we deduce that $\text{suf}(w) \subseteq F \cap F'$. We have shown that every infinite word w in D is in $\text{pref}^{-1}(\downarrow P') \cup \text{suf}^{-1}(\downarrow(F \cap F'))$, or equivalently, that D is included in the union of X^* , $\text{pref}^{-1}(\downarrow P')$, and $\text{suf}^{-1}(\downarrow(F \cap F'))$. Those three sets are closed, using Lemma 5.5 in the case of the second one, and Lemma 5.6 for the third one. Since D is irreducible, it must be included in one of them. It is not included in X^* by (*). It is not included in $\text{pref}^{-1}(\downarrow P')$, otherwise D would be included in $f^{-1}(\downarrow(P', F))$, contradicting the minimality of N . Therefore D is included in $\text{suf}^{-1}(\downarrow(F \cap F'))$. This entails that D is included in $f^{-1}(\downarrow(P, F \cap F'))$. Since F is minimal, $F = F \cap F'$, hence F is included in F' .

Now that we know that $D = f^{-1}(\downarrow(P'F'^*, F))$ with $F \subseteq F'$, we verify that $D = P'F'^*F^{\leq\omega}$. For every $w \in D$, $\text{suf}(w) \subseteq F$ so there is an index n_0 such that, for every $n \in \text{dom } w$ with $n \geq n_0$, w_n is in F . If w is a finite word, we may take n_0 equal to one plus the length of w . Whatever the case, $w_{\geq n_0}$ is in $F^{\leq\omega}$. Since $\text{pref}(w) \subseteq P'F'^*$, $w_{<n}$ is in $P'F'^*$, so w is in $P'F'^*F^{\leq\omega}$. Conversely, let $w \in P'F'^*F^{\leq\omega}$. If w is finite, then it is in $P'F'^*F^* \subseteq P'F'^*$ (since $F \subseteq F'$), so $\text{pref}(w) \subseteq P'F'^*$; also, $\text{suf}(w) = \emptyset \subseteq F$, so w is in $f^{-1}(\downarrow(P'F'^*, F)) = D$. Hence let us assume that w is infinite. There is an $n_0 \in \mathbb{N}$ such that $w_{<n_0} \in P'F'^*$ and $w_n \in F$ for every $n \geq n_0$. In particular, $\text{suf}(w)$ is included in $\text{cl}(\{w_n \mid n \in \text{dom } w, n \geq n_0\})$, hence in F . For every finite prefix $w_{<n}$ of w , either $n \leq n_0$, in which case $w_{<n}$ is a subword of $w_{<n_0}$ hence is in $P'F'^*$, or $n > n_0$, in which case we can write $w_{<n}$ as $w_{<n_0}w'$ where $w' \in F^*$. Since $F \subseteq F'$, $w_{<n}$ is then again in $P'F'^*$. It follows that $\text{pref}(w) \subseteq P'F'^*$, hence that $f(w) \in \downarrow(P'F'^*, F)$, so w is in D . \square

The last part of the previous proof shows the useful fact that for every word product P , for all closed subsets F and F' of X such that $F \subseteq F'$, $PF'^*F^{\leq\omega} = \langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(PF'^*, F))$. When $F = F'$, and since $PF'^*F^{\leq\omega} = PF^{\leq\omega}$ (resp., $PF^\omega = PF^{\leq\omega} \cap X^\omega$), we obtain:

Fact 5.12. *Let X be a Noetherian space. For every word product P , for every closed subset F of X , $PF^{\leq\omega} = \langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(PF^*, F))$. In particular, every finite-or-infinite word product $PF^{\leq\omega}$ is closed in $X^{\leq\omega}$ (resp., every infinite word product PF^ω is closed in X^ω). \square*

Recall that we have required the closed set F to be non-empty in infinite products PF^ω . This is unimportant in Fact 5.12, since $P\emptyset^\omega = \emptyset$ is closed anyway, but it matters in the following.

Theorem 5.13. *Let X be a Noetherian space. The irreducible closed subsets of $X^{\leq\omega}$ (resp., X^ω) are the finite-or-infinite word products (resp., the infinite word products).*

Proof. We deal with $X^{\leq\omega}$ first. Considering Proposition 5.11 and Fact 5.12, it remains to show that every finite-or-infinite word product $PF^{\leq\omega}$ is irreducible (where P is a word product, and F is closed in X).

We start by showing that $F^{\leq\omega}$ is irreducible in $X^{\leq\omega}$. It is more, namely it is *directed*, with respect to the quasi-ordering \leq^ω . In other words, we show that $F^{\leq\omega}$ is non-empty (which is clear, since it contains the empty word ϵ), and that any two elements w_1 and w_2 of $F^{\leq\omega}$ have an upper bound in $F^{\leq\omega}$ with respect to \leq^ω . For that upper bound, we can simply take: the concatenation w_1w_2 if w_1 is finite (or w_2w_1 if w_2 is finite), and the one-for-one interleaving of w_1 and w_2 if both are infinite (i.e., the letters at even positions are those from w_1 , the letters at odd positions are those from w_2). Every set that is directed with respect to \leq^ω is irreducible: if it intersects two open sets U_1 (say at w_1) and U_2 (say at w_2) then it intersects $U_1 \cap U_2$ (at the chosen upper bound of w_1 and w_2 in the directed set), using Fact 5.2.

Given any word product P , we know that P is irreducible closed in X^* , so $P \times F^{\leq\omega}$ is irreducible closed in $X^* \times X^{\leq\omega}$. Then, using the fact that cat is continuous (Proposition 5.9), $\text{cl}(\text{cat}[P \times F^{\leq\omega}])$ is irreducible closed. (Recall from Section 2 that $\text{cl}(f[C]) = \mathcal{S}(f)(C)$ is irreducible closed for every irreducible closed subset C and every continuous map f .) Evidently, $\text{cat}[P \times F^{\leq\omega}] = PF^{\leq\omega}$, and $\text{cl}(PF^{\leq\omega}) = PF^{\leq\omega}$ by Fact 5.12, so $PF^{\leq\omega}$ is irreducible closed in $X^{\leq\omega}$.

