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Domain-complete and LCS-complete Spaces

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**Abstract**

We study *Gδ* subspaces of continuous dcpos, which we call domain-complete spaces, and *Gδ* subspaces of locally compact sober spaces, which we call LCS-complete spaces. Those include all locally compact sober spaces—in particular, all continuous dcpos—, all topologically complete spaces in the sense of Cˇech, and all quasi-Polish spaces—in particular, all Polish spaces. We show that LCS-complete spaces are sober, Wilker, compactly Choquet-complete, completely Baire, and *⊙*-consonant—in particular, consonant; that the countably-based LCS-complete (resp., domain-complete) spaces are the quasi-Polish spaces exactly; and that the metrizable LCS-complete (resp., domain-complete) spaces are the completely metrizable spaces.

We include two applications: on LCS-complete spaces, all continuous valuations extend to measures, and

sublinear previsions form a space homeomorphic to the convex Hoare powerdomain of the space of continuous valuations.

*Keywords:* Topology, domain theory, quasi-Polish spaces, *Gδ* subsets, continuous valuations, measures

# Motivation

Let us start with the following question: for which class of topological spaces *X* is it true that every (locally finite) continuous valuation on *X* extends to a measure on *X*, with its Borel *σ*-algebra? The question is well-studied, and Klaus Keimel and

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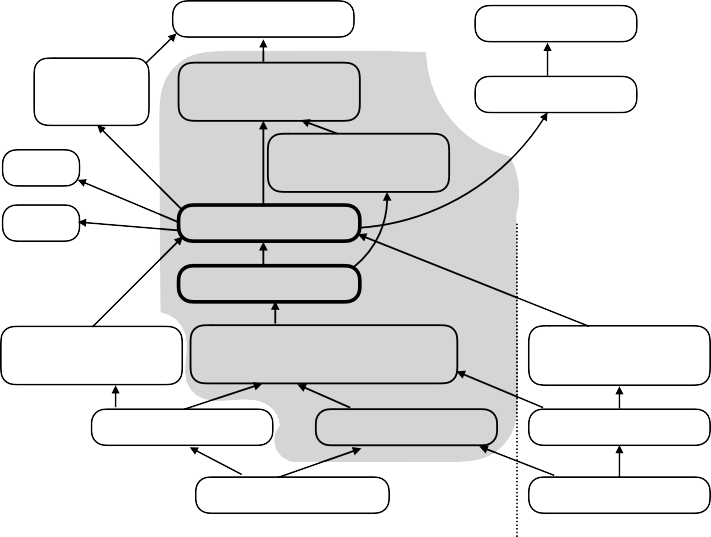
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Baire

consonant

completely Baire

compactly Choquet-complete

convergence Choquet-complete

LCS-complete

⊙-consonant

sober

Wilker

(Hausdorff spaces)

domain-complete

locally compact sober

continuous complete quasi- metric (*d*-Scott topology)

topologically complete

continuous dcpo

quasi-Polish

complete metric

ω-continuous dcpo

Polish

Fig. 1. Domain-complete and LCS-complete spaces in relation to other classes of spaces

Jimmie Lawson have rounded it up nicely in [[24](#_bookmark78)]. A result by Mauricio Alvarez- Manilla *et al.* [[2](#_bookmark56)] (see also Theorem 5.3 of the paper by Keimel and Lawson) states that every locally compact sober space fits.

Locally compact sober spaces are a pretty large class of spaces, including many non-Hausdorff spaces, and in particular all the continuous dcpos of domain theory. However, such a result will be of limited use to the ordinary measure theorist, who is used to working with Polish spaces, including such spaces as Baire space NN, which is definitely not a locally compact space.

It is not too hard to extend the above theorem to the following larger class of spaces (and to drop the local finiteness assumption as well):

**Theorem 1.1** *Let X bea (homeomorph of a) Gδ subset of a locally compact sober space Y . Every continuous valuation ν on X extends to a measure on X with its Borel σ-algebra.*

We defer the proof of that result to Section [18](#_bookmark52). The point is that we do have a measure extension theorem on a class of spaces that contains both the continuous dcpos of domain theory and the Polish spaces of topological measure theory. We will call such spaces *LCS-complete*, and we are aware that this is probably not an optimal name. *Topologically complete* would have been a better name, if it had not been taken already [[5](#_bookmark60)].

Another remarkable class of spaces is the class of *quasi-Polish* spaces, discovered and studied by the first author [[7](#_bookmark61)]. This one generalizes both *ω*-continuous dcpos and Polish spaces, and we will see in Section [5](#_bookmark13) that the class of LCS-complete spaces is a proper superclass. We will also see that there is no countably-based LCS-complete space that would fail to be quasi-Polish. Hence LCS-complete spaces can be seen as an extension of the notion of quasi-Polish spaces, and the extension is strict only for non-countably based spaces.

Generally, our purpose is to locate LCS-complete spaces, as well as the related *domain-complete* spaces inside the landscape formed by other classes of spaces. The result is summarized in Figure [1](#_bookmark3). The gray area is indicative of what happens with countably-based spaces: for such spaces, all the classes inside the the gray area coincide.

We proceed as follows. We recall some background in Section [2](#_bookmark5), and we give basic definitions in Section [3](#_bookmark6). The rest of the paper (apart from the final Sec- tion [18](#_bookmark52), which is independent of the others, and where we prove the promised Theorem [1.1](#_bookmark4)), is the result of our findings on domain-complete and LCS-complete spaces, in no particular order. We show that continuous complete quasi-metric spaces, quasi-Polish spaces and topologically complete spaces are all LCS-complete in Sections [4](#_bookmark10)–[6](#_bookmark16). Then we show that all LCS-complete spaces are sober (Section [7](#_bookmark18)), Wilker (Section [8](#_bookmark20)), Choquet-complete and in fact a bit more (Section [9](#_bookmark24)), Baire and even completely Baire (Section [10](#_bookmark29)), consonant and even *⊙*-consonant (Section [12](#_bookmark35)). In the process, we explore the Stone duals of domain-complete and LCS-complete spaces in Section [11](#_bookmark34). While the class of LCS-complete spaces is strictly larger than the class of domain-complete spaces, in Section [9](#_bookmark24), we also show that for countably- based spaces, LCS-complete, domain-complete, and quasi-Polish are synonymous. We give a first application in Section [13](#_bookmark37): when *X* is LCS-complete, the Scott and compact-open topologies on the space *LX* of lower semicontinuous maps from *X* to R+ coincide; hence *LX* with the Scott topology is locally convex, allowing us to apply an isomorphism theorem [[14](#_bookmark69), Theorem 4.11] beyond core-compact spaces, to the class of all LCS-complete spaces. In the sequel (Sections [14](#_bookmark43)–[16](#_bookmark48)), we explore the properties of the categories of LCS-complete, resp. domain-complete spaces: count- able products and arbitrary coproducts exist and are computed as in topological spaces, but those categories have neither equalizers nor coequalizers, and are not Cartesian-closed; we also characterize the exponentiable objects in the category of quasi-Polish spaces as the countably-based locally compact sober spaces. Section [17](#_bookmark49) is of independent interest, and characterizes the compact saturated subsets of LCS- complete spaces, in a manner reminiscent of a well-known theorem of Hausdorff on complete metric spaces. We prove Theorem [1.1](#_bookmark4) in Section [18](#_bookmark52), and we conclude in Section [19.](#_bookmark55)

# Acknowledgement

The second author thanks Szymon Dolecki for pointing him to [[9](#_bookmark64), Proposition 7.3].

# Preliminaries

We assume that the reader is familiar with domain theory [[12,](#_bookmark67)[1](#_bookmark57)], and with basic notions in non-Hausdorff topology [[13](#_bookmark68)].

We write **Top** for the category of topological spaces and continuous maps.

R+ denotes the set of non-negative real numbers, and R+ is R+ plus an ele- ment *∞*, larger than all others. We write *≤* for the underlying preordering of any

preordered set, and for the specialization preordering of a topological space. The notation *↑ A* denotes the upward closure of *A*, and *↓ A* denotes its downward clo-

sure. When *A* = *{y}*, this is simply written *↑ y*, resp. *↓ y*. We write [*↑*for directed

unions, sup*↑*for directed suprema, and \*↓*for filtered intersections.

Compactness does not imply separation, namely, a compact set is one such that one can extract a finite subcover from any open cover. A *saturated* subset is a subset that is the intersection of its open neighborhoods, equivalently that is an upwards-closed subset in the specialization preordering.

We writefor the way-below relation on a poset *Y* , and ***↑****y* for the set of points

*z ∈ Y* such that *y z*.

We write *int*(*A*) for the interior of a subset *A* of a topological space *X*, and *O X*

for its lattice of open subsets.

A space is *locally compact* if and only if every point has a base of compact saturated neighborhoods. It is *sober* if and only if every irreducible closed subset is the closure of a unique point. It is *well-ﬁltered* if and only if given any filtered family (*Qi*)*i∈I* of compact saturated subsets and every open subset *U* , if *i∈I Qi ⊆ U* then *Qi ⊆ U* for some *i ∈ I*. In a well-filtered space, the intersection *i∈I Qi* of any such filtered family is compact saturated. Sobriety implies well-filteredness, and the two properties are equivalent for locally compact spaces.

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A space *X* is *core-compact* if and only if *O X* is a continuous lattice. Every locally compact space is core-compact, and in that case the way-below relation on open subsets is given by *U* b *V* if and only if *U ⊆ Q ⊆ V* for some compact saturated set *Q*. Conversely, every core-compact sober space is locally compact.

# Definition and basic properties

A *Gδ* subset of a topological space *Y* is the intersection of a countable family

(*Wn*)*n∈*N of open subsets of *Y* . Replacing *Wn* by T*n Wi* if needed, we may assume

*i*=0

that the family is *descending*, namely that *W*0 *⊇ W*1 *⊇ · · ·⊇ Wn ···* .

**Definition 3.1** A *domain-complete space* is a (homeomorph of a) *Gδ* subset of a continuous dcpo, with the subspace topology from the Scott topology.

An *LCS-complete space* is a (homeomorph of a) *Gδ* subset of a locally compact sober space, with the subspace topology.

**Remark 3.2** There isa pattern here. Fora class *C* of topological spaces, one might call *C-complete* any homeomorph of a *Gδ* subset of a space in *C*. For example, if *C* is the class of stably (locally) compact spaces, we would obtain *SC-complete* (resp., *SLC-complete*) spaces. By an easy trick which we shall use in Lemma [14.1](#_bookmark44), SC-complete and SLC-complete are the same notion.

**Proposition 3.3** *Every locally compact sober space is LCS-complete, in particular every quasi-continuous dcpo is LCS-complete. Every continuous dcpo is domain- complete. Every domain-complete space is LCS-complete.*

**Proof.** Every space is *Gδ* in itself. Every quasi-continuous dcpo is locally compact (being locally finitary compact [[13](#_bookmark68), Exercise 5.2.31]) and sober [[13](#_bookmark68), Exercise 8.2.15]. The last part follows from the fact that every continuous dcpo is locally compact and sober. *2*

We will see other examples of domain-complete spaces in Sections [4,](#_bookmark10) [5](#_bookmark13), and [6.](#_bookmark16)

**Remark 3.4** Given any continuous dcpo (resp., locally compact sober space) *Y* ,

\

and any descending family (*W*

*n*)*n∈*N

of open subsets of *Y* , *X* d=ef

*↓*

*Wn* is

*n∈*N

domain-complete (resp., LCS-complete). We can then define *μ* : *Y →* R+ by

+

+

*μ*(*y*) d=ef

inf*{*1*/*2*n | y ∈ Wn*

*}*. This is continuous from *Y* to R*op*, i.e., R

with

the Scott topology of the reverse ordering *≥*. Indeed, *μ−*1([0*, a*)) = *Wn* where *n* is

the smallest natural number such that 1*/*2*n < a*. Then *X* is equal to the *kernel*

ker *μ* d=ef *μ−*1(*{*0*}*) of *μ*. Conversely, any space that is (homeomorphic to) the kernel

*op*

R

of some continuous map *μ* : *Y →* + from a continuous dcpo (resp., locally com-

\

pact space) *Y* is equal to *↓*

*n∈*N

*μ−*1([0*,* 1*/*2*n*)), hence is domain-complete (resp.,

LCS-complete). This should be compared with Keye Martin’s notion of *measure-*

*ment* [[28](#_bookmark83)], which is a map *μ* as above with the additional property that for every

*x ∈* ker *μ*, for every open neighborhood *V* of *x* in *Y* , there is an *ϵ >* 0 such that

*↓ x ∩ μ−*1([0*, ϵ*)) *⊆ V* .

# Continuous complete quasi-metric spaces

A *quasi-metric* on a set *X* is a map *d* : *X ×X →* R+ satisfying the laws: *d*(*x, x*)= 0; *d*(*x, y*) = *d*(*y, x*) = 0 implies *x* = *y*; and *d*(*x, z*) *≤ d*(*x, y*)+ *d*(*y, z*) (*triangular inequality* ). The pair *X, d* is then called a *quasi-metric space*.

Given a quasi-metric space, one can form its poset **B**(*X, d*) of *formal balls*. Its

elements are pairs (*x, r*) with *x ∈ X* and *r ∈* R+

, and are ordered by (*x, r*) *≤d*+ (*y, s*)

if and only if *d*(*x, y*) *≤ r−s*. Instead of spelling out what a complete (a.k.a., *Yoneda-*

*complete* quasi-metric space) is, we rely on the Kostanek-Waszkiewicz Theorem [[25]](#_bookmark79) (see also [[13](#_bookmark68), Theorem 7.4.27]), which characterizes them in terms of **B**(*X, d*): *X, d* is *complete* if and only if **B**(*X, d*) is a dcpo.

We will also say that *X, d* is a *continuous complete* quasi-metric space if and only if **B**(*X, d*) is a continuous dcpo. This is again originally a theorem, not a defi- nition [[16](#_bookmark71), Theorem 3.7]. The original, more complex definition, is due to Mateusz Kostanek and Pawe-l Waszkiewicz.

There isa map *η* : *X →* **B**(*X, d*) defined by *η*(*x*) d=ef (*x,* 0). The coarsest topology

that makes *η* continuous, once we have equipped **B**(*X, d*) with its Scott topology, is called the *d-Scott topology* on *X* [[13](#_bookmark68), Definition 7.4.43]. This is our default topology on quasi-metric spaces, and turns *η* into a topological embedding.

Every poset *X* can be seen as a quasi-metric space with equipping it with the quasi-metric *d*(*x, y*) d=ef 0 if *x ≤ y*, *∞* otherwise. In that case, the *d*-Scott topology coincides with the Scott topology [[25](#_bookmark79), Example 1.8], and if *X* is a continuous dcpo then *X, d* is continuous complete [[25](#_bookmark79), Example 3.12].

