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Introduction

Some observations on C_p-theory and bibliography

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The birth of General Topology to a great extent can be explained by the need to study convergence properties of sets of functions. In particular, topological questions about Banach spaces played a very important role. One of the central positions in Functional Analysis is occupied by the concept of the weak topology of a Banach space. These topologies form a natural strata of nonmetrizable topologies. There is a general metamathematical reason why it might be beneficial to consider weak topologies, or in general, topologies which are weaker than a given one. The reason is very simple: the weaker the topology you take, the more compact subsets you get. And working inside a compact set, you can use many powerful topological or linear topological principles which would not work even in a separable metrizable space!

Also global compactness properties of a space itself can only improve when its topology is weakened.

In particular, compact subspaces of a Banach space in the weak topology, called Eberlein compacta, play a prominent role in Functional Analysis, largely due to their very interesting topological properties.

In what follows, X is a Tychonoff space and $C_p(X)$ is the space of real-valued continuous functions on X in the topology of pointwise convergence. Clearly, C_p-spaces are an important source of examples of linear topological spaces.

Note that every Banach space in the weak topology is linearly homeomorphic to a closed linear subspace of the space $C_p(X)$ of continuous real-valued functions on a compact Hausdorff space X, in the topology of pointwise convergence. Also, as a very natural object combining topological and algebraic structures, $C_p(X)$ can serve as an important technical tool in the study of topological spaces, providing a bridge between General Topology and domains belonging to Topological Algebra and Functional Analysis.

The main objects studied in C_p-theory are $C_p(X)$ itself and compact subspaces of $C_p(X)$, as well as the relationships between properties of $C_p(X)$ and X.

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Grothendieck and Namioka theorems, Ala-Ogly theorem, Eberlein compacta, Corson compacta, Rosenthal compacta, Radon–Nikodym property, Hewitt–Nachbin completeness,—these and many other results and notions equally belong to General Topology and Functional Analysis (though they all have appeared in Functional Analysis and are applied there). *Thus, C_p-theory can itself be considered as an application of General Topology to Functional Analysis.*

A major direction of research in C_p-theory is the study of l-equivalence and t-equivalence and, accordingly, of l-invariants and t-invariants. Spaces X and Y are called *t-equivalent* (*l-equivalent*) if the spaces $C_p(X)$ and $C_p(Y)$ are homeomorphic (linearly homeomorphic). Topological properties which are preserved by t-equivalence and l-equivalence are called *t-invariants* and *l-invariants*, respectively. To identify those topological invariants which are, in fact, l-invariants or t-invariants, is one of the fundamental problems in C_p-theory.

This topic is closely related to the chapter of C_p-theory devoted to duality theorems. The relationship is obvious: as soon as we know that a property of a space X can be characterized by a topological (linear topological) property of $C_p(X)$, we can conclude that this property of X is t-invariant (l-invariant).

The third important direction of research in C_p-theory is the theory of continuous (and linear continuous) extenders; the first fundamental results here were obtained by J. Dugundji [109]; later contributions include those by E. van Douwen [105,106], C.J. Borges [62], R.W. Heath, D.J. Lutzer, Ph. Zenor (see [156–159]), and others.

In the last ten–fifteen years the study of C_p-spaces, especially, in the direction outlined by the two principal problems above, in the extender theory, and of special classes of compacta arising in Functional Analysis (Eberlein, Corson, Gul'ko, Valdivia, and others) was greatly enhanced, and several important problems were solved. The progress was described in books [23,212], and in several surveys: see, in particular, [14,16,17,22,27,234]. Here are some authors of important contributions to C_p-theory in the last 15–20 years: K. Alster, S. Argyros, M.O. Asanov, J. Baars, D. Baturov, J. Calbrix, M.M. Cioban, G. Debs, J. Dijkstra, T. Dobrowolski, J. de Groot, G. Gruenhage, S.P. Gul'ko, R. Haydon, I. Namioka, K. Kawamura, A. Leiderman, D. Lutzer, W. Marciszewski, R.A. McCoy, S. Mercourakis, Z. Piotrowski, J. van Mill, K. Morishita, L. Nahmanson, O.G. Okunev, J. Pelant, V.G. Pestov, R. Pol, E.G. Pytkeev, E. Reznichenko, M. Sakai, O.V. Sipacheva, G.A. Sokolov, V.V. Tkachuk, S. Todorcevic, V.V. Uspenskij, V. Valov, N.V. Velichko (see bibliography for their papers and for more names).

