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# One-parameter Semigroups of Positive Operators

Edited by R. Nagel

Lecture Notes in Mathematics

1184

Springer-Verlag  
Berlin Heidelberg New York Tokyo

Stand: March 26, 2025

Springer Nature



*This Latex version of the book  
“One-Parameter Semigroups of  
Positive Operators” is dedicated to the  
memory of our co-authors, Heinrich P.  
Lotz and Ulf Schlotterbeck. Their  
contributions to the first edition  
remain an inspiration to us all. We  
miss their presence and remain  
grateful for the legacy they have left in  
this work.*



# Preface

As early as 1948 in the first edition of his fundamental treatise on *Semigroups and Functional Analysis*, E. Hille expressed the need for

*... developing an adequate theory of transformation semigroups operating in partially ordered spaces* (l.c., Foreword).

In the meantime the theory of one-parameter semigroups of positive linear operators has grown continuously. Motivated by problems in probability theory and partial differential equations W. Feller (1952) and R. S. Phillips (1962) laid the first cornerstones by characterizing the generators of special positive semigroups. In the 60's and 70's the theory of positive operators on ordered Banach spaces was built systematically and is well documented in the monographs of H. H. Schaefer (1974) and A. C. Zaanen (1983). But in this process the original ties with the applications and, in particular, with initial value problems were at times obscured. Only in recent years an adequate and up-to-date theory emerged, largely based on the techniques developed for positive operators and thus recombining the functional analytic theory with the investigation of Cauchy problems having positive solutions to each positive initial value. Even though this development — in particular with respect to applications to concrete evolution equations in transport theory, mathematical biology, and physics — is far from being complete, the present volume is a first attempt to shape the multitude of available results into a coherent theory of one-parameter semigroups of positive linear operators on ordered Banach spaces.

The book is organized as follows. We concentrate our attention on three subjects of semigroup theory: *characterization*, *spectral theory* and *asymptotic behavior*. By *characterization*, we understand the problem of describing special properties of a semigroup, such as positivity, through the generator. By *spectral theory* we mean the investigation of the spectrum of a generator. *Asymptotic behavior* refers to the orbits of the initial values under a given semigroup and phenomena such as stability.

This program (characterization, spectral theory, asymptotic behavior) is worked out on four different types of underlying spaces.

- (A) On Banach spaces—Here we present the background for the subsequent discussions related to order.
- (B) On spaces  $C_0(X)$  ( $X$  locally compact), which constitute an important class of ordered Banach spaces and where our results can be presented in a form which makes them accessible also for the non-expert in order-theory.
- (C) On Banach lattices, which admit a rich theory and are still sufficiently general as to include many concrete spaces appearing in analysis; e.g.,  $C_0(X)$ ,  $\mathcal{L}^p(k)$  or  $l^p$ .
- (D) On non-commutative operator algebras such as  $C^*$ - or  $W^*$ -algebras, which are not lattice ordered but still possess an interesting order structure of great importance in mathematical physics.

In each of these cases we start with a short collection of basic results and notations, so that the contents of the book may be visualized in the form of a  $4 \times 4$  matrix in a way which will allow “row readers” (interested in semigroups on certain types of spaces) and “column readers” (interested in certain aspects) to find a path through the book corresponding to their interest.

We display this matrix, together with the names of the authors contributing to the subjects defined through this scheme.

	I Basic Results	II Characterization	III Spectral Theory	IV Asymptotics
A. Banach Spaces	R. Nagel U. Schlotterbeck	W. Arendt H. P. Lotz	G. Greiner R. Nagel	F. Neubrander
B. $C_0(X)$	R. Nagel U. Schlotterbeck	W. Arendt	G. Greiner	A. Grabosch G. Greiner U. Moustakas F. Neubrander
C. Banach Lattices	R. Nagel U. Schlotterbeck	W. Arendt	G. Greiner	A. Grabosch G. Greiner U. Moustakas R. Nagel F. Neubrander
D. Operator Algebras	U. Groh	U. Groh	U. Groh	U. Groh

This “matrix of contents” has been an indispensable guide line in our discussions on the scope and the spirit of the various contributions. However, we would not have succeeded in completing this manuscript, as a collection of independent contributions (personally accounted for by the authors), under less favorable conditions than we have actually met. For one thing, Rainer Nagel was an unfaltering and undisputed spiritus rector from the very beginning of the project. On the other hand we gratefully acknowledge the influence of Helmut H. Schaefer and his pioneering work on order structures in analysis. It was the team spirit produced by this common mathematical background which, with a little help from our friends, made it possible to overcome most difficulties.

We have prepared the manuscript with the aid of a word processor, but we confess that without the assistance of Klaus Kuhn the pitfalls of such a system would have been greater than its benefits.



*The authors*

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## Acronyms

$E_{\mathbb{R}}, E_{\mathbb{C}}$  real, complex Banach lattice  
 $E_+$  positive cone  
 $E'$  dual Banach space  
 $E^*$  semigroup dual  
 $E_F^T$   $\mathcal{F}$ -product of  $E$  with respect to semigroup  $\mathcal{T}$   
 $E_F$   $\mathcal{F}$ -product of  $E$   
 $E_f$  see C-I,4  
 $(E, \varphi)$  see C-I,4  
 $E \otimes F$  tensor product  
 $\mathcal{L}(E)$  Banach space of bounded linear operators on  $E$   
 $\mathcal{Z}(E)$  center of  $E$   
 $E_n$   $n$ -th Sobolev space  
 $B(H)$   $W^*$ -algebra of bounded linear operators on a Hilbert space  $H$



**Part A**  
**One-parameter Semigroups on Banach**  
**Spaces**



# Chapter A-I

## Basic Results on Semigroups on Banach Spaces

Since the basic theory of one-parameter semigroups can be found in several excellent books (e.g. Davies [1], Goldstein [4], Pazy [9] or Hille and Phillips [6]), we do not want to give a self-contained introduction to this subject here. It may however be useful to fix our notation, to collect briefly some important definitions and results (Section 1), to present a list of *standard examples* in Section 2 and to discuss standard constructions of new semigroups from a given one in Section 3 on p. 15.

In the entire chapter we denote by  $E$  a (real or) complex Banach space and consider one-parameter semigroups of bounded linear operators  $T(t)$  on  $E$ . By this we understand a subset  $\{T(t) : t \in \mathbb{R}_+\}$  of  $\mathcal{L}(E)$ , usually written as  $(T(t))_{t \geq 0}$ , such that

$$\begin{aligned} T(0) &= \text{Id}, \\ T(s+t) &= T(s) \cdot T(t) \text{ for all } s, t \in \mathbb{R}_+. \end{aligned}$$

In more abstract terms this means that the map  $t \mapsto T(t)$  is a homomorphism from the additive semigroup  $(\mathbb{R}_+, +)$  into the multiplicative semigroup  $(\mathcal{L}(E), \cdot)$ . Similarly, a one-parameter group  $(T(t))_{t \in \mathbb{R}}$  will be a homomorphic image of the group  $(\mathbb{R}, +)$  in  $(\mathcal{L}(E), \cdot)$ .

### 1 Standard Definitions and Results

We consider a one-parameter semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$  and observe that the domain  $\mathbb{R}_+$  and the range  $\mathcal{L}(E)$  of the (semigroup) homomorphism  $\tau : t \mapsto T(t)$  are topological semigroups for the natural topology on  $\mathbb{R}_+$  and any one of the standard operator topologies on  $\mathcal{L}(E)$ . We single out the strong operator topology on  $\mathcal{L}(E)$  and require  $\tau$  to be continuous.

**Definition 1.1** A one-parameter semigroup  $(T(t))_{t \geq 0}$  is called *strongly continuous* if the map  $t \mapsto T(t)$  is continuous for the strong operator topology on  $\mathcal{L}(E)$ , e.g.,

$$\lim_{t \rightarrow t_0} \|T(t)f - T(t_0)f\| = 0$$

for every  $f \in E$  and  $t, t_0 \geq 0$ .

Clearly one defines in a similar way *weakly continuous*, resp. *uniformly continuous* (compare A-II, Def. 1.19) semigroups, but since we concentrate on the strongly continuous case we agree on the following terminology.

If not stated otherwise, a *semigroup* is a strongly continuous one-parameter semigroup of bounded linear operators.

Next we collect a few elementary facts on the continuity and boundedness of one-parameter semigroups.

**Remarks 1.2** (i) A one-parameter semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$  is strongly continuous if and only if for any  $f \in E$  it is true that  $T(t)f \rightarrow f$  if  $t \rightarrow 0$ .  
(ii) For every strongly continuous semigroup there exist constants  $M \geq 1$ ,  $w \in \mathbb{R}$  such that  $\|T(t)\| \leq M \cdot e^{wt}$  for every  $t \geq 0$ .  
(iii) If  $(T(t))_{t \geq 0}$  is a one-parameter semigroup such that  $\|T(t)\|$  is bounded for  $0 < t \leq \delta$  then it is strongly continuous if and only if  $\lim_{t \rightarrow 0} T(t)f = f$  for every  $f$  in a total subset of  $E$ .

The exponential estimate from Remark 1.2(ii) for the growth of  $\|T(t)\|$  can be used to define an important characteristic of the semigroup.

**Definition 1.3** By the growth bound (or type) of the semigroup  $(T(t))_{t \geq 0}$  we understand the number

$$\begin{aligned} \omega_0 &:= \inf\{w \in \mathbb{R} : \text{There exists } M \in \mathbb{R}_+ \text{ such that } \|T(t)\| \leq M e^{wt} \text{ for } t \geq 0\} \\ &= \lim_{t \rightarrow \infty} \frac{1}{t} \log \|T(t)\| = \inf_{t > 0} \frac{1}{t} \log \|T(t)\|. \end{aligned}$$

Particularly important are semigroups such that for every  $t \geq 0$  we have  $\|T(t)\| \leq M$  (*bounded semigroups*) or  $\|T(t)\| \leq 1$  (*contraction semigroups*). In both cases we have  $\omega_0 \leq 0$ .

It follows from the subsequent examples and from Def. 1.3 that  $\omega_0$  may be any number  $-\infty \leq \omega < +\infty$ . Moreover the reader should observe that the infimum in Def. 1.3 need not be attained and that  $M$  may be larger than 1 even for bounded semigroups.

**Examples 1.4** (i) Take  $E = \mathbb{C}^2$ ,

$$A = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad \text{and} \quad T(t) = e^{tA} = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix}.$$

Then for the  $\ell^1$ -norm on  $E$  we obtain  $\|T(t)\| = 1+t$ , hence  $(T(t))_{t \geq 0}$  is an unbounded semigroup having growth bound  $\omega_0 = 0$ .



(ii) Take  $E = L^1(\mathbb{R})$  and for  $f \in E, t \geq 0$  define

$$T(t)f(x) := \begin{cases} 2 \cdot f(x+t) & \text{if } x \in [-t, 0] \\ f(x+t) & \text{otherwise.} \end{cases}$$

Each  $T(t), t > 0$ , satisfies  $\|T(t)\| = 2$  as can be seen by taking  $f := \chi_{[0,t]}$ . Therefore  $(T(t))_{t \geq 0}$  is a strongly continuous semigroup which is bounded, hence has  $\omega_0 = 0$ , but the constant  $M$  in (1.3) cannot be chosen to be 1.

The most important object associated to a strongly continuous semigroup  $(T(t))_{t \geq 0}$  is its *generator* which is obtained as the (right)derivative of the map  $t \mapsto T(t)$  at  $t = 0$ . Since for strongly continuous semigroups the functions  $t \mapsto T(t)f, f \in E$ , are continuous but not always differentiable, we have to restrict our attention to those  $f \in E$  for which the desired derivative exists. We then obtain the *generator* as a not necessarily everywhere defined operator.

**Definition 1.5** To every semigroup  $(T(t))_{t \geq 0}$  there belongs an operator  $(A, D(A))$ , called the *generator* and defined on the *domain*

$$D(A) := \{f \in E : \lim_{h \rightarrow 0} \frac{T(h)f - f}{h} \text{ exists in } E\} \text{ by}$$

$$Af := \lim_{h \rightarrow 0} \frac{T(h)f - f}{h} \quad (f \in D(A)).$$

Clearly,  $D(A)$  is a linear subspace of  $E$  and  $A$  is linear from  $D(A)$  into  $E$ . Only in certain special cases (see 2.1) the generator is everywhere defined and therefore bounded (use Prop. 1.9(ii) on p. 6). In general, the precise extent of the domain  $D(A)$  is essential for the characterization of the generator. But since the domain is canonically associated to the generator of a semigroup, we shall write in most cases  $A$  instead of  $(A, D(A))$ .

As a first result we collect some information on the domain of the generator.

**Proposition 1.6** For the generator  $A$  of a semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$  the following assertions hold.

- (i) If  $f \in D(A)$ , then  $T(t)f \in D(A)$  for every  $t \geq 0$ .
- (ii) The map  $t \mapsto T(t)f$  is differentiable on  $\mathbb{R}_+$  if and only if  $f \in D(A)$ . In that case one has

$$\frac{d}{dt}T(t)f = AT(t)f = T(t)Af. \quad (1.1)$$

- (iii) For every  $f \in E$  and  $t > 0$  the element  $\int_0^t T(s)f \, ds$  belongs to  $D(A)$  and one has

$$A \int_0^t T(s)f \, ds = T(t)f - f. \quad (1.2)$$

- (iv) If  $f \in D(A)$ , then

$$\int_0^t T(s)Af \, ds = T(t)f - f. \quad (1.3)$$

(v) The domain  $D(A)$  is dense in  $E$ .

The identity (1.1) is of great importance and shows how semigroups are related to certain Cauchy problems. We state this explicitly in the following theorem.

**Theorem 1.7** *Let  $(A, D(A))$  be the generator of a strongly continuous semigroup  $(T(t))_{t \geq 0}$  on the Banach space  $E$ . Then the abstract Cauchy problem*

$$\frac{d}{dt}\xi(t) = A\xi(t), \quad \xi(0) = f_0 \quad (1.4)$$

*has a unique solution  $\xi: \mathbb{R}_+ \rightarrow D(A)$  in  $C^1(\mathbb{R}_+, E)$  for every  $f_0 \in D(A)$ . In fact, this solution is given by  $\xi(t) := T(t)f_0$ .*

For more on the relation of semigroups to abstract Cauchy problems we refer to A-II, Section 1. Here we only point out that the above theorem implies that a semigroup is uniquely determined by its generator.

While the generator is bounded only for uniformly continuous semigroups (see Sec. 2 below), it always enjoys a weaker but useful property.

**Definition 1.8** An operator  $B$  with domain  $D(B)$  on a Banach space  $E$  is called *closed* if  $D(B)$  endowed with the *graph norm*

$$\|f\|_B := \|f\| + \|Bf\|$$

becomes a Banach space. Equivalently,  $(B, D(B))$  is closed if and only if its *graph*  $\{(f, Bf): f \in D(B)\}$  is closed in  $E \times E$ , i.e.,

$$f_n \in D(B), f_n \rightarrow f \text{ and } Bf_n \rightarrow g \text{ implies } f \in D(B) \text{ and } Bf = g.$$

It is clear from this definition that the *closedness* of an operator  $B$  depends very much on the size of the domain  $D(B)$ . For example, a bounded and densely defined operator  $(B, D(B))$  is closed if and only if  $D(B) = E$ .

On the other hand it may happen that  $(B, D(B))$  is not closed but has a closed *extension*  $(C, D(C))$ , i.e.,  $D(B) \subseteq D(C)$  and  $Bf = Cf$  for every  $f \in D(B)$ . In that case,  $B$  is called *closable*, a property which is equivalent to

$$f_n \in D(B), f_n \rightarrow 0 \text{ and } Bf_n \rightarrow g \text{ implies } g = 0.$$

The smallest closed extension of  $(B, D(B))$  will be called the *closure*  $\bar{B}$  with domain  $D(\bar{B})$ . In other words, the graph of  $\bar{B}$  is the closure of  $\{(f, Bf): f \in D(B)\}$  in  $E \times E$ .

Finally we call a subset  $D_0$  of  $D(B)$  a *core* for  $B$  if  $D_0$  is  $\|\cdot\|_B$ -dense in  $D(B)$ . This means that a closed operator is determined (via closure) by its restriction to a core in its domain.

We now collect the fundamental topological properties of semigroup generators, their domains (see also A-II, Cor. 1.34) and their resolvents.

**Proposition 1.9** *For the generator  $A$  of a strongly continuous semigroup  $(T(t))_{t \geq 0}$  the following hold.*

- (i) The generator  $A$  is a closed operator.
- (ii) If a subspace  $D_0$  of the domain  $D(A)$  is dense in  $E$  and  $(T(t))$ -invariant, then it is a core for  $A$ .
- (iii) Define  $D(A^n) := \{f \in D(A^{n-1}) : Af \in D(A^{n-1})\}$ ,  $D(A^1) = D(A)$ . Then  $D(A^\infty) := \bigcap_{n \in \mathbb{N}} D(A^n)$  is dense in  $E$  and a core for  $A$ .

**Example 1.10** Property (iii) above does not hold for general densely defined closed operators. Take  $E = C[0, 1]$ ,  $D(B) = C^1[0, 1]$  and  $Bf = q \cdot f'$  for some nowhere differentiable function  $q \in C[0, 1]$ . Then  $B$  is closed, but  $D(B^2) = \{0\}$ .

**Proposition 1.11** For the generator  $A$  of a strongly continuous semigroup on a Banach space  $E$  the following hold.

If  $\int_0^\infty e^{-\lambda t} T(t) f dt$  exists for every  $f \in E$  and some  $\lambda \in \mathbb{C}$ , then  $\lambda \in \varrho(A)$  and  $R(\lambda, A)f = \int_0^\infty e^{-\lambda t} T(t) f dt$ . In particular,

$$R(\lambda, A)^{n+1} f = \frac{(-1)^n}{n!} \left( \frac{d}{d\lambda} \right)^n R(\lambda, A) f = \int_0^\infty e^{-\lambda t} \frac{t^n}{n!} T(t) f dt \quad (1.5)$$

for every  $f \in E$ ,  $n \geq 0$  and  $\lambda \in \mathbb{C}$  with  $\operatorname{Re}(\lambda) > \omega$ .

