Appendix

Below we collect some basic results that we apply several times in our book.

We begin with a description of rank-one preserving linear transformations. If X is a real or complex Banach space, then let $X^\sharp$ denote its dual. If $x \in X$ and $f \in X^\sharp$, then $x \otimes f$ stands for the operator (of rank at most 1) defined by

$$(x \otimes f)(z) = f(z)x \qquad (z \in X).$$

Denote by $F(X)$ the algebra of all bounded linear finite rank operators on X. The following result could be derived from the arguments used in the first half of Section I in the paper [104] by Hou.

Theorem A.1. *Let X be a real or complex Banach space and $\phi : F(X) \to F(X)$ be a linear transformation which maps rank-one operators to rank-one operators. Suppose that the range of ϕ contains an operator with rank greater than 1. Then either there are linear operators $S : X \to X$ and $R : X^\sharp \to X^\sharp$ such that*

$$\phi(x \otimes f) = Sx \otimes Rf \qquad (x \in X, f \in X^\sharp)$$

or there are linear operators $R' : X \to X^\sharp$ and $S' : X^\sharp \to X$ such that

$$\phi(x \otimes f) = S'f \otimes R'x \qquad (x \in X, f \in X^\sharp).$$

The next result on the structure of linear maps between C^*-algebras which preserve the unitary group is due to Russo and Dye. See [219, Corollary 2].

Theorem A.2. *Let $\mathcal{A}, \mathcal{B}$ be C^*-algebras. Suppose that $\phi : \mathcal{A} \to \mathcal{B}$ is a linear map sending unitaries to unitaries. Then ϕ can be written in the form*

$$\phi(A) = U\psi(A) \qquad (A \in \mathcal{A})$$

where $U \in \mathcal{B}$ is a fixed unitary element and $\psi : \mathcal{A} \to \mathcal{B}$ is a unital Jordan *-homomorphism.

The following description of order-preserving linear bijections between C^*-algebras was obtained by Kadison. See [118, Corollary 5].

Theorem A.3. *Any bijective linear transformation between C^*-algebras which sends the unit to the unit and preserves the order in both directions is necessarily a Jordan *-isomorphism.*

The next result gives a very useful characterization of Jordan homomorphisms and Jordan *-homomorphisms. We present it with proof as we refer to the argument below several times in the previous parts of the book.

Theorem A.4. *Let $\mathcal{A}$ be a von Neumann algebra and $\mathcal{B}$ be a Banach algebra. If $\phi : \mathcal{A} \to \mathcal{B}$ is a continuous linear transformation which sends projections to idempotents, then ϕ is a Jordan homomorphism. If $\mathcal{B}$ is a C^*-algebra and $\phi : \mathcal{A} \to \mathcal{B}$ is a continuous linear transformation which maps projections to projections, then ϕ is a Jordan *-homomorphism.*

Proof. The argument is borrowed from the proof of [29, Proposition 3.7]. If $P, Q \in \mathcal{A}$ are orthogonal projections, then $P + Q$ is also a projection. It follows that $\phi(P), \phi(Q)$ and $\phi(P) + \phi(Q) = \phi(P + Q)$ are idempotents. From $(\phi(P) + \phi(Q))^2 = \phi(P) + \phi(Q)$ we infer that $\phi(P)\phi(Q) + \phi(Q)\phi(P) = 0$. One can verify that this implies the orthogonality (in the algebraic sense) of the idempotents $\phi(P)$ and $\phi(Q)$, i.e., that $\phi(P)\phi(Q) = \phi(Q)\phi(P) = 0$. Let $P_1, ..., P_n \in \mathcal{A}$ be pairwise orthogonal projections and $\lambda_1, ..., \lambda_n \in \mathbb{R}$. We compute

$$(\phi(\sum_{k=1}^{n} \lambda_k P_k))^2 = (\sum_{k=1}^{n} \lambda_k \phi(P_k))^2 = \sum_{k=1}^{n} \lambda_k^2 \phi(P_k) =$$

$$\phi(\sum_{k=1}^{n} \lambda_k^2 P_k) = \phi((\sum_{k=1}^{n} \lambda_k P_k)^2).$$