I just mention here a few results. G. Gruenhage characterized Corson compacta, Eberlein compacta, and Gul'ko compacta by covering (paracompactness type) properties of the complement to the diagonal in the square of the space [129,130]. P. Nyikos [237] gave an example of an Eberlein compactum of size ω_1 which is not bisequential. D.J. Lutzer and R.A. McCoy obtained a series of results on the Baire property in $C_p(X)$ [188], W. Marciszewski [203] constructed an infinite compact space X such that $C_p(X)$ is not linearly homeomorphic to $C_p(X) \times R$, J. Calbrix has shown [76] that if $C_p(X)$ is analytic, then X is σ-compact, N.V. Velichko established [350] that the Lindelöf property is preserved by l-equivalence, D.P. Baturov proved [56] that the Lindelöf degree coincides with the extent for any subspace Y of $C_p(X)$ whenever X is compact, R. Pol has constructed [267] an infinite metrizable compact space X such that the square of $C_p(X)$ is not linearly homeomorphic to $C_p(X)$ (this is related to well-known old problems of S. Banach).

An important source of applications of C_p-theory to Set-Theoretic Topology form duality theorems. Duality theorems characterize properties of a space X by topological properties of $C_p(X)$ (and vice-versa). In this way, seemingly unrelated, independent, properties are brought into rigid correspondence. For example, the density of X is characterized by the pseudocharacter (or by the diagonal number) of $C_p(X)$, to the cardinality of X corresponds the character of $C_p(X)$, and so on. There are many much more delicate results in this direction, almost all of them obtained in the course of the last fifteen years. In this way, set-theoretic topology gets a new tool which permits, starting from given topological spaces with certain collections of properties, to construct entirely new topological spaces with very different set of properties. For example, one of the most important duality theorems in C_p-theory, belonging to N.V. Velichko [351] and Ph. Zenor [363], establishes duality between hereditary separability of a space X in every finite power and hereditary Lindelöfness of the dual space $C_p(X)$ in every finite power. This relates seemingly independent S-space problem and L-space problems, the two famous problems lying at the heart of set-theoretic topology. Following this approach, we may start with Ivanov hereditarily separable (in every finite power) compactum X, and obtain a hereditarily Lindelöf (also in every finite power) space $C_p(X)$ with interesting properties.

Two other examples. Hewitt completeness of X was characterized by a tightness type property of $C_p(X)$ (see [23,345]) which has applications in the study of continuity properties of mappings of products. A.V. Arhangel'skii and V.V. Tkachuk proved [38] that X is a space with *small diagonal* if and only if ω_1 is a caliber of $C_p(X)$, which presented in the new light the well-known problem of Hušek concerning metrizability of compacta with small diagonal.

Another very important contribution of C_p-theory to set-theoretic topology: it brought into it new classes of compacta, such as Eberlein compacta, Corson compacta, Talagrand compacta, Gul'ko compacta, Rosenthal compacta, Radon–Nikodym compacta, Valdivia compacta, strong Miluytin and strong Dugundji compacta. Actually, C_p-theory provided a new method for classifying compact spaces (according to topological properties of $C_p(X)$). All these types of compact spaces, arising naturally in Functional Analysis, are also very interesting from purely topological point of view. For example, G. Gruenhage proved [130], extending an earlier result on Eberlein compacta, that every Gul'ko compactum contains a dense subspace metrizable by a complete metric (this implies, for example, that every Gul'ko compactum with the countable Souslin number is metrizable). Gul'ko, Marciszewski, Lutzer, McCoy established new connections between properties of ultrafilters and C_p-theory. In particular, a result of Lutzer and McCoy [188] provides us with a rich collection of spaces $C_p(X)$ which have the Baire property without being Čech-complete.

The study of compacta arising in Functional Analysis in C_p-theory enriched set-theoretic topology with new very natural notions such as monolithicity, for example, which have already shown their importance in General Topology. Many classical notions, such as of a Σ-product, of a Lindelöf Σ-space, of caliber, were illuminated in a new way from the positions of C_p-theory.

Though C_p-theory itself is an application of General Topology to Functional Analysis, one might wonder, whether in the recent period the objects, methods, and results of C_p-theory had important new applications in other parts of Functional Analysis or in other domains of Mathematics.

The answer is "yes". The earlier applications are well described in S. Negrepontis' article "Banach Spaces and Topology" [234] refered to above. Here are a few more recent references.

D.P. Baturov and E.A. Reznichenko proved that a Banach space in the weak topology is Lindelöf if and only if it is normal (see [56,58], and [23]).

P.S. Kenderov used results of G. Gruenhage, A. Leiderman and G. Sokolov to prove that if a Banach space in the weak topology is a Lindelöf Σ-space, then it is Asplund in the same topology [170], which means that continuous convex functions are Gateux differentiable at all points of a dense G_δ-subset of this space (this was also independently proved by S. Merkourakis).