The *d*-Scott topology coincides with the usual open ball topology when *d* is a metric (i.e., *d*(*x, y*) = *d*(*y, x*) for all *x, y*) or when *X, d* is a so-called Smyth- complete quasi-metric space [[13](#_bookmark68), Propositions 7.4.46, 7.4.47]. We will not say what Smyth-completeness is (see Section 7.2, ibid.), except that every Smyth-complete quasi-metric space is continuous complete, by the Romaguera-Valero theorem [[33]](#_bookmark87) (see also [[13](#_bookmark68), Theorem 7.3.11]).

**Theorem 4.1** *For every continuous complete quasi-metric space X, d, the space X*

*with its d-Scott topology is domain-complete.*

**Proof.** Every standard quasi-metric space *X, d* embeds as a *Gδ* set into **B**(*X, d*) [[16,](#_bookmark71) Proposition 2.6], and every complete quasi-metric space is standard (Proposition 2.2,

ibid.) Explicitly, *X* is homeomorphic to T

*n∈*N

*Wn* where *Wn* d=ef *{*(*x, r*) *∈* **B**(*X, d*) *|*

*r <* 1*/*2*n}* is Scott-open. Since *X, d* is continuous complete, **B**(*X, d*) isa continuous

dcpo. *2*

When *d* is a metric, **B**(*X, d*) is a continuous poset [[11](#_bookmark66), Corollary 10], with (*x, r*)(*y, s*) if and only if *d*(*x, y*) *< r − s*; also, **B**(*X, d*) is a dcpo if and only if *X, d* is complete in the usual, Cauchy sense [[11](#_bookmark66), Theorem 6]. Hence every complete metric space is continuous complete in our sense.

**Corollary 4.2** *Every complete metric space is domain-complete in its open ball topology.* *2*

# Quasi-Polish spaces

Quasi-Polish spaces were introduced in [[7](#_bookmark61)], and can be defined in many equiva- lent ways. The original definition is: a quasi-Polish space is a separable Smyth- complete quasi-metric space *X, d*, seen as a topological space with the open ball topology. By *separable* we mean the existence of a countable dense subset in

*X* with the open ball topology of *dsym*, where *dsym* is the symmetrized metric *dsym*(*x, y*) d=ef max(*d*(*x, y*)*, d*(*y, x*)). By a lemma due to Ku¨nzi [[27](#_bookmark80)], a quasi-metric space is separable if and only if its open ball topology is countably-based.

Since Smyth-completeness implies continuous completeness and also that the open ball and *d*-Scott topologies coincide [[13](#_bookmark68), Theorem 7.4.47], Theorem [4.1](#_bookmark11) implies:

**Proposition 5.1** *Every quasi-Polish space is domain-complete.*

Not every domain-complete space is quasi-Polish. In fact, the following remark implies that not every domain-complete space is even first-countable. We will see that all countably-based domain-complete spaces *are* quasi-Polish in Section [9.](#_bookmark24)

**Remark 5.2** Let us fix an uncountable set *I*, and let *X* d=ef *Y* d=ef P(*I*), with the Scott topology of inclusion. This is an algebraic, hence continuous dcpo, hence a domain-complete space. *I* is its top element. We claim that every collection of open neighborhoods of *I* whose intersection is *{I}* must be uncountable. Imagine we had

a countable collection (*Vn*)*n∈*N of open neighborhoods of *I* whose intersection is *{I}*.

For each *n ∈* N, *I* is in some basic open set *↑ An* d=ef *{B ∈* P(*I*) *| An ⊆ B}* (where each *An* isTa finite subset of *I*) included in *Vn*. Then T*n∈*N *↑ An* is still equal to *{I}*.

However,

*n∈*N *↑ An* = *↑ A∞*, where *A∞* is the countable set

*n∈*N *An*, and must

contain some (uncountably many) points other than *I*.

# Topologically complete spaces

In 1937, Eduard Cˇech defined *topologically complete* spaces as those topological spaces that are *Gδ* subsets of some compact Hausdorff space, or equivalently those completely regular Hausdorff spaces that are *Gδ* subsets of their Stone-Cˇech com- pactification [[5](#_bookmark60)], and proved that a metrizable space is completely metrizable if and

only if it is topologically complete.

The following is then clear:

**Fact 6.1** *Every topologically complete space in Cˇech’s sense is LCS-complete.*

# Sobriety

A **Π**0 subset of a topological space *Y* is a space of the form *{y ∈ Y | ∀n ∈* N*,y ∈*

2

*Un ⇒ y ∈ Vn}*, where *Un* and *Vn* are open in *Y* . Every *Gδ* subset of *Y* is **Π**0 (take

2

*Un* = *Y* for every *n*), and every closed subset of *Y* is **Π**0

2

(take *Un* equal to the

complement of that closed subset for every *n*, and *Vn* empty). More generally, we consider *Horn* subsets of *Y* , defined as sets of the form *{y ∈ Y | ∀i ∈ I, y ∈ Ui ⇒ y ∈ Vi}*, where *Ui*, *Vi* are (not necessarily countably many) open subsets of *Y* .

**Proposition 7.1** *Every Horn subset X of a sober space Y is sober. In particular, every LCS-complete space is sober.*

**Proof.** We prove the first part. In the case of **Π**0 subsets, that was already proved in [[8](#_bookmark63), Lemma 4.2]. Let *X* d=ef *{y ∈ Y | ∀i ∈ I, y ∈ Ui ⇒ y ∈ Vi}*, with *Ui* and *Vi* open. P(*I*), with the inclusion ordering, is an algebraic dcpo, whose finite elements

2

are the finite subsets of *I*. Let *f* : *Y →* P(*I*) map *y* to *{i ∈ I | y ∈ Ui}*, and *g* map

*y* to *{i ∈ I | y ∈ Ui ∩ Vi}*. Both are continuous, since *f−*1(*↑{i*1*, ··· , ik}*)= T*k Ui*

*j*=1

*j*

and *g−*1(*↑{i*1*, ··· , ik}*) = T*k Ui ∩ Vi* are open. The equalizer of *f* and *g* is

*j*=1

*j j*

*{y ∈ Y | f* (*y*) = *g*(*y*)*}* = *{y ∈ Y | ∀i ∈ I, y ∈ Ui ⇔ y ∈ Ui ∩ Vi}* = *X*, with the

subspace topology. But every equalizer of continuous maps from a sober space to a *T*0 topological space is sober [[13](#_bookmark68), Lemma 8.4.12] (note that “*T*0” is missing from the statement of that lemma, but *T*0-ness is required). *2*

# The Wilker condition

A space *X* satisfies *Wilker’s condition*, or is *Wilker*, if and only if every compact saturated set *Q* included in the union of two open subsets *U*1 and *U*2 of *X* is included in the union of two compact saturated sets *Q*1 *⊆ U*1 and *Q*2 *⊆ U*2. The notion is

used by Keimel and Lawson [[24](#_bookmark78), Theorem 6.5], and is due to Wilker [[35](#_bookmark90), Theorem 3]. Theorem 8 of the latter states that every KT4 space, namely every space in which every compact subspace is *T*4, is Wilker. In particular, every Hausdorff space is Wilker.

We will need the following lemma several times in this paper. The proof of Theorem [8.2](#_bookmark22) is typical of several arguments in this paper.

**Lemma 8.1** *Let X be a subspace of a topological space Y . For every subset E of*

*X,*

1. *E is compact in X if and only if E is compact in Y ;*
2. *if X is upwards-closed in Y , then E is saturated in X if and only if E is saturated in Y ;*
3. *if X is a Gδ subset of Y , then E is Gδ in X if and only if E is Gδ in Y .*

**Proof.** 1. Assume *E* compact in *X*. For every open cover (*U*^*i*)*i∈I* of *E* by open subsets of *Y* , (*U*^*i ∩ X*)*i∈I* is an open cover of *E* by open subsets of *X*. Hence *E* has a subcover (*Ui ∩ X*)*i∈J* , with *J* finite, and (*Ui*)*i∈J* is a finite subcover of the original cover of *E*, showing that *E* is compact in *Y* .

^ ^

Conversely, if *E* is compact in *Y* (and included in *X*), we consider an open cover (*Ui*)*i∈I* of *E* by open subsets of *X*. For each *i ∈ I*, we can write *Ui* as *U*^*i ∩ X* for some open subset *U*^*i* of *Y* . Then (*U*^*i*)*i∈I* is an open cover of *E* in *X*. We extract a subcover (*U*^*i*)*i∈J* with *J* finite. Since *E* is included in *X*, *E* is included in *X ∩ i∈J Ui* = *i∈J Ui*. This shows that *E* is compact in *X*.

^

* 1. This follows from the fact that the specialization preordering on *X* is the

restriction of the specialization preordering on *Y* to *X*. If *E* is saturated in *X*, then for every *x ∈ E* and every *y* above *x* in *Y* , then *y* is in *X* since *X* is saturated, and then in *E* by assumption. Therefore *E* is saturated in *Y* . Conversely, if *E* is saturated in *Y* , then for every *x ∈ E* and every *y* above *x* in *X*, *y* is also above *x* in *Y* , hence in *E* since *E* is saturated in *Y* . This shows that *E* is saturated in *X*.

* 1. Since *X* is *Gδ* in *Y* , *X* is equal to T*n∈*N *Wn* where each *Wn* is open in *Y* .

If *E* is a *Gδ* subset of *X*, say *E* d=ef T

^ ^

*m∈*N

*Um*, where each *Um* is open in *X*, we

write *Um* as *Um ∩ X* for some open subset *Um* of *Y* . It follows that *E* is equal to

T

*m,n∈*N(*Um ∩ Wn*). This is a countable intersection of open subsets of *Y* , hence a

^

*Gδ* subset.

Conversely, if *E* is a *Gδ* subset of *Y* , say *E* d=ef T

*m∈*N

*U*^*m*, then since *E* is included

in *X*, *E* is also equal to T*m∈*N(*U*^*m ∩ X*), showing that *E* is *Gδ* in *X*. *2*

**Theorem 8.2** *Every LCS-complete space is Wilker.*

**Proof.** We start by showing that every locally compact space *Y* is Wilker, and in fact satisfies the following stronger property: (*∗*) for every compact saturated subset *Q* of *Y* , for all open subsets *U*1 and *U*2 such that *Q ⊆ U*1 *∪ U*2, there are two compact saturated subsets *Q*1 and *Q*2 such that *Q ⊆ int*(*Q*1) *∪ int*(*Q*2), *Q*1 *⊆ U*1, and *Q*2 *⊆ U*2. For each *x ∈ Q*, if *x* is in *U*1, then we pick a compact saturated

neighborhood *Qx* of *x* included in *U*1, and if *x* is in *U*2 *\ U*1, then we pick a compact

saturated neighborhood *Qj* of *x* included in *U*2. From the open cover of *Q* consisting

*x*

of the sets *int*(*Qx*) and *int*(*Qj* ), we extract a finite cover. Namely, there are a finite set *E*1 of points of *Q∩U*1 and a finite set *E*2 of points of *Q\U*1 (hence in *Q∩U*2) such

*x*

that *Q ⊆* *x∈E*1

*int*(*Qx*)*∪* *x∈E*2

*int*(*Qj* ). We let *Q*1 d=ef

*x∈E*1

*Qx*, *Q*2 d=ef

*x∈E*2

*Qj* .

Let *X* be (homeomorphic to) the intersection *↓ W*

*x*

*x*

\

*n*

*n∈*N

of a descending se-

quence of open subsets of a locally compact sober space *Y* . Let *Q* be compact sat-

urated in *X*, and included in the union of two open subsets *U*1 and *U*2 of *X*. Let us write *U*1 as *U*1*∩X* where *U*1 is open in *Y* , and similarly *U*2 as *U*2*∩X*. By Lemma [8.1](#_bookmark21), *Q* is compact saturated in *Y* . By property (*∗*), there are two compact saturated subsets *Q*01 and *Q*02 of *Y* such that *Q ⊆ int*(*Q*01) *∪ int*(*Q*02), *Q*01 *⊆ U*1 *∩ W*0, *Q*02 *⊆ U*2 *∩W*0. By (*∗*) again, there are two compact saturated subsets *Q*11 and *Q*12 of *Y* such that *Q ⊆ int*(*Q*11) *∪int*(*Q*12), *Q*11 *⊆ int*(*Q*01) *∩W*1, *Q*12 *⊆ int*(*Q*02) *∩W*1. Continuing this way, we obtain two compact saturated subsets *Qn*1 and *Qn*2 for each *n ∈* N such that *Q ⊆ int*(*Qn*1) *∪ int*(*Qn*2), *Q*(*n*+1)1 *⊆ int*(*Qn*1) *∩ Wn*+1, and

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*Q*(*n*+1)2

*⊆ int*(*Qn*2

) *∩ W*

*n*+1

. Let *Q*1

d=ef *↓*

*n∈*N

*Qn*1

= *↓*

*n∈*N

*int*(*Qn*1

). This is a fil-

tered intersection of compact saturated sets in a well-filtered space, hence is compact

saturated. Since *Q*(*n*+1)1 *⊆ Wn*+1 for every *n ∈* N, *Q*1 is included in *X*, hence is com-

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pact saturated in *X* by Lemma [8.1](#_bookmark21). Similarly, *Q*2

is compact saturated in *X*.

d=ef *↓*

*n∈*N

*Qn*2

= *↓*

*n∈*N

*int*(*Qn*2)

We note that *Q* is included in *Q*1 *∪ Q*2. Otherwise, there would be a point *x* in *Q* and outside both *Q*1 and *Q*2, hence outside *int*(*Qm*1) for some *m ∈* N and outside *int*(*Qn*1) for some *n ∈* N, hence outside *int*(*Qk*1) *∪ int*(*Qk*2) with *k* d=ef max(*m, n*). That is impossible since *Q ⊆ int*(*Qk*1) *∪ int*(*Qk*2).

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Finally, *Q*1 is included in *U*1 because *Q*1 *⊆ Q*01 *∩ X ⊆ U*1 *∩ W*0 *∩ X* = *U*1, and similarly *Q*2 is included in *U*2. *2*

**Remark 8.3** The proof of Theorem [8.2](#_bookmark22) shows that *Q*1 and *Q*2 are even compact *Gδ*

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subsets of *X*, being obtained as *↓*

*n∈*N

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*int*(*Qn*1

), hence also as *↓*

*n∈*N

*int*(*Qn*1

) *∩ X*

(resp., *↓*

*n∈*N

*int*(*Qn*2

) *∩ X*). This suggests that there are many compact *Gδ*

sets

in every LCS-complete space. Note that not all compact saturated sets are *Gδ* in

general LCS-complete spaces: even the upward closures *↑ x* of single points may fail to be *Gδ*, as Remark [5.2](#_bookmark15) demonstrates.