**Remarks 1.12** (i) For continuous Banach space valued functions such as  $t \mapsto T(t)f$  we consider the Riemann integral and define

$$\int_0^\infty T(t) f dt \quad \text{as} \quad \lim_{t \rightarrow \infty} \int_0^t T(s) f ds.$$

Sometimes such integrals for strongly continuous semigroups are written as  $\int_a^b T(t) dt$  but understood in the strong sense.

(ii) Since the generator  $(A, D(A))$  determines the semigroup uniquely, we will speak occasionally of the growth bound of the generator instead of the semigroup, i.e., we write  $\omega_0 = \omega_0(A) = \omega_0((T(t))_{t \geq 0})$ .

(iii) For one-parameter groups it might seem to be more natural to define the generator as the *derivative* rather than just the *right derivative* at  $t = 0$ . This yields the same operator as the following result shows.

The strongly continuous semigroup  $(T(t))_{t \geq 0}$  with generator  $A$  can be extended to a strongly continuous one-parameter group  $(U(t))_{t \in \mathbb{R}}$  if and only if  $-A$  generates a semigroup  $(S(t))_{t \geq 0}$ .

In that case  $(U(t))_{t \in \mathbb{R}}$  is obtained as

$$U(t) = \begin{cases} T(t) & \text{for } t \geq 0, \\ S(-t) & \text{for } t \leq 0. \end{cases}$$

We refer to Davies [1, Prop.1.14] for the details.

## 2 Standard Examples

In this section we list and discuss briefly the most basic examples of semigroups together with their generators. These semigroups will reappear throughout this book and will be used to illustrate the theory. We start with the class of semigroups mentioned after Definition 1.1 on p. 3.

### 2.1 Uniformly Continuous Semigroups

It follows from elementary operator theory that for every bounded operator  $A$  in  $\mathcal{L}(E)$  the sum

$$\sum_{n=0}^{\infty} \frac{t^n A^n}{n!} =: e^{tA}$$

exists and determines a unique uniformly continuous (semi)group  $(e^{tA})_{t \in \mathbb{R}}$  having  $A$  as its generator. Conversely, any uniformly continuous semigroup is of this form.

If the semigroup  $(T(t))_{t \geq 0}$  is uniformly continuous, then  $\frac{1}{t} \int_0^t T(s) ds$  uniformly converges to  $T(0) = \text{Id}$  as  $t \rightarrow 0$ . Therefore for some  $t' > 0$  the operator  $\frac{1}{t'} \int_0^{t'} T(s) ds$  is invertible and every  $f \in E$  is of the form  $f = \frac{1}{t'} \int_0^{t'} T(s)g ds$  for some  $g \in E$ . But these elements belong to  $D(A)$  by (1.3), hence  $D(A) = E$ . Since the generator  $A$  is closed and everywhere defined, it must be bounded.

Remark that bounded operators are always generators of groups, not just semigroups. Moreover, the growth bound  $\omega$  satisfies  $|\omega| \leq \|A\|$  in this situation.

The above characterization of the generators of uniformly continuous semigroups as the bounded operators shows that these semigroups are—at least in many aspects—rather simple objects.

### 2.2 Matrix Semigroups

The above considerations especially apply in the situation  $E = \mathbb{C}^n$ . If  $n = 2$  and  $A = (a_{ij})_{2 \times 2}$  the following explicit formulas for  $e^{tA}$  might be of interest.

Set (i)  $s := \text{trace } A$ , (ii)  $d := \det A$  (iii) and  $D := (s^2 - 4d)^{1/2}$ . Then if  $D \neq 0$

$$e^{tA} = e^{ts/2} \cdot [D^{-1} 2 \sinh(tD/2) \cdot A + (\cosh(tD/2) - sD^{-1} \sinh(tD/2)) \cdot \text{Id}]$$

and if  $D = 0$

$$e^{ts/2} \cdot [tA + (1 - ts/2) \cdot \text{Id}].$$

### 2.3 Multiplication Semigroups

Many Banach spaces appearing in applications are Banach spaces of (real or) complex valued functions over a set  $X$ . As the most standard examples of these “function spaces”, we mention the space  $C_0(X)$  of all continuous complex valued functions vanishing at infinity on a locally compact space  $X$ , or the spaces  $L^p(X, \Sigma, \mu)$ ,  $1 \leq p \leq \infty$ , of all (equivalence classes of)  $p$ -integrable functions on a  $\sigma$ -finite measure space  $(X, \Sigma, \mu)$ .

On these function spaces  $E = C_0(X)$ , resp.  $E = L^p(X, \Sigma, \mu)$ , there is a simple way to define *multiplication operators*.

Take a continuous, resp. measurable function  $q: X \rightarrow \mathbb{C}$  and define

$$M_q f := q \cdot f, \quad \text{i.e.,} \quad M_q f(x) := q(x) \cdot f(x) \quad \text{for } x \in X$$

and for every  $f$  in the *maximal domain*  $D(M_q) := \{g \in E : q \cdot g \in E\}$ .

This natural domain is a dense subspace of  $C_0(X)$ , resp.  $L^p(X, \Sigma, \mu)$ , for  $1 \leq p < \infty$ . Moreover,  $(M_q, D(M_q))$  is a closed operator. This is easy in case  $E = C_0(X)$ .

For  $E = L^p(X, \Sigma, \mu)$ ,  $1 \leq p < \infty$ , we consider a sequence  $(f_n) \subset E$  such that  $\lim_{n \rightarrow \infty} f_n = f \in E$  and  $\lim_{n \rightarrow \infty} q f_n =: g \in E$ . Choose a subsequence  $(f_{n(k)})_{k \in \mathbb{N}}$  such that  $\lim_{k \rightarrow \infty} f_{n(k)}(x) = f(x)$  and  $\lim_{k \rightarrow \infty} q(x) f_{n(k)}(x) = g(x)$  for  $\mu$ -almost every  $x \in X$ . Then  $g = q \cdot f$  and  $f \in D(M_q)$ , i.e.,  $M_q$  is closed.

For such multiplication operators many properties can be checked quite directly. For example, the following statements are equivalent.

- (a)  $M_q$  is bounded.
- (b)  $q$  is ( $\mu$ -essentially) bounded.

One has  $\|M_q\| = \|q\|_\infty$  in this situation. Observe that on spaces  $C(K)$ ,  $K$  compact, there are no densely defined, unbounded multiplication operators.

By defining the multiplication semigroups

$$T(t)f(x) := \exp(t \cdot q(x))f(x), \quad x \in X, f \in E,$$

one obtains the following characterizations.

**Proposition 2.1** *Let  $M_q$  be a multiplication operator on  $E = C_0(X)$  or  $E = L^p(X, \Sigma, \mu)$ ,  $1 \leq p < \infty$ . Then the properties (a) and (b), resp. (a') and (b'), are equivalent.*

- (a)  $M_q$  generates a strongly continuous semigroup.
- (b)  $\sup\{\operatorname{Re}(q(x)) : x \in X\} < \infty$ .
- (a')  $M_q$  generates a uniformly continuous semigroup.
- (b')  $\sup\{|q(x)| : x \in X\} < \infty$ .

As a consequence one computes the growth bound of a multiplication semigroup as

$$\omega_0 = \sup\{\operatorname{Re}(q(x)) : x \in X\}$$

in the case  $E = C_0(X)$  and

$$\omega_0 = \mu\text{-ess- sup}\{\operatorname{Re}(q(x)) : x \in X\}$$

in the case  $E = L^p(\mu)$ . It is a nice exercise to characterize those multiplication operators which generate strongly continuous groups.

We point out that the above results cover the cases of sequence spaces such as  $c_0$  or  $\ell^p$ ,  $1 \leq p < \infty$ . An abstract characterization of generators of multiplication semigroups will be given in C-II, Thm.5.13.

## 2.4 Translation (Semi)Groups

Let  $E$  to be one of the following function spaces  $C_0(\mathbb{R}_+)$ ,  $C_0(\mathbb{R})$  or  $L^p(\mathbb{R}_+)$ ,  $L^p(\mathbb{R})$  for  $1 \leq p < \infty$ . Define  $T(t)$  to be the (left) translation operator

$$T(t)f(x) := f(x+t)$$

for  $x, t \in \mathbb{R}_+$ , resp.  $x, t \in \mathbb{R}$  and  $f \in E$ . Then  $(T(t))_{t \geq 0}$  is a strongly continuous semigroup, resp. group of contractions on  $E$  and its generator is the first derivative  $\frac{d}{dx}$  with *maximal* domain. In order to be more precise we have to distinguish the cases  $E = C_0$  and  $E = L^p$ .

The generator of the translation (semi)group on  $E = C_0(\mathbb{R}_+)$  is

$$Af := \frac{d}{dx}f = f'$$

$$D(A) := \{f \in E : f \text{ differentiable and } f' \in E\}.$$

**Proof** For  $f \in D(A)$  it follows that for every  $x \in \mathbb{R}_+$

$$\lim_{h \rightarrow 0} \frac{T(h)f(x) - f(x)}{h} = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} \text{ exists}$$

(uniformly in  $x$ ) and coincides with  $Af(x)$ . Therefore  $f$  is differentiable and  $f' \in E$ .

On the other hand, take  $f \in E$  differentiable such that  $f' \in E$ . Then

$$\left| \frac{f(x+h) - f(x)}{h} - f'(x) \right| \leq \frac{1}{h} \int_x^{x+h} |f'(y) - f'(x)| dy,$$

where the last expression tends to zero uniformly in  $x$  as  $h \rightarrow 0$ . Thus  $f \in D(A)$  and  $f' = Af$ .  $\square$

The generator of the translation (semi)group on  $E = L^p(\mathbb{R}_+)$ ,  $1 \leq p < \infty$ , is

$$Af := \frac{d}{dx}f = f',$$

$$D(A) := \{f \in E : f \text{ absolutely continuous, } f' \in E\}.$$

**Proof** Take  $f \in D(A)$  such that  $\lim_{h \rightarrow 0} \frac{1}{h}(T(h)f - f) = g \in E$ . Since integration is continuous, we obtain for every  $a, b \in \mathbb{R}_{(+)}$  that

$$(*) \quad \frac{1}{h} \int_{b+h}^b f(x) dx - \frac{1}{h} \int_{a+h}^a f(x) dx = \int_a^b \frac{f(x+h) - f(x)}{h} dx$$

converges to  $\int_a^b g(x) dx$  as  $h \rightarrow 0+$ . But for almost all  $a, b$  the left hand side of  $(*)$  converges to  $f(b) - f(a)$ . By redefining  $f$  on a nullset we obtain

$$f(y) = \int_a^y g(x) dx + f(a), \quad y \in \mathbb{R}_{(+)},$$

which is an absolutely continuous function whose derivative is (almost everywhere) equal to  $g$ .

On the other hand, let  $f$  be absolutely continuous such that  $f' \in L^p$ . Then

$$\begin{aligned} \lim_{h \rightarrow 0} \int \left| \frac{f(x+h) - f(x)}{h} - f'(x) \right|^p dx &= \lim_{h \rightarrow 0} \int \left| \frac{1}{h} \int_0^h (f'(x+s) - f'(x)) ds \right|^p dx \\ &= \lim_{h \rightarrow 0} \int \left| \int_0^1 (f'(x+uh) - f'(x)) du \right|^p dx \\ &\leq \lim_{h \rightarrow 0} \int \int_0^1 |f'(x+uh) - f'(x)|^p du dx \\ &= \int_0^1 \lim_{h \rightarrow 0} \int |f'(x+uh) - f'(x)|^p dx du = 0, \end{aligned}$$

hence  $f \in D(A)$ . □

## 2.5 Rotation Groups

On  $E = C(\Gamma)$ , resp.  $E = L^p(\Gamma, m)$ ,  $1 \leq p < \infty$ ,  $m$  Lebesgue measure we have canonical groups defined by rotations of the unit circle  $\Gamma$  with a certain period, i.e., for  $0 < \tau \in \mathbb{R}$  the operators

$$R_\tau(t)f(z) := f(e^{2\pi it/\tau} \cdot z), \quad z \in \Gamma$$

yield a group  $(R_\tau(t))_{t \in \mathbb{R}}$  having period  $\tau$ , i.e.,  $R_\tau(\tau) = \text{Id}$ . As in Example 2.4 one shows that its generator has the form

$$\begin{aligned} D(A) &= \{f \in E : f \text{ absolutely continuous, } f' \in E\}, \\ Af(z) &= (2\pi i/\tau) \cdot z \cdot f'(z). \end{aligned}$$

An isomorphic copy of the group  $(R_\tau(t))_{t \in \mathbb{R}}$  is obtained if we consider  $E = \{f \in C[0, 1] : f(0) = f(1)\}$ , resp.  $E = L^p([0, 1])$  and the group of *periodic translations*

$$T(t)f(x) := f(y) \quad \text{for } y \in [0, 1], y = x + t \bmod 1$$

with generator

$$D(A) := \{f \in E : f \text{ absolutely continuous, } f' \in E\}, \quad Af := f'.$$

## 2.6 Nilpotent Translation Semigroups

Take  $E = L^p([0, \tau], m)$  for  $1 \leq p < \infty$  and define

$$T(t)f(x) := \begin{cases} f(x+t) & \text{if } x+t \leq \tau \\ 0 & \text{otherwise.} \end{cases}$$

Then  $(T(t))_{t \geq 0}$  is a semigroup satisfying  $T(t) = 0$  for  $t \geq \tau$ . Its generator is still the first derivative  $A = \frac{d}{dx}$ , but with domain is

$$D(A) = \{f \in E : f \text{ absolutely continuous, } f' \in E, f(\tau) = 0\}.$$

In fact, if  $f \in D(A)$ , then  $f$  is absolutely continuous with  $f' \in E$ . By Prop. 1.6(i) on p. 5 it follows that  $T(t)f$  is absolutely continuous and hence  $f(\tau) = 0$ .

## 2.7 One-dimensional Diffusion Semigroup

For the second derivative

$$Bf(x) := \frac{d^2}{dx^2}f(x) = f''(x)$$

we take the domain

$$D(B) := \{f \in C^2[0, 1] : f'(0) = f'(1) = 0\}$$

in the Banach space  $E = C[0, 1]$ . Then  $D(B)$  is dense in  $C[0, 1]$ , but closed for the graph norm. Obviously, each function

$$e_n(x) := \cos \pi n x, \quad n \in \mathbb{Z},$$

is contained in  $D(B)$  and is an eigenfunction of  $B$  pertaining to the eigenvalue  $\lambda_n := -\pi^2 n^2$ . The linear hull  $\text{span}\{e_n : n \in \mathbb{Z}\} =: E_0$  forms a subalgebra of  $D(B)$  which by the Stone-Weierstrass theorem is dense in  $E$ .

We now use  $e_n$  to define bounded linear operators



$$e_n \otimes e_n : f \mapsto \left( \int_0^1 f(x) e_n(x) dx \right) e_n = (f|e_n) e_n$$

satisfying  $\|e_n \otimes e_n\| \leq 1$  and  $(e_n \otimes e_n)(e_m \otimes e_m) = \delta_{n,m}(e_n \otimes e_n)$  for  $n \in \mathbb{Z}$ .

For  $t > 0$  we define

$$\begin{aligned} T(t) &:= \sum_{n \in \mathbb{Z}} \exp(-\pi^2 n^2 t) \cdot e_n \otimes e_n \\ &= e_0 \otimes e_0 + 2 \sum_{n=1}^{\infty} \exp(-\pi^2 n^2 t) \cdot e_n \otimes e_n, \end{aligned}$$

or

$$T(t)f(x) = \int_0^1 k_t(x, y) f(y) dy$$

$$\text{where } k_t(x, y) = 1 + 2 \sum_{n=1}^{\infty} \exp(-\pi^2 n^2 t) \cos \pi n x \cos \pi n y.$$

The Jacobi identity

$$\begin{aligned} w_t(x) &:= 1/(4\pi t)^{\frac{1}{2}} \sum_{m \in \mathbb{Z}} \exp(-(x+2m)^2/4t) \\ &= \frac{1}{2} + \sum_{n \in \mathbb{N}} \exp(-\pi^2 n^2 t) \cos \pi n x \end{aligned}$$

and trigonometric relations show that

$$k_t(x, y) = w_t(x+y) + w_t(x-y)$$

which is a positive function on  $[0, 1]^2$ . Therefore  $T(t)$  is a bounded operator on  $C[0, 1]$  with

$$\|T(t)\| = \|T(t)\mathbb{1}\| = \sup_{x \in [0, 1]} \int_0^1 k_t(x, y) dy = 1.$$

From the behavior of  $T(t)$  on the dense subspace  $E_0$  it follows that  $(T(t))_{t \geq 0}$  with  $T(0) = \text{Id}$  is a strongly continuous semigroup on  $E$  and its generator  $A$  coincides with  $B$  on  $E_0$ . Finally, we observe that  $E_0$  is a core for  $(A, D(A))$  by Prop.1.9(ii).

Consequently,  $(T(t))_{t \geq 0}$  is the semigroup generated by the closure of the second derivative with domain  $D(B)$ .

## 2.8 n-dimensional Diffusion Semigroup

On  $E = L^p(\mathbb{R}^n)$ ,  $1 \leq p \leq \infty$ , the operators

$$\begin{aligned} T(t)f(x) &:= (4\pi t)^{-n/2} \int_{\mathbb{R}^n} \exp(-|x-y|^2/4t) f(y) dy \\ &= \mu_t * f(x) \end{aligned}$$

for  $x \in \mathbb{R}^n$ ,  $t > 0$  and  $\mu_t(x) := (4\pi t)^{-n/2} \exp(-|x|^2/4t)$  form a strongly continuous semigroup:

In fact the integral exists for every  $f \in L^p(\mathbb{R}^n)$  since  $\mu_t$  is an element of the Schwartz space  $S(\mathbb{R}^n)$  of all rapidly decreasing smooth functions on  $\mathbb{R}^n$ .

Moreover,

$$\|T(t)f\|_p \leq \|\mu_t\|_1 \|f\|_p = \|f\|_p$$

by Young's inequality, Reed and Simon [11, p.28], hence  $\|T(t)\| \leq 1$  for every  $t > 0$ . Next we observe that  $S(\mathbb{R}^n)$  is dense in  $E$  and invariant under each  $T(t)$ . Therefore we can apply the Fourier transformation  $F$  which leaves  $S(\mathbb{R}^n)$  invariant and yields

$$F(\mu_t * f) = (2\pi)^{n/2} F(\mu_t) \cdot F(f) = (2\pi)^{n/2} \hat{\mu}_t \cdot \hat{f}$$

where  $f \in S(\mathbb{R}^n)$ ,  $\hat{f} = Ff \in S(\mathbb{R}^n)$ .