J.E. Jayne and C.A. Rogers introduced in 1985 the notion of fragmentability of a topological space (a condition of metrizability type), which turned out to be important in the study of Banach spaces with the Radon–Nicodym property (see [162,163]), in particular, in the theory of Radon–Nikodym compacta, which significantly extends the classical theory of weakly compact subsets of Banach spaces (called also Eberlein compacta). This is important for the investigation of Asplund spaces and their duals in Functional Analysis. I. Namioka, J.E. Jayne, C.A. Rogers, N.K. Ribarska, and many others obtained new results on fragmentability using effectively C_p-theory. In particular, E.A. Reznichenko, and, independently, J. Orihuela, W. Schachermayer, and M. Valdivia [248] proved that every Radon–Nikodym Corson compact space is also an Eberlein compactum.

G. Debs, R. Deville, G. Godefroy, R. Haydon, I. Namioka, and R. Pol (see [93,233]) used parts of C_p-theory (among other things, they considered certain properties of mappings of Baire spaces into C_p-spaces over compacta) in renorming theory of Banach spaces. Scattered compacta were shown to be of special importance in these matters.

One of the most useful for applications results of C_p-theory is Namioka's well-known theorem on the points of joint continuity of separately continuous functions on products of two spaces, where one factor is compact [230]. J.P. Troallic pointed to applications of this theorem in the theory of almost periodic functions, in the proof of R. Ellis's theorem (that every locally compact semi-topological group is a topological group), in the theory of compact semi-topological semi-groups (see [337,338]).

A considerable work was done on the extension of Namioka's theorem to wider classes of spaces (A. Szymanski [310], Z. Piotrowski [255], A. Bouziad [68–71], R.G. Haydon [151,152], M. Talagrand [319], and others). These extensions were applied by the same authors to get new results in Functional Analysis.

R. Pol [263] obtained new results on the space $P(S)$ of probability measures.

New connections between C_p-theory and descriptive theory of sets were discovered by R. Cauty, T. Dobrowolski, W. Marciszewski, J. van Mill, J. Dijkstra, T. Grilliot, J. Calbrix, D. Lutzer, R. Pol, T. Dobrowolski, W. Marciszewski, J. Mogilski, and others (see [75,76,82,96,103,189,200,204]).

There are important applications of C_p-theory, in particular, of descriptive properties of C_p-spaces, to infinite dimensional topology—to the theory of adsorbers: it was shown by T. Dobrowolski, W. Marciszewski and J. Mogilski [103] that, for a countable X, $C_p(X)$ is a generalized $\mathcal{F}_\sigma$-absorber (and hence homeomorphic to σ^N) whenever $C_p(X) \in \mathcal{F}_{\sigma\delta}$.

Since $C_p(X)$ is not only a linear topological space, but also a topological ring, C_p-theory can be applied in the theory of topological groups and topological rings. For example, taking this approach, we can easily describe a solution to an old problem of A.A. Markov: whether there exists a topological group the space of which is not normal. Originally, this problem was solved by a difficult and very delicate construction of the free topological group of a Tychonoff space. Now, taking into account that a Tychonoff space X naturally embeds into the second dual space $C_p(C_p(X))$ (by the evaluation mapping) as a closed subspace, we answer Markov's question easily, even in the class of topological rings. Results on duality in C_p-theory allow to apply this construction to obtain more delicate results on topological embeddings of topological spaces into topological groups; to prove, in particular, that every monolithic Tychonoff space can be embedded as a closed subspace into a monolithic topological group. Results of this kind are often not obvious; for example, it is still unknown, whether every normal (or Lindelöf) topological space can be embedded as a closed subspace into a normal (Lindelöf) topological group.

A.V. Korovin [173] and E.A. Reznichenko [279] have applied C_p-theory (in particular, generalizations of Grothendieck's theorem) in the study of the continuity of the separately continuous multiplication in pseudocompact groups, and made new important steps in the direction of Wallace's problem on cancellative topological semigroups.

Of course, the above exposition is not a survey of C_p-theory; we only presented a sample of results to give a reader who is not working in C_p-theory himself, the flavor of the subject, and the idea how vigorously it is now developing. It would have taken a very long survey to present all the progress here in detail.

This volume contains further contributions to C_p-theory. I believe, it was not a bad idea to collect them together. The authors do not need presentation; and the results their papers contain, taking also into account the wide scope of the domain they cover, will speak for C_p-theory probably better than any elaborate survey.

To conclude this introduction, we present a bibliography on C_p-theory and closely related matters. Since C_p-theory is organically connected to practically all domains of Set-theoretic topology and many domains of Functional Analysis, the boundaries of the domain can not be determined very well. Therefore, the list can not be complete. Besides, I did not really make an attempt to made it as complete as I could, since this would have probably doubled it. Thus, it is just a first approximation to a somewhat complete from a very personal point of view list of relevant to C_p-theory publications. Still, one may be amazed how rich the bibliography presented is, and probably will enjoy it.

A bibliography on and around C_p-theory

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