Using the continuity of ϕ and the spectral theorem of self-adjoint operators, we obtain that $\phi(A^2) = \phi(A)^2$ holds for every self-adjoint element $A \in \mathcal{A}$. Linearizing this equality, i.e., replacing A by $A + B$ ($B \in \mathcal{A}$ is also self-adjoint), we obtain $\phi(AB + BA) = \phi(A)\phi(B) + \phi(B)\phi(A)$. Next, it follows that

$$\phi((A + iB)^2) = \phi(A^2) - \Phi(B^2) + i\phi(AB + BA) =$$
$$\phi(A)^2 - \phi(B)^2 + i(\phi(A)\phi(B) + \phi(B)\phi(A)) = (\phi(A) + i\phi(B))^2$$

which implies that ϕ is a Jordan homomorphism. If ϕ sends projections to projections, then we see that ϕ maps self-adjoint elements to self-adjoint elements and one can easily verify that this gives us that ϕ is a Jordan *-homomorphism. □

The following theorem is due to Jacobson and Rickart [106]. It states that every Jordan homomorphism from a locally matrix algebra can be written as

the sum of a homomorphism and an antihomomorphism. We point out that in [106, Theorem 8] the authors presented their result in the setting of rings. However, for our purpose we need the following version of the statement (cf. [206, 6.3.12 Theorem]).

Theorem A.5. *Let $\mathcal{A}, \mathcal{B}$ be algebras over a field $\mathbb{F}$. Suppose that $\mathcal{A}$ is a locally matrix algebra, i.e., every finite subset of $\mathcal{A}$ can be included in a subalgebra of $\mathcal{A}$ which is isomorphic to a full matrix algebra $M_n(\mathbb{F})$ with $n \geq 2$. If $\phi : \mathcal{A} \to \mathcal{B}$ is a Jordan homomorphism, then we have a homomorphism $\phi_1 : \mathcal{A} \to \mathcal{B}$ and an antihomomorphism $\phi_2 : \mathcal{A} \to \mathcal{B}$ such that $\phi = \phi_1 + \phi_2$.*

The following analogue of the theorem of Jacobson and Rickart concerning Jordan *-homomorphisms of C^*-algebras was obtained by Størmer in [235] (also see pp. 773–776 in [120]).

Theorem A.6. *Let $\mathcal{A}$ be a C^*-algebra and H be a Hilbert space. Suppose that $\phi : \mathcal{A} \to B(H)$ is a Jordan *-homomorphism. Then there exist two central projections E, F in the von Neumann algebra generated by the range of ϕ such that the map $\phi_1 : A \mapsto \phi(A)E$ is a *-homomorphism, the map $\phi_2 : A \mapsto \phi(A)F$ is a *-antihomomorphism, $E + F = I$, and $\phi = \phi_1 + \phi_2$.*

The next theorem is due Herstein [100]. Recall that a ring $\mathcal{R}$ is prime if $a\mathcal{R}b = \{0\}$ implies $a = 0$ or $b = 0$ $(a, b \in \mathcal{R})$.

Theorem A.7. *If ϕ is a Jordan homomorphism of a ring onto a prime ring of characteristic different from 2 and 3, then either ϕ is a homomorphism or an antihomomorphism.*

It is easy to see that every standard operator algebra on an arbitrary Banach space is prime. Therefore, any Jordan homomorphism onto such an algebra is either a homomorphism or an antihomomorphism. The next folklore result describes the forms of the algebra automorphisms, algebra antiautomorphisms, algebra *-automorphisms and algebra *-antiautomorphisms of standard operator algebras. One can easily demonstrate it after having a look at the proof of [223, Theorem] (also see [51]).

Theorem A.8. *Let H be a (real or complex) Hilbert space and $\mathcal{A}$ be a standard operator algebra on H. Then the following assertions hold.*

(i) Every algebra automorphism of $\mathcal{A}$ is of the form $A \mapsto TAT^{-1}$ for some invertible bounded linear operator T on H.
(ii) Every algebra antiautomorphism of $\mathcal{A}$ is of the form $A \mapsto TA^{tr}T^{-1}$ for some invertible bounded linear operator T on H.
*(iii) If $\mathcal{A}$ is a *-subalgebra of $B(H)$, then every algebra *-automorphism of $\mathcal{A}$ is of the form $A \mapsto UAU^*$ for some unitary operator U on H.*
*(iv) If $\mathcal{A}$ is a *-subalgebra of $B(H)$, then every algebra *-antiautomorphism of $\mathcal{A}$ is of the form $A \mapsto UA^{tr}U^*$ for some unitary operator U on H.*

It is easy to verify that the statement (ii) above can be reformulated in the following way. Every algebra antiautomorphism of $\mathcal{A}$ is of the form $A \mapsto TA^*T^{-1}$ for some invertible bounded conjugate-linear operator T on H. Of course, similar reformulation applies also for the statement (iv).