In other words,  $F$  transforms  $(T(t)|_{S(\mathbb{R}^n)})_{t \geq 0}$  into a multiplication semigroup on  $S(\mathbb{R}^n)$  which is pointwise continuous for the usual topology of  $S(\mathbb{R}^n)$ . The generator, i.e., the right derivative at 0, of this semigroup is the multiplication operator

$$B\hat{f}(x) := -|x|^2 \hat{f}(x) \quad (x \in \mathbb{R}^n)$$

for every  $f \in S(\mathbb{R}^n)$ .

Applying the inverse Fourier transformation and observing that the topology of  $S(\mathbb{R}^n)$  is finer than the topology induced from  $L^p(\mathbb{R}^n)$ , we obtain that  $(T(t))_{t \geq 0}$  is a semigroup which is strongly continuous (use Rem. 1.2 (iii) on p. 4).

Its generator  $A$  coincides with

$$\Delta f(x) = \sum_{i=1}^n \frac{\partial^2}{\partial x_i^2} f(x_1, \dots, x_n)$$

for every  $f \in S(\mathbb{R}^n)$ . Since  $S(\mathbb{R}^n)$  is  $(T(t))$ -invariant, we have determined the generator on a core of its domain (see Prop. 1.9.ii). In particular, the above semigroup solves the initial value problem for the *heat equation*

$$\frac{\partial}{\partial t} f(x, t) = \Delta f(x, t), \quad f(x, 0) = f_0(x), \quad x \in \mathbb{R}^n.$$

For the analogous discussion of the unitary group on  $L^2(\mathbb{R}^n)$  generated by

$$C := i\Delta$$

we refer to Section IX.7 in Reed and Simon [11].

Analogous examples to 2.7 are valid in  $L^p [0, 1]$ , resp. to 2.8 in  $C_0(\mathbb{R}^n)$ .

### 3 Standard Constructions

Starting with a semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$  it is possible to construct new semigroups on spaces naturally associated with  $E$ . Such constructions will be important technical devices in many of the subsequent proofs. Although most of these constructions are rather routine, we present in the sequel a systematic account of them for the convenience of the reader.

We always start with a semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$ , and denote its generator by  $A$  on the domain  $D(A)$ .

#### 3.1 Similar Semigroups

There is an easy way how to obtain different (but isomorphic) semigroups out of a given semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$ .

Let  $V$  be an isomorphism from  $E$  onto  $E$ . Then  $S(t) := VT(t)V^{-1}$ ,  $t \geq 0$ , defines a strongly continuous semigroup. If  $A$  is the generator of  $(T(t))_{t \geq 0}$  then

$$B := VAV^{-1} \text{ with domain } D(B) := \{f \in E : V^{-1}f \in D(A)\}$$

is the generator of  $(S(t))_{t \geq 0}$ .

#### 3.2 The Rescaled Semigroup

For fixed  $\lambda \in \mathbb{C}$  and  $\alpha > 0$  the operators

$$S(t) := \exp(\lambda t)T(\alpha t)$$

yield a new semigroup having generator

$$B := \alpha A + \lambda \text{Id with } D(B) = D(A).$$

This *rescaled semigroup* enjoys most of the properties of the original semigroup and the same is true for the corresponding generators. However, by using this procedure certain constants associated with  $(T(t))_{t \geq 0}$  and  $A$  can be normalized. For example, by this rescaling we may in many cases suppose without loss of generality that the growth bound  $\omega_0$  is zero.

Another application is the following. For  $\lambda \in \mathbb{C}$  and  $S(t) := \exp(-\lambda t)T(t)$  the formulas (1.3) and (1.4) yield:

$$\begin{aligned} e^{-\lambda t}T(t)f - f &= (\lambda - A) \int_0^t e^{-\lambda s}T(s)f \, ds \text{ or} \\ (e^{\lambda t} - T(t))f &= (\lambda - A) \int_0^t e^{\lambda(t-s)}T(s)f \, ds \quad \text{for } f \in E, \end{aligned}$$

and

$$\begin{aligned} e^{-\lambda t}T(t)f - f &= \int_0^t e^{-\lambda s}T(s)(\lambda - A)f \, ds \text{ or} \\ (e^{\lambda t} - T(t))f &= \int_0^t e^{\lambda(t-s)}T(s)(\lambda - A)f \, ds \quad \text{for } f \in D(A). \end{aligned}$$

### 3.3 The Subspace Semigroup

Assume  $F$  to be a closed  $(T(t))$ -invariant or, equivalently,  $R(\lambda, A)$ -invariant for  $\lambda \in \mathbb{C}$ ,  $\operatorname{Re}(\lambda) > \omega_0$ , subspace of  $E$ . Then the semigroup  $(T(t)|_F)_{t \geq 0}$  of all restrictions  $T(t)|_F := T(t)|_F$  is strongly continuous on  $F$ . If  $(A, D(A))$  denotes the generator of  $(T(t))_{t \geq 0}$  it follows from the  $(T(t))$ -invariance and closedness of  $F$  that  $A$  maps  $D(A) \cap F$  into  $F$ . Therefore

$$A|_F := A|_{(D(A) \cap F)} \text{ with domain } D(A|_F) := D(A) \cap F$$

is the generator of  $(T(t)|_F)$ . Conversely, if  $F$  is a closed *linear subspace* of  $E$  with  $A(D(A) \cap F) \subset F$  such that  $A|_F$  is a generator on  $F$ , then  $F$  is  $(T(t))$ -invariant.

An  $A$ -invariant subspace need not necessarily be  $(T(t))$ -invariant: Take for example the translation group with  $T(t)f(x) = f(x + t)$  on  $E = C_0(\mathbb{R})$  and  $F := \{f \in E : f(x) = 0 \text{ for } x \leq 0\}$ .

### 3.4 The Quotient Semigroup

Let  $F$  be a closed  $(T(t))$ -invariant subspace of  $E$  and consider the quotient space  $E_F := E/F$  with quotient map  $q: E \rightarrow E_F$ . The quotient operators

$$T(t)_F q(f) := q(T(t)f), \quad f \in E,$$

are well defined and form a strongly continuous semigroup  $(T(t)_F)_{t \geq 0}$  on  $E_F$ . For the generator  $(A_F, D(A_F))$  of  $(T(t)_F)_{t \geq 0}$  the following holds:

$$D(A_{|}) = q(D(A)) \quad \text{and} \quad A_{|}q(f) = q(Af)$$

for every  $f \in D(A)$ . Here we use the fact that every  $\hat{f} := q(f) \in D(A_{|})$  can be written as

$$\hat{f} = \int_0^\infty e^{-\lambda s} \hat{T}(s) \hat{g} \, ds = \int_0^\infty e^{-\lambda s} q(T(s)g) \, ds = q\left(\int_0^\infty e^{-\lambda s} T(s)g \, ds\right) = q(h)$$

where  $h \in D(A)$  and  $\lambda > \omega$  (see Proposition–1.6). In particular we point out that for every  $\hat{f} \in D(A_{|})$  there exist representatives  $f \in \hat{f}$  belonging to  $D(A)$ .

*Example 3.1* We start with the Banach space  $E = L^1(\mathbb{R})$  and the translation semigroup  $(T(t))_{t \geq 0}$  where  $T(t)f(x) := f(x+t)$  (see Example 2.4). Then  $L^1((-\infty, 1])$  can be identified with the closed,  $(T(t))$ -invariant subspace

$$J := \{f \in E : f(x) = 0 \text{ for } 1 < x < \infty\}.$$

There we obtain the subspace semigroup

$$T(t)|_{(-\infty, 1]}(x) \cdot f(x+t),$$

where  $f \in L^1((-\infty, 1])$ ,  $-\infty < x \leq 1$  and  $t \geq 0$ .

By 2.4 and 3.2 its generator is

$$A|f := f'$$

for  $f \in D(A|) := \{f \in E : f \in AC \text{ with } f' \in E \text{ and } f(x) = 0 \text{ for } x \geq 1\}$ .

Next we identify  $L^1([0, 1])$  with the quotient space  $L^1((-\infty, 1])/I$  where

$$I := \{f \in L^1((-\infty, 1]) : f(x) = 0 \text{ for } 0 \leq x \leq 1\}.$$

Again  $I$  is invariant for the restricted semigroup  $(T(t)|_I)$  and the quotient semigroup  $(T(t)|_I)$  on  $L^1([0, 1])$  is the nilpotent translation semigroup as in Example 2.6. In particular it follows that the domain of its generator is

$$D(A_{|_I}) = \{f \in L^1([0, 1]) : f \in AC \text{ with } f' \in L^1([0, 1]) \text{ and } f(1) = 0\}.$$

### 3.5 The Adjoint Semigroup

The adjoint operators  $(T(t)')_{t \geq 0}$  of a strongly continuous semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$  form a semigroup on  $E'$  which need, however, not be strongly continuous.

*Example 3.2* Take the translation operators  $T(t)f(x) = f(x+t)$  on  $E = L^1(\mathbb{R})$  (see Example 2.4) and their adjoints

$$T(t)'f(x) = f(x-t)$$

on  $E' = L^\infty(\mathbb{R})$ . Then  $(T(t)')_{t \in \mathbb{R}}$  is a one-parameter group which is not strongly continuous on  $L^\infty(\mathbb{R})$  (take any non-trivial characteristic function).

Since the semigroup  $(T(t)')_{t \geq 0}$  is obviously *weak\*-continuous* in the sense that  $\lim_{t \rightarrow s} \langle f, (T(t)' - T(s)')\varphi \rangle = 0$  for every  $f \in E$ ,  $\varphi \in E'$  and  $s, t \geq 0$ , it is natural to associate  $(T(t)')_{t \geq 0}$  its a *weak\*-generator*

$$A'\varphi := \sigma(E', E)\text{-}\lim_{h \rightarrow 0} \frac{1}{h}(T(h)'\varphi - \varphi) \text{ for every } \varphi \text{ in the domain}$$

$$D(A') := \{\varphi \in E' : \sigma(E', E)\text{-}\lim_{h \rightarrow 0} \frac{1}{h}(T(h)'\varphi - \varphi) \text{ exists}\}.$$

This operator coincides with the *adjoint* of the generator  $(A, D(A))$ , i.e.,

$$D(A') = \{\varphi \in E' : \text{there exists } \psi \in E' \text{ such that } \langle f, \psi \rangle = \langle Af, \varphi \rangle \text{ for all } f \in D(A)\}$$

and  $A'\varphi = \psi$ . In particular,  $A'$  is a closed and  $\sigma(E', E)$ -densely defined operator in  $E'$ .

It follows from Kato [7, Thm.III.5.30] that the resolvent  $R(\lambda, A')$  of  $A'$  is  $R(\lambda, A)'$ . In particular, the spectra  $\sigma(A)$  and  $\sigma(A')$  coincide.

However, it is still necessary in some situations to have strong continuity for the adjoint semigroup. In order to achieve this we restrict  $T(t)'$  to an appropriate subspace of  $E'$ .

**Definition 3.3** (Phillips [10]) The *semigroup dual* of the Banach space  $E$  with respect to the strongly continuous semigroup  $(T(t))_{t \geq 0}$  is

$$E^* := \{\varphi \in E' : \|\cdot\| \text{-}\lim_{t \rightarrow 0} T(t)'\varphi = \varphi\}.$$

The adjoint semigroup on  $E^*$  is given by the operators

$$T(t)^* := T(t)'|_{E^*}, \quad t \geq 0.$$

Since  $(T(t)^*)_{t \geq 0}$  is strongly continuous on  $E^*$  we call its generator  $(A^*, D(A^*))$  the *adjoint generator*.

The above definition makes sense since  $E^*$  is norm-closed in  $E'$  and  $(T(t)')$ -invariant. The main point is that  $E^*$  is still reasonably large. In fact, since  $\int_0^t T(s)'\varphi \, ds$ , understood in the weak sense, is contained in  $E^*$  for every  $\varphi \in E'$  and  $t \geq 0$ , it follows that

$$\sup\{\langle f, \varphi \rangle : \varphi \in E^*, \|\varphi\| \leq 1\} \leq \|f\| \leq M \cdot \sup\{\langle f, \varphi \rangle : \varphi \in E^*, \|\varphi\| \leq 1\}$$

where  $M := \limsup_{t \rightarrow 0} \|T(t)\|$ . In particular,  $E^*$  separates  $E$ , i.e.,  $E^*$  is  $\sigma(E', E)$ -dense in  $E'$ . In addition the estimate of  $\|\cdot\|$  given above yields

$$\|T(t)^*\| \leq \|T(t)\| \leq M\|T(t)^*\| \quad \text{for all } t \geq 0.$$

In the following proposition we describe the relation between  $A^*$  and  $A'$ .

**Proposition 3.4** *For the adjoint generator  $A^*$  of a strongly continuous semigroup  $(T(t))_{t \geq 0}$  on  $E$  the following assertions hold.*

- (i)  $E^*$  is the  $\|\cdot\|$ -closure of  $D(A')$ .
- (ii)  $D(A^*) = \{\varphi \in D(A') : A'\varphi \in E^*\}$ .
- (iii)  $A^*$  and  $A'$  coincide on  $D(A^*)$ .

**Proof** (i) Take  $\varphi \in D(A')$  fixed. For every  $f \in D(A)$  with  $\|f\| \leq 1$  we define a continuously differentiable function

$$t \mapsto \xi_f(t) := \langle T(t)f, \varphi \rangle$$

on  $[0, 1]$  with derivative  $\xi'_f(t) = \langle T(t)Af, \varphi \rangle = \langle T(t)f, A'\varphi \rangle$ .

Since  $\{\xi'_f(t) : t \in [0, 1], f \in D(A), \|f\| \leq 1\}$  is bounded, it follows that the set

$$\{\xi_f : f \in D(A), \|f\| \leq 1\}$$

is equicontinuous at 0, i.e., for every  $\varepsilon > 0$  there exists  $0 < t_0 < 1$  such that

$$|\xi_f(s) - \xi_f(0)| = |\langle f, T(s)' \varphi - \varphi \rangle| < \varepsilon$$

for every  $0 \leq s \leq t_0$  and  $f \in D(A)$ ,  $\|f\| \leq 1$ . But this implies  $\|T(s)' \varphi - \varphi\| < \varepsilon$  and hence  $\varphi \in E^*$ .

Conversely, take  $\psi \in E^*$ . Then  $\frac{1}{t} \int_0^t T(s)' \psi \, ds$ ,  $t > 0$ , belongs to  $D(A')$  and norm converges to  $\psi$  as  $t \rightarrow 0$ , i.e.,  $\psi$  belongs to the norm closure of  $D(A')$ .

(ii) and (iii): Since the weak\* topology on  $E'$  is weaker than the norm topology, it follows that  $A'$  is an extension of  $A^*$ . Now take  $\varphi \in D(A')$  such that  $A'\varphi \in E^*$ . As above define the functions  $\xi_f$ . The assumption on  $\varphi$  implies the set of all derivatives

$$\{\xi'_f : f \in D(A), \|f\| \leq 1\}$$

to be equicontinuous at  $t = 0$ . This means that for every  $\varepsilon > 0$  there exists  $0 < t_o < 1$  such that  $|f'_f(0) - f'_f(s)| < \varepsilon$  for every  $f \in D(A)$ ,  $\|f\| \leq 1$  and  $0 < s < t_o$ . In particular,

$$\varepsilon > |f'_f(0) - \frac{1}{s}(\xi_f(s) - \xi_f(0))| = |\langle f, A'\varphi - \frac{1}{s}(T(s)' \varphi - \varphi) \rangle|,$$

hence

$$\varepsilon > \|A'\varphi - \frac{1}{s}(T(s)' \varphi - \varphi)\|$$

for all  $0 \leq s \leq t_o$ . From this it follows that  $\varphi \in D(A^*)$ . □

On reflexive Banach spaces we have  $A^* = A'$  by the above proposition. In other cases this construction is more interesting.

*Example 3.5 (continued)* The adjoints of the (left) translation  $T(t)$  on  $E = L^1(\mathbb{R})$  are the (right) translations  $T(t)'$  on  $E' = L^\infty(\mathbb{R})$ . The largest subspace of  $L^\infty(\mathbb{R})$  on which these translations form a strongly-continuous semigroup with respect to the

sup-norm, is the space of all bounded uniformly continuous functions on  $\mathbb{R}$ , i.e.,  $E^* = C_{bu}(\mathbb{R})$ .

Calculating  $D(A')$  and  $D(A^*)$  respectively, one obtains

$$\begin{aligned} D(A') &= \{f \in L^\infty(\mathbb{R}) : f \in AC, f' \in L^\infty(\mathbb{R})\}, \\ D(A^*) &= \{f \in L^\infty(\mathbb{R}) : f \in C^1(\mathbb{R}), f' \in C_{bu}(\mathbb{R})\}. \end{aligned}$$

Obviously, the function  $x \mapsto |\sin x|$  belongs to  $D(A')$ , but not to  $D(A^*)$ .