**Remark 8.4** Pursuing Remark [3.2](#_bookmark7), every SC-complete space *X* is not only LCS- complete, but also *coherent* : the intersection of two compact saturated sets *Q*1, *Q*2 is compact. Indeed, let *X* be *Gδ* in some stably compact space *Y* ; by Lemma [8.1](#_bookmark21), items 1 and 2, *Q*1 and *Q*2 are compact saturated in *Y* , then *Q*1 *∩ Q*2 is compact saturated in *Y* and included in *X*, hence compact in *X*. This implies that there are LCS-complete, and even domain-complete spaces, that are not SC-complete: take any non-coherent dcpo, for example Z*− ∪ {a, b}*, where Z*−* is the set of negative integers with the usual ordering, and *a* and *b* are incomparable and below Z*−*.

# Choquet completeness

The *strong Choquet game* on a topological space *X* is defined as follows. There are two players, *α* and *β*. Player *β* starts, by picking a point *x*0 and an open neighborhood *V*0 of *x*0. Then *α* must produce a smaller open neighborhood *U*0 of *x*0, i.e., one such that *U*0 *⊆ V*0. Player *β* must then produce a new point *x*1 in *U*0, and a new open neighborhood *V*1 of *x*1, included in *U*0, and so on. An *α-history* is a sequence *x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn, Vn* where *V*0 *⊇ U*0 *⊇ V*1 *⊇ U*1 *⊇ V*2 *⊇ ... ⊇ Vn* is a decreasing sequence of opens and *x*0 *∈ U*0, *x*1 *∈ U*1, *x*2 *∈ U*2, . . . , *xn−*1 *∈ Un−*1, *xn ∈ Vn*, *n ∈* N. A *strategy* for *α* is a map *σ* from *α*-histories to open subsets *Un* with *xn ∈ Un ⊆ Vn*, and defines how *α* plays in reaction to *β*’s moves. (For details, see Section 7.6.1 of [[13](#_bookmark68)].)

*X* is *Choquet-complete* if and only if *α* has a winning strategy, meaning that whatever *β* plays, *α* has a way of playing such that *n∈*N *Un* (= *n∈*N *Vn*) is non- empty. *X* is *convergence Choquet-complete* if and only if *α* can always win in such a way that (*Un*)*n∈*N is a base of open neighborhoods of some point. The latter notion is due to Dorais and Mummert [[10](#_bookmark65)]. We introduce yet another, related notion: a space is *compactly Choquet-complete* if and only if *α* can always win in such that way that (*Un*)*n∈*N is a base of open neighborhoods of some non-empty compact saturated set. We do not assume the strategies to be stationary, that is, the players have access to all the points *xn* and all the open sets *Un*, *Vn* played earlier.

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The following generalizes [[16](#_bookmark71), Theorem 4.3], which states that every continuous

complete quasi-metric space is convergence Choquet-complete in its *d*-Scott topol- ogy.

**Proposition 9.1** *Every domain-complete space is convergence Choquet-complete. Every LCS-complete space is compactly Choquet-complete.*

**Proof.** Let *X* be the intersection of a descending sequence (*Wn*)*n∈*N of open subsets of *Y* . Given any open subset *U* of *X*, we write *U* for some open subset of *Y* such that *U ∩ X* = *U* (for example, the largest one).

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We first assume that *Y* is a continuous dcpo. The proof is a variant of [[13](#_bookmark68), Exercise 7.6.6]. We define *α*’s winning strategy so that *Un* is of the form

***↑****yn ∩ X* for some *yn ∈ Y* . Given the last pair (*xn, Vn*) played by *β*, *xn* is the supremum of a directed family of elements way-below *xn*. One of them

will be in *V*^*n ∩ Wn*, and also in ***↑****yn−*1 if *n ≥* 1, because *xn ∈ Vn ⊆ V*^*n*,

*xn ∈ X ⊆ Wn*, and (if *n ≥* 1) *xn ∈ Un−*1 = ***↑****yn−*1 *∩ X ⊆* ***↑****yn−*1. Pick one

such element *yn* from *V*^*n ∩ Wn ∩ ↑yn−*1 (if *n ≥* 1, otherwise from *V*^*n ∩ Wn*),

and let *α* play *Un* d=ef ***↑****yn ∩ X*, as announced. Formally, the strategy *σ*

that we are defining for *α* is *σ*(*x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn, Vn*) d=ef

***↑****y*(*x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn, Vn*) *∩ X*, where

*y*(*x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn, Vn*) is defined by induction on *n* as a

point in

*n ≥* 1.

*V*^*n ∩ Wn*, and also in ***↑****y*(*x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn−*1*, Vn−*1) if

Given any play *x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn, Vn, Un, ···* in the game, let

*x* d=ef sup *yn* (where *yn* d=ef *y*(*x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn, Vn*)). This is a directed supremum, since *y*0 *y*1 *··· yn · · · x*. Since *yn ∈ Wn* for every *n ∈* N, *x* is in *n∈*N *Wn* = *X*. For every *n ∈* N, we have *yn x*, so *x* is in

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*n∈*N

*Un* = ***↑****yn ∩ X*. In order to show that (*Un*)*n∈*N is a base of open neighborhoods of *x*

in *X*, let *U* be any open neighborhood of *x* in *X*. Since *x* = sup*n∈*N *yn*, some *yn* is in *U* , so *Un* = ***↑****yn ∩ X* is included in *↑ yn ∩ X ⊆ U ∩ X* = *U* .

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The argument is similar when *Y* is a locally compact sober space instead. Instead of picking a point *yn* in *Vn ∩ Wn* (and in ***↑****yn−*1 if *n ≥* 1), *α* now picks a compact saturated subset *Qn* whose interior contains *xn*, and included in *Vn ∩ Wn* (and in *int*(*Qn−*1) if *n ≥* 1), and defines *Un* as *int*(*Qn*) *∩ X*. This is possible because *Y*

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is locally compact. We let *Q* d=ef

*Q*0 *⊇ Q*1 *⊇ · · ·⊇ Qn ⊇ · · ·* .

T*n∈*N

*Qn*. This is a filtered intersection, since

Because *Y* is sober hence well-filtered, *Q* is compact saturated in *Y* . It is also non-empty: if *Q* = *n∈*N *Qn* were empty, namely, included in *∅*, then *Qn* would be included in *∅* by well-filteredness, which is impossible since *xn ∈ int*(*Qn*). Also, since *Qn ⊆ Wn* for every *n ∈* N, *Q* is included in *n∈*N *Wn* = *X*. By Lemma [8.1](#_bookmark21), item 3, *Q* is a compact saturated subset of *X*.

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Since *Q ⊆ Qn*+1 *⊆ Vn*+1 for every *n ∈* N, we have *Q* = *Q ∩ X ⊆ Vn*+1 *∩ X* =

*Vn*+1 *⊆ Un*. In order to show that (*Un*)*n∈*N forms a base of open neighborhoods of *Q* in *X*, let *U* be any open neighborhood of *Q* in *X*. Then *U*^ contains *Q* = T*n∈*N *Qn*, so by well-filteredness some *Qn* is included in *U*^ . Now *Un* = *int*(*Qn*) *∩X* is included

in *U*^ *∩ X* = *U* . *2*

In the case of LCS-complete spaces, notice that *Q* = T*n∈*N *Un* is not only com- pact, but also a *Gδ* subset of *X*. This again suggests that there are many compact *Gδ* sets in every LCS-complete space, as in Remark [8.3](#_bookmark23).

The following—at last—justifies the “complete” part in “LCS-complete”.

**Theorem 9.2** *The metrizable LCS-complete (resp., domain-complete) spaces are the completely metrizable spaces.*

**Proof.** One direction is Corollary [4.2.](#_bookmark12) Conversely, an LCS-complete space is Choquet-complete (Proposition [9.1](#_bookmark25)) and every metrizable Choquet-complete space is completely metrizable [[13](#_bookmark68), Corollary 7.6.16]. *2*

**Remark 9.3** There is an LCS-complete but not domain-complete space. The space

*{*0*,* 1*}I* , where *{*0*,* 1*}* is given the discrete topology, is compact Hausdorff, hence trivially LCS-complete. We claim that it is not domain-complete if *I* is uncountable.

In order to show that, we first show that: (*∗*) for every point ***a*** of *{*0*,* 1*}I* , every countable family of open neighborhoods (*Vn*)*n∈*N of ***a*** must be such that T*n∈*N *Vn /*=

*{****a****}*. We write *ai* for the *i*th component of ***a***. For each subset *J* of *I*, let *VJ* (***a***) d=ef

*{****b*** *∈ {*0*,* 1*}I | ∀i ∈ J, ai* = *bi}*; this is a basic open subset of the product topology if *J* is finite. Since ***a*** *∈ Vn*, there is a finite subset *Jn* of *I* such that ***a*** *∈ VJn* (***a***) *⊆ Vn*. Then *n∈*N *Vn* contains *n∈*N *VJn* (***a***) = *V*S*n∈*N *Jn* (***a***), which contains uncountably many elements other than ***a***. Having established (*∗*), it is clear that no point has

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a countable base of open neighborhoods. In particular, *{*0*,* 1*}I* is not convergence Choquet-complete, hence not domain-complete.

The situation simplifies for countably-based spaces. We will use the notion of *supercompact* set: *Q ⊆ X* is *supercompact* if and only if for every open cover (*Ui*)*i∈I* of *Q*, there is an index *i ∈ I* such that *Q ⊆ Ui*. By [[18](#_bookmark73), Fact 2.2], the supercompact subsets of a topological space *X* are exactly the sets *↑ x*, *x ∈ X*.

**Proposition 9.4** *Every countably-based, compactly Choquet-complete space X is convergence Choquet-complete.*

**Proof.** Let *σ* be a strategy for *α* such that the open sets (*Un*)*n∈*N played by *α* form a base of open neighborhoods of some compact saturated set.TLet also (*Bn*)*n∈*N be

a countable base of the topology, and let us write *B*(*x, n*) for

*{Bi |* 0 *≤ i ≤ n, x ∈*

*Bi}*. (In case there is no *Bi* containing *x* for any *i*, 0 *≤ i ≤ n*, this is the whole of *X*.) We define a new strategy *σj* for *α* by using a game stealing argument: when *β* plays *xn* and *Vn*, *α* simulates what he would have done if *β* had played *xn* and *Vn ∩ B*(*xn, n*) instead. Formally, we define *σj*(*x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn, Vn*) d=ef

*σ*(*x*0*, V*0*, U*0*, x*1*, V*1*, U*1*, x*2*, V*2*, ··· , xn, Vn ∩ B*(*xn, n*)). Let (*Uj* )

*n n∈*N

denote the open

sets played by *α* using *σj*: *Uj* = *σ*(*x*0*, V*0*,Uj , x*1*, V*1*,Uj , x*2*, V*2*, ··· , xn, Vn∩B*(*xn, n*)).

*n* 0 1

Since *X* is compactly Choquet-complete, (*Uj* ) is a countable base of open neigh-

*n n∈*N

borhoods of some non-empty compact saturated set *Q*. We claim that *Q* is of the form *↑ x*.

We only need to show that *Q* is supercompact. We start by assuming that *Q* is included in the union of two open sets *U* and *V* , and we will show that *Q* is included in one of them. We can write *U* and *V* as unions of basic open sets *Bn*, hence by compactness there are two finite sets *I* and *J* of natural numbers such

that *Q ⊆* *Bi*, *Bi ⊆ U* , and *Bj ⊆ V* . Since (*Uj* ) is a base of

*i∈I∪J*

*i∈I*

*j∈J*

*j*

*n n∈*N

open neighborhoods of *Q*, some *Un* is included in *i∈* *I∪J Bi*. We choose *n* higher

than every element of *I ∪ J*. Since *xn ∈ Uj* , *xn* is in

*Bi*. If *xn* is in *Bi* for

some *i ∈ I*, then *B*(*xn, n*) is included in *Bi*, and then *Q ⊆ Uj*

*n*

*n*

*i∈I∪J*

*⊆ B*(*xn, n*) (by the

definition of *σj*) *⊆ B**i ⊆ U* . Otherwise, by a similar argument *Q ⊆ V* .

It follows that if *Q* is included in the union of *n ≥* 1 open sets, then it is included in one of them. Given any open cover (*Ui*)*i∈I* of *Q*, there is a finite subcover (*Ui*)*i∈J* of *Q*. *J* is non-empty, since *Q /*= *∅*. Hence *Q* is included in *Ui* for some *i ∈ J*.

This shows that *Q* is supercompact. Hence *Q* = *↑ x* for some *x*. Since (*Uj* )

*n n∈*N

is a

countable base of open neighborhoods of *Q*, it is also one of *x*. *2*

**Theorem 9.5** *The following are equivalent for a countably-based T*0 *space X:*

1. *X is domain-complete;*
2. *X is LCS-complete;*
3. *X is quasi-Polish;*
4. *X is compactly Choquet-complete;*
5. *X is convergence Choquet-complete.*

**Proof.** (iii)*⇒*(i) is by Proposition [5.1](#_bookmark14), (i)*⇒*(ii) is by Proposition [3.3](#_bookmark8), (ii)*⇒*(iv) is by Proposition [9.1](#_bookmark25), (iv)*⇒*(v) is by Proposition [9.4](#_bookmark26). Finally, (v)*⇒*(iii) is the contents of Theorem 51 of [[7](#_bookmark61)], see also [[6](#_bookmark62), Theorem 11.8]. *2*

**Remark 9.6** Q, with the usual metric topology, is not quasi-Polish. Theorem [9.5](#_bookmark27) implies that it is not LCS-complete either. One can show directly that it is not Choquet-complete, as follows. We fix an enumeration (*qn*)*n∈*N of Q, and we call first element of a non-empty set *A* the element *qk ∈ A* with *k* least. At step 0, *β* plays *x*0 d=ef *q*0, *V*0 d=ef Q. At step *n* + 1, *β* plays *Vn*+1, defined as *Un* minus its first element, and lets *xn*+1 be the first element of *Vn*+1. This is possible since every

non-empty open subset of Q is infinite. One checks easily that, whatever *α* plays,

T*n∈*N *Vn* is empty.

# The Baire property

Every Choquet-complete space is *Baire* [[13](#_bookmark68), Theorem 7.6.8], where a Baire space is a space in which every intersection of countably many dense open sets is dense.

**Corollary 10.1** *Every LCS-complete space is Baire.*

This generalizes Isbell’s result that every locally compact sober space is Baire [[21](#_bookmark76)].

We will refine this below. We need to observe the following folklore result.