According to an important result of Kadison [117], every surjective linear isometry between C^*-algebras can be written as a Jordan *-isomorphism multiplied by a fixed unitary element. This together with the previous two theorems provides the structure of all surjective linear isometries of $B(H)$.

Theorem A.9. *Let H be a Hilbert space. If $\phi : B(H) \to B(H)$ is a surjective linear isometry, then there are unitary operators U, V on H such that ϕ is either of the form*

$$\phi(A) = UAV \qquad (A \in B(H))$$

or of the form

$$\phi(A) = UA^{tr}V \qquad (A \in B(H)).$$

The following statement which is called Banach-Stone theorem describes the form of all surjective linear isometries of the function spaces $C_0(L)$. If L is a locally compact Hausdorff space, then let $C_0(L)$ denote the space of all continuous complex valued functions on L which vanish at infinity. We endow $C_0(L)$ with the usual sup-norm.

Theorem A.10. *Let X and Y be locally compact Hausdorff spaces, and $\phi : C_0(X) \to C_0(Y)$ be a surjective linear isometry. Then ϕ is of the form*

$$\phi(f) = \tau \cdot f \circ \varphi \qquad (f \in C_0(X)),$$

where $\tau : X \to \mathbb{C}$ is a continuous function of modulus 1 and $\varphi : Y \to X$ is a homeomorphism.

It is an important consequence of the representation theory of $B(H)$ that in the case of a separable space, the *-endomorphisms of $B(H)$ can be written in a regular form. The following result can be found in [121, 10.4.14. Corollary].

Theorem A.11. *Let H be a separable infinite dimensional Hilbert space. If $\phi : B(H) \to B(H)$ is an algebra *-homomorphism, then there exists a collection $\{U_\alpha\}$ of isometries on H with pairwise orthogonal ranges such that ϕ is of the form*

$$\phi(A) = \sum_\alpha U_\alpha A U_\alpha^* \qquad (A \in B(H)).$$

The next result is due to Bunce and Wright [35]. It gives the solution of the famous Mackey-Gleason problem.

Theorem A.12. *Let $\mathcal{A}$ be a von Neumann algebra without type I_2 direct summand and let $P(\mathcal{A})$ be its lattice of projections. Let X be a Banach space. Suppose that $m : P(\mathcal{A}) \to X$ is a bounded function such that $m(P + Q) = m(P) + m(Q)$ holds whenever $P, Q \in \mathcal{A}$ are orthogonal projections. Then m has a unique extension to a bounded linear transformation from $\mathcal{A}$ to X.*

The following important result was obtained by Ovchinnikov [204]. It describes the general form of the order automorphisms of the poset of all idempotents on a Hilbert space.

Theorem A.13. *Let H be a Hilbert space with $\dim H \geq 3$. Denote $I(H)$ the set of all idempotents in $B(H)$ equipped with the partial order $\leq$ defined as $P \leq Q$ iff $PQ = QP = P$. Then every automorphism of $I(H)$ as a poset (i.e., every bijective map of $I(H)$ which preserves the order in both directions) is either of the form $P \mapsto APA^{-1}$ or of the form $P \mapsto AP^*A^{-1}$ with some $A \in \mathfrak{S}$. Here $\mathfrak{S}$ is the set of all semilinear bijections $A : H \to H$ if H is finite dimensional and the set of all invertible bounded linear or conjugate-linear operators on H if H is infinite dimensional.*

The content of the last result which is well-known for real or complex vector spaces is that under mild conditions locally linearly dependent linear operators are necessarily linearly dependent. The presented version of the result can be found in [30, Theorem 2.3].