In the case of X^ω , the inclusion map i of X^ω into $X^{\leq\omega}$ is a topological embedding (hence initial), and its image $X^\omega = \langle (\infty)X \rangle$ is open. By Lemma 4.4, item 1, the irreducible closed subsets of X^ω are the sets of the form $i^{-1}(PF^{\leq\omega}) = PF^{\leq\omega} \cap X^\omega$ (P word product, F closed) such that $PF^{\leq\omega}$ intersects X^ω . Those are the sets of the form PF^ω where, additionally, F is non-empty. \square

5.5. The specialization preordering on $X^{\leq\omega}$ and Property (B). Our first step in characterizing the specialization preordering on $X^{\leq\omega}$ is to characterize the downward closure, equivalently, the closure, of its points.

Lemma 5.14. *Let X be a Noetherian space. Given a fixed word $w \in X^{\leq\omega}$, let n_0 be such that $\text{suf}(w) = \text{cl}(\{w_m \mid m \in \text{dom } w, m \geq n\})$ for every $n \geq n_0$. For every $n \geq n_0$:*

- (1) *the closure of w in $X^{\leq\omega}$ is $(\downarrow w_0)^?(\downarrow w_1)^? \cdots (\downarrow w_{n-1})^?(\text{suf}(w))^{\leq\omega}$;*
- (2) *if $w \in X^\omega$, then its closure in X^ω is $(\downarrow w_0)^?(\downarrow w_1)^? \cdots (\downarrow w_{n-1})^?(\text{suf}(w))^\omega$.*

Proof. Let $P \stackrel{\text{def}}{=} (\downarrow w_0)^?(\downarrow w_1)^? \cdots (\downarrow w_{n-1})^?$, $F \stackrel{\text{def}}{=} \text{suf}(w)$, and $C \stackrel{\text{def}}{=} PF^{\leq\omega}$.

1. C certainly contains w , and is closed by Fact 5.12, so $\text{cl}(\{w\}) \subseteq C$. (We write cl for closure in $X^{\leq\omega}$ here.)

We turn to the converse implication. Since $\text{cl}(\{w\})$ is irreducible closed (the closures of points are always irreducible closed), it must be a finite-or-infinite word product $P'F'^{\leq\omega}$ by Theorem 5.13. $P'F'^{\leq\omega}$ is equal to $\langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(P'F'^*, F'))$ by Fact 5.12. Since w is in its closure $P'F'^{\leq\omega}$, $\text{pref}(w)$ is included in $P'F'^*$ and $\text{suf}(w)$ is included in F' . The latter means that $F \subseteq F'$. Using the former, we claim that $PF^* \subseteq P'F'^*$. Since $F \subseteq F'$, it is equivalent to show that $P \subseteq P'F'^*$. That is obvious, since every element of P is a subword of $w_{<n}$, hence a subword of a finite prefix of w , hence belongs to $\text{pref}(w)$, which is included in $P'F'^*$.

Now that $PF^* \subseteq P'F'^*$ and $F \subseteq F'$, $C = \langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(PF^*, F))$ (Fact 5.12) is included in $\langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(P'F'^*, F')) = \text{cl}(\{w\})$.

2. The closure of w in X^ω is $\text{cl}(\{w\}) \cap X^\omega = PF^{\leq\omega} \cap X^\omega = PF^\omega$. \square

Lemma 5.14 yields a description of the specialization preordering of $X^{\leq\omega}$ and of X^ω , since w' is below w in that ordering if and only if w' is in the closure of w . That is far from explicit.

We can improve on that situation when X is a wqo, obtaining an analogue of Property (B) for $X^{\leq\omega}$ and X^ω .

Lemma 5.15. *If X is a wqo, then for every $w \in X^{\leq\omega}$, $\text{suf}(w)$ is the set of letters that are below infinitely many letters from w , and is equal to $\bigcup_{m \in \text{dom } w, m \geq n} \downarrow w_m$ for n large enough.*

Proof. If w is finite, then $\text{suf}(w)$ is empty, and the claim is clear. Let us assume that w is an infinite word. Since X is a wqo, for every $n \in \mathbb{N}$, $\text{cl}(\{w_m \mid m \geq n\})$ is equal to $\downarrow\{w_m \mid m \geq n\} = \bigcup_{m \geq n} \downarrow w_m$. Hence $\text{suf}(w) = \bigcap_{n \in \mathbb{N}} \bigcup_{m \geq n} \downarrow w_m$ is the set of letters that are below infinitely many letters from w . Since $\text{suf}(w) = \downarrow\{w_m \mid m \geq n\}$ for n large enough, it is also equal to $\bigcup_{m \geq n} \downarrow w_m$ for n large enough. \square

Proposition 5.16. *If X is a wqo, then the specialization preordering on $X^{\leq\omega}$ is the subword preordering \leq^ω .*

Proof. Let us fix $w \in X^{\leq\omega}$. It suffices to show that the closure of w is exactly the set of finite-or-infinite subwords of w . By Fact 5.2, every subword of w is in the closure of w . Conversely, let w' be any element of the closure of w . Using Lemma 5.14 and Lemma 5.15, there is a natural number n_0 such that, for every $n \geq n_0$, $\text{suf}(w) = \bigcup_{m \in \text{dom } w, m \geq n} \downarrow w_m$, and then w' is in $(\downarrow w_0)^?(\downarrow w_1)^? \cdots (\downarrow w_{n-1})^?(\text{suf}(w))^{\leq\omega}$.