**Lemma 10.2** *Let Y be a continuous dcpo, and C be a closed subset of Y . The way-below relation on C is the restriction of the way-below relation on Y to C. C is a continuous dcpo, with the restriction of the ordering ≤ of Y to C.*

**Proof.** First, *C* is a dcpo under the restriction *≤C* of *≤* to *C*, and directed suprema are computed as in *Y* .

Let *C* denote the way-below relation on *C*. For all *x, y ∈ C*, if *x y* (in *Y* ) then *x C y*: every directed family of elements of *C* whose supremum (in *C*, equivalently in *Y* ) lies above *y* must contain an element above *x*.

It follows that *C* is a continuous dcpo: every element *x* of *C* is the supremum of the directed family of elements *y* that are way-below *x* in *Y* , and all those elements are in *C* and way-below *x* in *C*.

Conversely, we assume *x C y*, and we consider a directed family *D* in *Y* whose supremum lies above *y*. Every continuous dcpo is meet-continuous [[12](#_bookmark67), Theorem III- 2.11], meaning that if *y ≤* sup *D* for any directed family *D* in *Y* , then *y* is in the Scott-closure of *↓ D ∩↓ y*. (The theory of meet-continuous dcpos is due to Kou, Liu and Luo [[26](#_bookmark81)].) In the case at hand, *↓ D ∩↓ y* is included in *↓ y* hence in *C*. Since *C* is a continuous dcpo and *x C y*, the set ***↑****Cx* d=ef *{z ∈ C | x C z}* is Scott-open in *C*, and contains *y*. Then ***↑****Cx* intersects the Scott-closure of *↓ D ∩↓ y*, and since it is open, it also intersects *↓ D ∩↓ y* itself, say at *z*. Then *x C z ≤ d* for some *d ∈ D*, which implies *x ≤ d*. Therefore *x y*. *2*

**Proposition 10.3** *Every Gδ subset, every closed subset of a domain-complete (resp., LCS-complete) space is domain-complete (resp., LCS-complete).*

**Proof.** Let *X* be the intersection of a descending sequence (*Wn*)*n∈*N of open subsets of *Y* , where *Y* is a continuous dcpo (resp., a locally compact sober space).

Given any *Gδ* subset *A* d=ef T *Vm* of *X*, where each *Vm* is open in *X*, let *V*^*m*

*m∈*N

be some open subset oTf *Y* such that *V*^*m ∩ X* = *Vm*. Then *A* is also equal to the

countable intersection *m,n∈*N *V*^*m ∩ Wn*, hence *A* is *Gδ* in *Y* .

Given any closed subset *C* of *X*, *C* is the intersection of *X* with some closed

subset *Cj* of *Y* . If *Y* is a continuous dcpo, then *Cj* is also a continuous dcpo by Lemma [10.2](#_bookmark31). Then *C* = T*n∈*N(*Cj ∩Wn*), showing that *C* is a *Gδ* subset of *Cj*, hence is domain-complete. If *Y* is a locally compact sober space, *Cj* is sober as a subspace

(being the equalizer of the indicator function of its complement and of the constant 0

map), and is locally compact: for every *x ∈ Cj*, for every open neighborhood *U ∩Cj* of *x* in *Cj* (where *U* is open in *Y* ), there is a compact saturated neighborhood *Q* of *x* in *Y* included in *U* ; then *Q ∩ Cj* is a compact saturated neighborhood of *x* in *Cj*

included in *U ∩ Cj*. Again *C* = T*n∈*N(*Cj ∩ Wn*), showing that *C* is a *Gδ* subset of

*Cj*, hence is LCS-complete. *2*

A space is *completely Baire* if and only if all its closed subspaces are Baire. This is strictly stronger than the Baire property. Proposition [10.3](#_bookmark32) and Corollary [10.1](#_bookmark30) together entail the following, which generalizes the fact that every quasi-Polish space is completely Baire [[8](#_bookmark63), beginning of Section 5].

**Corollary 10.4** *Every LCS-complete space is completely Baire.*

# Stone duality for domain-complete and LCS- complete spaces

There is an adjunction *O E* pt between **Top** and the category of locales **Loc**—the opposite of the category of frames **Frm**. (See [[13](#_bookmark68), Section 8.1], for example.) The functor *O* : **Top** *→* **Loc** maps every space *X* to *O X*, and every continuous map *f* to the frame homomorphism *O f* : *U '→ f—*1(*U* ). Conversely, pt: **Loc** *→* **Top** maps every frame *L* to its set of completely prime filters, with the topology whose open sets are *Ou* d=ef *{x ∈* pt *L | u ∈ x}*, for each *u ∈ L*. This adjunction restricts to an adjoint equivalence between the full subcategories of sober spaces and spatial locales, between the category of locally compact sober spaces and the opposite of the category of continuous distributive complete lattices by the Hofmann-Lawson theorem [[19](#_bookmark74)] (see also [[13](#_bookmark68), Theorem 8.3.21]), and between the category of continuous dcpos and the opposite of the category of completely distributive complete lattices [[13](#_bookmark68), Theorem 8.3.43].

Let us recall what quotient frames are, following [[17](#_bookmark72), Section 3.4]. More gen- erally, the book by Picado and Pultr [[31](#_bookmark86)] is a recommended reference on frames and locales. A *congruence preorder* on a frame *L* is a transitive relation *≤* such that *u ≤ v* implies *u ≤ v* for all *u, v ∈ L*, *i∈I ui ≤ v* whenever *ui ≤ v* for every

*i ∈ I*, and *u ≤* *n vi* whenever *u ≤ vi* for every *i*, 1 *≤ i ≤ n*. We can then form

*i*=1

the *quotient frame L/≤*, whose elements are the equivalence classes of *L* modulo

*≤∩ ≥*. Given any binary relation *R* on *L*, there is a least congruence preorder *≤R* such that *u ≤R v* for all (*u, v*) *∈ R*. In particular, for every subset *A* of *L*, there is a least congruence preorder *≤A* such that *T ≤A v* for every *v ∈ A*, where *T* is the largest element of *L*. Using [[31](#_bookmark86), Section 11.2] for instance, one can check that *L/≤A* can be equated with the subframe of *L* consisting of the *A-saturated* elements of *L*, namely those elements *u ∈ L* such that *u* = (*a ⇒ u*) for every *a ∈ A*, where *⇒* is Heyting implication in *L* (*a ⇒ u* d=ef *{b | a ∧ b ≤ u}*).

**Theorem 11.1** *The adjunction O E* pt *restricts to an adjoint equivalence between the category of LCS-complete spaces (resp., domain-complete spaces) and the oppo- site of the category of quotient frames L/≤A, where A is a countable subset of L and L is a continuous distributive (resp., completely distributive) continuous lattice.*

**Proof.** We use the following theorem, due to Heckmann [[17](#_bookmark72), Theorem 3.13]: given any completely Baire space *Y* , and any countable relation *R ⊆ O Y × O Y* , the quotient frame *O Y/≤R* is spatial, and isomorphic to the frame of open sets of

T

(*U,V* )*∈R*(*Y \ U* ) *∪ V* .

For every domain-complete (resp., LCS-complete) space *X*, written as

\

*↓*

*n∈*N

*Wn*, where each *Wn*

is open in the continuous dcpo (resp., locally sober

space) *Y* , *Y* is itself LCS-complete (Proposition [3.3](#_bookmark8)) hence completely Baire (Corol-

lary [10.4](#_bookmark33)). It follows from Heckmann’s theorem that *O X* is isomorphic to *O Y/≤A* where *A* d=ef *{Wn | n ∈* N*}*. Therefore *O X* is a quotient frame of a continuous distributive (resp., completely distributive) continuous lattice by the countable set *A*.

By Proposition [7.1](#_bookmark19), every LCS-complete space is sober, so the unit *x ∈ X '→*

*{U ∈ O X | x ∈ U} ∈* pt *O X* is a homeomorphism [[13](#_bookmark68), Proposition 8.2.22, Fact 8.2.5].

In the other direction, let *L* be a completely distributive (resp., continuous dis- tributive) continuous lattice. By the Hofmann-Lawson theorem, *L* is isomorphic to the open set lattice of some locally compact sober space *Y* . Without loss of general- ity, we assume that *L* = *O Y* . As above, *Y* is LCS-complete hence completely Baire. By Heckmann’s theorem, for every countable relation *R* on *L*, *L/≤R* is isomorphic

to *O X* where *X* d=ef T

(*U,V* )*∈R*

(*Y \ U* ) *∪ V* . In particular, for any countable subset

*A* d=ef *{Wn | n ∈* N*}* of *L*, we can equate *L/≤A* with *O X* where *X* d=ef T

*n∈*N

*Wn*.

By construction, *X* is domain-complete (resp., LCS-complete). Finally, the counit

*U ∈ L '→ OU* is an isomorphism because *L* is spatial [[13](#_bookmark68), Proposition 8.1.17]. *2*

# Consonance

For a subset *Q* of a topological space *X*, let □*Q* be the family of open neighborhoods of *Q*. A space is *consonant* if and only if, given any Scott-open family *U* of open sets, and given any *U ∈ U* , there is a compact saturated set *Q* such that *U ∈* □*Q ⊆ U* .

Equivalently, if and only if every Scott-open family of opens is a union of sets of the form □*Q*, *Q* compact saturated.

In a locally compact space, every open subset *U* is the union of the interiors *int*(*Q*) of compact saturated subsets *Q* of *U* , and that family is directed. It follows immediately that every locally compact space is consonant. Another class of conso- nant spaces is given by the regular Cˇech-complete spaces, following Dolecki, Greco

and Lechicki [[9](#_bookmark64), Theorem 4.1 and footnote 8].

Consonance is not preserved under the formation of *Gδ* subsets [[9](#_bookmark64), Proposi- tion 7.3]. Nonetheless, we have:

**Proposition 12.1** *Every LCS-complete space is consonant.*

**Proof.** Let *X* be the intersection of a descending sequence (*Wn*)*n∈*N of open subsets of a locally compact sober space *Y* . Let *U* be a Scott-open family of open subsets of *X*, and *U ∈ U* .

By the definition of the subspace topology, there is an open subset *U* of *Y* such that *U ∩ X* = *U* . By local compactness, *U ∩ W*0 is the union of the directed family of the sets *int*(*Q*), where *Q* ranges over the family *Q*0 of compact saturated subsets

^ ^

^

of *U*^ *∩ W* . We have [*↑ int*(*Q*) *∩ X* = *U*^ *∩ W ∩ X* = *U*^ *∩ X* = *U* . Since *U*

0

*Q∈Q*0

0

is in *U* and *U* is Scott-open, *int*(*Q*) *∩ X* is in *U* for some *Q ∈ Q*0. Let *Q*0 be this

compact saturated set *Q*, *U*^0 *U*^0 *⊆ Q*0 *⊆ U*^ *∩ W*0.

d=ef *int*(*Q*0), and *U*0

d=ef

*U*^0 *∩ X*. Note that *U*0 *∈ U* ,

We do the same thing with *U*^0 *∩ W*1 instead of *U*^ *∩ W*0. There is a compact

saturated subset *Q*1 of *U*^0 *∩ W*1 such that *int*(*Q*1) *∩ X* is in *U* . Then, letting

*U*1 = *int*(*Q*1), *U*1 = *U*1 *∩ X*, we obtain that *U*1 *∈ U* , *U*1 *⊆ Q*1 *⊆ U*0 *∩ W*1.

^ ^ ^ ^

def

def

Iterating this construction, we obtain for each *n ∈* N a compact saturated subset *Qn* and an open subset *U*^*n* of *Y* , and an open subset *Un* of *X* such that *Un ∈U* for each *n*, and *U*^*n*+1 *⊆ Qn*+1 *⊆ U*^*n ∩ Wn*.

Let *Q* d=ef T

in *Y* .

*n∈*N

*Qn*. Since *Y* is sober hence well-filtered, *Q* is compact saturated

Since *Q ⊆* T*n∈*N *Wn* = *X*, *Q* is a compact saturated subset of *Y* that is included in *X*, hence a compact subset of *X* by Lemma [8.1](#_bookmark21), item 3.

We have *Q ⊆ Q*0 *⊆ U ∩ W*0 *⊆ U* , and *Q ⊆ X*, so *Q ⊆ U ∩ X* = *U* . Therefore

^ ^ ^

*U ∈* □*Q*.

For every *W ∈ Q*, write *W* as the intersection of some open subset *W*^ of *Y*

□

with *X*. Since *Q* = T*n∈*N *Qn ⊆ W*^, by well-filteredness some *Qn* is included in *W*^.

^ ^

Hence *Un ⊆ Qn ⊆ W* . Taking intersections with *X*, *Un ⊆ W* . Since *Un* is in *U* , so is *W* . *2*

**Remark 12.2** In the proof of Proposition [12.1](#_bookmark36), *Q* is a *Gδ* subset of *X*. Indeed,

^*n*+1 *n*+1 ^*n n* T*n∈*N *n* T*n∈*N *n*

*U ⊆ Q ⊆ U ∩ W* for every *n ∈* N, hence *Q* = *Q* = *Q ∩ X* = T*n∈*N(*Un ∩ X*). Hence we can refine Proposition [12.1](#_bookmark36) to: in an LCS-complete space *X*, every Scott-open family *U* of open subsets of *X* is a union of sets □*Q*, where

^

the sets *Q* are compact *Gδ*, not just compact.

# The space *LX* for *X* LCS-complete

The topological coproduct of two consonant spaces is not in general consonant [[29,](#_bookmark84) Example 6.12], whence the need for the following definition. Let *n ⊙ X* denote the coproduct of *n* identical copies of *X*.

**Definition 13.1** [*⊙*-consonant] A topological space *X* is called *⊙-consonant* if and only if, for every *n ∈* N, *n ⊙ X* is consonant.

In particular, every *⊙*-consonant space is consonant.

**Lemma 13.2** *Every LCS-complete space is ⊙-consonant.*

**Proof.** Every topological coproduct of LCS-complete spaces is LCS-complete, as we will see in Proposition [15.1](#_bookmark46). For now, let us just write the LCS-complete space *X*

\

as *↓*

*m∈*N

*Wm*, where each *Wm*

is open in the locally compact sober space *Y* . Then

*n ⊙ Y* is sober, because coproducts of sober spaces are sober [[13](#_bookmark68), Lemma 8.4.2].