Theorem A.14. *Let X be a linear space over an infinite field. Let $A, B : X \to X$ be linear operators. Suppose that for every $x \in X$ the vectors Ax, Bx are linearly dependent. Then either the operators A, B are linearly dependent or the ranges of A and B are included in the same one-dimensional subspace of X.*

Recent Results Added in Revision

This short chapter is devoted to overview some of the very recent papers relating the topics discussed in our work which have come out or come to our knowledge after the submission of the manuscript.

In Section 1.4 we mentioned the problem of additivity of bijective multiplicative or multiplicative-like maps between general rings or operator algebras. For recent results in this direction we first refer to the paper [255] by An and Hou. There they considered the products $(A, B) \mapsto ABA$, $(A, B) \mapsto AB + BA$ and $(A, B) \mapsto \frac{1}{2}(AB + BA)$ on the set of all self-adjoint operators on a Hilbert space H and also on nest algebras. They proved that if $\dim H > 1$, then every bijective map on the set of all self-adjoint operators which is multiplicative with respect to any one of the above listed products is automatically additive. In fact, they determined the general forms of those transformations. Furthermore, they presented a similar result concerning the second product on standard subalgebras of nest algebras.

Next we mention our paper [282] where we considered bijective maps on the set of all invertible positive (respectively, all invertible self-adjoint) operators which are multiplicative with respect to the Jordan triple product $(A, B) \mapsto ABA$. Under the assumption of continuity we determined the general forms of those transformations. It turned out that in the infinite dimensional case any such map defined on the set of all invertible positive operators is equal, up to composition by a linear *-automorphism or a linear *-antiautomorphism of the full operator algebra, either to the identity map $A \mapsto A$ or to the inverse operation $A \mapsto A^{-1}$ which is obviously non-additive. In the finite dimensional case the function of the determinant also shows up in the general forms of our transformations. What concerns our maps on the set of all invertible self-adjoint operators, the situation with them is a little bit more complicated. In the proofs we used some of our former results from the paper [283]. There we described the general forms of all continuous (non-linear) functionals on the sets of positive definite, positive semi-definite and Hermitian matrices which are multiplicative on the commuting elements. That

investigation was motivated by the famous Kochen-Specker theorem concerning the problem of hidden variables in quantum mechanics. As applications we obtained new characterizations of the determinant on the above mentioned classes of matrices by means of its multiplicativity property with respect to the Jordan triple product.

In relation with the same product we refer to the paper [271] by Lešnjak and Sze where they described all injective maps (surjectivity was not assumed) of the full matrix algebra over a field which are multiplicative with respect to the Jordan triple product.

There are some recent results on automatic additivity also for the so-called elementary maps and Jordan elementary maps. These transformations are abstract generalizations of some algebraic transformations like double centralizers and isomorphisms. For corresponding results we refer to the papers [274, 275, 276, 277] by Li, Jing and Lu and to the paper [296] by Timmermann. In our paper [285] we obtained the additivity of surjective Jordan elementary maps defined on self-adjoint operators. Namely, we proved the following statement. Assume that $M : \mathcal{A}_s \to \mathcal{B}_s$ and $M^* : \mathcal{B}_s \to \mathcal{A}_s$ are surjective maps between the self-adjoint parts of standard *-operator algebras $\mathcal{A}$ and $\mathcal{B}$ on an infinite dimensional Hilbert space which satisfy the equations $M(AM^*(B)A) = M(A)BM(A)$ and $M^*(BM(A)B) = M^*(B)AM^*(B)$ for every pair $A \in \mathcal{A}_s$, $B \in \mathcal{B}_s$. Then there exist an invertible bounded linear or conjugate-linear operator $T : H \to H$ and a constant $c \in \{-1, 1\}$ such that $M(A) = cTAT^*$ $(A \in \mathcal{A}_s)$ and $M^*(B) = cT^*BT$ $(B \in \mathcal{B}_s)$.

Finally, we draw the reader's attention to the interesting papers [262, 263, 264] of Chebotar et al. where they discussed linear or additive maps on operator algebras, matrix algebras or general rings with certain product preserving properties. Their approaches were based on deep algebraic tools like the modern theory of functional identities. This idea was utilized already in the basic paper [256] by Beidar, Brešar, Chebotar and Fong where functional identities were applied to certain linear preserver problems, for example, to the problem of commutativity preservers. For important new achievements in this direction we refer to the papers [257, 258] of Brešar and Šemrl.