### 3.6 The Associated Sobolev Semigroups

Since the generator  $A$  of a strongly continuous semigroup  $(T(t))_{t \geq 0}$  is closed, its domain  $D(A)$  becomes a Banach space for the graph norm

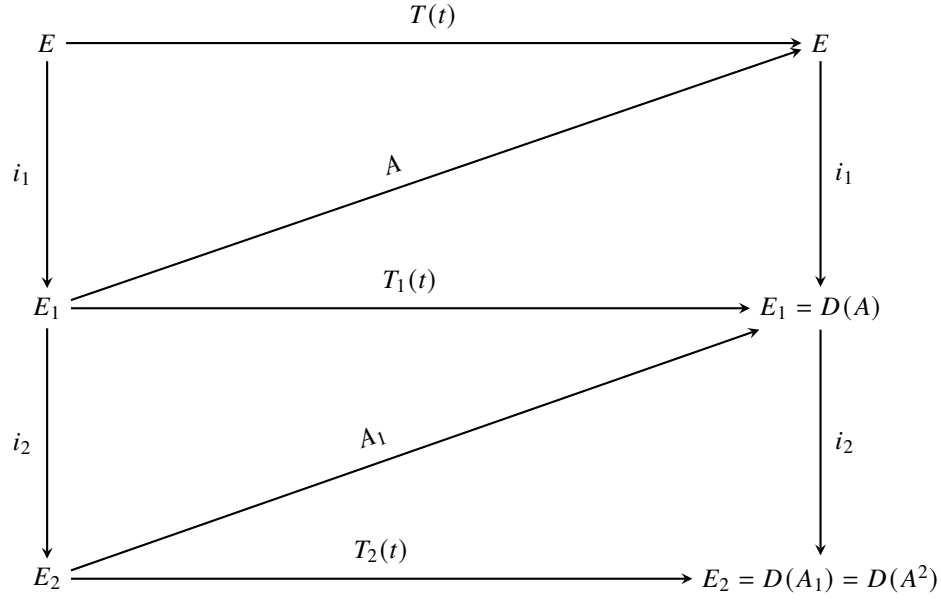
$$\|f\|_1 := \|f\| + \|Af\|.$$

We denote this Banach space by  $E_1$  and the continuous injection from  $E_1$  into  $E$  by  $i_1$ . Since  $E_1$  is invariant under  $(T(t))_{t \geq 0}$ , apply Prop. 1.6(i), it makes sense to consider the semigroup  $(T_1(t))_{t \geq 0}$  of all restrictions  $T_1(t) := T(t)|_{E_1}$ . The results of Prop. 1.6 imply that  $T_1(t) \in LE_1$  and  $\|T_1(t)f - f\|_1 \rightarrow 0$  as  $t \rightarrow 0$  for every  $f \in E_1$ . Thus  $(T_1(t))_{t \geq 0}$  is a strongly continuous semigroup on  $E_1$  and has a generator denoted by  $(A_1, D(A_1))$ .

Using 1.6 again we see that  $A_1$  is the restriction of  $A$  to  $E_1$  with maximal domain, i.e.,  $D(A_1) = \{f \in E_1 : Af \in E_1\} = D(A^2)$  and  $A_1f = Af$  for every  $f \in D(A_1)$ .

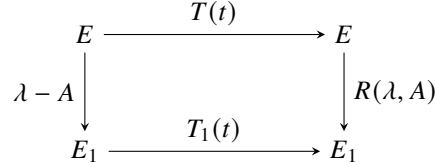
It is now possible to repeat this construction in order to obtain Banach spaces  $E_n$  and semigroups  $(T_n(t))_{t \geq 0}$  with generators  $(A_n, D(A_n))$  which are related as visualized in the following diagram.





For the translation semigroup on  $L^p(\mathbb{R})$  (see 2.3) the above construction leads to the usual *Sobolev spaces*. Therefore we might call  $E_n$  the *n-th Sobolev space* and  $(T_n(t))_{t \geq 0}$  the *n-th Sobolev semigroup* associated to  $E$  and  $(T(t))_{t \geq 0}$ .

*Remark 3.6* For  $\lambda \in \varrho(A)$  the operator  $(\lambda - A)$  and the resolvent  $R(\lambda, A)$  are isomorphisms from  $E_1$  onto  $E$ , resp. from  $E$  onto  $E_1$  (show that  $\|\cdot\|_1$  and  $\|\cdot\|_\lambda$  with  $\|\cdot\|_\lambda := \|(\lambda - A) \cdot\|$  are equivalent). In addition, the following diagram commutes.



Therefore all Sobolev semigroups  $(E_n, T_n(t))_{t \geq 0}$ ,  $n \in \mathbb{N}$ , are isomorphic.

*Remark 3.7* For  $\lambda \in \varrho(A)$  consider the norm

$$\|f\|_{-1} := \|R(\lambda, A)f\|$$

for every  $f \in E$  and define  $E_{-1}$  as the completion of  $E$  for  $\|\cdot\|_{-1}$ .

Then  $(T(t))_{t \geq 0}$  extends continuously to a strongly continuous semigroup  $(T_{-1}(t))_{t \geq 0}$  on  $E_{-1}$  and the above diagram can be extended to the negative integers.

## 4 The $\mathcal{F}$ -Product Semigroup

It is standard in functional analysis to consider a sequence of points in a certain space as a point in a new and larger space. In particular such a method can serve to convert an approximate eigenvector of a linear operator into an eigenvector. Occasionally we will need such a construction and refer to Section V.1 of Schaefer [12].

If we try to adapt this construction to strongly continuous semigroups we encounter the difficulty that the semigroup extended to the larger space will not remain strongly continuous. An idea already used in 3.4 will help to overcome this difficulty.

Let  $\mathcal{T} = (T(t))_{t \geq 0}$  be a strongly continuous semigroup on the Banach space  $E$ . Denote by  $m(E)$  the Banach space of all bounded  $E$ -valued sequences endowed with the norm

$$\|(f_n)_{n \in \mathbb{N}}\| := \sup\{\|f_n\| : n \in \mathbb{N}\}.$$

It is clear that every  $T(t)$  extends canonically to a bounded linear operator

$$\hat{T}(t)(f_n) := (T(t)f_n)$$

on  $m(E)$ , but the semigroup  $(\hat{T}(t))_{t \geq 0}$  is strongly continuous if and only if  $T$  has a bounded generator. Therefore we restrict our attention to the closed,  $(\hat{T}(t))$ -invariant subspace

$$m^{\mathcal{T}}(E) := \{(f_n) \in m(E) : \lim_{t \rightarrow 0} \|T(t)f_n - f_n\| = 0 \text{ uniformly for } n \in \mathbb{N}\}.$$

Then the restricted semigroup

$$\hat{T}(t)(f_n) = (T(t)f_n), \quad (f_n) \in m^{\mathcal{T}}(E)$$

is strongly continuous and we denote its generator by  $(\hat{A}, D(\hat{A}))$ .

The following lemma shows that  $\hat{A}$  is obtained canonically from  $A$ .

**Lemma 4.1** *For the generator  $\hat{A}$  of  $(\hat{T}(t))_{t \geq 0}$  on  $m^{\mathcal{T}}(E)$  one has the following properties.*

- (i)  $D(\hat{A}) = \{(f_n) \in m^{\mathcal{T}}(E) : f_n \in D(A) \text{ and } (Af_n) \in m^{\mathcal{T}}(E)\},$
- (ii)  $\hat{A}(f_n) = (Af_n) \text{ for } (f_n) \in D(\hat{A}).$

For the proof we refer to Lemma 1.4. of Derndinger [2].

Now let  $\mathcal{F}$  be any filter on  $\mathbb{N}$  finer than the Frechét filter (i.e., the filter of sets with finite complement. In most cases  $\mathcal{F}$  will be either the Frechét filter or some free ultra filter.) The space of all  $\mathcal{F}$ -null sequences in  $m(E)$ , i.e.,

$$c_{\mathcal{F}}(E) := \{(f_n) \in m(E) : \mathcal{F}\text{-}\lim \|f_n\| = 0\}$$

is closed in  $m(E)$  and invariant under  $(\hat{T}(t))_{t \geq 0}$ . We call the quotient spaces

$$E_{\mathcal{F}} := m(E)/c_{\mathcal{F}}(E) \quad \text{and} \quad E_{\mathcal{F}}^T := m^{\mathcal{T}}(E)/c_{\mathcal{F}}(E) \cap m^{\mathcal{T}}(E)$$

the  $\mathcal{F}$ -product of  $E$  and the  $\mathcal{F}$ -product of  $E$  with respect to the semigroup  $T$ , respectively.

Thus  $E_{\mathcal{F}}^T$  can be considered as a closed linear subspace of  $E_{\mathcal{F}}$ . We have  $E_{\mathcal{F}}^T = E_{\mathcal{F}}$  if (and only if)  $T$  has a bounded generator.

The canonical quotient norm on  $E_{\mathcal{F}}$  is given by

$$\|(f_n) + c_{\mathcal{F}}(E)\| = \mathcal{F}\text{-}\limsup \|f_n\|.$$

We can apply Subsec. 3.4 in order to define the  $\mathcal{F}$ -product semigroup  $(T_{\mathcal{F}}(t))_{t \geq 0}$  on  $E_{\mathcal{F}}^T$  by

$$T_{\mathcal{F}}(t)((f_n) + c_{\mathcal{F}}(E)) := (T(t)f_n) + c_{\mathcal{F}}(E) \cap m^{\mathcal{T}}(E)$$

Thus  $T_{\mathcal{F}}(t)$  is the restriction of  $T(t)_F$  where  $T(t)_F$  denotes the canonical extension of  $T(t)$  to the  $\mathcal{F}$ -product  $E_{\mathcal{F}}$ . But note that  $(T(t)_F)_{t \geq 0}$  is not strongly continuous unless  $T$  has a bounded generator.

With the canonical injection  $j: f \mapsto (f, f, f, \dots) + c_{\mathcal{F}}(E)$  from  $E$  into  $E_{\mathcal{F}}^T$  the operators  $T_{\mathcal{F}}(t)$  are extensions of  $T(t)$  satisfying  $\|T_{\mathcal{F}}(t)\| = \|T(t)\|$ . The basic facts about the generator  $(A_{\mathcal{F}}, D(A_{\mathcal{F}}))$  of  $(T_{\mathcal{F}}(t))_{t \geq 0}$  follow from 3.3 and are collected in the following proposition.

**Proposition 4.2** *For the generator  $(A_{\mathcal{F}}, D(A_{\mathcal{F}}))$  of the  $\mathcal{F}$ -product semigroup the following holds.*

- (i)  $D(A_{\mathcal{F}}) = \{(f_n) + c_{\mathcal{F}}(E) : f_n \in D(A); (f_n), (Af_n) \in m^{\mathcal{T}}(E)\},$
- (ii)  $A_{\mathcal{F}}((f_n) + c_{\mathcal{F}}(E)) = (Af_n) + c_{\mathcal{F}}(E).$

In case  $A$  is a bounded operator then  $D(A_{\mathcal{F}}) = E_{\mathcal{F}}^T = E_{\mathcal{F}}$  and  $A_{\mathcal{F}}$  is the canonical extension of  $A$  to  $E_{\mathcal{F}}$ .

We will show in A-III,4.5 that the above construction preserves and even improves many spectral properties of the semigroup and its generator.

## 5 The Tensor Product Semigroup

Real- or complex-valued functions of two variables  $x, y$  are often limits of functions of the form  $\sum_{i=1}^n f_i(x)g_i(y)$  which, to some extent, allows one to consider the variables  $x$  and  $y$  separately. Since algebraic manipulation with these latter functions is governed by the formal rules of a tensor product, it is customary to identify (for example) the function

$$(x, y) \mapsto f(x)g(y)$$

with the tensor product  $f \otimes g$  and to consider limits of linear combinations of such functions as elements of a completed tensor product.

To be more precise, we briefly present the most important examples for this situation.

**Examples 5.1** (i) Let  $(X, \Sigma, \mu)$  and  $(Y, \Omega, \nu)$  be measure spaces. If we identify for  $f_i \in L^p(\mu)$ ,  $g_i \in L^p(\nu)$  the elements  $\sum_{i=1}^n f_i \otimes g_i$  of the tensor product

$$L^p(\mu) \otimes L^p(\nu)$$

with the (class of  $\mu \times \nu$ -a.e.-defined) functions

$$(x, y) \mapsto \sum_{i=1}^n f_i(x) g_i(y),$$

then  $L^p(\mu) \otimes L^p(\nu)$  becomes a dense subspace of  $L^p(X \times Y, \Sigma \times \Omega, \mu \times \nu)$  for  $1 \leq p < \infty$ .

(ii) Similarly, let  $X, Y$  be compact spaces. Then  $C(X) \otimes C(Y)$  becomes a dense subspace of  $C(X \times Y)$  by identifying, for  $f \in C(X)$  and  $g \in C(Y)$ ,  $f \otimes g$  with the function

$$(x, y) \mapsto f(x)g(y).$$

We do not intend to go deeper into the quite sophisticated problems related to normed tensor products of general Banach spaces, but will rather confine ourselves to the discussion of certain special cases. These will always be related to one of the following standard methods to define a norm on the tensor product of two Banach spaces  $E, F$ .

Let  $u := \sum_{i=1}^n f_i \otimes g_i$  be an element of  $E \otimes F$ . Then

(i)  $\|u\|_\pi := \inf\{\sum_{j=1}^m \|h_j\| \|k_j\| : u = \sum_{j=1}^m h_j \otimes k_j, h_j \in E, k_j \in F\}$  defines the *greatest cross norm*  $\pi$  on  $E \otimes F$ .

(ii)  $\|u\|_\varepsilon := \sup\{\langle u, \varphi \otimes \psi \rangle : \varphi \in E', \psi \in F', \|\varphi\|, \|\psi\| \leq 1\}$  defines the *least cross norm*  $\varepsilon$  on  $E \otimes F$ . Here,  $\langle u, \varphi \otimes \psi \rangle$  denotes the canonical bilinear form on  $(E \otimes F) \times (E' \otimes F')$ , i.e.,  $\langle \sum_{i=1}^n f_i \otimes g_i, \varphi \otimes \psi \rangle = \sum_{i=1}^n \langle f_i, \varphi \rangle \langle g_i, \psi \rangle$ .

(iii) if  $E$  and  $F$  are Hilbert spaces,  $\|u\|_h = (u|u)_h^{1/2}$ , where the scalar product  $(\cdot|\cdot)_h$  is defined as in (ii), defines the *Hilbert norm*  $h$  on  $E \otimes F$ .

In the following we write  $E \otimes_\alpha F$  for the tensor product of  $E$  and  $F$  endowed—with if applicable—with one of the norms  $\pi, \varepsilon, h$  just defined. In each case one has  $\|f \otimes g\| = \|f\| \|g\|$  for  $f \in E, g \in F$ .

By  $E \widetilde{\otimes}_\alpha F$  we mean the completion of  $E \otimes_\alpha F$ . Moreover we recall how examples (i) and (ii) above fit into this pattern

$$L^1(\mu \otimes \nu) = L^1(\mu) \widetilde{\otimes}_\pi L^1(\nu), \quad L^2(\mu \otimes \nu) = L^2(\mu) \widetilde{\otimes}_h L^2(\nu),$$

$$C(X \otimes Y) = C(X) \widetilde{\otimes}_\varepsilon C(Y).$$

Finally, we point out that for any  $S \in \mathcal{L}(E), T \in \mathcal{L}(F)$ , the mapping

$$\sum_{i=1}^n f_i \otimes g_i \mapsto \sum_{i=1}^n S f_i \otimes T g_i$$

defined on  $E \otimes F$  is linear and continuous on  $E \otimes_\alpha F$ , hence has a continuous extension to  $E \widetilde{\otimes}_\alpha F$ . This operator, as well as its continuous extension, will be denoted by  $S \otimes T$  and satisfies  $\|S \otimes T\| = \|S\| \|T\|$ . The notation  $A \otimes B$  will also be used in the obvious

way if  $A$  and  $B$  are not necessarily bounded operators on  $E$  and  $F$ . We are now ready to consider semigroups induced on the tensor product.

**Proposition 5.2** *Let  $(S(t))_{t \geq 0}$  and  $(T(t))_{t \geq 0}$  be strongly continuous semigroups on Banach spaces  $E$ ,  $F$ , and let  $A$ ,  $B$  be their generators. Then the family  $(S(t) \otimes T(t))_{t \geq 0}$  is a strongly continuous semigroup on  $E \widetilde{\otimes}_\alpha F$ . The closure of  $A \otimes \text{Id} + \text{Id} \otimes B$ , defined on the core  $D(A) \otimes D(B)$ , is its generator.*

**Proof** It is immediately verified that  $(S(t) \otimes T(t))_{t \geq 0}$  is in fact a semigroup of operators on  $E \widetilde{\otimes}_\alpha F$ . The strong continuity need only be verified at  $t = 0$  and on elements of the form  $u = f \otimes g \in E \otimes F$ .

This verification being straightforward, there remains to show that the generator of  $(S(t) \otimes T(t))_{t \geq 0}$  is obtained as the closure of

$$(A \otimes \text{Id} + \text{Id} \otimes B, D(A) \otimes D(B)).$$

To this end, let  $f \in D(A)$  and  $g \in D(B)$ . Then

$$\begin{aligned} & \lim_{h \rightarrow 0} \frac{1}{h} (T(h) \otimes S(h)(f \otimes g) - f \otimes g) \\ &= \lim_{h \rightarrow 0} \frac{1}{h} (T(h)f \otimes (S(h)g - g) + (T(h)f - f) \otimes g) \\ &= (f \otimes Bg) + (Af \otimes g). \end{aligned}$$

Since the elements of the form  $f \otimes g$ ,  $f \in D(A)$ ,  $g \in D(B)$ , generate the linear subspace  $D(A) \otimes D(B)$  of  $E \otimes_\alpha F$ , this subspace belongs to the domain of the generator. Moreover,  $D(A) \otimes D(B)$  is dense in  $E \widetilde{\otimes}_\alpha F$  and invariant under  $(S(t) \otimes T(t))_{t \geq 0}$ , hence it is a core of  $A \otimes \text{Id} + \text{Id} \otimes B$  by Prop. 1.9(ii).  $\square$

## 6 The Product of Commuting Semigroups

Let  $(S(t))_{t \geq 0}$  and  $(T(t))_{t \geq 0}$  be semigroups with generators  $A$  and  $B$ , respectively on some Banach space  $E$ . It is not difficult to see that the following assertions are equivalent.

- (a)  $S(t)T(t) = S(t)T(t)$  for all  $t \geq 0$ .
- (b)  $R(\mu, A)R(\mu, B) = R(\mu, B)R(\mu, A)$  for some  $\mu \in \varrho(A) \cap \varrho(B)$ .
- (c)  $R(\mu, A)R(\mu, B) = R(\mu, B)R(\mu, A)$  for all  $\mu \in \varrho(A) \cap \varrho(B)$ .

In that case  $U(t) = S(t)T(t)$  ( $t \geq 0$ ) defines a semigroup  $(U(t))_{t \geq 0}$ . Using Prop. 1.9(ii) on p. 6 one easily shows that  $D_0 := D(A) \cap D(B)$  is a core for its generator  $C$  and  $Cf = Af + Bf$  for all  $f \in D_0$ .

## Notes

For more complete information on semigroup theory we refer the reader to Hille and Phillips [6], to the monographs by Davies [1], Goldstein [4] and Pazy [9], to the survey article by Krein and Khazan [8], to the bibliography by Goldstein [5] and to Engel and Nagel [3].