Since *O*(*n ⊙ Y* ) is isomorphic to (*O Y* )*n*, it is a continuous lattice, so *n ⊙ Y* is core-

\

compact, hence locally compact. Then *n⊙X* arises as the *Gδ*

subset *↓*

*m∈*N

*n⊙Wm*

of *n ⊙ Y* . Finally, by Proposition [12.1](#_bookmark36), *n ⊙ X* is consonant. *2*

Let [*X → Y* ] denote the space of all continuous maps from *X* to *Y* . A *step function g* from *X* to *Y* is a continuous map whose image is finite. For every *y* in the image Im *g* of *g*, there is an open neighborhood *Vy* of *y* such that *Vy ∩* Im *g* =

*↑ y∩* Im *g*, namely, that contains only the elements from Im *g* that are above *y*. This is because *↑ y* is the filtered intersection of the family (*Vi*)*i∈I* of open neighborhoods of *y*, and (*Vi ∩* Im *g*)*i∈I* is filtered and finite, hence reaches its infimum. Then

*Uy* d=ef

*g—*1(*↑ y*) is open because it is also equal to *g—*1(*Vy*). Moreover, *g* is the

map that sends every element of *Uy \* *y′∈*Im *g,y<y′ Uy′* to *y*. When *Y* also has a least element *⊥*, *g* is then also the pointwise supremum sup*y∈*Im *g Uy y*, where the elementary step function *Uy y* maps every element of *Uy* to *y* and all other elements to *⊥*. (The sup is always defined in this case, whatever *Y* is provided it has a least element.) This generalizes the usual notion of step function. The following should be familiar to domain theorists—except that the step functions we build are not required to be way-below *f* .

A *bounded* family is a set of elements that has an upper bound.

**Lemma 13.3** *Let X be a topological space, and Y be a continuous poset in which every ﬁnite bounded family of elements has a least upper bound, with its Scott topol- ogy. Every continuous map f* : *X → Y is the pointwise supremum of a directed family of step functions.*

**Proof.** In *Y* , the empty family has a least upper bound, meaning that *Y* has a least element *⊥*. The constant *⊥* map is a step function below *f* . Given any two step functions *g*, *h* below *f* , let *k* map every *x ∈ X* to the supremum of *g*(*x*) and *h*(*x*), which exists because the family *{g*(*x*)*, h*(*x*)*}* is bounded by *f* (*x*). The image of *k* is clearly finite. We claim that *k* is continuous. For every open subset *V* of *Y* ,

let *DV* be the set of pairs (*y*1*, y*2) *∈* Im *g ×* Im *h* such that the supremum of *y*1 and

*y*2 is in *V* . This is a finite set. Then *k—*1(*V* )= (*y ,y* )*∈D g—*1(*↑ y*1) *∩ h—*1(*↑ y*2) is

1

2

*V*

open. Since *k* is continuous and Im *k* is finite, *k* is a step function. This shows that

the family *D* of step functions pointwise below *f* is directed.

For every *x ∈ X*, and every *y f* (*x*) in *Y* , the step function *f—*1(***↑****y*) *y* is in *D*, and its value at *x* is *y*. Since the supremum of all the elements *y* way-below *f* (*x*) is *f* (*x*), sup*{g*(*x*) *| g ∈ D}* = *f* (*x*). *2*

Given a finite subset *B* of *Y* , where *Y* is a poset in which every finite bounded family *J* of elements has a least upper bound sup *J*, and given any *|B|*-tuple (*Vy*)*y∈B* of open subsets of *X*, the notation sup*y∈B Vy y* defines a step function if and only if every subset *J ⊆ B* such that *y∈J Vy /*= *∅* is bounded: in that case sup*y∈B Vy y* maps every point *x ∈ X* to sup *J*, where *J* d=ef *{y ∈ B | x ∈ Vy}*; otherwise, we say that sup*y∈B Vy y* is *undeﬁned*.

T

**Proposition 13.4** *Let X be a ⊙-consonant space. Let Y be a continuous poset in which every ﬁnite bounded family of elements has a least upper bound, with its Scott topology. The compact-open topology on* [*X → Y* ] *is equal to the Scott topology.*

**Proof.** The compact-open topology has subbasic open sets [*Q ⊆ V* ] d=ef *{f ∈* [*X → Y* ] *| Q ⊆ f—*1(*V* )*}*, where *Q* is compact saturated in *X* and *V* is open in *Y* . It is easy to see that [*Q ⊆ V* ] is Scott-open. In the converse direction, let *W* be a Scott-open subset of [*X → Y* ], and *f ∈ W*. Our task is to find an open neighborhood of *f* in the compact-open topology that is included in *W*.

The function *f* is the pointwise supremum of a directed family of step functions, by Lemma [13.3,](#_bookmark39) hence one of them, say *g*0, is in *W*. We can write *g*0 as *g*0 d=ef sup*y∈B Uy y*, with *B* finite, and where each *Uy* is open.

Consider the maps sup*y∈B Uy zy*, where *zy y* for each *y ∈ B*. Those maps are defined: for every *J ⊆ B* such that *y∈J Uy /*= *∅*, sup *J* exists and is an upper bound of *{zy | y ∈ J}*. Explicitly, those maps sup*y∈B Uy zy* send each *x ∈ X* to sup*{zy | y ∈ J}*, where *J* d=ef *{y ∈ B | x ∈ Uy}*. Those maps form a directed family whose supremum is *g*0, hence one of them, say *g* d=ef sup *Uy zy*, is in *W*.

T

*y∈B*

Let *G* be the set of subsets *J* of *B* such that *ZJ* d=ef *{zy | y ∈ J}* is bounded. For each *J ∈ G*, *ZJ* has a least upper bound sup *ZJ* , by assumption. Let *V* be the set of *|B|*-tuples (*Vy*)*y∈B* of open subsets of *X* such that sup*y∈B Vy zy* is undefined or in *W*. Ordering those tuples by componentwise inclusion, we claim that *V* is Scott-open.

We first check that *V* is upwards-closed. Let (*Vy*)*y∈B* be an element of *V*, and

(*V j*)

*y*

*y∈B*

be a family of open sets such that *Vy ⊆ V j* for every *y ∈ B*. If sup*y∈B Vy*

*zy* is undeTfined, then there is a subset *J* of *B*, not in *G*, and such that T*y∈J Vy /*=

*y*

*V*

*y*

*∅*. Then

*y∈J*

*j*

*y*

is non-empty as well, so sup*y∈B V j*

*zy* is undefined, too. If

sup*y∈B Vy zy* is defined, then either sup*y∈B V j zy* is undefined, or sup*y∈B Vy*

*y*

*zy ≤* sup*y∈B V j zy*. In both cases, (*V j*)

*y y y∈B*

is in *V*.

Next, let (*Vy*)*y∈B* be a *|B|*-tuple of open subsets of *X*, let *I* be some indexing

set and assume that for every *y ∈ B*, *Vy*

= *†*

*i∈I*

[

*Vyi*

, where each *Vyi*

is open. If

sup*y∈B Vy zy* is undefined, then there is a subset *J* of *B*, not in *G*, and such

T T

that *y∈J Vy /*= *∅*. We pick an element *x* from *y∈J Vy*. For each *y ∈ B*, there is an index *i ∈ I* such that *x ∈ Vyi*, and we can take the same *i* for every *y ∈ B* by directedness. Then sup*y∈B Vyi zy* is undefined, hence (*Vyi*)*y∈B* is in *V*. If instead sup*y∈B Vy zy* is defined, then every map sup*y∈B Vyi zy*, *i ∈ I*, is defined, too.

We claim that sup*y∈B Vy zy* = sup*†*

*i∈I*

(sup

*y∈B*

*Vyi zy*). We fix *x ∈ X*, and we

let *J* d=ef *{y ∈ B | x ∈ Vy}*. For every *y ∈ J*, *x* is in *Vy* = sup*†*

*i∈I*

*Vyi* so *x ∈ Vyi* for

some *i ∈ I*. By directedness, we can choose the same *i* for every *y ∈ J*. It follows that (sup*y∈B Vyi zy*)(*x*)= sup *ZJ* = (sup*y∈B Vy zy*)(*x*). This shows the claim.

Now that we know that sup*y∈B Vy zy* = sup*†*

*i∈I*

(sup

*y∈B*

*Vyi zy*), and since that

is in the Scott-open set *W*, sup*y∈B Vyi zy* is in *W* for some *i ∈ I*, in particular

(*Vyi*)*y∈B* is in *V*.

We know that *V* is Scott-open. Moreover, and recalling that *g* = sup*y∈B Uy zy* is in *W*, the *|B|*-tuple (*Uy*)*y∈B* is in *V*. We may equate *|B|*-tuples of open subsets with open subsets of *|B|⊙ X*, and then the compact saturated subsets of *|B|⊙ X* are naturally equated with *|B|*-tuples of compact saturated subsets of *X*. Since *X* is *⊙*-consonant, there is a *|B|*-tuple of compact saturated subsets *Qy*, *y ∈ B*, such that *Qy ⊆ Uy* for every *y ∈ B* and such that every *|B|*-tuple (*Vy*)*y∈B* of open sets such that *Qy ⊆ Vy* for every *y ∈ B* is in *V*.

Let us consider the compact-open open subset *Wj* d=ef T

*y∈B*

[*Qy ⊆ ↑zy*]. Since

*Qy ⊆ Uy* for every *y ∈ B*, *f* is in *Wj*: for every *y ∈ B*, for every *x ∈ Qy*, *x* is in *Uy*, so *f* (*x*), which is larger than or equal to *g*0(*x*), hence to *y*, is in ***↑****zy*. We

claim that *Wj* is included in *W*. Let *h* be any element of *Wj*. For every *y ∈ B*,

let *Vy* d=ef *h—*1(***↑****zy*). Since *h ∈* [*Qy ⊆ ↑zy*], *Qy ⊆ Vy*, so (*Vy*)

*y∈B*

is in *V*, meaning

that sup*y∈B Vy zy* is undefined or in *W*. But it cannot be undefined: for every

*x ∈ X*, letting *J* d=ef *{y ∈ B | x ∈ Vy}*, *h*(*x*) is an upper bound of *{zy | y ∈ J}*, by the definition of *Vy*. The same argument shows that sup*y∈B Vy zy ≤ h*. Since sup*y∈B Vy zy* is in *W* and *W* is upwards-closed, *h* is also in *W*. *2*

Let *LX* denote the space of all continuous maps from *X* to R+*σ*, the set of extended non-negative real numbers under the Scott topology. Those are usually

known as the *lower semicontinuous* maps from *X* to R+. *Y* d=ef

satisfies the assumptions of Proposition [13.4.](#_bookmark40) Hence:

R+*σ* certainly

**Corollary 13.5** *Let X be a ⊙-consonant space, for example an LCS-complete space. The compact-open topology on LX is equal to the Scott topology on LX. 2*

As an application, let us consider Theorem 4.11 of [[14](#_bookmark69)]. (We will give an- other application in Section [16](#_bookmark48).) This expresses a homeomorphism between two kinds of objects. The first one is the space PAP(*X*) of *sublinear previsions* on *X*, namely Scott-continuous sublinear maps *F* from *LX* to R+*σ*, where sublin- ear means that *F* (*ah*) = *aF* (*h*) and *F* (*h* + *hj*) *≤ F* (*h*)+ *F* (*hj*) for all *a ∈* R+, *h, hj ∈ LX*. PAP(*X*) is equipped with the *weak topology*, whose subbasic open

sets are [*h > r*] d=ef

*{F ∈* PAP(*X*) *| F* (*h*) *> r}*, *h ∈ LX*, *r ∈* R+. The second

one is *Hcvx*(**V**w(*X*)), where **V**w(*X*) is the space of continuous valuations on *X*

[[23,](#_bookmark82)[22](#_bookmark77)] (more details in Section [18](#_bookmark52)), or equivalently the space of *linear* previsions (defined as sublinear previsions, except that *F* (*h* + *hj*) = *F* (*h*)+ *F* (*hj*) replaces the inequality *F* (*h* + *hj*) *≤ F* (*h*)+ *F* (*hj*)), *H*(*Y* ) is the space of non-empty closed subsets of *Y* with the lower Vietoris topology, and *Hcvx*(*Y* ) is the subspace of *H*(*Y* ) consisting of its convex sets. The already cited Theorem 4.11 of [[14](#_bookmark69)] states that PAP(*X*) and *Hcvx*(**V**w(*X*)) are homeomorphic if *LX* is *locally convex* in its Scott topology, meaning that every element of *LX* has a base of convex open neighborhoods. The homeomorphism is given by *r*AP : *Hcvx*(**V**w(*X*)) *'→* PAP(*X*),

*r*AP(*C*)(*h*) d=ef

sup

*ν∈C*

∫*x∈*∫*X*

*h*(*x*)*dν*, and *s*AP : PAP(*X*) *→ Hcvx*(**V**w(*X*)), *s*AP(*F* ) d=ef

a homeomorphism is when *X* is core-compact. We have a second class of spaces where that holds:

*{ν ∈* **V**w(*X*) *| ∀h ∈ LX,*

*x∈X h*(*x*)*dν ≤ F* (*h*)*}*. The primary case when those form

**Lemma 13.6** *For every ⊙-consonant space X, for example an LCS-complete space,*

*LX is locally convex in its Scott topology.*

**Proof.** By Corollary [13.5](#_bookmark41), it suffices to show that it is locally convex in its compact- open topology, namely that every element of *LX* has a base of convex open neigh-

borhoods. It is routine to show that every basic open T*n* [*Qi ⊆* (*ai, ∞*]] is convex.*2*

*i*=1

**Corollary 13.7** *For every LCS-complete space X, the maps s*AP *and r*AP *deﬁne a homeomorphism between* PAP(*X*) *and Hcvx*(**V***w*(*X*))*.* *2*

This holds in particular for all continuous complete quasi-metric spaces in their *d*-Scott topology, in particular for all complete metric spaces in their open ball topology.

# 14 Categorical limits

**Lemma 14.1** *Every domain-complete space is a Gδ subset of a pointed continuous dcpo. Every LCS-complete space is a Gδ subset of a compact, locally compact and sober space.*

**Proof.** Let *X* be the intersection T*n∈*N *Wn* of a descending family of open subsets of *Y* . We define the lifting *Y⊥* of *Y* as *Y* plus a fresh element *⊥* below all others (when *Y* is a dcpo), or as *Y* plus a fresh element, with open sets those of *Y* plus

*Y⊥* itself (if *Y* is a topological space). If *Y* is a continuous dcpo, then so is *Y⊥* (it is easy to see that *x* is way-below *y* in *Y⊥* if and only if it is in *Y* , or *x* = *⊥*), and *Y⊥* is pointed; if *Y* is locally compact then so is *Y⊥* [[13](#_bookmark68), Exercise 4.8.6]; and if *Y* is sober then so is *Y⊥* [[13](#_bookmark68), Exercise 8.2.9]; and *Y⊥* is compact. Every open subset of *Y* is open in *Y⊥*. Therefore *X* is the *Gδ* subset *n∈*N *Wn* of *Y⊥*. *2*

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**Proposition 14.2** *The topological product of a countable family of domain- complete (resp., LCS-complete) spaces is domain-complete (resp., LCS-complete).*

**Proof.** For each *i ∈* N, let *Xi* be the intersection T*n∈*N *Win* of a descending fam- ily of open subsets of a continuous dcpo *Yi*. We may assume that *Yi* is pointed, too, by Lemma [14.1](#_bookmark44). The product of pointed continuous dcpos is a continu- ous dcpo, and the Scott topology on the product is the product topology [[13,](#_bookmark68)

TPropo s ition 5.1.56]. Th en the to polog ical product *i∈*N *Xi* arises as the *Gδ* subset

*n∈*N

*n i*=0

*Wi*(*n—i*) *×*

+*∞*

*i*=*n*+1

*Yi*

of

*i∈*N *Yi*.