In Section 2.2 we presented a generalization of Uhlhorn's theorem concerning orthogonality preserving maps for the case of indefinite inner product spaces. Our approach was based on the description of all bijective maps on the set of rank-one idempotents which preserve zero product in both directions (see Theorem 2.2.1). In relation with this result we refer to a series of recent papers by Šemrl in which he presented a number of deep results concerning various transformations on the set of idempotents. In fact, in those papers he continued and extended his previous work that we already mentioned in 2.2.4. Remarks. First of all, we refer to his substantial work [291] where he gave a complete and fine analysis of transformations on the set of all $n \times n$ $(n \geq 3)$ idempotent matrices over a division ring which preserve either commutativity, or order, or orthogonality. This analysis extends to the study of

non-bijective maps as well as maps which preserve any of the mentioned relations only in one direction. As an application, he obtained a quaternionic analogue of Ovchinnikov's theorem (see Theorem A.13). Other applications were also given on automorphisms of operator and matrix semigroups, local automorphisms, linear preserver problems and the geometry of matrices and Grassmannians. The main results in [291] appear also in the expository paper [292]. There he gave a short proof of the well-known statement that every automorphism of the full matrix algebra is inner and discussed several extensions of this theorem. Those include, among others, the descriptions of multiplicative maps on matrix algebras and some non-linear preserver results. In the paper [293], beside structural results concerning non-linear maps on full matrix algebras preserving commutativity and maps on idempotent matrices and operators preserving orthogonality, the general form of all bijective non-linear maps which preserve the Lie product of operators was completely determined both in the finite and in the infinite dimensional cases. In [294] it was shown that in infinite dimensional Banach spaces the structural results concerning bijective maps on idempotent operators which preserve the order or the orthogonality in both directions can be derived from the corresponding result concerning commutativity preserving maps. Moreover, the form of bijective maps which preserve comparability in both directions was also described. Next we mention another expository paper of Šemrl [295] where beside order or orthogonality preserving maps on idempotent matrices or operators, he surveyed some recent results concerning adjacency preserving maps on linear matrix spaces, maps on the set of space-time events preserving coherency, maps on bounded observables preserving compatibility, Wigner's unitary-antiunitary theorem, and the geometry of Grassmann spaces. Moreover, in that paper he pointed out the interrelations between those, seemingly rather unrelated areas of research.

In the paper [290] Rodman and Šemrl presented an Uhlhorn-type result for orthogonality preserving maps between projective spaces corresponding to different indefinite inner products on $\mathbb{K}^n$ ($n \geq 3$ and $\mathbb{K}$ denotes the field of real or complex numbers) which arise from invertible $n \times n$ matrices. The authors obtained their result for bijective maps which preserve orthogonality only in one direction.

Next we refer to the papers [266, 267] of Fošner. It turns out from [266] that the structure of the order automorphisms of the set of all upper triangular idempotent matrices is not so nice as in the case of the set of all idempotent matrices. In [267] Fošner described the general form of all bijective maps on the set of upper triangular idempotent matrices which preserve both the order and the orthogonality in one direction.

Finally, we mention the papers [265] and [297] for interesting results on additive or linear maps defined on operator algebras which preserve certain kinds of orthogonality relations between operators.

Section 2.3 was devoted to determine the fidelity preserving bijective maps on the sets of states and density operators. In our recent paper [286] we obtained a generalization of the corresponding result. Namely, among others, we determined the so-called Θ-fidelity preserving bijective maps on the same sets.