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**Chapter A-II**  
**Characterization of Semigroups on Banach**  
**Spaces**



# Chapter A-III

## Spectral Theory

### 1 Introduction

In this chapter we start a systematic analysis of the spectrum of a strongly continuous semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  on a complex Banach space  $E$ . By the spectrum of the semigroup we understand the spectrum  $\sigma(A)$  of the generator  $A$  of  $\mathcal{T}$ . In particular, we are interested in precise relations between  $\sigma(A)$  and  $\sigma(T(t))$ . The heuristic formula

$$T(t) = e^{tA}$$

serves as a leitmotiv and suggests relations of the form

$$\sigma(T(t)) = e^{t\sigma(A)} = \{e^{t\lambda} : \lambda \in \sigma(A)\},$$

called *spectral mapping theorem*. These—or similar—relations will be of great use in Chapter IV and enable us to determine the asymptotic behavior of the semigroup  $\mathcal{T}$  by the spectrum of its generator.

As a motivation as well as a preliminary step we concentrate here on the *spectral radius*

$$r(T(t)) := \sup\{|\lambda| : \lambda \in \sigma(T(t))\}, \quad t \geq 0, \quad (1.1)$$

and show how it is related to the *spectral bound*

$$s(A) := \sup\{\operatorname{Re} \lambda : \lambda \in \sigma(A)\} \quad (1.2)$$

of the generator  $A$  and to the *growth bound*

$$\omega_0 := \inf\{\omega \in \mathbb{R} : \|T(t)\| \leq M_\omega \cdot e^{\omega t} \text{ for all } t \geq 0 \text{ and suitable } M_\omega\} \quad (1.3)$$

of the semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$ . (Recall that we sometimes write  $\omega_0(\mathcal{T})$  or  $\omega_0(A)$  instead of  $\omega_0$ ). The Examples 1.3 and 1.4 below illustrate the main difficulties to be encountered.

**Proposition 1.1** *Let  $\omega_0$  be the growth bound of the strongly continuous semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$ . Then*

$$r(T(t)) = e^{\omega_0 t} \quad (1.4)$$

for every  $t \geq 0$ .

**Proof** From A-I, (1.1) we know that

$$\omega_0(\mathcal{T}) = \lim_{t \rightarrow \infty} \frac{1}{t} \log \|T(t)\|$$

Since the spectral radius of  $T(t)$  is given as

$$r(T(t)) = \lim_{n \rightarrow \infty} \|T(nt)\|^{1/n},$$

we obtain for  $t > 0$

$$r(T(t)) = \lim_{n \rightarrow \infty} \exp \left( \frac{t}{nt} \log \|T(nt)\| \right) = e^{\omega_0 t}.$$

It was shown in A-I, Proposition 1.11 that the spectral bound  $s(A)$  is always dominated by the growth bound  $\omega_0$  and therefore  $e^{s(A)t} \leq r(T(t))$ . If the above mentioned spectral mapping theorem holds — as is the case for bounded generators (e.g., see Theorem VII.3.11 of Dunford and Schwartz [5]) — we obtain the equality

$$e^{s(A)t} = r(T(t)) = e^{\omega_0(\mathcal{T})t},$$

hence  $s(A) = \omega_0(\mathcal{T})$ . Therefore the following corollary is a consequence of the definitions of  $s(A)$  and  $\omega_0(\mathcal{T})$ .

**Corollary 1.2** *Consider the semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  generated by some bounded linear operator  $A \in LE$ . If  $\operatorname{Re} \lambda < 0$  for each  $\lambda \in \sigma(A)$ , then  $\lim_{t \rightarrow \infty} \|T(t)\| = 0$ .*

Through this corollary we have re-established a famous result of Liapunov which assures that the solutions of the linear Cauchy problem

$$\dot{x}(t) = Ax(t), \quad x(0) = x_0 \in \mathbb{C}^n \quad \text{and} \quad A = (a_{ij})_{n \times n}$$

are *stable*, i.e., they converge to zero as  $t \rightarrow \infty$  if the real parts of all eigenvalues of the matrix  $A$  are smaller than zero.

For unbounded generators the situation is much more difficult and  $s(A)$  may differ drastically from  $\omega_0(\mathcal{T})$ .

**Example 1.3** (Banach function space, Greiner et al. [11]) Consider the Banach space  $E$  of all complex valued continuous functions on  $\mathbb{R}_+$  which vanish at infinity and are integrable for  $e^x dx$ , i.e.,

$$E := C_0(\mathbb{R}_+) \cap L^1(\mathbb{R}_+, e^x dx)$$

endowed with the norm

$$\|f\| := \|f\|_\infty + \|f\|_1 = \sup\{|f(x)| : x \in \mathbb{R}_+\} + \int_0^\infty |f(x)|e^x dx.$$

The translation semigroup

$$T(t)f(x) := f(x+t)$$

is strongly continuous on  $E$  and one shows as in A-I,2.4 that its generator is given by

$$Af = f', \quad D(A) = \{f \in E : f \in C^1(\mathbb{R}_+), f' \in E\}.$$

First we observe that  $\|T(t)\| = 1$  for every  $t \geq 0$ , hence  $\omega_0(\mathcal{T}) = 0$ . Moreover it is clear that  $\lambda$  is an eigenvalue of  $A$  as soon as  $\operatorname{Re} \lambda < -1$  (in fact: the function

$$x \mapsto e_\lambda(x) := e^{\lambda x}$$

belongs to  $D(A)$  and is an eigenvector of  $A$ ), hence  $s(A) \geq -1$ . For  $f \in E$ ,  $\operatorname{Re} \lambda > -1$ ,

$$\|\cdot\|_1\text{-}\lim_{t \rightarrow \infty} \int_0^t e^{-\lambda s} T(s)f \, ds$$

exists since  $\|T(s)f\|_1 \leq e^{-s}\|f\|_1$ ,  $s \geq 0$ , and

$$\|\cdot\|_\infty\text{-}\lim_{t \rightarrow \infty} \int_0^t e^{-\lambda s} T(s)f \, ds$$

exists since  $\int_0^\infty e^x |f(x)| \, dx < \infty$ . Therefore  $\int_0^\infty e^{-\lambda s} T(s)f \, ds$  exists in  $E$  for every  $f \in E$ ,  $\operatorname{Re} \lambda > -1$ . As we observed in A-I, Proposition 1.11, this implies  $\lambda \in \varrho(A)$ . Therefore  $\mathcal{T} = (T(t))_{t \geq 0}$  is a semigroup having  $s(A) = -1$ , but  $\omega_0(\mathcal{T}) = 0$ .

*Example 1.4* (Hilbert space, Zabczyk [27]) For every  $n \in \mathbb{N}$  consider the  $n$ -dimensional Hilbert space  $E_n := \mathbb{C}^n$  and operators  $A_n \in \mathcal{L}(E_n)$  defined by the matrices

$$A_n = \begin{pmatrix} 0 & 1 & \cdots & 0 \\ \cdot & 0 & 1 & \cdot \\ \cdot & \cdot & \cdot & 1 \\ 0 & \cdot & \cdot & 0 \end{pmatrix}_{n \times n}.$$

These matrices are nilpotent and therefore  $\sigma(A_n) = \{0\}$ . The elements

$$x_n := n^{-1/2}(1, \dots, 1) \in E_n$$

satisfy the following properties.

- (i)  $\|x_n\| = 1$  for every  $n \in \mathbb{N}$ ,
- (ii)  $\lim_{n \rightarrow \infty} \|A_n x_n - x_n\| = 0$ ,
- (iii)  $\lim_{n \rightarrow \infty} \|\exp(tA_n)x_n - e^t x_n\| = 0$ .

Consider now the Hilbert space  $E := \bigoplus_{n \in \mathbb{N}} E_n$  and the operator  $A := (A_n + 2\pi i n)_{n \in \mathbb{N}}$  with maximal domain in  $E$ . Analogously we define a semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  by

$$T(t) := (e^{2\pi i n t} \exp(tA_n))_{n \in \mathbb{N}}.$$

Since  $\|\exp(tA_n)\| \leq e^t$  for every  $n \in \mathbb{N}$ ,  $t \geq 0$ , and since  $t \mapsto T(t)x$  is continuous on each component  $E_n$ , it follows that  $\mathcal{T}$  is strongly continuous. Its generator is the operator  $A$  as defined above.

For  $\lambda \in \mathbb{C}$ ,  $\operatorname{Re} \lambda > 0$ , we have  $\lim_{n \rightarrow \infty} \|R(\lambda - 2\pi i n, A_n)\| = 0$ , hence

$$(R(\lambda, A_n + 2\pi i n))_{n \in \mathbb{N}} = (R(\lambda - 2\pi i n, A_n))_{n \in \mathbb{N}}$$

is a bounded operator on  $E$  representing the resolvent  $R(\lambda, A)$ . Therefore we obtain  $s(A) \leq 0$ . On the other hand, each  $2\pi i n$  is an eigenvalue of  $A$ , hence  $s(A) = 0$ . Take now  $x_n \in E_n$  as above and consider the sequence  $(x_n)_{n \in \mathbb{N}}$ . From (iii) it follows that for  $t > 0$  the number  $e^t$  is an approximate eigenvalue of  $T(t)$  with approximate eigenvector  $(x_n)_{n \in \mathbb{N}}$  (see Definition 2.1 below). Therefore  $e^t \leq r(T(t)) \leq \|T(t)\|$  and hence  $\omega_0(\mathcal{T}) \geq 1$ . On the other hand, it is easy to see that  $\|T(t)\| = e^t$ , hence  $\omega_0(\mathcal{T}) = 1$ .

Finally, if we take  $S(t) := e^{-t/2}T(t)$ , we obtain a semigroup  $\mathcal{S}$  having spectral bound  $-\frac{1}{2}$  but satisfying  $\lim_{t \rightarrow \infty} \|S(t)\| = \infty$  in contrast with Corollary 1.2. These examples show that neither the conclusion of Corollary 1.2, i.e., “ $s(A) < 0$  implies stability”, nor the “spectral mapping theorem”

$$\sigma(T(t)) = \exp(t \cdot \sigma(A))$$

is valid for arbitrary strongly continuous semigroups. A careful analysis of the general situation will be given in Section 6 below, but we will first develop systematically the necessary spectral theoretic tools for unbounded operators.

## 2 The Fine Structure of the Spectrum

As usual, with a closed linear operator  $A$  with dense domain  $D(A)$  in a Banach space  $E$ , we associate its spectrum  $\sigma(A)$ , its resolvent set  $\varrho(A)$  and its resolvent

$$\lambda \mapsto R(\lambda, A) := (\lambda - A)^{-1}$$

which is a holomorphic map from  $\varrho(A)$  into  $L(E)$ . In contrast to the finite dimensional situation, where a linear operator fails to be surjective if and only if it fails to be injective, we now have to distinguish different cases of *non-invertibility* of  $\lambda - A$ . This distinction gives rise to a subdivision of  $\sigma(A)$  into different subsets. We point out that these subsets need not be disjoint. Our definitions are justified by the fact that for each of the following subsets of  $\sigma(A)$  there exist canonical constructions converting the corresponding spectral values into eigenvalues (see Proposition 2.2.(ii) and Proposition 4.4 below).

**Definition 2.1** For a closed, densely defined, linear operator  $A$  with domain  $D(A)$  in the Banach space  $E$  denote by the

- (i) *point spectrum*  $P\sigma(A)$  the set of all  $\lambda \in \mathbb{C}$  such that  $A - \lambda$  is not injective.
- (ii) *approximate point spectrum*  $A\sigma(A)$  the set of all  $\lambda \in \mathbb{C}$  such that  $A - \lambda$  is not injective or  $(A - \lambda)D(A)$  is not closed in  $E$ .
- (iii) *residual spectrum*  $R\sigma(A)$  the set of all  $\lambda \in \mathbb{C}$  such that  $(A - \lambda)D(A)$  is not dense in  $E$ .

From these definitions it follows that  $\lambda \in P\sigma(A)$  if and only if there exists a non-zero *eigenvector*  $f \in D(A)$  such that  $Af = \lambda f$ , i.e.,  $\lambda$  is an *eigenvalue*. It follows from the Open Mapping Theorem that  $\lambda \in A\sigma(A)$  if and only if  $\lambda$  is an *approximate eigenvalue*, i.e., there exists a sequence  $(f_n)_{n \in \mathbb{N}} \subset D(A)$ , called an *approximate eigenvector*, such that  $\|f_n\| = 1$  and  $\lim_{n \rightarrow \infty} \|Af_n - \lambda f_n\| = 0$ .

Clearly we have  $P\sigma(A) \subset A\sigma(A)$  and  $\sigma(A) = A\sigma(A) \cup R\sigma(A)$  where the union need not be disjoint.

The following proposition is a first indication that the subdivision we made yields nice properties.

**Proposition 2.2** *For a closed, densely defined, linear operator  $(A, D(A))$  in a Banach space  $E$  the following holds.*

- (i) *The topological boundary  $\partial\sigma(A)$  of  $\sigma(A)$  is contained in  $A\sigma(A)$ .*
- (ii)  *$R\sigma(A) = P\sigma(A')$  for the adjoint operator  $A'$  on  $E'$ .*

**Proof** (i) Take  $\lambda_0 \in \partial\sigma(A)$  and  $\lambda_n \in \varrho(A)$  such that  $\lambda_n \rightarrow \lambda_0$ .

Since  $\|R(\lambda_n, A)\| \geq r(R(\lambda_n, A)) = (\text{dist}(\lambda_n, \sigma(A)))^{-1}$  (see Proposition 2.5.(ii)), by the uniform boundedness principle we find  $f \in E$  such that

$$\lim_{n \rightarrow \infty} \|R(\lambda_n, A)f\| = \infty.$$

Define  $g_n \in D(A)$  by

$$g_n := \|R(\lambda_n, A)f\|^{-1} R(\lambda_n, A)f$$

and use the identity

$$(\lambda_0 - A)g_n = (\lambda_0 - \lambda_n)g_n + (\lambda_n - A)g_n$$

to show that  $(g_n)_{n \in \mathbb{N}}$  is an approximate eigenvector corresponding to  $\lambda_0$ .

(ii) This is a simple consequence of the Hahn-Banach theorem.  $\square$

In order to illuminate the above definitions we now return to the Standard Examples introduced in Section 2 of A-I and discuss the fine structure of the spectrum of these strongly continuous semigroups, i.e., of their generators and their semigroup operators.

**Example 2.3** (The Spectrum of Multiplication Semigroups)

Take  $E = C_0(X)$  for some locally compact space  $X$  and take a continuous function  $q: X \rightarrow \mathbb{C}$  whose real part is bounded above. As observed in A-I,2.3 the multiplication operator

$$M_q: f \mapsto q \cdot f$$

with maximal domain  $D(M_q)$  generates the multiplication semigroup

$$T(t)f := e^{tq} \cdot f, \quad f \in E.$$

Since  $M_q$  is bounded if and only if  $q$  is bounded, we conclude that  $M_q$  is invertible (with bounded inverse  $M_{1/q}$ ) if and only if

$$0 \notin \overline{\{q(x) : x \in X\}}.$$

Therefore we obtain

$$\sigma(M_q) = \overline{q(X)} = \overline{\{q(x) : x \in X\}},$$

and

$$\sigma(T(t)) = \overline{\{\exp(tq(x)) : x \in X\}}.$$

In particular the following *weak spectral mapping theorem* is valid

$$\sigma(T(t)) = \overline{\exp(t\sigma(M_q))}.$$

In addition, we observe that to each spectral value of  $A$  (resp. of  $T(t)$ ) there exists an approximate eigenvector and hence

$$\sigma(A) = A\sigma(A) \text{ and } \sigma(T(t)) = A\sigma(T(t)).$$

Since each Dirac functional is an eigenvector for the adjoint multiplication operator, we obtain

$$q(X) \subset R\sigma(M_q) \text{ and } e^{tq(X)} \subset R\sigma(T(t)).$$

The eigenvalues of  $M_q$  can be characterized as follows.

$\lambda \in P\sigma(M_q)$  if and only if the set  $\{x \in X : q(x) = \lambda\}$  has non empty interior (analogously for  $P\sigma(T(t))$ ).

For example, it follows that  $P\sigma(M_q) = \emptyset$  for  $E = C_0(\mathbb{R}_+)$  and  $q(x) = -x$ ,  $x \in \mathbb{R}_+$ . On  $E = L^p(X, \Sigma, \mu)$  analogous results are valid, but their exact formulation—using the notion *essential range*, see Goldstein [8]—is left to the reader.

#### Example 2.4 (The Spectrum of Translation Semigroups)

We consider the translation semigroup

$$T(t)f(x) := f(x+t)$$

on  $E = C_0(\mathbb{R}_+)$  (or  $L^p(\mathbb{R}_+)$ , see A-I,2.4). Its generator  $A$  is the first derivative and for every  $\lambda \in \mathbb{C}$ ,  $\operatorname{Re} \lambda < 0$ , the function  $\varepsilon_\lambda : x \mapsto e^{\lambda x}$  belongs to  $D(A)$  and satisfies

$$A\varepsilon_\lambda = \lambda\varepsilon_\lambda,$$

hence  $\lambda \in P\sigma(A)$ . Since  $\mathcal{T} = (T(t))_{t \geq 0}$  is a contraction semigroup it follows that  $\sigma(A) = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda \leq 0\}$  and  $i\mathbb{R} \subset A\sigma(A)$  (use Proposition 2.2.(i)) or show



directly that  $f_n(x) = e^{i\alpha x} e^{-x/n}$  defines an approximate eigenvector for  $i\alpha$ ,  $\alpha \in \mathbb{R}$ . Using the same functions one obtains

$$\begin{aligned} P\sigma(T(t)) &= \{e^{\lambda t} : \operatorname{Re} \lambda < 0\} = \{z \in \mathbb{C} : |z| < 1\}, \\ \sigma(T(t)) &= \{z \in \mathbb{C} : |z| \leq 1\} \text{ for every } t > 0. \end{aligned}$$

In the case of the translation group on  $E = C_0(\mathbb{R})$  one has that  $\sigma(A) \subset i\mathbb{R}$ . As above one obtains approximate eigenvectors for every  $\alpha \in \mathbb{R}$  from  $f_n(x) = e^{i\alpha x} e^{-|x|/n}$ , hence

$$\sigma(A) = A\sigma(A) = i\mathbb{R}.$$

The generator  $A$  of the nilpotent translation semigroup A-I,2.6 has empty spectrum by A-I, Proposition 1.11. The resolvent is given by

$$R(\lambda, A)f(x) = e^{\lambda x} \int_x^\infty e^{-\lambda s} f(s) \, ds \quad (f \in L^p([0, \tau]), \lambda \in \mathbb{C}).$$

Finally, the generator of the periodic translation group from A-I,2.5 on  $E = \{f \in C[0, 1] : f(0) = f(1)\}$  has point spectrum

$$P\sigma(A) = 2\pi i\mathbb{Z}$$

with eigenfunctions  $\varepsilon_n(x) := \exp(2\pi i n x)$ . In Section 5 we show that  $\sigma(A) = 2\pi i\mathbb{Z}$ .