We use a similar argument when each *Yi* is locally compact and sober instead.

By Lemma [14.1](#_bookmark44), we may assume that *Yi* is compact. Every product of a family of compact, locally compact spaces is (compact and) locally compact [[13](#_bookmark68), Proposi- tion 4.8.10], and every product of sober spaces is sober [[13](#_bookmark68), Theorem 8.4.8]. *2*

**Proposition 14.3** *The categories of domain-complete, resp. LCS-complete spaces, do not have equalizers.*

**Proof.** Let *X* d=ef R, with its usual topology, and *Y* d=ef P(R), with the Scott topology of inclusion. Those are domain-complete spaces. Define *f, g* : *X → Y* by *f* (*x*) = (R *\ {x}*) *∪* Q and *g*(*x*) d=ef R. Those are continuous maps: in the case of *f* , this is because *f—*1(*↑ A*), for every finite *A ⊆* R, is the complement of the finite set *A \* Q. The equalizer of *f* and *g* in **Top** is Q, which is not LCS-complete (Remark [9.6](#_bookmark28)). That is not enough to show that *f* and *g* do not have an equalizer in the category of LCS-complete (resp., domain-complete) spaces, hence we argue as follows.

Assume *f* and *g* have an equalizer *i* : *Z → X* in the category of LCS-complete spaces, resp. of domain-complete spaces. For every *z ∈ Z*, *f* (*i*(*z*)) = *g*(*i*(*z*)), so *i*(*z*) *∈* Q. Since *i* is a (regular) mono, and the one-point space *{∗}* is domain- complete, *i* is injective: any two distinct points in *Z* define two distinct morphisms from *{∗}* to *Z*, whose compositions with *i* must be distinct. If there is a rational point *q* that is not in the image of *i*, then the inclusion map *j* : *{q} → X* is con- tinuous, *{q}* is domain complete, *f ◦ j* = *g ◦ j* since *q* is rational, but *j* does not factor through *i*: contradiction. Hence the image of *i* is exactly Q. This allows us to equate *Z* with Q, with some topology, and *i* with the inclusion map. Since *i* is continuous, the topology on *Z* is finer than the usual topology on Q—the subspace topology from R.

We claim that the topology of *Z* is exactly the usual topology on Q. Let *C* be a closed subset of *Z*, and let *cl*(*C*) be its closure in R. It suffices to show that *cl*(*C*) *∩ Z* is included in, hence equal to *C*: this will show that *C* is closed in Q with its usual topology. Take any point *x* from *cl*(*C*) *∩ Z*. Since R is first-countable, there is a sequence (*xn*)*n∈*N of elements of *C* that converges to *x*. Let us consider N*∞*, the one-point compactification of N, where N is given the discrete topology. This is a compact Hausdorff space, hence it is trivially LCS-complete. It is also countably-based, hence domain-complete (and quasi-Polish) by Theorem [9.5](#_bookmark27). The

map *j* : N*∞ → X* defined by *j*(*n*) d=ef *xn*, *j*(*∞*) d=ef *x* is continuous, and *f ◦ j* = *g ◦ j* since the image of *j* is included in Q. By the universal property of equalizers, *j* = *i ◦ h* for some continuous map *h* : N*∞ → Z*. We must have *h*(*n*) = *xn* and *h*(*∞*) = *x*. Since *∞* is a limit of the numbers *n ∈* N in N*∞*, *x* must be a limit of (*xn*)*n∈*N in *Z*. The fact that *C* is closed in *Z* implies that *x* is in *C*, too, completing

the argument.

Hence *Z* is Q, and has the same topology. But this is impossible, since Q is not LCS-complete. *2*

**Remark 14.4** In contrast, the category of quasi-Polish spaces has equalizers, and they are obtained as in **Top**. Indeed, for all continuous maps *f, g* : *X → Y* between

two countably-based *T*0 spaces *X* and *Y* , the coequalizer [*f* = *g*] d=ef

*{x ∈ X |*

*f* (*x*)= *g*(*x*)*}* in **Top** is a **Π**0 subspace of *X* [[7](#_bookmark61), Corollary 10], and the **Π**0 subspaces

2 2

of a quasi-Polish space are exactly its quasi-Polish subspaces [[7](#_bookmark61), Corollary 23]. We

note that those properties fail in domain-complete and LCS-complete spaces: the singleton subspace *{I}* of P(*I*) (see Remark [5.2](#_bookmark15)) is trivially quasi-Polish but not **Π**0 in P(*I*), because the **Π**0 subsets of P(*I*) that contain *I*, the top element, must be *Gδ* subsets, and we have seen that *{I}* is not *Gδ* in P(*I*). The reason of the failure is deeper: as the following proposition shows, the **Π**0 subspaces of an LCS-complete

2

2

2

space can fail to be LCS-complete.

Using a named coined by Heckmann [[17](#_bookmark72)], let us call *UCO subset* of a space *X* any union of a closed subset with an open subset. All UCO subsets are trivially **Π**0, and **Π**0 subsets are countable intersections of UCO subsets.

2 2

**Proposition 14.5** *The UCO subsets of compact Hausdorff spaces are not in gen- eral compactly Choquet-complete. In particular, the UCO subsets of LCS-complete spaces are not in general LCS-complete.*

**Proof.** The second part follows from the first part by Fact [6.1](#_bookmark17) and Proposition [9.1](#_bookmark25).

Let *X* d=ef

[0*,* 1]*I* , for some uncountable set *I*, and where [0*,* 1] has the usual

metric topology. This is compact Hausdorff. Let us fix a closed subset *C* of [0*,* 1] with empty interior and containing 0 and at least one other point *a* (for example,

*{*0*, a}*), and let *U* be its complement. Note that *U* is dense in [0*,* 1]. *CI* is closed in *X*, since its complement is the open subset *i∈I π—*1(*U* ), where *πi* : *X →* [0*,* 1] is projection onto coordinate *i*. Let us define *Y* as the UCO set *{***0***}∪* (*X \ CI* ), where **0** is the point whose coordinates are all 0. We claim that *Y* is not compactly Choquet-complete.

*i*

To this end, we assume it is, and we aim for a contradiction. In the strong

Choquet game, let *β* play *xn* d=ef **0** at each round of the game. Let *Un*, *n ∈* N, be the open sets played by *α*. By assumption, T*n∈*N *Un* is a compact subset *Q* of *Y* , hence also of *X* by Lemma [8.1](#_bookmark21). For each *n ∈* N, *Un* is the intersection of *Y* with an

open neighborhood of **0** in *X*, and that open neighborhood contains a basic open set

T*i∈Jn*

*π—*1(*Vni*), where *Jn* is finite and *Vni* is an open neighborhood of 0 in [0*,* 1]. In

particular, *Un* contains T*i∈Jn π* (*{*0*}*) *∩ Y* . It follows that *K* = T*n∈*N *Un* contains

*i*

*—*1

*i*

T*i∈J*

*π—*1(*{*0*}*) *∩ Y* , where *J* d=ef

*n∈*N

*Jn* is countable.

Then *I\J* is uncountable, hence non-empty. Let *k* be any element of *I \J*. Since

*i*

*π—*1(*C*) contains *CI* , and *Y* contains *X \ CI* , *Y* contains *π—*1(*U* ), so *K* contains

T*k —*1 *—*1 T *k* 1

*i∈J πi* (*{*0*}*)T*∩ πk* (*U* ). We claim that *K* must contain *i∈J πi* (*{*0*}*). For every

element ***x*** in

*i∈J π—*1(*{*0*}*), let *xk* be its *k*th coordinate, and for every *b ∈* [0*,* 1],

*i*

write ***x***[*k* := *b*] for the same element with coordinate *k* changed to *b*. Since *U* is dense in [0*,* 1], *xk* is the limit of a sequence (*bn*)*n∈*N of elements of *U* . Then ***x***[*k* := *bn*], *n ∈* N, form a sequence in *K* that converges to ***x***. Since *K* is compact in a Hausdorff space, hence closed, ***x*** is in *K*.

Since *K* is included in *Y* , *Y* contains T*i∈J π—*1(*{*0*}*), too. However **0**[*k* := *a*] is

*i*

in the latter, but not in the former since it is different from **0** and in *CI* . *2*

# Colimits

**Proposition 15.1** *The topological coproduct of an arbitrary family of domain- complete (resp., LCS-complete) spaces is domain-complete (resp., LCS-complete).* **Proof.** For each *i ∈ I*, let *Xi* be the intersection T*n∈*N *Win* of a descending family

of open subsets of a continuous dcpo *Yi*. The coproduct of continuous dcpos is

a continuous dcpo again, and the Scott topology is the coproduct topology [[13,](#_bookmark68)

TPropo sition 5.1.59] . Then we can express the coproduct *i∈I Xi* as the *Gδ* subset

*n∈*N

*i∈I Win* of

*i∈I Yi*.

When each *Yi* is locally compact and sober, we use a similar argument, observing

the following facts. First, the compact saturated subsets of each *Yi* are compact sat- urated in *i∈I Yi*. It follows easily that *i∈I Yi* is locally compact. The coproduct of arbitrarily many sober spaces is sober, too [[13](#_bookmark68), Lemma 8.4.2]. *2*

In order to show that coequalizers fail to exist, we make the following observa- tion.

**Lemma 15.2** *Every countable compactly Choquet-complete space is ﬁrst-countable, hence countably-based.*

**Proof.** Let *X* be countable and compactly Choquet-complete. Assume that *X* is not first-countable. There is a point *x* that has no countable base of open neigh- borhoods. For each *y ∈ X \ ↑ x*, *X \ ↓ y* is an open neighborhood of *x*, and the intersection of those sets is *↑ x*. Since *X* is countable, we can therefore write *↑ x* as the intersection of countably many open sets (*Wn*)*n∈*N. Note that this does *not*

say that those open set form a base of open neighborhoods: we do not have a

contradiction yet.

In the strong Choquet game, we let *β* play the same point *xn* d=ef

*x* at each

step. Initially, *V*0 d=ef *W*0, and at step *n* + 1, *β* plays *Vn*+1 d=ef *Un ∩ Wn*+1, where

\

\

*U* was the last open set played by *α*. Note that *↓ V*

*n*

*n*

*n∈*N

*⊆ ↓ W*

*n∈*N

*n*

= *↑ x*,

while the converse inclusion is obvious. Since *X* is compactly Choquet-complete,

(*Vn*)*n∈*N is a base of open neighborhoods of some compact saturated set *Q*, and since

\*↓ V*

= *↑ x*, *Q* = *↑ x*, and therefore (*V* )

is a base of open neighborhoods of

*n∈*N *n*

*n n∈*N

*x*: contradiction.

Finally, every countable first-countable space is countably-based. *2*

**Proposition 15.3** *The categories of domain-complete, resp. LCS-complete spaces, do not have coequalizers.*

**Proof.** Let N*∞* be the one-point compactification of N, the latter with its discrete topology. Let us form the coproduct *Y* of countably many copies of N*∞*. Its elements are (*k, n*) where *k ∈* N, *n ∈* N*∞*. The *sequential fan* is the quotient of *Y* by the equivalence relation that equates every (*k, ∞*), *k ∈* N. This is a known example of a countable space that is not countably-based. That can be realized as the coequalizer of *f, g* : *X → Y* in **Top**, where *X* is N with the discrete topology, *f* (*k*) d=ef (*k, ∞*), *g*(*k*) d=ef (0*, ∞*). Note that *X* and *Y* are domain-complete: *X* is trivially locally compact and sober (since Hausdorff), and countably-based, then use Theorem [9.5](#_bookmark27); for similar reasons, N*∞* is domain-complete, then use Proposition [15.1](#_bookmark46) to conclude that *Y* is, too.

Let us assume that *f* and *g* have a coequalizer *q* : *Y → Z* in the category of LCS- complete spaces, resp. of domain-complete spaces. There is no reason to believe that *Z* is the sequential fan, hence we have to work harder. There is no reason to believe that *q* is surjective either, since epis in concrete categories may fail to be surjective. However, *q* is indeed surjective, as we now show. This is done in several steps. Let *z ∈ Z*.

def

The closure of *z* is *↓ z*, so *χZ\↓ z* : *Z →* S is continuous, where S = *{*0 *<* 1*}* is Sierpin´ski space—trivially a continuous dcpo, hence a domain-complete space. Let **1** be the constant map equal to 1 *∈* S. If *↓ z* did not intersect the image of *q*, then *χZ\↓ z ◦ q* would be equal to **1** *◦ q*, although *χZ\↓ z /*= **1**, and that is impossible since *q* is epi. Therefore *↓ z* intersects the image of *q*.

Imagine that there were two distinct points *q*(*k*1*, n*1), *q*(*k*2*, n*2) in *↓ z*. In par- ticular, (*k*1*, n*1) and (*k*2*, n*2) are distinct. Also, not both *n*1 and *n*2 are equal to

*∞*, since otherwise *q*(*k*1*, n*1) = *q*(*k*1*, ∞*) = *q*(*f* (*k*1)) = *q*(*g*(*k*1)) = *q*(*g*(*k*2)) (since *g* is a constant map) = *q*(*f* (*k*2)) = *q*(*k*2*, ∞*) = *q*(*k*2*, n*2). Without loss of general- ity, let us say that *n*1 */*= *∞*. We consider the map *χ{*(*k*1*,n*1)*}* : *Y → {*0*,* 1*}*, where

*{*0*,* 1*}* has the discrete topology (and is a continuous dcpo with the equality order-

ing, hence domain-complete). Observe that this is a continuous map, owing to the fact that *n*1 */*= *∞*. Since *χ{*(*k*1*,n*1)*} ◦ f* = *χ{*(*k*1*,n*1)*} ◦ g* (= 0), *χ{*(*k*1*,n*1)*}* = *h ◦ q* for some unique continuous map *h* : *Z → {*0*,* 1*}*, by the definition of a coequalizer. Then *h*(*q*(*k*1*, n*1)) = 1, while *h*(*q*(*k*2*, n*2)) = 0, but since *h* is continuous it must be monotonic with respect to the underlying specialization orderings, so *q*(*k*1*, n*1) *≤ z* implies *h*(*q*(*k*1*, n*1)) = *h*(*z*), and similarly *h*(*q*(*k*2*, n*2)) = *h*(*z*). This would imply 1= *h*(*z*) = 0, a contradiction. Hence there is exactly one point *zj ≤ z* in the image of *q*.