We first use this formula for $\text{suf}(w)$ with $n \stackrel{\text{def}}{=} n_0$. Then $w' = us$ where u is in $(\downarrow w_0)^?(\downarrow w_1)^? \cdots (\downarrow w_{n_0-1})^?$, hence is a subword of $w_{<n_0}$, and s is in $(\text{suf}(w))^{\leq\omega}$. The latter means that s is an (infinite) word whose letters are all in $\text{suf}(w)$. We claim that s is a subword of $w_{\geq n_0}$, namely that there is a monotonic injective map $f: \text{dom } s \rightarrow \text{dom } w_{\geq n_0}$ such that $s_i \leq w_{\geq n_0}(f(i)) = w_{f(i)+n_0}$ for every $i \in \text{dom } s$. We define $f(i)$ by induction on $i \in \text{dom } s$ as follows. If $i = 0$ is in $\text{dom } s$, then s_0 is in $\text{suf}(w)$. Using the formula for $\text{suf}(w)$ with $n \stackrel{\text{def}}{=} n_0$, s_0 is in $\downarrow w_m$ for some $m \geq n_0$. We define $f(0)$ as $m - n_0$. For every non-zero $i \in \text{dom } s$, and remembering that $f(i-1)$ is already defined by induction hypothesis, we use the formula for $\text{suf}(w)$ with $n \stackrel{\text{def}}{=} f(i-1) + n_0 + 1$. Then s_{i+1} is in $\downarrow w_m$ for some $m > f(i-1) + n_0$, and we let $f(i)$ be $m - n_0$, so that $f(i) > f(i-1)$ and $s_i \leq w_{f(i)+n_0}$.

This establishes that s is a subword of $w_{\geq n_0}$. It follows that $w' = us$ is a subword of $w_{<n_0}w_{\geq n_0} = w$. \square

5.6. Property (C). We now investigate when $X^{\leq\omega}$ and X^ω are themselves wqos. In particular, this means when their topology is Alexandroff. As with powersets, this is a different question from asking when \leq^ω is a well-quasi-ordering on X^ω , which is equivalent to \leq being an ω^2 -wqo. (That equivalence is the special case $\alpha = \omega^2$ of Theorem 2.8 of [10], paying attention that what Marcone calls α -wqo is what we call ω^α -wqo—some authors also use the term ω^α -bqo.)

Proposition 5.17. *If X is essentially finite, then the asymptotic subword topology on $X^{\leq\omega}$ (resp., X^ω) is the Alexandroff topology of \leq^ω .*

Proof. We only deal with $X^{\leq\omega}$. The case of X^ω will follow, because the subspace topology of a space with the Alexandroff topology of a preordering \preceq is the Alexandroff topology of the restriction of \preceq to the subspace.

Considering Proposition 5.16, it suffices to show that every upwards-closed subset of $X^{\leq\omega}$, with respect to \leq^ω , is open in the asymptotic subword topology. To that end, it suffices to show that the upward closure $\uparrow^\omega w$ of

any $w \in X^{\leq \omega}$ with respect to \leq^ω is open, since every upwards-closed set is a union of such upward closures.

If w is finite, then $\uparrow^\omega w = \langle \uparrow w_0; \uparrow w_1; \cdots; \uparrow w_{n-1} \rangle$ where n is the length of w . Note that each set $\uparrow w_i$ is open in X , because the topology of an essentially finite space is always Alexandroff.

Let us assume w infinite. Since X is essentially finite, there are only finitely many distinct sets of the form $\uparrow w_n$, $n \in \mathbb{N}$. Some of them occur at only finitely many positions n in w : let n_0 be any index exceeding all those positions. Then every $\uparrow w_n$, $n \geq n_0$, is also equal to $\uparrow w_m$ for infinitely many indices $m \geq n_0$. Let $\{V_1, \dots, V_\ell\}$ be the (finite, non-empty) set $\{\uparrow w_n \mid n \geq n_0\}$, and let $U \stackrel{\text{def}}{=} \langle \uparrow w_0; \uparrow w_1; \cdots; \uparrow w_{n_0-1}; (\infty)V_1 \cap \cdots \cap (\infty)V_\ell \rangle$. This is open in the asymptotic subword topology. U contains w , by construction. Using Fact 5.2, $\uparrow^\omega w$ is entirely included in U . Conversely, let w' be any element of U . Then $w' = us$ where u is a finite word that contains a letter above w_0 , a later letter above w_1, \dots , and a letter above w_{n_0-1} , and $s \in X^\omega$ contains infinitely many letters from each of V_1, \dots, V_ℓ —in other words, for every $n \geq n_0$, s contains infinitely many letters above w_n . Hence s contains a letter above w_{n_0} , then a later letter above w_{n_0+1} , etc., so $w_{\geq n_0} \leq^\omega s$. It follows that $w \leq^\omega w'$. Therefore $U \subseteq \uparrow^\omega w$, whence equality follows. \square

Proposition 5.18. *Let X be a Noetherian space. The asymptotic subword topology on $X^{\leq \omega}$ (resp., X^ω) is Alexandroff if and only if X is essentially finite.*

Proof. One direction is by Proposition 5.17. In the converse direction, we assume that X^ω is Alexandroff, and we wish to show that X is essentially finite. The case of $X^{\leq \omega}$ reduces to that case: if $X^{\leq \omega}$ is Alexandroff, so is its subspace X^ω .

Let $C_0 \subsetneq C_1 \subsetneq \cdots \subsetneq C_n \subsetneq \cdots$ be a strictly ascending sequence of closed subsets of X , and let x_n be a point of $C_{n+1} \setminus C_n$ for every $n \in \mathbb{N}$. For each $n \in \mathbb{N}$, C_n^ω is closed in X^ω , by Theorem 5.13. Let $\mathcal{C} \stackrel{\text{def}}{=} \bigcup_{n \in \mathbb{N}} C_n^\omega$: since the topology of X^ω is Alexandroff, this is again closed.

Note that $w \stackrel{\text{def}}{=} x_0 x_1 \cdots x_n \cdots$ is in no C_n^ω , hence not in \mathcal{C} . By Lemma 5.10, there is a basic open subset $W \stackrel{\text{def}}{=} \langle U_1; U_2; \cdots; U_k; (\infty)V_1 \cap \cdots \cap (\infty)V_\ell \rangle$ of X^ω that contains w and is disjoint from \mathcal{C} . Since it contains w , we can write w as $w_{< n_0} w_{\geq n_0}$ where $w_{< n_0} \in \langle U_1; U_2; \cdots; U_k \rangle$ and $w_{\geq n_0}$ contains infinitely many letters from each of V_1, \dots, V_ℓ . Let us pick one letter x_{n_1} from $w_{\geq n_0}$ in V_1, \dots , one letter x_{n_ℓ} from $w_{\geq n_0}$ in V_ℓ . Then the infinite word $w_{< n_0} (x_{n_1} \cdots x_{n_\ell})^\omega$ is in W , but it is also in C_{n+1}^ω , where n is any natural

number exceeding $\max(n_0, n_1, \dots, n_\ell)$. In particular, W intersects \mathcal{C} , which is impossible.