In Section 2.5 we described the form of all bijective maps (no linearity was assumed) on the set $B_s(H)$ of all bounded observables (i.e., self-adjoint operators) which preserve the usual order $\leq$ in both directions. The order is a rather important relation between observables but there is another even more important correspondence which is called compatibility. Mathematically this means simply commutativity. In our paper [284] we characterized those bijective maps on $B_s(H)$ (once again without assuming linearity) which preserve commutativity in both directions. In particular, we proved that for a complex separable Hilbert space H with $\dim H \geq 3$, if $\phi : B_s(H) \to B_s(H)$ is a bijective map preserving commutativity in both directions, then there exists an either unitary or antiunitary operator U on H, and for every operator $A \in B_s(H)$ there is a real valued bounded Borel function f_A on the spectrum $\sigma(A)$ of A such that $\phi(A) = Uf_A(A)U^*$. In other words, this means that, up to composition by either a linear *-isomorphism or a linear *-antiisomorphism of the operator algebra $B(H)$, for every $A \in B_s(H)$ the operator $\phi(A)$ is a real valued bounded Borel function of A. Concerning the same problem for full matrix algebras we refer to the papers [293] by Šemrl and [268] by Fošner. There they described all the continuous bijective maps on the algebra of $n \times n$ ($n \geq 3$) complex, respectively real matrices which preserve commutativity in both directions.

In Section 2.8 we studied the structure of sequential isomorphisms between the sets of von Neumann algebra effects. In 2.8.4. Remarks we mentioned a result of Marovt on the form of sequential isomorphisms between the sets of commutative C^*-algebra effects. In fact, in [280] he described all the bijective multiplicative maps on the set $C(X, I)$ of continuous functions from a first countable compact Hausdorff space X into the unit interval I. Furthermore, in his recent paper [279] he presented a similar structural result for the bijective maps of $C(X, I)$ preserving the order in both directions, while in [281] he gave the complete description of the affine bijections of $C(X, I)$.

In Chapter 3 we considered certain local transformations on structures of linear operators and continuous functions.

As for recent results in this direction concerning function spaces we mention the paper [259] of Cabello Sánchez. In Section 3.2 we proved the algebraic reflexivity of the automorphism and isometry groups of the complex function space $C(X)$ on a first countable compact Hausdorff space X. In our proof we used the theorem of Russo and Dye (see Theorem A.2) concerning the structure of linear maps on C^*-algebras preserving the unitary group which

result do require that the underlying field is $\mathbb{C}$. In the paper [259] Cabello Sánchez proved that for various classes of locally compact spaces L, the space $C_0^{\mathbb{R}}(L)$ of all real-valued continuous functions on L vanishing at infinity has the property that its local isometries are all surjective. This means the algebraic reflexivity of the isometry group of $C_0^{\mathbb{R}}(L)$. The classes in question include totally disconnected locally compact spaces whose one-point compactification is metrizable and manifolds with and without boundary.

In the paper [287] Pop studied bounded linear maps from a von Neumann algebra into $B(H)$ which are (1-)local or 2-local representations (the definition should be self-explanatory). He obtained the interesting result that every bounded 2-local representation is necessarily a representation but, in contrast, 1-local representations may fail to be multiplicative even at the 2 by 2 matrix algebra level.

In a series of papers Zhang and his coauthors studied 1-local and 2-local transformations on nest subalgebras of von Neumann algebras. In [299] they proved that every norm-continuous linear local derivation of a nest subalgebra of a factor von Neumann algebra is a derivation and that every linear 2-local derivation (not necessarily norm-continuous) of the same structure is a derivation. In [300] it was shown that every surjective weakly continuous linear local automorphism of a nest subalgebra corresponding to a non-trivial nest in a factor von Neumann algebra is an automorphism and that every surjective linear 2-local automorphism (no continuity is assumed) of the same structure is an automorphism. In the paper [298] they considered local 2-cocyles of operator algebras. It was proved there that every weakly continuous local 2-cocycle of a nest subalgebra of a factor von Neumann algebra M with coefficients in M is a 2-cocycle. In their paper [278] Liu and Wong presented results on the 2-local automorphisms of standard operator algebras over locally convex spaces, especially, over Fréchet spaces with Schauder basis and also on the 2-local automorphisms of some function algebras.

Finally, we recall Theorem 3.4.1 which was our key tool in the proof of a theorem on the 2-local automorphisms of standard operator algebras over Banach spaces. This result gives a non-linear characterization of the automorphisms of matrix algebras by means of their property that they leave the set of eigenvalues (counted according to multiplicity) of matrix products invariant. In the papers [260, 261, 272, 273] by Chan, Li, Poon, Sze and [270] by Hou and Di one can find several recent results of similar spirit concerning the invariance of certain functional values of matrix or operator products. Corresponding results for function algebras relating maps which preserve the range of products were presented in the papers [269, 288, 289].

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