Consider the two maps *χZ\↓ z′ , χZ\↓ z* : *Z →* S. For every (*k, n*) *∈ Y* , if *χZ\↓ z′* (*q*(*k, n*)) = 0, then *q*(*k, n*) *≤ zj ≤ z*, so *χZ\↓ z* (*q*(*k, n*)) = 0; conversely, if *χZ\↓ z* (*q*(*k, n*)) = 0, then *q*(*k, n*) is below *z* and is therefore the unique point *zj ≤ z* in the image of *q*, so *χZ\↓ z′* (*q*(*k, n*)) = *χZ\↓ z′* (*zj*) = 0. Hence we have two mor- phisms which yield the same map when composed with *q*. Since *q* is epi, they must be equal. It follows that *↓ z* = *↓ zj*, and since *Z* is *T*0 (since sober, see Proposi-

tion [7.1](#_bookmark19)), *z* = *zj*. Therefore *z* is in the image of *q*. This completes the proof that *q*

is surjective.

Since *q* is surjective, and *Y* is countable, so is *Z*. By Lemma [15.2](#_bookmark47), *Z* is first- countable. Let *ω* d=ef *q*(0*, ∞*). For every *k ∈* N, *q*(*k, ∞*) = *q*(*f* (*k*)) = *q*(*g*(*k*)) = *ω*. Let (*Bk*)*k∈*N be a countable base of open neighborhoods of *ω* in *Z*. For each *k ∈* N, since (*k, n*)*n∈*N converges to (*k, ∞*) in *Y* , (*q*(*k, n*))*n∈*N converges to *ω*, so *q*(*k, n*) is in *Bk* for *n* large enough. Let us fix some *nk ∈* N such that (*k, n*) *∈ q—*1(*Bk*) for every *n ≥ nk*. Let *h* : *Y → {*0*,* 1*}* map every point (*k, n*) to 0 if *n ≤ nk*, to 1 if *n > nk*. This is continuous, *h ◦ f* = **1** = *h ◦ g*, so *h* = *hj ◦ q* for some unique continuous map *hj* : *Z → {*0*,* 1*}*. Since *h*(0*, ∞*) = 1, *hj*(*ω*) = 1. By definition of a base, the open neighborhood *hj—*1(*{*1*}*) of *ω* contains some *Bk*. Recall that (*k, nk*) is in *q—*1(*Bk*),

hence also in *q—*1(*hj—*1(*{*1*}*)) = *h—*1(*{*1*}*), so *h*(*k, nk*) = 1. However, by definition of

*h*, *h*(*k, nk*) = 0. We reach a contradiction, so the coequalizer of *f* and *g* does not exist. *2*

**Remark 15.4** The same proof shows that the category of quasi-Polish spaces does not have coequalizers.

# The failure of Cartesian closure

**Proposition 16.1** *In the category of domain-complete, resp. LCS-complete spaces, every exponentiable object is locally compact sober. The categories of domain- complete, resp. LCS-complete spaces, are not Cartesian-closed.*

**Proof.** Let *X* be an exponentiable object in any of those categories. By [[13](#_bookmark68), The- orem 5.5.1], in any full subcategory of **Top** with finite products and containing 1 d=ef *{∗}* as an object, and up to a unique isomorphism, the exponential *Y X* of two objects *X*, *Y* is the space [*X → Y* ] of all continuous maps from *X* to *Y* , with some uniquely determined topology. We take *Y* d=ef S. Then [*X → Y* ] can be equated with the lattice *O X* of open subsets of *X*. The application map from [*X → Y* ] *× X* to *Y* is continuous, and notice that product *×* here is just topolog- ical product (Proposition [15.1](#_bookmark46)). It follows that the graph (*∈*) of the membership relation on the topological product *X × O X* is open. By [[13](#_bookmark68), Exercise 5.2.7], this happens if and only if *X* is core-compact. Since *X* is also sober (Proposition [7.1](#_bookmark19)), and sober core-compact spaces are locally compact [[13](#_bookmark68), Theorem 8.3.10], *X* must be locally compact. Now take any non-locally compact LCS-complete space, for example Baire space NN, which is Polish but not locally compact. *2*

**Remark 16.2** The same proof shows that the category of quasi-Polish spaces is not Cartesian-closed. A similar proof, with [0*,* 1] replacing S, would show that the category of Polish spaces is not Cartesian-closed, using Arens’ Theorem [[3]](#_bookmark58) (see also [[13](#_bookmark68), Exercise 6.7.25]): the completely regular Hausdorff spaces that are exponentiable in the category of Hausdorff spaces are exactly the locally compact Hausdorff spaces.

We can be more precise on the subject of quasi-Polish spaces.

**Theorem 16.3** *The exponentiable objects X in the category of quasi-Polish spaces are the locally compact quasi-Polish spaces, i.e., the countably-based locally compact sober spaces. For every quasi-Polish space Y , the exponential object is* [*X → Y* ] *with the compact-open topology.*

**Proof.** We first note that every quasi-Polish space is sober and countably-based, and that conversely every countably-based locally compact sober is quasi-Polish [[7,](#_bookmark61) Theorem 44].

Assume *X* is locally compact quasi-Polish, and *Y* is quasi-Polish. The only thing we must show is that [*X → Y* ], with the compact-open topology, is quasi- Polish. Indeed, the application map from [*X → Y* ] *× X* to *Y* will automatically be continuous, and the currification *z '→* (*x '→ f* (*z, x*)) of every continuous map *f* : *Z×X → Y* will be continuous from *Z* to [*X → Y* ], because *X* is exponentiable in **Top** [[13](#_bookmark68), Theorem 5.4.4] and the exponential object is [*X → Y* ], with the compact- open topology, owing to the fact that *X* is locally compact [[13](#_bookmark68), Exercise 5.4.8].

Up to homeomorphism *Y* is a **Π**0 subspace of P(N) [[7](#_bookmark61), Corollary 24]. Hence write *Y* as *{z ∈* P(N) *| ∀n ∈* N*,z ∈ Un ⇒ z ∈ Vn}*, where *Un* and *Vn* are open. As in the proof of Proposition [7.1](#_bookmark19), we define *f, g* : P(N) *→* P(N) by *f* (*z*) d=ef *{n ∈* N *| z ∈ Un}*, *g*(*z*) d=ef *{n ∈* N *| z ∈ Un ∩ Vn}*. The equalizer of *f* and *g* in **Top** is *Y* .

2

Since *X* is exponentiable, the exponentiation functor *X* on **Top** is well-defined

and is right adjoint to the product functor *× X* on **Top**. Since right ad- joints preserve limits, in particular equalizers, *Y X* is the equalizer of the maps *f X, gX* : (P(N))*X →* (P(N))*X* . Since *X* is locally compact, we know that *Y X* is [*X → Y* ] with the compact-open topology (see [[13](#_bookmark68), Exercise 5.4.11] for example).

Similarly, (P(N))*X* = [*X →* P(N)] with the compact-open topology. Recall that every quasi-Polish space is LCS-complete hence *⊙*-consonant (Lemma [13.2](#_bookmark38)), and P(N) is an algebraic complete lattice. By Proposition [13.4,](#_bookmark40) the compact-open topology on [*X →* P(N)] is the Scott topology.

We now use [[12](#_bookmark67), Proposition II-4.6], which says that if *X* is core-compact and *L* (here P(N)) is an injective *T*0 space (i.e., a continuous complete lattice by [[12,](#_bookmark67) Theorem II-3.8]), then [*X → L*] is a continuous complete lattice. We claim that [*X →* P(N)] is countably-based. This follows froms [[12](#_bookmark67), Corollary III-4.10], which says that when *X* is a *T*0 core-compact space and *L* is a continuous lattice such that *w* d=ef max(*w*(*X*)*, w*(*L*)) is infinite (*w*(*L*) is the minimal cardinality of a basis of *L*, and is *ω* in our case; *w*(*X*) is the *weight* of *X*, namely the minimal cardinality of a base of *X*, and is less than or equal to *ω*, by assumption), then *w*([*X → L*]) *≤ w*(*O*[*X → L*]) *≤ w*. We have shown that (P(N))*X* = [*X →* P(N)] is a countably- based continuous dcpo, hence an *ω*-continuous dcpo by a result of Norberg [[30,](#_bookmark85) Proposition 3.1] (see also [[13](#_bookmark68), Lemma 7.7.13]), hence a quasi-Polish space.

The equalizer (in **Top**) of two continuous maps between countably-based *T*0

spaces is a **Π**0 subspace of the source space [[7](#_bookmark61), Corollary 10]. Hence *Y X* is **Π**0 in

2 2

(P(N))*X* . Since the **Π**0 subspaces of a quasi-Polish space are exactly its quasi-Polish subspaces [[7](#_bookmark61), Corollary 23], *Y X* = [*X → Y* ] is quasi-Polish. *2*

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# Compact subsets of LCS-complete spaces

A well-known theorem due to Hausdorff states that, in a complete metric space, a subset is compact if and only if it is closed and precompact, where precompact means that for every *ϵ >* 0, the subset can be covered by finitely many open balls of radius *ϵ*. An immediate consequence is as follows. Build a finite union *A*0 of closed balls of radii at most 1. Then build a finite union *A*1 of closed balls of radii at most 1*/*2 included in *A*0, then a finite union *A*2 of closed balls of radii at most

1*/*4 included in *A* , and so on. Then \*↓ A* is compact. (That argument is the

1 *n∈*N *n*

key to showing that every bounded measure on a Polish space is tight, for example.)

We show that a similar construction works in LCS-complete spaces.

In this section, we fix a presentation of an LCS-complete space *X* as ker *μ* for

*op*

R

some continuous map *μ* : *Y →* + , *Y* locally compact sober (see Remark [3.4](#_bookmark9)).

Replacing *μ* by 2 arctan *◦μ*, we may assume that *μ* takes its values in [0*,* 1].

*π*

For every non-empty compact saturated subset *Q* of *Y* , the image *μ*[*Q*] of *Q* by *μ* is compact in [0*,* 1]*op*, hence has a largest element. Let us call that largest value the *radius r*(*Q*) of *Q*. Note that this depends not just on *Y* , but also on *μ*. Note also

that *r*(*↑ y*)= *μ*(*y*) for every *y ∈ Y* , and that *r*( *n Qi*)= max*{r*(*Qi*) *|* 1 *≤ i ≤ n}*.

*i*=1

**Remark 17.1** . The name “radius” comes from the following observation. In the special case where *Y* = **B**(*X, d*) for some continuous complete quasi-metric space *X, d*, we may define *μ*(*x, r*) d=ef *r*, and in that case the radius of *Q* is max*{r | x ∈ X,* (*x, r*) *∈ Q}*.

**Lemma 17.2** *Let X, Y , μ be as above. For every ﬁltered family* (*Qi*)*i∈I of non-*

*empty compact saturated subsets of Y such that* inf *r*(*Q* ) = 0*,* \*↓ Q is a*

*non-empty compact saturated subset of X.*

*i∈I* *i*

*i∈I i*

**Proof.** Since *Y* is sober hence well-filtered, *Q* d=ef *↓ Q*

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*i*

*i∈I*

is a non-empty compact

saturated subset of *Y* . We show that *Q* is included in *X* by showing that, for every

*y ∈ Q*, for every *ϵ >* 0, *μ*(*y*) *< ϵ*. Indeed, since inf*i∈I r*(*Qi*) = 0, we can find an index *i ∈ I* such that *r*(*Qi*) *< ϵ*. Then *μ*(*y*) *≤ r*(*Qi*), by definition of radii, and since *y ∈ Qi*.

Hence *Q* is compact saturated in *Y* , and included in *X*, hence it is compact saturated in *X*, by Lemma [8.1](#_bookmark21), items 1 and 2. *2*

**Lemma 17.3** *Let X, Y , μ be as above. For every non-empty compact saturated subset Q of X, for every open neighborhood U of Q in Y , for every ϵ >* 0*, there is a non-empty compact saturated subset Qj of Y such that Q ⊆ int*(*Qj*) *⊆ Qj ⊆ U and r*(*Qj*) *< ϵ.*

*If Y is a continuous dcpo, we can even take Qj of the form ↑ A for some non- empty ﬁnite set A* = *{y*1*,* *, yn}, where μ*(*yi*) *< ϵ for every i.*

**Proof.** *U ∩ μ—*1([0*, ϵ*)) is open, hence by local compactness it is the directed union of sets of the form *int*(*Qj*), where each *Qj* is compact saturated and included in

*U ∩μ—*1([0*, ϵ*)). The open sets *int*(*Qj*) form a cover of *Q*, which is compact saturated in *Y* by Lemma [8.1,](#_bookmark21) items 1 and 2, so some *Qj* as above is such that *Q ⊆ int*(*Qj*). By construction, *Qj ⊆ U* . Also, *r*(*Qj*) *< ϵ* because *Qj ⊆ μ—*1([0*, ϵ*)).

We prove the second part of the lemma in the more general case where *Y* is quasi-continuous. Then *Y* is locally finitary compact [[13](#_bookmark68), Exercise 5.2.31], meaning that we can replay the above argument with *Qj* of the form *↑ A* for *A* finite. *2*

**Theorem 17.4** *Let X, Y , μ be as above. The non-empty compact saturated sub-*

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*sets of X are exactly the ﬁltered intersections ↓ Q*

*i*

*i∈I*

*of (interiors of) non-empty*

*compact saturated subsets Qi of Y such that* inf*i∈I r*(*Qi*) = 0*. Moreover, we can*

\

*choose that ﬁltered intersection to be equal to ↓*

*i∈I*

*int*(*Qi*)*.*

*When Y is a continuous dcpo, we can even take Qi of the form ↑ Ai, Ai ﬁnite.*

**Proof.** One direction is Lemma [17.2.](#_bookmark50) Conversely, let *Q* be compact saturated in *X*, and let (*Qi*)*i∈I* be the family of compact saturated subsets of *Y* such that *Q ⊆ int*(*Qi*) (respectively, only those of the form *↑ Ai* with *Ai* finite, if *Y* is a continuous dcpo). By Lemma [17.3](#_bookmark51) with *U* d=ef *Y* , for every *ϵ >* 0 there is an index *i ∈ I* such that *r*(*Qi*) *< ϵ*, so inf*i∈I r*(*Qi*) = 0. This also shows that the family is non-empty. For any two elements *Qi*, *Qj* of the family, we apply Lemma [17.3](#_bookmark51) with *U* d=ef *int*(*Qi*) *∩ int*(*Qj*) (and *ϵ* arbitrary), and we obtain an element *Qk* such that *Qk ⊆ int*(*Qi*) *∩ int*(*Qj*). This shows that the family is filtered.