We conclude that there cannot be any infinite strictly ascending sequence of closed subsets of X . By Lemma 3.3, X must be essentially finite. \square

5.7. An S-representation on $X^{\leq\omega}$ and on X^ω , and Property (D).

Testing inclusion of finite-or-infinite word products is as easy as testing inclusion of finite word products.

Lemma 5.19. *Let X be a Noetherian space.*

- (1) *For all finite-or-infinite word products $PF^{\leq\omega}$ and $P'F'^{\leq\omega}$, $PF^{\leq\omega} \subseteq P'F'^{\leq\omega}$ if and only if $PF^* \subseteq P'F'^*$ and $F \subseteq F'$.*
- (2) *For all infinite word products PF^ω and $P'F'^\omega$, $PF^\omega \subseteq P'F'^\omega$ if and only if $PF^* \subseteq P'F'^*$ and $F \subseteq F'$.*

Recall that F and F' are required to be non-empty in infinite word products, not in finite-or-infinite word products.

Proof. We first show: (i) If F is non-empty, then $PF^\omega \subseteq P'F'^\omega$ implies $PF^* \subseteq P'F'^*$ and $F \subseteq F'$. Henceforth, let us assume $PF^\omega \subseteq P'F'^\omega$. We first show that F is included in F' . Since F is non-empty, we can pick an element x from F . Note that the empty word ϵ is in P . Hence $x^\omega (= \epsilon x^\omega)$ is in PF^ω , and therefore in $P'F'^\omega$. This means that we can write x^ω as uv where $u \in P'$ and $v \in F'^\omega$; the latter, together with the fact that $v = x^\omega$, implies $x \in F'$. It follows that $F \subseteq F'$. We now claim that $PF^* \subseteq P'F'^*$. Let us pick any finite word w from PF^* . The infinite word wx^ω is in PF^ω , hence in $P'F'^\omega$. It follows that wx^ω is of the form uv where $u \in P'$ and $v \in F'^\omega$. If u is a prefix of w , then w is equal to the concatenation of u with a prefix of v , hence is in $P'F'^*$. Otherwise, w is a prefix of u . Since u is in P' , it is also in $P'F'^*$, and since the latter is closed under \leq^* , w is also in $P'F'^*$.

We deduce: (ii) $PF^{\leq\omega} \subseteq P'F'^{\leq\omega}$ implies $PF^* \subseteq P'F'^*$ and $F \subseteq F'$. If F is non-empty, then since $PF^\omega = PF^{\leq\omega} \cap X^\omega \subseteq P'F'^{\leq\omega} \cap X^\omega = P'F'^\omega$, we can use (i) and conclude. Otherwise, since $F = \emptyset$, $PF^{\leq\omega} = P$, so P is included in $P'F'^{\leq\omega}$. Since all the elements of P are finite words, P is in fact included in $P'F'^{\leq\omega} \cap X^* = P'F'^*$. The inequality $F \subseteq F'$ is trivial.

In the converse direction, we have: (iii) if $PF^* \subseteq P'F'^*$ and $F \subseteq F'$, then $PF^{\leq\omega} \subseteq P'F'^{\leq\omega}$. Indeed:

$$\begin{aligned} PF^{\leq\omega} &= \langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(PF^*, F)) && \text{(Fact 5.12)} \\ &\subseteq \langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(P'F'^*, F')) = P'F'^{\leq\omega}. \end{aligned}$$

Finally: (iv) if $PF^* \subseteq P'F'^*$ and $F \subseteq F'$, then $PF^\omega \subseteq P'F'^\omega$. This follows from (iii) by taking intersections with X^ω .

Item 1 follows from (ii) and (iii). Item 2 follows from (i) and (iv). \square

Computing intersections of infinite word products also reduces to the case of finite word products, as we will see in Lemma 5.21 below. We notice the following. The point is that F_i is the same for every i .

Lemma 5.20. *Let X be a Noetherian space. For all finite word products P, P' , for all closed subsets F, F' of X , $PF^* \cap P'F'^*$ is a finite union of word products $P_i F_i^*$ where $F_i = F \cap F'$ for every i .*

Proof. Since X^* is Noetherian, $PF^* \cap P'F'^*$ is a finite union $\bigcup_{i=1}^n P_i$ where each P_i is a word product. For every $i, 1 \leq i \leq n$, for every $w \in P_i$, for every $w' \in (F \cap F')^*$, ww' is in $PF^*(F \cap F')^* \subseteq PF^*$ and in $P'F'^*(F \cap F')^* \subseteq P'F'^*$, hence in $PF^* \cap P'F'^*$, and therefore in some $P_j, 1 \leq j \leq n$. It follows that $\bigcup_{i=1}^n P_i(F \cap F')^* \subseteq \bigcup_{i=1}^n P_i$. The converse inclusion is obvious. \square

Lemma 5.21. *Let X be a Noetherian space. Given any two finite-or-infinite word products $PF^{\leq \omega}$ and $P'F'^{\leq \omega}$, one can write $PF^* \cap P'F'^*$ as a finite union of finite word products of the form $P_i(F \cap F')^*$, $1 \leq i \leq n$, and then $PF^{\leq \omega} \cap P'F'^{\leq \omega} = \bigcup_{i=1}^n P_i(F \cap F')^{\leq \omega}$.*

Proof. The fact that $PF^* \cap P'F'^*$ can be written as a finite union of finite word products of the form $P_i(F \cap F')^*$, $1 \leq i \leq n$, is by Lemma 5.20.

Let $\mathcal{F} \stackrel{\text{def}}{=} \{C \in \mathcal{S}(X^*) \mid C \subseteq PF^* \cap P'F'^*\}$. We claim that $\mathcal{F} = \bigcup_{i=1}^n \downarrow_{\mathcal{S}(X^*)}(P_i(F \cap F')^*)$. For every $C \in \mathcal{F}$, C is included in $PF^* \cap P'F'^* = \bigcup_{i=1}^n P_i(F \cap F')^*$, hence in some $P_i(F \cap F')^*$ because C is irreducible. Hence C is also in $\bigcup_{i=1}^n \downarrow_{\mathcal{S}(X^*)}(P_i(F \cap F')^*)$. Conversely, every element C of $\bigcup_{i=1}^n \downarrow_{\mathcal{S}(X^*)}(P_i(F \cap F')^*)$ is included in some $P_i(F \cap F')^*$, hence in $PF^* \cap P'F'^*$.