We now return to the general theory and recall from Corollary 1.2 that it is very useful (e.g., for stability theory) to be able to convert spectral values of the generator  $A$  into spectral values of the semigroup operator  $T(t)$  and vice versa. As shown in Examples 1.3 and 1.4 this is not possible in general. Therefore we tackle first a much easier *spectral mapping theorem*: the relation between  $\sigma(A)$  and  $\sigma(R(\lambda_0))$ , where  $R(\lambda_0) := R(\lambda_0, A)$  for some  $\lambda_0 \in \varrho(A)$ .

**Proposition 2.5** *Let  $(A, D(A))$  be a densely defined closed linear operator with non-empty resolvent set  $\varrho(A)$ . For each  $\lambda_0 \in \varrho(A)$  the following assertions hold.*

- (i)  $\sigma(R(\lambda_0)) \setminus \{0\} = (\lambda_0 - \sigma(A))^{-1}$ , in particular,  $r(R(\lambda_0)) = (\operatorname{dist}(\lambda_0, \sigma(A)))^{-1}$ .
- (ii) Analogous statements hold for the point-, approximate point-, residual spectra of  $A$  and  $R(\lambda_0, A)$ .
- (iii) The point  $\alpha$  is isolated in  $\sigma(A)$  if and only if  $(\lambda_0 - \alpha)^{-1}$  is isolated in  $\sigma(R(\lambda_0))$ . In that case the residues (resp. the pole orders) in  $\alpha$  and in  $(\lambda_0 - \alpha)^{-1}$  coincide.

**Proof** (i) is well known. It can be found for example in Dunford and Schwartz [5, VII.9.2].

(ii) We show that  $\alpha \in A\sigma(A)$  if  $(\lambda_0 - \alpha)^{-1} \in A\sigma(R(\lambda_0))$  and leave the proof of the remaining statements to the reader.

Take  $(f_n)_{n \in \mathbb{N}} \subset E$  such that  $\|f_n\| = 1$ ,  $\|(\lambda_0 - \alpha)^{-1} f_n - R(\lambda_0, A)f_n\| \rightarrow 0$  and  $\|R(\lambda_0, A)f_n\| \geq \frac{1}{2}|\lambda_0 - \alpha|^{-1}$ . Define

$$g_n := \|R(\lambda_0, A)f_n\|^{-1} R(\lambda_0, A)f_n \in D(A)$$

and deduce from

$$\begin{aligned} (\alpha - A)g_n &= \|R(\lambda_0, A)f_n\|^{-1} \cdot [(\lambda_0 - A) - (\lambda_0 - \alpha)]R(\lambda_0, A)f_n \\ &= \|R(\lambda_0, A)f_n\|^{-1} \cdot (\lambda_0 - \alpha)[(\lambda_0 - \alpha)^{-1} - R(\lambda_0, A)]f_n \end{aligned}$$

that  $(g_n)$  is an approximate eigenvector of  $A$  to the eigenvalue  $\alpha$ .

(iii) First we recall the wellknown *resolvent equation*. For any  $z, \lambda_0 \in \varrho(A)$  we have  $R(\lambda_0, A) - R(z, A) = -(\lambda_0 - z)R(\lambda_0, A)R(z, A)$ . From this it follows that  $(\lambda_0 - z)^2 \cdot R(z, A) = ((\lambda_0 - z)^{-1} - R(\lambda_0, A))^{-1} - (\lambda_0 - z)$ . If we now take a circle  $\Gamma$  with center  $\alpha$  and sufficiently small radius. Then the residue  $P$  of  $R(\cdot, A)$  at  $\alpha$  is

$$\begin{aligned} P &= \frac{1}{2\pi i} \int_{\Gamma} R(z, A) dz = \\ &= \frac{1}{2\pi i} \left[ \int_{\Gamma} (\lambda_0 - z)^{-2} R((\lambda_0 - z)^{-1}, R(\lambda_0, A)) dz - \int_{\Gamma} (\lambda_0 - z)^{-1} dz \right]. \end{aligned}$$

If  $\lambda_0$  lies in the exterior of  $\Gamma$ , the second integral is zero. The substitution  $\tilde{z} := (\lambda_0 - z)^{-1}$  yields a path  $\tilde{\Gamma}$  around  $(\lambda_0 - \alpha)^{-1}$  and we obtain

$$P = \frac{1}{2\pi i} \int_{\tilde{\Gamma}} R(\tilde{z}, R(\lambda_0, A)) d\tilde{z}$$

which is the residue of  $R(\cdot, R(\lambda_0, A))$  at  $(\lambda_0 - \alpha)^{-1}$ . The final assertion on the pole order follows from the identities

$$V_{-n} = ((\lambda_0 - \alpha)^{-1} R(\lambda_0, A))^{n-1} U_{-n}, \quad n \in \mathbb{N},$$

where  $U_n$ , resp.  $V_n$  stand for the  $n$ -th coefficient in the Laurent series of  $R(\cdot, A)$ , resp.  $R(\cdot, R(\lambda_0, A))$  at  $\alpha$ , resp.  $(\lambda_0 - \alpha)^{-1}$ . This has already been proved for  $n = 1$  and follows for  $n > 1$  by induction using the relations

$$U_{-n-1} = (A - \alpha)U_{-n} \quad \text{and} \quad V_{-n-1} = (R(\lambda_0, A) - (\lambda_0 - \alpha)^{-1})V_{-n}.$$

### 3 Spectral Decomposition

In the next two sections we develop some important techniques for our further investigation of semigroups and their generators. Even though these methods are well known (compare, e.g. Section VII.3 of Dunford and Schwartz [5]) or rather technical, it is useful to present them in a coherent way.

Our interest in this section is the following: Let  $E$  be a Banach space and  $\mathcal{T} = (T(t))_{t \geq 0}$  a strongly continuous semigroup with generator  $A$ . Suppose that the spectrum  $\sigma(A)$  splits into the disjoint union of two closed subsets  $\sigma_1$  and  $\sigma_2$ . Does there exist a corresponding decomposition of the space  $E$  and the semigroup  $\mathcal{T}$ ?

In the following definition we explain what we understand by “corresponding decomposition”.

**Definition 3.1** Assume that  $\sigma(A)$  is the disjoint union

$$\sigma(A) = \sigma_1 \cup \sigma_2$$

of two non-empty closed subsets  $\sigma_1, \sigma_2$ . A decomposition

$$E = E_1 \oplus E_2$$

of  $E$  into the direct sum of two non-trivial closed  $\mathcal{T}$ -invariant subspaces is called a *spectral decomposition* corresponding to  $\sigma_1 \cup \sigma_2$  if the spectrum  $\sigma(A_i)$  of the generator  $A_i$  of  $\mathcal{T}_i := (T(t)|_{E_i})_{t \geq 0}$  coincides with  $\sigma_i$  for  $i = 1, 2$ .

For a better understanding of the above definition we recall that to every direct sum decomposition  $E = E_1 \oplus E_2$  there corresponds a continuous projection  $P \in \mathcal{L}(E)$  such that  $PE = E_1$  and  $P^{-1}(0) = E_2$ . Moreover, the subspaces  $E_1, E_2$  are  $\mathcal{T}$ -invariant if and only if  $P$  commutes with the semigroup  $\mathcal{T}$ , i.e.,  $T(t)P = PT(t)$  for every  $t \geq 0$ . In this case it follows that the domain  $D(A)$  of the generator  $A$  splits analogously and  $D(A) \cap E_i$  is the domain  $D(A_i)$  of the generator  $A_i$  of the restricted semigroup  $\mathcal{T}_i, i = 1, 2$ . We write

$$A = A_1 \oplus A_2.$$

and say that  $A$  commutes with  $P$  and call  $P$  a *spectral projection*. In terms of the generator  $A$  this means that for  $f \in D(A)$  we have  $Pf \in D(A)$  and  $APf = PAf$ . The existence of such projections reduces the semigroup  $\mathcal{T}$  into two (possibly simpler) semigroups  $\mathcal{T}_1, \mathcal{T}_2$  such that

$$\sigma(A) = \sigma(A_1) \cup \sigma(A_2) \quad \text{and} \quad \sigma(T(t)) = \sigma(T_1(t)) \cup \sigma(T_2(t)).$$

For example, in some cases (see Theorem 3.3 below) it can be shown that one of the reduced semigroups has additional properties.

In order to achieve such decompositions we will assume that  $\sigma(A)$  decomposes into sets  $\sigma_1$  and  $\sigma_2$  and will then try to find a corresponding spectral projection. Unfortunately such spectral decompositions do not exist in general.

*Example 3.2* Take the rotation semigroup from A-I,2.4 on the Banach space  $L^p(\Gamma)$ ,  $1 \leq p < \infty, \tau = 2\pi$ . It was stated in Example 2.4 and will be proved in Section 5 that its generator  $A$  has spectrum

$$\sigma(A) = P\sigma(A) = i\mathbb{Z}$$

where  $\varepsilon_k(z) := z^k$  spans the eigenspace corresponding to  $ik, k \in \mathbb{Z}$ .

Now,  $\sigma(A)$  is the disjoint union of  $\sigma_1 := \{0, i, 2i, \dots\}$  and  $\sigma_2 := \{-i, -2i, \dots\}$ . By a result of M. Riesz there is no projection  $P \in LL^1(\Gamma)$  satisfying  $P\varepsilon_k = \varepsilon_k$  for  $k \geq 0, P\varepsilon_k = 0$  for  $k < 0$ , hence there is no spectral decomposition of  $L^1(\Gamma)$  corresponding to  $\sigma_1, \sigma_2$  (Lindenstrauss and Tzafriri [19, p.165]).

On the other hand, for  $L^p(\Gamma)$ ,  $1 < p < \infty$ , such a spectral projection exists (l.c., 2.c.15). As long as  $p \neq 2$  we can always decompose  $\sigma(A)$  into suitable subsets admitting no spectral decomposition (l.c., remark before 2.c.15). Clearly, for  $p = 2$  such spectral decompositions always exist.

In the above example both subsets  $\sigma_1, \sigma_2$  of  $\sigma(A)$  are unbounded. But as soon as one of these sets is bounded a corresponding spectral decomposition can always be found.

**Theorem 3.3** *Let  $\mathcal{T}$  be a strongly continuous semigroup on a Banach space  $E$  and assume that the spectrum  $\sigma(A)$  of the generator  $A$  can be decomposed into the disjoint union of two non-empty closed subsets  $\sigma_1, \sigma_2$ .*

*If  $\sigma_1$  is compact, then there exists a unique corresponding spectral decomposition  $E = E_1 \oplus E_2$  such that the restricted semigroup  $\mathcal{T}_1$  has a bounded generator.*

**Proof** We assume the reader to be familiar with the spectral decomposition theorem for bounded operators (see, e.g., Dunford and Schwartz [5, p.572]) and apply the spectral mapping theorem for the resolvent (Proposition 2.5.(i)) in order to decompose  $R(\lambda, A)$  instead of  $A$ .

For  $\lambda_0 > \omega_0(\mathcal{T})$  it follows from Proposition 2.5 that  $\sigma(R(\lambda_0, A)) \setminus \{0\} = (\lambda_0 - \sigma(A))^{-1}$ . From  $\sigma(A) = \sigma_1 \cup \sigma_2$  we obtain a decomposition of  $\sigma(R(\lambda_0, A)) \setminus \{0\}$  into

$$\tau_1 := (\lambda_0 - \sigma_1)^{-1}, \quad \tau_2 := (\lambda_0 - \sigma_2)^{-1}.$$

Since  $\sigma_1$  is compact, the set  $\tau_1$  is compact and does not contain 0. Only in the case that  $\sigma_2$  is unbounded the point 0 will be an accumulation point of  $\tau_2$ . Therefore  $\sigma(R(\lambda_0, A)) \cup \{0\}$  is the disjoint union of the closed sets  $\tau_1$  and  $\tau_2 \cup \{0\}$ .

Take now  $P$  to be the spectral projection of  $R(\lambda_0, A)$  corresponding to this decomposition. Then  $P$  commutes with  $R(\lambda_0, A)$  (by definition), with  $R(\lambda, A)$  for every  $\lambda > \omega_0(\mathcal{T})$  (use the series representation of the resolvent), with  $T(t)$  for each  $t \geq 0$  (use A-II, Proposition 1.10) and therefore with the generator  $A$  (in the sense explained above). In particular, we obtain

$$R(\lambda_0, A)P = R(\lambda_0, A_1), \quad R(\lambda_0, A)(Id - P) = R(\lambda_0, A_2)$$

for the generator  $A_1$  of  $T_1 = (T(t)P)_{t \geq 0}$  and  $A_2$  of  $T_2 = (T(t)(Id - P))_{t \geq 0}$ . Applying the Spectral Mapping Theorem 2.5 we conclude

$$\sigma(A_1) = \sigma_1 \text{ and } \sigma(A_2) = \sigma_2,$$

i.e.,  $P$  is a spectral projection corresponding to  $\sigma_1, \sigma_2$ . Finally, the above spectral decomposition of  $R(\lambda_0, A)$  is unique and satisfies  $0 \notin \sigma(R(\lambda_0, A_1))$ . Therefore  $R(\lambda_0, A_1)^{-1} = (\lambda_0 - A_1)$  is bounded.  $\square$

If we do not require  $\mathcal{T}_1$  to be uniformly continuous, the above spectral decomposition need not be unique, as can be seen from the following example.

Consider a decomposition  $E = E_1 \oplus E_2$  and add a direct summand  $E_3$  with a strongly continuous semigroup  $T_3$  whose generator  $A_3$  has empty spectrum (e.g.,

A-I, Example 2.6). Then still  $\sigma(A) = \sigma_1 \cup \sigma_2$ , but  $E_1 \oplus (E_2 \oplus E_3)$  and  $(E_1 \oplus E_3) \oplus E_2$  are two different spectral decompositions corresponding to  $\sigma_1, \sigma_2$ .

The importance of the above theorem stems from the fact that  $\mathcal{T}_1$  has a bounded generator and therefore is easy to deal with. In particular the asymptotic behavior of  $\mathcal{T}_1$  can be deduced from the location of  $\sigma_1$ .

**Corollary 3.4** *Assume that  $\sigma(A)$  splits into non-empty closed sets  $\sigma_1, \sigma_2$  where  $\sigma_1$  is compact and consider the corresponding spectral decomposition  $E = E_1 \oplus E_2$  for which  $\mathcal{T}_1$  is uniformly continuous.*

*For all constants  $\nu, \omega \in \mathbb{R}$  satisfying*

$$\nu < \inf\{\operatorname{Re} \lambda : \lambda \in \sigma_1\} \leq \sup\{\operatorname{Re} \lambda : \lambda \in \sigma_1\} < \omega$$

*there exist  $m \leq 1, M \geq 1$  such that*

$$m \cdot e^{\nu t} \|f\| \leq \|T_1(t)f\| \leq M \cdot e^{\omega t} \|f\|$$

*for every  $f \in E_1, t \geq 0$ .*

**Proof** Since the generator  $A_1$  of  $\mathcal{T}_1$  is bounded, we have  $T_1(t) = \exp(tA_1)$  and  $\sigma(T_1(t)) = \exp(t\sigma(A_1))$ . Therefore by the remark following Proposition 1.1, the spectral bound  $s(A_1)$  coincides with the growth bound  $\omega_0(T_1)$  and we have the upper estimate. The lower estimate is obtained by applying the same reasoning to  $-A_1$  which generates the semigroup  $(T_1(t)^{-1})_{t \geq 0}$  on  $E_1$ .  $\square$

It is clear from Examples 1.3 and 1.4 on page 33 that no norm estimates for  $(T_2(t))_{t \geq 0}$  can be obtained from the location of  $\sigma_2$ . Only by adding appropriate hypotheses we will achieve spectral decompositions admitting norm estimates on both components (see Theorem 6.6 below).

Another way of obtaining such norm estimates is by constructing spectral decompositions starting from a semigroup operator  $T(t_0)$  (instead of  $A$ , and  $R(\lambda, A)$  resp., as in Theorem 3.3).

**Corollary 3.5** *If  $\sigma(T(t_0)) = \tau_1 \cup \tau_2$  for two non-empty, closed, disjoint sets  $\tau_1, \tau_2$  and if  $P$  is the spectral projection corresponding to  $T(t_0)$  and  $\tau_1, \tau_2$ , then  $\sigma(A)$  splits into closed subsets  $\sigma_1, \sigma_2$  and  $P$  is the corresponding spectral projection for  $\mathcal{T}$  and  $\sigma_1, \sigma_2$ .*

**Proof** The spectral projection  $P$  of  $T(t_0)$  is obtained by integrating  $R(\lambda, T(t_0))$  (see, e.g., Dunford and Schwartz [5, Section VII.3]). Since every  $T(t), t \geq 0$ , commutes with  $T(t_0)$ , it must commute with  $R(\lambda, T(t_0))$ , hence with  $P$ . The statement on the decomposition  $\sigma(A) = \sigma_1 \cup \sigma_2$  follows from the Spectral Inclusion Theorem 6.2 below.  $\square$

This decomposition can be applied to the study of the asymptotic behavior of  $\mathcal{T}$ . In the situation of Corollary 3.5 assume

$$\sup\{|\lambda| : \lambda \in \tau_2\} < \alpha < \inf\{|\lambda| : \lambda \in \tau_1\}.$$

for some  $\alpha > 0$ . If we set  $\beta := (\log \alpha)/t_0$  and use Pazy [21, Chap.I, Theorem 6.5] we obtain  $\omega_0(\mathcal{T}_2) < \beta$  and  $\omega_0(\mathcal{T}_1^{-1}) < \beta$  by Proposition 1.1. Therefore we have constants  $m, M$  with  $m \leq 1 \leq M$  such that

$$\begin{aligned} \|T(t)f\| &\leq M \cdot e^{\beta t} \|f\| \quad \text{for } f \in E_2, \\ \|T(t)f\| &\geq m \cdot e^{-\beta t} \|f\| \quad \text{for } f \in E_1. \end{aligned}$$

As nice as they might look, results of this type are unsatisfactory. We need information on the semigroup in order to estimate its asymptotic behavior. In Chapter IV we will try to obtain such results by exploiting information about the generator only.