For every open neighborhood *U* of *Q* in *Y* , Lemma [17.3](#_bookmark51) (again) shows the

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existence of an index *i ∈ I* such that *Qi*

*⊆ U* . Therefore *Q* = *↓*

*i∈I*

*Qi*. Finally,

*Q ⊆ int*(*Q* ) for every *i ∈ I*, so *Q ⊆* \*↓ int*(*Q* ) *⊆* \*↓ Q* = *Q*, so all the terms

*i i∈I i i∈I i*

involved are equal. *2*

In particular, if *X, d* is a continuous complete quasi-metric space, and taking *Y* d=ef **B**(*X, d*) and *μ*(*x, r*) d=ef *r*, then the compact saturated subsets of *X* (in its *d*- Scott topology) are exactly the filtered intersections of sets *Ci* d=ef *Qi ∩X*. For each *i*, we can take *Qi* of the form *↑{*(*x*1*, r*1)*,...,* (*xn, rn*)*}* where *r*(*Qi*)= max*{r*1*,* *, rn}*

is arbitrarily small. Then the sets *Ci* are easily seen to be finite unions of closed balls *Bxi,≤ri* of arbitrarily small radius. That explains the connection with Hausdorff’s theorem cited earlier. Note, however, that closed balls are in general not closed (except when *X, d* is metric), and need not be compact either.

# Extensions of continuous valuations

Continuous valuations were introduced in [[23,](#_bookmark82)[22](#_bookmark77)]. As far as measure theory is concerned, we refer the reader to any standard reference, such as [[4](#_bookmark59)].

A *valuation ν* on a space *X* is a map from the lattice of open subsets *O X* of *X*

to R+ that is *strict* (*ν*(*∅*) = 0) and *modular* (*ν*(*U* )+*ν*(*V* )= *ν*(*U ∪V* )+*ν*(*U ∩V* )). A

*continuous valuation* is additionally Scott-continuous. Every continuous valuation

*ν* defines a linear prevision *G* by *G*(*h*) d=ef ∫

*x∈X*

*h*(*x*)*dν*, and conversely any linear

prevision defines a continuous valuation *ν* by *ν*(*U* ) d=ef

characteristic map of *U* .

*G*(*χU* ), where *χU* is the

Any pointwise directed supremum of continuous valuations is a continuous val- uation again.

A continuous valuation *ν* is *locally ﬁnite* if and only if every point has an open neighborhood *U* such that *ν*(*U* ) *< ∞*. It is *bounded* if and only if *ν*(*X*) *< ∞*. Let *A*(*O X*) be the smallest Boolean algebra of subsets of *X* containing *O X*. The elements of *A*(*O X*) are the finite disjoint unions of *crescents*, where a crescent is a difference *U \ V* of two open sets. The Smiley-Horn-Tarski theorem [[34,](#_bookmark89)[20](#_bookmark75)] states that every bounded valuation extends to a unique strict modular map from *A*(*O X*) to R+.

Given any open set *U* , *ν* is the continuous valuation defined by *ν* (*V* ) d=ef

*|U |U*

*ν*(*U ∩ V* ); that is bounded if and only if *ν*(*U* ) *< ∞*.

Let us write *B*(*X*) for the Borel *σ*-algebra of *X*. A measure on *X* is a *σ*-additive map from *B*(*X*) to R+, or equivalently a strict, modular and *ω*-continuous map from *B*(*X*) to R+. The latter makes it clear that the pointwise directed supremum of a family (even uncountable) of measures is a measure.

We will use the following standard fact, which we shall call *Kolmogorov’s crite- rion*: given a bounded measure *μ*, and a descending sequence (*Wn*)*n∈*N of Borel sets,

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*μ*( *↓*

*n∈*N

*Wn*) = inf

*n∈*N

*μ*(*Wn*

). We will also use the following: any two bounded

measures that agree on *O X* agree on the whole of *B*(*X*).

If *X* is countably-based, or more generally if *X* is *hereditarily Lindelo¨f* (viz., every directed family of open subsets has a cofinal monotone sequence), every mea- sure *μ* on *X* with its Borel *σ*-algebra restricts to a continuous valuation on the open sets. The following theorem shows that, conversely, every continuous valuation *ν* on an LCS-complete space extends to a measure *μ*. We recall that this holds for locally finite continuous valuations on locally compact sober spaces [[2,](#_bookmark56)[24](#_bookmark78)].

**Lemma 18.1** *Let ν be a bounded valuation on a topological space X. If ν has an extension to a measure μ on B*(*X*)*, then μ coincides with the* crescent outer measure

*ν∗ on B*

(*X*)*: ν*

*def*

(*E*) = inf*F*

*∗*

Σ*C∈F*

*ν*(*C*)*, where F ranges over the countable families*

*of crescents whose union contains E.*

Note that *ν*(*C*) makes sense by the Smiley-Horn-Tarski theorem.

**Proof.** For every open set *U* , taking *F* d=ef *{U}*, we obtain *ν∗*(*U* ) *≤ ν*(*U* )= *μ*(*U* ). Conversely, for every countable family *F* of crescents *C* whose union contains *U* ,

Σ Σ

*C∈F ν*(*C*)= *C∈F μ*(*C*) *≥ μ*( *C∈F C*) *≥ μ*(*U* )= *ν*(*U* ), so *ν∗*(*U* )= *μ*(*U* ).

It is standard that *ν∗* defines a measure on the *σ*-algebra of *measurable sets*, where a subset *A* of *X* is called measurable if and only if for all subsets *B* of *X*, *ν∗*(*B*)= *ν∗*(*B ∩ A*)+ *ν∗*(*B \ A*) (see, e.g., [[24](#_bookmark78), Theorem 3.2]). We claim that every open set *U* is measurable. Let us fix a subset *B* of *X*. For every crescent *C*, *C ∩ U*

and *C \ U* are crescents again. Hence, for every countable family *F* d=ef (*Cn*) of

*n∈*N

crescents whose union contains *B*, Σ*C∈F ν*(*C*) = Σ*n∈*N *ν*(*Cn ∩ U* )+ *ν*(*Cn \ U* ) *≥*

*ν∗*(*B ∩ U* )+ *ν∗*(*B \ U* ). Taking infima over *F*, *ν∗*(*B*) *≥ ν∗*(*B ∩ U* )+ *ν∗*(*B \ U* ). Conversely, for every countable family *F* of crescents whose union contains *B ∩ U* , for every countable *Fj* of crescents whose union contains *B\U* , *F ∪Fj* is a countable family of crescents whose union contains *B*, so *ν∗*(*B ∩ U* )+ *ν∗*(*B \ U* ) *≥ ν∗*(*B*), whence the equality. Since the measurable sets contain all the open sets, they also contain *B*(*X*).

Hence we have two measures on *B*(*X*), *μ* and *ν∗*, which coincide on the open sets. In particular, *μ*(*X*)= *ν∗*(*X*) *< ∞*, so they are bounded. It follows that *μ* and *ν∗* agree on the whole of *B*(*X*). *2*

**Theorem** [**1.1**](#_bookmark4) **(recap).** Let *X* be an LCS-complete space. Every continuous valuation *ν* on *X* extends to a measure on *X* with its Borel *σ*-algebra.

**Proof.** Let *ν* be a continuous valuation on *X*, and let *X* be written as *↓*

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*n∈*N

*Wn*,

where each *Wn* is open in some locally compact sober space *Y* .

Let (*Ui*)*i∈I* be the family of open subsets of *X* of finite *ν*-measure. This is a

directed family, since *ν*(*U ∪ U* ) *≤ ν*(*U* )+ *ν*(*U* ). We write *U* for [*† U* . If *ν*

*i j i j*

*∞ i∈I i*

were locally finite, then *U∞* would be equal to *X*, but we do not assume so much.

For each *i ∈ I*, *ν|Ui* is a bounded continuous valuation. Letting *e* : *X → Y* be the inclusion map, the image of *ν|Ui* by *e* is another bounded continuous valuation, which we write as *νj*: for every open subset *V* of *Y* , *νj*(*V* ) = *ν|U* (*e—*1(*V* )) = *ν*(*V ∩ Ui*).

*i i* *i*

Note that *i ± j* implies *νj ≤ νj* (namely, *νj*(*V* ) *≤ νj* (*V* ) for every *V* ).

*i j i j*

We claim that *i ± j* implies that for every crescent *C*, *νj*(*C*) *≤ νj* (*C*). In order

*i j*

to show that, let us write *C* as *U \ V* , where *U* and *V* are open in *Y* . Replacing *V*

by *U ∩ V* if needed, we may assume *V ⊆ U* . For every *k ± j*, we have:

*ν|Uj* (*C ∩ Uk*)= *ν|Uj* ((*U ∩ Uk*) *\* (*V ∩ Uk*))

= *ν|Uj* (*U ∩ Uk*) *− ν|Uj* (*V ∩ Uk*) since *ν|Uj* is additive on *A*(*O X*)

= *ν*(*U ∩ Uk*) *− ν*(*V ∩ Uk*) since *Uk ⊆ Uj*

= *ν|Uk* (*U* ) *− ν|Uk* (*V* )= *ν|Uk* (*C*)*.* (1)

Taking *k* d=ef *i* in ([1](#_bookmark54)), *ν* (*C*)= *ν* (*C∩Ui*), which is less than or equal to *ν* (*C∩Uj*) (the difference is *ν|Uj* (*C ∩ Uj \ Ui*) *≥* 0), and the latter is equal to *ν|Uj* (*C*) by ([1](#_bookmark54)) with *k* d=ef *j*.

*|Ui |Uj |Uj*

We have seen that *νj* extends to a measure *μi* on *Y* . By Lemma [18.1](#_bookmark53), *μi* = *νj∗*.

*i* *i*

Using the formula for the crescent outer measure, we obtain that if *i ± j*, then

*μi*(*E*) *≤ μj*(*E*) for every *E ∈ B*(*Y* ).

Since *X* is *Gδ* hence Borel in *Y* , *B*(*X*) is included in *B*(*Y* ). Hence *μi* also defines a measure on the smaller *σ*-algebra *B*(*X*). We still write it as *μi*, and we note that *i ± j* implies that *μi*(*E*) *≤ μj*(*E*) for every *E ∈ B*(*X*). Also, *μi* extends *ν|Ui* , as we now claim. Let *U* be any open subset of *X*. By definition of the subspace topology, *U* is the intersection of some open subset *U*^ of *Y* with *X*. *U* is then equal to

\*↓ U*^ *∩W* . Now *μ* (*U* )= *μ* ( \*↓ U*^ *∩W* )= inf *μ* (*U*^ *∩W* ) (Kolmogorov’s

*n∈*N

*n*

*i*

*i*

*n∈*N

*n*

*n∈*N

*i*

*n*

criterion) = inf*n∈*N *νj*(*U*^ *∩ Wn*) = inf*n∈*N *ν|U* (*U* ) (since *U*^ *∩ Wn ∩ Ui* = *U ∩ Ui*)

*i* *i*

= *ν|Ui* (*U* ).

Any directed supremum of measures is a measure. Hence consider *μ*(*E*) d=ef

*†*

sup

*i∈I*

*μi*(*E*). For every open subset *U* of *X*, *μ*(*U* ) = sup*† μi*(*U* ) =

sup*† ν|U* (*U* )= sup*† ν*(*U ∩ Ui*)= *ν*(*U ∩ U∞*)= *ν|U* (*U* ), so *μ* extends *ν|U*

*i∈I*

. Let

*i∈I i i∈I ∞ ∞*

*ι* be the indiscrete measure on *X \ U∞*, namely *ι*(*E*) is equal to *∞* if *E* intersects

*X \ U∞*, to 0 if *E ⊆ U∞*. We check that the measure *μ* + *ι* extends *ν*. For every open subset *U* of *X*, either *U ⊆ U∞* and *ν*(*U* ) = *ν|U∞* (*U* ) = *μ*(*U* ) = *μ*(*U* )+ *ι*(*U* ), or *U* intersects *X \ U∞*, say at *x*. In the latter case, *ι*(*U* )= *∞* so *μ*(*U* )+ *ι*(*U* )= *∞*, while *ν*(*U* )= *∞* because, by definition, *x* has no open neighborhood of finite *ν*-measure.*2*

**Remark 18.2** More generally, the proof of Theorem [1.1](#_bookmark4) would work on **Π**0 subsets of locally compact sober spaces. (That is a strict extension, by Proposition [14.5](#_bookmark45).) In that case, we write *X* as *n*T*∈*N *Wn* where each *Wn* is the union of a closed and

2

T

an open set. Replacing *Wn* by

*n i*=0

*Wi*, we make sure that the sequence of sets *Wn*

is descending, and *Wn* is still in *A*(*O Y* ). The rest of the proof is unchanged.

# Conclusion

We have given two applications of the theory of LCS-complete spaces (Theorem [1.1](#_bookmark4), Corollary [13.7](#_bookmark42)). We should mention a final application [[15](#_bookmark70), Theorem 9.4], which will be published elsewhere: given a projective system (*pij* : *Xj → Xi*))*i±j∈I* of LCS- complete spaces such that *I* has a countable cofinal subset, given locally finite continuous valuations *νi* on *Xi* that are compatible in the sense that for all *i ± j*

in *I*, *νi* is the image valuation of *νj* by *pij*, there is a unique continuous valuation *ν* on the projective limit *X* of the projective system such that *ν* projects back to *νi* for every *i ∈ I*. This extends a famous theorem of Prohorov’s [[32](#_bookmark88)], which appears as the subcase where each *Xi* is Polish and each *νi* is a measure.

One question that remains open, though, is: (*i*) Is the projective limit *X* of a projective system of LCS-complete spaces as above again LCS-complete?

That is only one of many remaining open questions: (*ii*) Is every sober com- pactly Choquet-complete space LCS-complete? (*iii*) Is every sober convergence Choquet-complete space domain-complete? (*iv*) Is every coherent LCS-complete space a *Gδ* subset of a stably (locally) compact space? (*v*) Is every **Π**0 subset of an domain-complete space again domain-complete? (A similar result fails for LCS- complete spaces, by Proposition [14.5](#_bookmark45).) (*vi*) Is every *countably correlated* space (i.e., every space homeomorphic to a **Π**0 subset of P(*I*) for some, possibly uncountable

2

2

set *I*, see [[6](#_bookmark62)]) LCS-complete? (*vii*) Is every LCS-complete space countably corre- lated? (*viii*) Are regular Cˇech-complete spaces LCS-complete, where Cˇech-complete is understood as in [[13](#_bookmark68), Exercise 6.21]? (*ix*) Are all regular LCS-complete spaces Cˇech-complete?

*Note added to the ﬁnal version.* Conjecture (*v*) was recently solved positively by the second author: every **Π**0 subset of a domain-complete space is domain-complete. As a consequence, (*vi*) is true as well; in fact, every countably correlated space is

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even domain-complete. This will be published elsewhere.

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