Then $\downarrow(PF^*, F) \cap \downarrow(P'F'^*, F') = \mathcal{F} \times \downarrow_{\mathcal{H}(X)}(F \cap F')$, so:

$$\begin{aligned} PF^{\leq \omega} \cap P'F'^{\leq \omega} &= \langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(PF^*, F)) \cap \langle \text{pref}, \text{suf} \rangle^{-1}(\downarrow(P'F'^*, F')) \\ &\quad \text{by Fact 5.12} \\ &= \langle \text{pref}, \text{suf} \rangle^{-1}(\mathcal{F} \times \downarrow_{\mathcal{H}(X)}(F \cap F')) \\ &= \langle \text{pref}, \text{suf} \rangle^{-1}\left(\bigcup_{i=1}^n \downarrow(P_i(F \cap F')^*, F \cap F')\right) \\ &= \bigcup_{i=1}^n P_i(F \cap F')^{\leq \omega}, \end{aligned}$$

by Fact 5.12 again. \square

We have a similar result for infinite words. We only have to pay attention that $P_i(F \cap F')^*$ is an infinite word product (an irreducible closed set) if and only if $F \cap F'$ is non-empty.

Lemma 5.22. *Let X be a Noetherian space. Given any two infinite word products PF^ω and $P'F'^\omega$,*

- *either $F \cap F'$ is empty and $PF^\omega \cap P'F'^\omega = \emptyset$;*
- *or $F \cap F'$ is non-empty, and one can write $PF^\omega \cap P'F'^\omega$ as a finite union of finite word products of the form $P_i(F \cap F')^*$, $1 \leq i \leq n$; in that case, $PF^\omega \cap P'F'^\omega = \bigcup_{i=1}^n P_i(F \cap F')^\omega$.*

Proof. If $F \cap F'$ is empty, then it is clear that $PF^\omega \cap P'F'^\omega = \emptyset$. Otherwise,

$$\begin{aligned} PF^\omega \cap P'F'^\omega &= PF^{\leq \omega} \cap P'F'^{\leq \omega} \cap X^\omega \\ &= \bigcup_{i=1}^n P_i(F \cap F')^{\leq \omega} \cap X^\omega && \text{by Lemma 5.21} \\ &= \bigcup_{i=1}^n P_i(F \cap F')^\omega. \end{aligned}$$

□

Let us turn to actual S-representations. We assume an S-representation $(S, \llbracket - \rrbracket, \trianglelefteq, \tau, \wedge)$ of X . For every finite subset $u \stackrel{\text{def}}{=} \{a_1, \dots, a_n\}$ of S , let $\llbracket u \rrbracket$ denote $\llbracket a_1 \rrbracket \cup \dots \cup \llbracket a_n \rrbracket$. For all finite subsets u and v of S , we also write $u \wedge v$ for $\bigcup_{a \in u, b \in v} a \wedge b$, so that $\llbracket u \wedge v \rrbracket = (\bigcup_{a \in u} \llbracket a \rrbracket) \cap (\bigcup_{b \in v} \llbracket b \rrbracket) = \llbracket u \rrbracket \cap \llbracket v \rrbracket$.

Lemma 5.20 has the following computable equivalent, which says that for *syntactic* word products Pu^* and Qv^* , $Pu^* \wedge' Qv^*$ computes the intersection $\llbracket Pu^* \rrbracket' \cap \llbracket Qv^* \rrbracket' = \llbracket P \rrbracket' \llbracket u \rrbracket^* \cap \llbracket Q \rrbracket' \llbracket v \rrbracket^*$ as a finite set of syntactic word products of the form $P_i(u \wedge v)^*$. For this result, we need to use the optimized version of \wedge' described in Remark 2.2.

Lemma 5.23. *Let X be a Noetherian space, and $(S, \llbracket - \rrbracket, \trianglelefteq, \tau, \wedge)$ be an S-representation of X . For all (syntactic) word products of the form Pu^* and Qv^* , their intersection, as computed using Proposition 2.1, item (5), and removing subsumed word products as per Remark 2.2, is a finite set of word products of the form $R(u \wedge v)^*$.*

Proof. By induction on the sum of the length n of P and the length n' of Q . This is a direct appeal to the induction hypothesis if $n \geq 1$ and $n' \geq 1$. The interesting case is when $n' = 0$ (or, symmetrically, $n = 0$). If $n = n' = 0$, then $Pu^* \wedge' Qv^* = u^* \wedge' v^* = \{(u \wedge v)^* R \mid R \in (\varepsilon \wedge' v^*) \cup (u^* \wedge' \varepsilon)\} = \{(u \wedge v)^*\}$, by (2.4) and (2.1). If $n \geq 1$ and $n' = 0$, then we need to show the claim for intersections of the form: (1) $a^i Pu^* \wedge' v^*$ and (2) $u_0^* Pu^* \wedge' v^*$.

In case (1), we use (2.3): the elements of $a^?Pu^* \wedge' v^*$ are of the form $c^?R$ (where c ranges over $u \wedge v$, if $u \wedge v \neq \emptyset$) or just R (if $u \wedge v = \emptyset$), where $R \in Pu^* \wedge' v^*$, plus elements of $a^?Pu^* \wedge' \varepsilon = \{\varepsilon\}$. Since we remove subsumed word products, as per Remark 2.2, the latter elements do not occur. The elements that remain are of the form $c^?R$ or just R , where $R \in Pu^* \wedge' v^*$ has the required form by induction hypothesis.