**Example 3.6 (Isolated singularities and poles)**

In case that  $\lambda_0$  is an isolated point of  $\sigma(A)$  the holomorphic function  $\lambda \mapsto R(\lambda, A)$  can be expanded as a Laurent series

$$R(\lambda, A) = \sum_{n=-\infty}^{+\infty} U_n(\lambda - \lambda_0)^n \quad \text{for } 0 < |\lambda - \lambda_0| < \delta \text{ and some } \delta > 0.$$

The coefficients  $U_n$  are bounded linear operators given by

$$U_n = \frac{1}{2\pi i} \int_{\Gamma} (z - \lambda_0)^{-(n+1)} R(z, A) dz, \quad n \in \mathbb{Z}, \quad (3.1)$$

where  $\Gamma = \{z \in \mathbb{C} : |z - \lambda_0| = \delta/2\}$ . The coefficient  $U_{-1}$  is the spectral projection corresponding to the spectral set  $\{\lambda_0\}$  (see Definition 3.1) is called the *residue* of  $R(\cdot, A)$  at  $\lambda_0$ , and will be denoted by  $P$ . From (3.1) one deduces

$$U_{-(n+1)} = (A - \lambda_0)^n \circ P \quad \text{and} \quad U_{-(n+1)} \circ U_{-(m+1)} = U_{-(n+m+1)} \quad \text{for } n, m \geq 0. \quad (3.2)$$

If there exists  $k > 0$  such that  $U_{-k} \neq 0$  while  $U_{-n} = 0$  for all  $n > k$ , the point  $\lambda_0$  is called a *pole of  $R(\cdot, A)$  of order  $k$* . In view of (3.2) this is true if  $U_{-k} \neq 0$  and  $U_{-(k+1)} = 0$ . In this case one can retrieve  $U_{-k}$  as

$$U_{-k} = \lim_{\lambda \rightarrow \lambda_0} (\lambda - \lambda_0)^k R(\lambda, A). \quad (3.3)$$

The dimension of  $PE$  (i.e., the dimension of the spectral subspace corresponding to  $\{\lambda_0\}$ ) is called the *algebraic multiplicity*  $m_a$  of  $\lambda_0$ , while the *geometric multiplicity* is  $m_g := \dim \ker(\lambda_0 - A)$ . In case  $m_a = 1$ , we call  $\lambda_0$  an *algebraically simple pole*.

If  $k$  is the pole order ( $k = \infty$  in case of an essential singularity), we have

$$\max\{m_g, k\} \leq m_a \leq k \cdot m_g \quad (3.4)$$

where  $\infty \cdot 0 = \infty$ .

These inequalities yield the following implications.

- (i)  $m_a < \infty$  if and only if  $\lambda_0$  is a pole with  $m_g < \infty$ ,
- (ii) if  $\lambda_0$  is a pole with order  $k$ , then  $\lambda_0 \in P\sigma(A)$  and  $PE = \ker(\lambda_0 - A)^k$ .

If  $A$  has compact resolvent, then every point of  $\sigma(A)$  is a pole of finite algebraic multiplicity. This is a consequence of Proposition 2.5.(iii) and the well-known Riesz-Schauder Theory for compact operators (see Dunford and Schwartz [5, VII.4.5]).

**Example 3.7 (The essential spectrum)**

For an operator  $T \in \mathcal{L}(E)$  the *Fredholm domain*  $\varrho_F(T)$  is

$$\begin{aligned} \varrho_F(T) &:= \{\lambda \in \mathbb{C} : \lambda - T \text{ is a Fredholm operator}\} \\ &= \{\lambda \in \mathbb{C} : \ker(\lambda - T) \text{ and } E/\text{im}(\lambda - T) \text{ are finite dimensional}\}. \end{aligned} \quad (3.5)$$

An equivalent characterization of  $\varrho_F(T)$  is obtained through the Calkin algebra  $\mathcal{L}(E)/\mathcal{K}(E)$ , where  $\mathcal{K}(E)$  stands for the closed ideal of all compact operators. In fact,  $\varrho_F(T)$  coincides with the resolvent set of the canonical image of  $T$  in the Calkin algebra. The complement of  $\varrho_F(T)$  is called *essential spectrum* of  $T$  and denoted by  $\sigma_{\text{ess}}(T)$ . The corresponding spectral radius, called *essential spectral radius*, satisfies

$$r_{\text{ess}}(T) := \sup\{|\lambda| : \lambda \in \sigma_{\text{ess}}(T)\} = \lim_{n \rightarrow \infty} \|T^n\|_{\text{ess}}^{1/n}, \quad (3.6)$$

where  $\|T\|_{\text{ess}} = \text{dist}(T, \mathcal{K}(E)) := \inf\{\|T - K\| : K \in \mathcal{K}(E)\}$  is the norm of  $T$  in  $\mathcal{L}(E)/\mathcal{K}(E)$ .

For every compact operator  $K$  we have  $\|T - K\|_{\text{ess}} = \|T\|_{\text{ess}}$ , hence

$$r_{\text{ess}}(T - K) = r_{\text{ess}}(T). \quad (3.7)$$

A detailed analysis of  $\varrho_F(T)$  can be found in Section IV.5.6 of Kato [16]. In particular we recall that the poles of  $R(\cdot, T)$  with finite algebraic multiplicity belong to  $\varrho_F(T)$ . Conversely, an element of the unbounded component of  $\varrho_F(T)$  either belongs to  $\varrho_F(T)$  or is a pole of finite algebraic multiplicity. Thus  $r_{\text{ess}}(T)$  can be characterized as

$$\begin{aligned} r_{\text{ess}}(T) &\text{ is the smallest } r \in \mathbb{R}_+ \text{ such that every } \lambda \in \sigma(T), |\lambda| > r \\ &\text{ is a pole of finite algebraic multiplicity.} \end{aligned} \quad (3.8)$$

Now, if  $\mathcal{T} = (T(t))_{t \geq 0}$  is a strongly continuous semigroup, then VIII.1, Lemma 4 of Dunford and Schwartz [5] applied to the function  $t \mapsto \log \|T(t)\|_{\text{ess}}$  ensures that

$$\omega_{\text{ess}}(\mathcal{T}) := \lim_{t \rightarrow \infty} \frac{1}{t} \log \|T(t)\|_{\text{ess}} = \inf\left\{\frac{1}{t} \log \|T(t)\|_{\text{ess}} : t > 0\right\} \quad (3.9)$$

is well defined (possibly  $-\infty$ ). By the definition of  $\omega_{\text{ess}}(\mathcal{T})$  and by (3.6) we have

$$r_{\text{ess}}(T(t)) = \exp(t\omega_{\text{ess}}(\mathcal{T})), \quad t \geq 0. \quad (3.10)$$

Obviously,  $\omega_{\text{ess}} \leq \omega_0$  and equality occurs if and only if  $r_{\text{ess}}(T(t)) = r(T(t))$  for  $t \geq 0$ .

If  $\omega_{\text{ess}} < \omega_0$ , there exists an eigenvalue  $\lambda$  of  $T(t)$  satisfying  $|\lambda| = r(T(t))$ , hence by Theorem 6.3 below there exists  $\lambda_1 \in P\sigma(A)$  such that  $\text{Re } \lambda_1 = \omega_0$ . Thus  $\omega_{\text{ess}} < \omega_0$  implies  $s(A) = \omega_0(\mathcal{T})$ , i.e., we have

$$\omega_0(\mathcal{T}) = \max\{\omega_{\text{ess}}(\mathcal{T}), s(A)\}. \quad (3.11)$$

As a final observation we point out that

$$\omega_{\text{ess}}(\mathcal{T}) = \omega_{\text{ess}}(\mathcal{S}), \quad (3.12)$$

whenever  $\mathcal{T}$  is generated by  $A$  and  $\mathcal{S}$  is generated by  $A + K$  for some compact operator  $K$  see Proposition 2.8 and Proposition 2.9 of B-IV).

## 4 The Spectrum of Induced Semigroups

In the previous section we tried to decompose a semigroup into the direct sum of two, hopefully simpler objects. Here we present other methods to reduce the complexity of a semigroup and its generator. Forming subspace or quotient semigroups as in A-I,3.2, A-I,3.3 are such methods. But also the constructions of new semigroups on canonically associated spaces such as the dual space, see A-I,3.4, or the  $\mathcal{F}$ -product, see A-I,3.6, might be helpful. We review these constructions under the spectral theoretical point of view and collect a number of technical properties for later use.

We start by studying the spectrum of subspace and quotient semigroups. To that purpose assume that the strongly continuous semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  leaves invariant some closed subspace  $N$  of the Banach space  $E$ . There are canonically induced semigroups  $\mathcal{T}|_N$  on  $N$ , resp.  $\mathcal{T}_N$  on  $E/N$  and their generators  $A|_N$ , resp.  $A_N$  are canonically obtained from the generator  $A$  of  $\mathcal{T}$  (see A-I, Section 3). The following example shows that the spectra of  $A$ ,  $A|_N$  and  $A_N$  may differ quite drastically.

*Example 4.1* As in the example in A-I,3.3 we consider the translation semigroup on  $E = L^1(\mathbb{R})$  and the invariant subspace  $N := \{f \in E : f(x) = 0 \text{ for } x \geq 1\}$ . Then  $\sigma(A) = i\mathbb{R}$  but  $\sigma(A|_N) = \{\lambda \in \mathbb{C} : \text{Re } \lambda \leq 0\}$ . Next we take the translation invariant subspace  $M := \{f \in N : f(x) = 0 \text{ for } 0 \leq x \leq 1\}$  and obtain  $\sigma(A|_M) = \emptyset$  for the generator  $A|_M$  of the quotient semigroup  $\mathcal{T}|_M$  (use the fact that  $\mathcal{T}|_M$  is nilpotent).

In the next proposition we collect the information on  $\sigma(A)$  which in general can be obtained from the “subspace spectrum”  $\sigma(A|_N)$  and the “quotient spectrum”  $\sigma(A_N)$ .

**Proposition 4.2** *Using the standard notations the following inclusions hold.*

- (i)  $\varrho(A) \subset [\varrho(A|_N) \cap \varrho(A_N)] \cup [\sigma(A|_N) \cap \sigma(A_N)]$ ,
- (ii)  $[\varrho(A|_N) \cap \varrho(A_N)] \subset \varrho(A)$ ,
- (iii)  $\varrho_+(A) \subset [\varrho(A|_N) \cap \varrho(A_N)]$ ,



where  $\varrho_+(A)$  denotes the connected component of  $\varrho(A)$  which is unbounded to the right.

**Proof** (i) Assume  $\lambda \in \varrho(A)$ , i.e.,  $(\lambda - A)$  is a bijection from  $D(A)$  onto  $E$ . Since  $N$  is  $T$ -invariant, we have  $D(A|_N) = D(A) \cap N$  and  $(\lambda - A)D(A|_N) \subset N$ . If  $(\lambda - A)D(A|_N) = N$ , then  $R(\lambda, A)N = D(A|_N)$  and the induced operators  $R(\lambda, A)|_N$ , resp.  $R(\lambda, A)_N$  are the inverses of  $(\lambda - A|_N)$ , resp.  $(\lambda - A)_N$ . If  $(\lambda - A)D(A|_N) \neq N$ , then  $\lambda \in \sigma(A|_N)$ .

In addition there exists  $f \in D(A) \setminus N$  such that  $g := (\lambda - A)f \in N$ . Hence for  $\hat{f} := f + N$ ,  $\hat{g} := g + N \in E_N$  it follows that  $(\lambda - A_N)\hat{f} = \hat{g} = 0$ , i.e.,  $\lambda \in \sigma(A_N)$ .  
(ii) Take  $\lambda \in \varrho(A|_N) \cap \varrho(A_N)$ . Then  $(\lambda - A)$  is injective, since  $(\lambda - A)f = 0$  implies  $(\lambda - A_N)\hat{f} = 0$ , hence  $\hat{f} = 0$ , i.e.,  $f \in N$  and therefore  $f = 0$ . In addition,  $(\lambda - A)$  is surjective: For  $g \in E$  there exists  $\hat{f} \in E_N$  such that  $(\lambda - A_N)\hat{f} = \hat{g}$ , i.e., there exists  $h \in N$  such that  $(\lambda - A)f - g = h = (\lambda - A)k$  for some  $k \in D(A|_N)$ . Therefore we obtain  $(\lambda - A)(f - k) = g$ .

(iii) The integral representation of the resolvent for  $\lambda > \omega_0(\mathcal{T})$  (see A-I, Proposition 1.11) shows that  $R(\lambda, A)N \subset N$ . By the power series expansion for holomorphic functions this extends to all  $\lambda \in \varrho_+(A)$ . Therefore the restriction  $R(\lambda, A)|_N$  coincides with the resolvent  $R(\lambda, A|_N)$ . On the other hand  $R(\lambda, A)_N$  is well defined on  $E_N$  and satisfies

$$R(\lambda, A)_N(f + N) = R(\lambda, A)f + N$$

(use again the integral representation). This proves that  $R(\lambda, A)_N = R(\lambda, A|_N)$ .  $\square$

**Corollary 4.3** *Under the above assumptions take a point  $\mu$  in the closure of  $\varrho_+(A)$ .*

*Then*

(i)  $\mu \in \sigma(A)$  if and only if  $\mu \in \sigma(A|_N)$  or  $\mu \in \sigma(A_N)$ .

(ii)  $\mu$  is a pole of  $R(\cdot, A)$  if and only if  $\mu$  is a pole of  $R(\cdot, A|_N)$  and of  $R(\cdot, A_N)$ .

*In that case,*

$$\max\{k|, k_N\} \leq k \leq k| + k_N$$

*for the respective pole orders. Note that hereby pole orders 0 are allowed.*

**Proof** (i) follows from Proposition 4.2, inclusions (ii) and (iii).

(ii) By the previous assertion we may assume that for some  $\delta > 0$  the pointed disc

$$\{\lambda \in \mathbb{C}: 0 < |\lambda - \mu| < \delta\}$$

is contained in  $\varrho(A) \cap \varrho(A|_N) \cap \varrho(A_N)$ .

Call  $U_n$  the coefficients of the Laurent expansion of  $R(\cdot, A)$ . Since  $N$  is  $R(\lambda, A)$ -invariant for  $\lambda \in \varrho_+(A)$ , the same holds for each  $U_n$ . With the obvious notations we have  $R(\lambda, A) = \sum_n U_n(\lambda - \mu)^n$ ,  $R(\lambda, A|_N) = \sum U_n|_N(\lambda - \mu)^n$  and  $R(\lambda, A)_N = \sum U_n|_N(\lambda - \mu)^n$  which shows  $\max\{k|, k_N\} \leq k$ .

If  $R(\cdot, A|_N)$  has a pole in  $\mu$  of order  $\ell$ , then  $U_{-(\ell+1)}|_N = 0$ , i.e.,  $U_{-(\ell+1)}N = \{0\}$ .

Similarly it follows that  $U_{-(m+1)}E \subset N$  if  $R(\cdot, A)_N$  has a pole in  $\mu$  of order  $m$ .

Therefore  $U_{-(\ell+1)} \circ U_{-(m+1)} = 0$ .

The relations (3.2) imply  $U_{-(m+\ell+1)} = 0$ , hence the pole order of  $R(\cdot, A)$  is dominated by  $\ell + m$ .  $\square$

#### 4.1 Spectrum of the adjoint semigroup

We recall from A-I,3.4 that to every strongly continuous semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  there corresponds a strongly continuous adjoint semigroup  $\mathcal{T}^* = (T(t)^*)_{t \geq 0}$  on the semigroup dual

$$E^* = \{\varphi \in E' : \lim_{t \rightarrow \infty} \|T(t)'\varphi - \varphi\| = 0\}.$$

Its generator  $A^*$  is the maximal restriction of the adjoint  $A'$  to  $E^*$ . For these operators the spectra coincide, or more precisely.

- (i)  $\sigma(T(t)) = \sigma(T(t)') = \sigma(T(t)^*)$ ,  
 $R\sigma(T(t)) = P\sigma(T(t)') = P\sigma(T(t)^*)$ ,
- (ii)  $\sigma(A) = \sigma(A') = \sigma(A^*)$ ,  $R\sigma(A) = P\sigma(A') = P\sigma(A^*)$ ,
- (iii)  $s(A) = s(A^*)$ ,  $\omega_0(A) = \omega_0(A^*)$ .

**Proof** The left part of these equalities is either well known or has been stated in 2.2(ii). The first statement of (iii) follows from (ii), while the second is an immediate consequence of the estimate  $\|T(t)^*\| \leq \|T(t)\| \leq M \cdot \|T(t)^*\|$  given in A-I,3.4. As a sample for the remaining assertions we show that  $0 \notin \sigma(A)$  if and only if  $0 \notin \sigma(A^*)$ : If  $A$  and therefore  $A'$  is invertible, it follows from A-I,3.4 that  $A^*$  is a bijection from  $D(A^*)$  onto  $e^*$ .

Conversely assume that  $A^*$  is invertible. Then  $A'$  must be injective by the Proposition in A-I,3.4. Moreover  $A'(D(A'))$  contains  $A^*(D(A^*)) = e^*$  and is  $\sigma(E', E)$ -dense in  $E'$ . By standard duality arguments it follows that  $A$  is injective with dense image. Next we show that  $A(D(A))$  is closed: For  $f \in D(A)$  choose  $\varphi \in D(A')$  such that  $\|\varphi\| \leq 1$  and  $|\langle f, \varphi \rangle| \geq \frac{1}{2}\|f\|$ . Then

$$\begin{aligned} \|(A^*)^{-1}\| \|Af\| &\geq \|(A^*)^{-1}\| |\langle Af, \varphi \rangle| \geq |\langle Af, (A^*)^{-1}\varphi \rangle| \\ &= |\langle f, \varphi \rangle| \geq \frac{1}{2}\|f\|, \end{aligned}$$

hence

$$\|Af\| \geq \frac{1}{2}\|(A^*)^{-1}\|^{-1}\|f\|,$$

and  $A(D(A))$  is closed since  $A$  is closed.  $\square$

## 4.2 Spectrum of the $\mathcal{F}$ -product semigroup

As stated in A-I,3.6 the  $\mathcal{F}$ -product semigroup  $\mathcal{T}_{\mathcal{F}} = (T_{\mathcal{F}}(t))_{t \geq 0}$  on  $E_{\mathcal{F}}^{\mathcal{T}}$  of a strongly continuous semigroup  $\mathcal{T}$  on  $E$  serves to convert sequences in  $E$  into points in  $E_{\mathcal{F}}^{\mathcal{T}}$ . In particular it can be used to convert approximate eigenvectors of the generator  $A$  into eigenvectors of  $A_{\mathcal{F}}$ .