In case (2), we use (2.4): the elements of $u_0^*Pu^* \wedge' v^*$ are of the form $(u_0 \wedge v)^*R$ where $R \in (Pu^* \wedge' v^*) \cup (u_0^*Pu^* \wedge' \varepsilon) = (Pu^* \wedge' v^*) \cup \{\varepsilon\}$. Let us enumerate $Pu^* \wedge' v^*$: by induction hypothesis, we can write its elements as $R_1(u \wedge v)^*, \dots, R_n(u \wedge v)^*$. We note that $n \geq 1$, because $\llbracket Pu^* \rrbracket' \cap \llbracket v^* \rrbracket$ is non-empty: indeed, that intersection contains the empty word ε . Then the element $(u_0 \wedge v)^*\varepsilon$ of the set $u_0^*Pu^* \wedge' v^*$ is subsumed by, say, $(u_0 \wedge v)^*R_1(u \wedge v)^*$, and will be removed, following Remark 2.2. The only elements that remain are $(u_0 \wedge v)^*R_i(u \wedge v)^*$, when i varies over some subset of $\{1, \dots, n\}$, and they are of the required form. \square

Instead of redesigning an S -representation for $X^{\leq\omega}$ (or X^ω) from scratch, this allows us to reuse most of what we know for X^* . Item (3) below is justified by Lemma 5.19, and item (5) is by Lemma 5.21 (resp., Lemma 5.22), refined using Lemma 5.23 (i.e., every element of $Pu^* \wedge' Qv^*$ is of the form $R(u \wedge v)^*$ for some R , where $u \wedge v \stackrel{\text{def}}{=} \bigcup_{a \in u, b \in v} (a \wedge b)$).

Theorem 5.24. *Given an S -representation $(S, \llbracket - \rrbracket, \leq, \tau, \wedge)$ of a Noetherian space X , let $(S', \llbracket - \rrbracket', \leq', \tau', \wedge')$ be the S -representation of X^* given in Proposition 2.1, with the optimization of Remark 2.2. Then the following tuple $(S'', \llbracket - \rrbracket'', \leq'', \tau'', \wedge'')$ is an S -representation of $X^{\leq\omega}$ (resp., X^ω):*

- (1) S'' is the collection of pairs (P, u) where $P \in S'$ and u is a finite (resp., and non-empty) subset of S .
- (2) $\llbracket (P, u) \rrbracket'' = \llbracket P \rrbracket' (\bigcup_{a \in u} \llbracket a \rrbracket)^{\leq\omega}$ (resp., $\llbracket P \rrbracket' (\bigcup_{a \in u} \llbracket a \rrbracket)^\omega$).
- (3) $(P, u) \leq'' (Q, v)$ if and only if $Pu^* \leq' Qv^*$ and for every $a \in u$, there is an $b \in v$ such that $a \leq b$.
- (4) τ'' is (ε, τ) .
- (5) $(P, u) \wedge'' (Q, v)$ is defined as follows: writing $u \wedge v$ for $\bigcup_{a \in u, b \in v} (a \wedge b)$, $Pu^* \wedge' Qv^*$ is a finite set of finite word products of the form $R_i(u \wedge v)^*$, $1 \leq i \leq n$, and $(P, u) \wedge'' (Q, v)$ is then the set of pairs $(R_i, u \wedge v)$, $1 \leq i \leq n$ (resp., the same formula if $u \wedge v \neq \emptyset$, otherwise \emptyset). \square

6. FINAL NOTES

Related work. We must cite Simon Halfon's PhD thesis [5], and especially Section 9.1 there. Our study of X^ω is very close to his. At first glance, it may seem that we add some generality to his study, in the sense that Halfon studies X^ω (as a preordered set) in the special case where X is an ω^2 -wqo. In that case, X^ω is wqo (as a set preordered by \leq^ω).

In a world of preorders, it is natural to replace sobrifications by ideal completions. Indeed, the ideal completion of a preordered set X coincides with the sobrification of X , provided that X is given its Alexandroff topology. Halfon obtains that the ideal completion of X^ω (as a preordered set) is characterized in terms of ω -regular expressions that are similar to the infinite word products we introduce in Section 5.4, although slightly more complicated, as the F^ω part of ω -regular expressions no longer involves elements F of $\mathcal{H}(X)$ but ideals of $\mathcal{H}(X)$. The mismatch is due to the fact that our space X^ω will almost never have an Alexandroff topology (unless X is essentially finite, see Proposition 5.18), and therefore the ideal completion of X^ω in general differs from $\mathcal{S}(X^\omega)$ (where X^ω is given the asymptotic subword topology, as we do, not the Alexandroff topology of \leq^ω), for every ω^2 -wqo X that is not essentially finite.

Other initial maps. Our study of $X^{\leq\omega}$ (resp., X^ω) proceeds by finding an initial map $\langle \text{pref}, \text{suf} \rangle$ from $X^{\leq\omega}$ to the more familiar space $\mathcal{S}(X^*) \times \mathcal{H}(X)$. This has notable advantages. For example, the fact that $X^{\leq\omega}$ (and its subspace X^ω) is Noetherian if and only if X follows immediately from previously known results on sobrifications, on the Hoare powerspace, and on spaces of *finite* words. We took this further in the study of S-representations of $X^{\leq\omega}$ (resp., X^ω), where we insisted on *reducing* the question to S-representations for finite words (and powersets). We could have computed intersections of infinite word products directly, notably, but we feel that would have been less interesting.

Remarkably, there are many other initial maps that we could have used instead of $\langle \text{pref}, \text{suf} \rangle$. The advantage of the latter is that it shows how the asymptotic subword topology splits into the study of finite chunks of information (prefixes) and infinite behaviors (suffixes). Here are two different initial maps that we could have used.

The first one is the composition:

$$X^{\leq\omega} \xrightarrow{\langle \text{pref}, \text{suf} \rangle} \mathcal{S}(X^*) \times \mathcal{H}(X) \xrightarrow{\text{id} \times j} \mathcal{S}(X^*) \times \mathcal{S}(X^*) \cong \mathcal{S}(X^* \times X^*) \xrightarrow{\mathcal{S}(c)} \mathcal{S}((X + X)^*)$$

where $j: \mathcal{H}(X) \rightarrow \mathcal{S}(X^*)$ maps F to F^* , and c maps every pair of finite words $(a_1 \cdots a_m, b_1 \cdots b_n)$ to the word $\iota_1(a_1) \cdots \iota_1(a_m) \iota_2(b_1) \cdots \iota_2(b_n)$, where ι_1, ι_2 are the two canonical injections of X into $X + X$. Note that $j^{-1}(\diamond \langle U_1; U_2; \cdots; U_n \rangle) = \diamond U_1 \cap \diamond U_2 \cap \cdots \cap \diamond U_n$, showing that j is initial. As for c , every open subset of $X + X$ can be written as $U + V$ where U and V are open in X , and we have $c^{-1}(\langle U_1 + V_1; \cdots; U_n + V_n \rangle) = \bigcup_{k=0}^n \langle U_1; \cdots; U_k \rangle \times \langle V_{k+1}; \cdots; V_n \rangle$, showing that c is continuous, and as special case (with $n = 2$, V_1 and U_2 empty) that $\langle U_1 \rangle \times \langle V_2 \rangle = c^{-1}(\langle U_1 + \emptyset; \emptyset + V_2 \rangle)$, which allows us to conclude that c is initial with the help of Remark 4.1. This implies that $\mathcal{S}(c)$ is initial, hence that the whole composition shown above is initial, too. The point of using this, as an alternative to $\langle \text{pref}, \text{suf} \rangle$, is to realize that using the Hoare powerspace is not required at all, and that the study of X^ω reduces to the study of the sobrification of a space of finite words only, on the extended alphabet $X + X$.

A second alternative to $\langle \text{pref}, \text{suf} \rangle$ is the following map $q: X^{\leq \omega} \rightarrow \mathcal{S}((X + X)^*)$ (see Appendix A for a proof that q is initial, when X is Noetherian). For short, let us write $-a \stackrel{\text{def}}{=} (0, a)$ for every $a \in X$, $+a \stackrel{\text{def}}{=} (1, a)$, $\pm A \stackrel{\text{def}}{=} \{-a, +a \mid a \in A\}$ for every $A \subseteq X$. For every $w \in X^{\leq \omega}$ and every $n \in \text{dom } w$, let $q_n(w) \stackrel{\text{def}}{=} (\downarrow -w_0)^? (\downarrow -w_1)^? \cdots (\downarrow -w_n)^? (\text{cl}(\pm\{w_m \mid m \geq n + 1\}))^*$. The sequence $(q_n(w))_{n \in \mathbb{N}}$ is a descending sequence of (irreducible) closed sets. When X is Noetherian, there must therefore be an index $n_0 \in \mathbb{N}$ such that $q_n(w) = q_{n_0}(w)$ for every $n \geq n_0$, and we define $q(w)$ as $q_{n_0}(w)$. Notice the similarity with Remark 5.4. Note also that q is slightly different from our previous alternative, which maps w to $(\downarrow -w_0)^? (\downarrow -w_1)^? \cdots (\downarrow -w_n)^? (\text{cl}(\{-w_m \mid m \geq n + 1\}))^* (\text{cl}(\{+w_m \mid m \geq n + 1\}))^*$ instead. A similar approach will turn out to be the right one in our study of infinite trees (which should be part III of this work).

Transfinite sequences. We have dealt with the space X^ω , but what would be a proper, analogous treatment of spaces of sequences of length α , for an arbitrary (or countable) indecomposable ordinal α ? The bqo theory of such preordered sets is well-known [11]. We will deal with that aspect in part II.

Acknowledgements. I would like to thank the anonymous referee for her/his valuable comments, in particular for insisting on some small issues that I missed repeatedly.

REFERENCES

- [1] A. Finkel and J. Goubault-Larrecq. Forward analysis for WSTS, part I: Completions. In S. Albers and J.-Y. Marion, editors, *Proceedings of the 26th Annual Symposium*

- on *Theoretical Aspects of Computer Science (STACS'09)*, volume 3 of *Leibniz International Proceedings in Informatics*, pages 433–444, Freiburg, Germany, Feb. 2009. Leibniz-Zentrum für Informatik.
- [2] A. Finkel and J. Goubault-Larrecq. Forward analysis for WSTS, part I: Completions. *Mathematical Structures in Computer Science*, 30(7):752–832, 2020. Revised and expanded version of [1].
- [3] J. Goubault-Larrecq. On Noetherian spaces. In *Proceedings of the 22nd Annual IEEE Symposium on Logic in Computer Science (LICS'07)*, pages 453–462, Wrocław, Poland, July 2007. IEEE Computer Society Press.
- [4] J. Goubault-Larrecq. *Non-Hausdorff Topology and Domain Theory—Selected Topics in Point-Set Topology*, volume 22 of *New Mathematical Monographs*. Cambridge University Press, Mar. 2013.
- [5] S. Halfon. *On Effective Representations of Well Quasi-Orderings*. PhD thesis, ENS Paris-Saclay, Université Paris-Saclay, 2018.
- [6] G. Higman. Ordering by divisibility in abstract algebras. *Proceedings of the London Mathematical Society*, 2(7):326–336, 1952.
- [7] P. Jančar. A note on well quasi-orderings for powersets. *Information Processing Letters*, 72(5-6):155–160, 1999.
- [8] R. Laver. Well-quasi-orderings and sets of finite sequences. *Mathematical Proceedings of the Cambridge Philosophical Society*, 79(1):1–10, 1976.
- [9] J. Leroux and S. Schmitz. Demystifying reachability in vector addition systems. In *30th Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2015, Kyoto, Japan, July 6-10, 2015*, pages 56–67. IEEE Computer Society, 2015.
- [10] A. Marcone. Foundations of bqo theory. *Transactions of the American Mathematical Society*, 345(2):641–660, 1994.
- [11] C. S.-J. A. Nash-Williams. On better-quasi-ordering transfinite sequences. *Mathematical Proceedings of the Cambridge Philosophical Society*, 64(2):273–290, 1968.
- [12] R. Rado. Partial well-ordering of sets of vectors. *Mathematika*, 1:89–95, 1954.
- [13] A. Schalk. *Algebras for Generalized Power Constructions*. PhD thesis, Technische Hochschule Darmstadt, 1993. Available from <http://www.cs.man.ac.uk/~schalk/publ/diss.ps.gz>.
- [14] W. Thomas. Automata on infinite objects. In J. van Leeuwen, editor, *Formal Models and Semantics*, Handbook of Theoretical Computer Science, chapter 4, pages 133–191. Elsevier, Amsterdam, 1990.

APPENDIX A. q IS INITIAL

We use an alternate definition of q . Given any $w \in X^\omega$, let $A_n \stackrel{\text{def}}{=} \{w_m \mid m \geq n+1\}$. Then $(cl(\pm A_n))_{n \in \mathbb{N}}$ is a descending sequence of closed subsets of $X+X$. If X is Noetherian, then there must be an index n_1 such that for every $n \geq n_1$, $cl(\pm A_n) = cl(\pm A_{n_1})$. We pick n_1 larger than or equal to the n_0 given in the definition of q . Then $q(w) \stackrel{\text{def}}{=} (\downarrow -w_0)^? (\downarrow -w_1)^? \cdots (\downarrow -w_n)^? (cl(\pm A_n))^*$ for every $n \geq n_1$, by definition of q .

We proceed and show that q is continuous.

For that, we claim that: (*) $q^{-1}(\diamond\langle U_1 + V_1; \cdots; U_\ell + V_\ell \rangle)$ is equal to $\bigcup_{k=0}^\ell \langle U_1; \cdots; U_k; (\infty)(U_{k+1} \cup V_{k+1}) \cap \cdots \cap (\infty)(U_\ell \cup V_\ell) \rangle$, where $U_1, V_1, \dots, U_\ell, V_\ell$ are arbitrary open subsets of X .

Let $w \in X^{\leq \omega}$, let us fix $n \stackrel{\text{def}}{=} n_1$ in the definition of $q(w)$, and let us imagine that $q(w)$ is in $\diamond\langle U_1 + V_1; \cdots; U_\ell + V_\ell \rangle$. There are letters $a_1 \in$

$U_1 + V_1, \dots, a_\ell \in U_\ell + V_\ell$, and indices k ($0 \leq k \leq \ell$) and $i_1 < \dots < i_k$ between 0 and $n_1 - 1$ such that $a_1 \leq -w_{i_1}, \dots, a_k \leq -w_{i_k}$, and a_{k+1}, \dots, a_ℓ are all in $cl(\pm A_{n_1})$. In particular, every $U_i + V_i$ with $i \geq k + 1$ intersects $cl(\pm A_{n_1})$ —which is equal to $cl(\pm A_n)$ for every $n \geq n_1$ —hence also $\pm A_n$ for every $n \geq n_1$. This means that there are infinitely many indices $n \geq n_1$ such that $-w_n$ or $+w_n$ is in $U_i + V_i$, in particular such that $w_n \in U_i \cup V_i$, and that holds for every $i \geq k + 1$. Therefore w is in $\langle U_1; \dots; U_k; (\infty)(U_{k+1} \cup V_{k+1}) \cap \dots \cap (\infty)(U_\ell \cup V_\ell) \rangle$.

In the reverse direction, let w be in $\langle U_1; \dots; U_k; (\infty)(U_{k+1} \cup V_{k+1}) \cap \dots \cap (\infty)(U_\ell \cup V_\ell) \rangle$ for some k , $0 \leq k \leq \ell$. Let us write w as us where $u \in \langle U_1; \dots; U_k \rangle$ and (if $\ell > k$) s contains infinitely many letters from each $U_i \cup V_i$, $k + 1 \leq i \leq \ell$. There are letters $a_1 \in U_1, \dots, a_k \in U_k$ such that $a_1 \dots a_k$ is a subword of u . We write again $q(w)$ as $(\downarrow -w_0)^? (\downarrow -w_1)^? \dots (\downarrow -w_{n-1})^? (cl(\pm A_n))^*$, with $n \geq n_1$ arbitrary. We pick such an n so that it exceeds the length of u . This way, the finite word $(-a_1) \dots (-a_k)$ is in $(\downarrow -w_0)^? (\downarrow -w_1)^? \dots (\downarrow -w_{n-1})^?$. For each i , $k + 1 \leq i \leq \ell$, since s contains infinitely many letters from $U_i \cup V_i$, so does w , and we can therefore find at least one of the form w_m with $m \geq n$, hence in A_n . This implies that A_n intersects $U_i \cup V_i$. We pick a letter b_i in the intersection, for each i with $k + 1 \leq i \leq \ell$. If b_i is in U_i , we let $c_i \stackrel{\text{def}}{=} -b_i$, otherwise $c_i \stackrel{\text{def}}{=} +b_i$, so that c_i is in $U_i + V_i$. Then the word $(-a_1) \dots (-a_k) c_{k+1} \dots c_\ell$ is in $q(w)$, and in $\langle U_1; \dots; U_k; U_{k+1} \cup V_{k+1}; \dots; U_\ell \cup V_\ell \rangle$. It follows that $q(w)$ is in $\diamond \langle U_1 + V_1; \dots; U_\ell + V_\ell \rangle$.

That finishes to prove (*), hence that q is continuous.

Specializing (*) to the case where $V_1, \dots, V_j, U_{j+1}, \dots, U_\ell$ are empty (for some arbitrary j , $0 \leq j \leq \ell$), the terms $\langle U_1; \dots; U_k; (\infty)(U_{k+1} \cup V_{k+1}) \cap \dots \cap (\infty)(U_\ell \cup V_\ell) \rangle$ with $k \geq j + 1$ are all empty (because U_k is empty). The same terms with $k \leq j$ instead are of the form $\langle U_1; \dots; U_k; (\infty)U_{k+1} \cap \dots \cap (\infty)U_j \cap (\infty)V_{j+1} \cap \dots \cap (\infty)V_\ell \rangle$, and it is easy to see that they are all included in the term obtained when $k = j$, namely $\langle U_1; \dots; U_j; (\infty)V_{j+1} \cap \dots \cap (\infty)V_\ell \rangle$. It follows that $q^{-1}(\diamond \langle U_1 + \emptyset; \dots; U_j + \emptyset; \emptyset + V_{j+1}; \dots; \emptyset + V_\ell \rangle)$ is equal to $\langle U_1; \dots; U_j; (\infty)V_{j+1} \cap \dots \cap (\infty)V_\ell \rangle$. The latter is the general form of the basic open subsets on $X^{\leq \omega}$ given in Lemma 5.10. Using Remark 4.1, q is initial.