**Proposition 4.4** *Let  $A$  be the generator of a strongly continuous semigroup. Then the generator  $A_{\mathcal{F}}$  of the  $\mathcal{F}$ -product semigroup satisfies.*

- (i)  $A\sigma(A) = A\sigma(A_{\mathcal{F}}) = P\sigma(A_{\mathcal{F}})$ ,
- (ii)  $\sigma(A) = \sigma(A_{\mathcal{F}})$ .

**Remark 4.5** In case  $A$  is bounded, then the canonical extension  $A_{\mathcal{F}}$  is a generator and  $E_{\mathcal{F}}^{\mathcal{T}} = E_{\mathcal{F}}$  (cf. A-I,3.6). Thus the proposition applies to bounded linear operators and their canonical extensions to the  $\mathcal{F}$ -product  $E_{\mathcal{F}}$ .

**Proof (Proof of the proposition)** (i) The inclusion  $P\sigma(A_{\mathcal{F}}) \subset A\sigma(A_{\mathcal{F}})$  holds trivially.

We show that  $A\sigma(A_{\mathcal{F}}) \subset A\sigma(A)$ : Take  $\lambda \in A\sigma(A_{\mathcal{F}})$  and an associated approximate eigenvector  $(\hat{f}^m)_{m \in \mathbb{N}}$ , i.e.,  $\hat{f}^m \in D(A_{\mathcal{F}})$ ,  $\|\hat{f}^m\| = 1$  and  $(\lambda - A_{\mathcal{F}})\hat{f}^m \rightarrow 0$  as  $m \rightarrow \infty$ .

By the considerations in A-I,3.6 we can represent each  $\hat{f}^m$  as a normalized sequence  $(f_n^m)_{n \in \mathbb{N}}$  in  $D(A)$  such that

$$\lim_{m \rightarrow \infty} \limsup_{n \rightarrow \infty} \|(\lambda - A)f_n^m\| = 0.$$

Therefore we can find a sequence  $g_k = f_k^{m(k)}$  satisfying

$$\lim_{k \rightarrow \infty} \|(\lambda - A)g_k\| = 0,$$

i.e.,  $\lambda \in A\sigma(A)$ .

Finally we show  $A\sigma(A) \subset P\sigma(A_{\mathcal{F}})$ : For  $\lambda \in A\sigma(A)$  take a corresponding approximate eigenvector  $(f_n)$ . By A-I,(3.2) we have

$$\begin{aligned} \|T(t)f_n - f_n\| &\leq \|T(t)f_n - e^{\lambda t}f_n\| + |e^{\lambda t} - 1| \\ &= \left\| \int_0^t e^{\lambda(t-s)}T(s)(\lambda - A)f_n \, ds \right\| + |e^{\lambda t} - 1| \end{aligned}$$

which converges to zero uniformly in  $n$  as  $t \rightarrow 0$ , i.e.,  $(f_n) \in m^{\mathcal{T}}(E)$ . From the characterization of  $D(A_{\mathcal{F}})$  given in A-I,3.6 it follows that

$$\hat{f} := (f_n) + c_F(E) \in D(A_{\mathcal{F}})$$

and  $A_{\mathcal{F}}\hat{f} = \lambda\hat{f}$ , i.e.,  $\lambda \in P\sigma(A_{\mathcal{F}})$ .

(ii) The inclusion  $A\sigma(A) \subset \sigma(A_{\mathcal{F}})$  follows from (i). Now we show  $R\sigma(A) \subset R\sigma(A_{\mathcal{F}})$ : For  $\lambda \in R\sigma(A)$  choose  $f \in E$  such that  $\|(\lambda - A)g - f\| \geq 1$  for every  $g \in$

$D(A)$ . Then  $\|(\lambda - A_{\mathcal{F}})g - \hat{f}\| \geq 1$  for every  $\hat{g} \in D(A_{\mathcal{F}})$  and  $\hat{f} = (f, f, \dots) + c_{\mathcal{F}}(E)$ . Therefore  $\lambda \in R\sigma(A_{\mathcal{F}})$ .

We now show  $\varrho(A) \subset \varrho(A_{\mathcal{F}})$ : Assume  $\lambda \in \varrho(A)$ . By (i)  $(\lambda - A_{\mathcal{F}})$  has to be injective. Choose  $\hat{f} = (f_1, f_2, \dots) + c_{\mathcal{F}}(E)$  such that  $(f_n) \in m^{\mathcal{T}}(E)$ . Then  $(R(\lambda, A)f_n) \in m^{\mathcal{T}}(E)$  and  $(\lambda - A_{\mathcal{F}})((R(\lambda, A)f_n) + c_{\mathcal{F}}(E)) = (f_n) + c_{\mathcal{F}}(E)$ , i.e.,  $(\lambda - A_{\mathcal{F}})$  is surjective and  $\lambda \in \varrho(A_{\mathcal{F}})$ .  $\square$

Applying this proposition to a single operator  $T(t)$ , we obtain

$$A\sigma(T(t)) = P\sigma(T(t)_{\mathcal{F}}).$$

Note that in general  $A\sigma(T(t)) \neq P\sigma(T_{\mathcal{F}}(t))$  (see the Examples 1.3 and 1.4 in combination with Theorem 6.3).

## 5 The Spectrum of Periodic Semigroups

In this section we determine the spectrum of a particularly simple class of strongly continuous semigroups and thereby achieve a rather complete description of the semigroup itself. Besides being nice and simple these semigroups gain their importance as building blocks for the general theory.

**Definition 5.1** A strongly continuous semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  on a Banach space  $E$  is called *periodic* if  $T(t_0) = \text{Id}$  for some  $t_0 > 0$ .

The *period*  $\tau$  of  $\mathcal{T}$  is obtained as

$$\tau := \inf\{t_0 > 0 : T(t_0) = \text{Id}\}.$$

We immediately observe that periodic semigroups are groups with inverses  $T(t)^{-1} = T(n\tau - t)$  for  $0 \leq t \leq n\tau$ ,  $\tau$  the period of  $\mathcal{T}$ . Moreover, they are bounded, hence the growth bound is zero and  $\sigma(A) \subset i\mathbb{R}$ .

**Lemma 5.2** Let  $T$  be a strongly continuous semigroup with period  $\tau > 0$  and generator  $A$ . Then

$$\sigma(A) \subset 2\pi i/\tau \cdot \mathbb{Z}$$

and

$$R(\mu, A) = (1 - e^{-\mu\tau})^{-1} \int_0^\tau e^{-\mu s} T(s) \, ds \quad (5.1)$$

for  $\mu \notin 2\pi i/\tau \cdot \mathbb{Z}$ .

**Proof** From the basic identities A-I,(3.1) and A-I,(3.2) for  $t = \tau$ , it follows that  $(\mu - A)$  has a left and right inverse if  $\mu \neq 2\pi in/\tau$ ,  $n \in \mathbb{Z}$ , and that the inverse is given by the above expression.  $\square$

The representation of  $R(\mu, A)$  given in A-I, Proposition 1.11 shows that the resolvent of the generator of a periodic semigroup is a meromorphic function having only poles of order one and the residues

$$P_n := \lim_{\mu \rightarrow \mu_n} (\mu - \mu_n)R(\mu, A) \quad \text{in} \quad \mu_n := 2\pi i n / \tau, \quad n \in \mathbb{Z},$$

are

$$P_n = \frac{1}{\tau} \int_0^\tau \exp(-\mu_n s) T(s) \, ds. \quad (5.2)$$

Moreover, it follows that the spectrum of  $A$  consists of eigenvalues only and each  $P_n$  is the spectral projection belonging to  $\mu_n$  (see 3.6). Another way of looking at  $P_n$  is given by saying that  $P_n$  is the  $n$ -th Fourier coefficient of the  $\tau$ -periodic function  $s \mapsto T(s)$ . From this it follows that no non-zero  $\varphi \in E'$  vanishes on all  $P_n E$  simultaneously. By the Hahn-Banach theorem we conclude that  $\text{span} \cup_{n \in \mathbb{Z}} P_n E$  is dense in  $E$ .

Since  $P_n E \subset D(A)$ , we obtain from A-I,(3.1) that

$$AP_n f = \mu_n P_n f \quad (5.3)$$

for every  $f \in E, n \in \mathbb{Z}$ . This and A-I,(3.2) imply

$$T(t)P_n f = \exp(\mu_n t) \cdot P_n f \quad (5.4)$$

for every  $t \geq 0$ . Therefore  $\mu_n$  is an eigenvalue of  $A$  and  $\exp(\mu_n t)$  is an eigenvalue of  $T(t)$  if and only if  $P_n \neq 0$ . In that case,  $P_n E$  is the corresponding eigenspace and we have the following lemma.

**Lemma 5.3** *For a  $\tau$ -periodic semigroup  $\mathcal{T}$  we take  $\mu_n := 2\pi i n / \tau, n \in \mathbb{Z}$ , and consider*

$$P_n := \frac{1}{\tau} \int_0^\tau \exp(-\mu_n s) T(s) \, ds.$$

*Then the following assertions are equivalent.*

- (a)  $P_n \neq 0$ ,
- (b)  $\mu_n \in P\sigma(A)$ ,
- (c)  $\exp(\mu_n t) \in P\sigma(T(t))$  for every  $t > 0$ .

The action of  $A$ , resp.  $T(t)$  on the subspaces  $P_n E, n \in \mathbb{Z}$ , is determined by (5.3), resp. (5.4). Moreover,

$$\begin{aligned} P_m P_n f &= \frac{1}{\tau} \int_0^\tau \exp(-\mu_m s) T(s) P_n f \, ds \\ &= \frac{1}{\tau} \int_0^\tau \exp((\mu_n - \mu_m)s) P_n f \, ds = 0 \end{aligned}$$

for  $n \neq m$ , i.e., the subspaces  $P_n E$  are “orthogonal”. Since their union is total in  $E$ , one expects to be able to extend the representations (5.3) and (5.4) of  $A$  and  $T(t)$ . This is possible if

$$\sum_{n=-\infty}^{+\infty} P_n = \text{Id},$$

where the series should be summable for the strong operator topology.

Unfortunately this is false in general since the family of projections

$$Q_H := \sum_{n \in H} P_n,$$

where  $H$  runs through all finite subsets of  $\mathbb{Z}$ , may be unbounded (see the example below). Nevertheless the following is true.

**Theorem 5.4** *Let  $\mathcal{T} = (T(t))_{t \geq 0}$  be a  $\tau$ -periodic semigroup on a Banach space  $E$  with generator  $A$  and associated spectral projections*

$$P_n := \frac{1}{\tau} \int_0^\tau \exp(-\mu_n s) T(s) \, ds, \quad \mu_n := 2\pi i n / \tau, \quad n \in \mathbb{Z}.$$

For every  $f \in D(A)$  one has  $f = \sum_{-\infty}^{+\infty} P_n f$  and therefore

- (i)  $T(t)f = \sum_{-\infty}^{+\infty} \exp(\mu_n t) P_n f$  if  $f \in D(A)$ ,
- (ii)  $Af = \sum_{-\infty}^{+\infty} \mu_n P_n f$  if  $f \in D(A^2)$ .

**Proof** It suffices to prove the first statement. Then (i) and (ii) follow by (5.3) and (5.4).

We assume  $\tau = 2\pi$  and show first that  $\sum_{-\infty}^{+\infty} P_n f$  is summable for  $f \in D(A)$ : For  $g := Af$  we obtain  $P_n g = P_n A f = A P_n f = i n P_n f$ . Take  $H$  to be a finite subset of  $\mathbb{Z} \setminus \{0\}$  and  $\varphi \in E'$ . Then

$$\begin{aligned} \left| \sum_{n \in H} \langle P_n f, \varphi \rangle \right| &= \left| \sum_{n \in H} (in)^{-1} \langle P_n g, \varphi \rangle \right| \\ &\leq \left( \sum_{n \in H} n^{-2} \right)^{1/2} \left( \sum_{n \in H} |\langle P_n g, \varphi \rangle|^2 \right)^{1/2}. \end{aligned}$$

From Bessel's inequality we obtain for the second factor

$$\begin{aligned} \sum_{n \in H} |\langle P_n g, \varphi \rangle|^2 &\leq \frac{1}{2\pi} \cdot \int_0^{2\pi} |\langle T(s)g, \varphi \rangle|^2 \, ds \\ &\leq \|\varphi\|^2 \cdot \frac{1}{2\pi} \cdot \int_0^{2\pi} \|T(s)g\|^2 \, ds. \end{aligned}$$

With the constant  $c := \left( \frac{1}{2\pi} \cdot \int_0^{2\pi} \|T(s)g\|^2 \, ds \right)^{1/2}$  we obtain

$$\left\| \sum_{n \in H} P_n f \right\| \leq c \left( \sum_{n \in H} n^{-2} \right)^{1/2}$$

for every finite subset  $H$  of  $\mathbb{Z}$ , i.e.,  $\sum_{-\infty}^{+\infty} P_n f$  is summable.

Next we set  $h := \sum_{-\infty}^{+\infty} P_n f$  and observe that for every  $\varphi' \in E'$  the Fourier coefficients of the continuous,  $\tau$ -periodic functions  $s \mapsto \langle T(s)h, \varphi' \rangle$  and  $s \mapsto \langle T(s)f, \varphi' \rangle$

coincide. Therefore these functions are identical for  $s \geq 0$  and in particular for  $s = 0$ , i.e.,  $\langle h, \varphi \rangle = \langle f, \varphi \rangle$ . By the Hahn-Banach Theorem we obtain  $f = h$ .  $\square$

The above theorem contains rather precise information on periodic semigroups. In particular, it characterizes periodic semigroups by the fact that  $\sigma(A)$  is contained in  $i\alpha\mathbb{Z}$  for some  $\alpha \in \mathbb{R}$  and the eigenfunctions of  $A$  form a total subset of  $E$ . For a periodic semigroup with bounded generator only a finite number of spectral projections  $P_n$  are distinct from 0 and we have the following characterization.

**Corollary 5.5** *Let  $\mathcal{T} = (T(t))_{t \geq 0}$  be a semigroup with bounded generator on some Banach space  $E$ .*

*This semigroup has period  $\tau/k$  for some  $k \in \mathbb{N}$  if and only if there exist finitely many pairwise orthogonal projections  $P_n$ ,  $-m \leq n \leq m$ ,  $P_{-m} \neq 0$  or  $P_m \neq 0$ , such that*

- (i)  $\sum_{-m}^{+m} P_n = \text{Id}$ ,
- (ii)  $T(t) = \sum_{-m}^{+m} \exp(2\pi i n t / \tau) P_n$ ,
- (iii)  $A = \sum_{-m}^{+m} (2\pi i n / \tau) P_n$ .

*Example 5.6* From A-I,2.5 we recall briefly the rotation group

$$R_\tau(t)f(z) := f(\exp(2\pi i t / \tau) \cdot z)$$

on  $E = C(\Gamma)$ , resp.  $E = L^p(\Gamma, m)$  for  $1 \leq p < \infty$ . The spectrum of the generator  $Af(z) = (2\pi i / \tau)z \cdot f'(z)$  is  $\sigma(A) = (2\pi i / \tau) \cdot \mathbb{Z}$ . The eigenfunctions  $\varepsilon_n(z) := z^n$  yield the projections

$$P_n = (1/2\pi i) \cdot \varepsilon_{-(n+1)} \otimes \varepsilon_n, \text{ i.e.,}$$

$$P_n f(z) = (1/2\pi i) \cdot \left( \int_{\Gamma} f(w) w^{-(n+1)} dw \right) \cdot z^n.$$

It is left as an exercise to compute the norms of  $Q_m := \sum_{-m}^{+m} P_n$  in  $L^p(\Gamma, m)$  for various  $p$  and then check the assertions of Theorem 5.4.

Clearly, this proves some classical convergence theorems for Fourier series (compare Davies [3, Chap.8.1]).

## 6 Spectral Mapping Theorems

We now return to the question posed in the introduction to this chapter: In which form and under which conditions is it true that the spectrum  $\sigma(T(t))$  of the semigroup operators is obtained—via the exponential map—from the spectrum  $\sigma(A)$  of the generator, or briefly

$$\text{Do we have } \sigma(T(t)) = \exp(t\sigma(A)) \text{ or at least } \sigma(T(t)) = \overline{\exp(t\sigma(A))} \text{ ?}$$

This and similar statements will be called *spectral mapping theorems* for the semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  and its generator  $A$ . In addition, we saw in Proposition 1.1 that the validity of such a spectral mapping theorem implies

$$s(A) = \omega_0(A)$$

for the spectral- and growth bounds and therefore guarantees that the location of the spectrum of  $A$  determines the asymptotic behavior of  $\mathcal{T}$ . As we have seen in Examples 1.3 and 1.4 the last statement does not hold in general. We therefore present a detailed analysis, where and why it fails and what additional assumptions are needed for its validity. Before doing so, we have another look at the examples.

*Example 6.1* (The counterexamples revisited)

(i) Take the nilpotent translation semigroup from A-I,2.6. Then  $\sigma(A) = \emptyset$  and  $\sigma(T(t)) = 0$  for every  $t > 0$ . By this trivial example and since  $e^z \neq 0$  for every  $z \in \mathbb{C}$ , it is natural to read the spectral mapping theorem modulo the addition of  $\{0\}$ , i.e.,

$$\sigma(T(t)) \setminus \{0\} = \exp(t\sigma(A)) \text{ for } t \geq 0.$$

(ii) The spectrum of the generator  $A$  of the  $\tau$ -periodic rotation group  $(R_\tau(t))_{t \geq 0}$  on  $C(\Gamma)$  is  $\sigma(A) = 2\pi i/\tau \cdot \mathbb{Z}$  and  $\exp(2\pi i n t/\tau)$ ,  $n \in \mathbb{Z}$ , is an eigenvalue of  $R_\tau(t)$  for every  $t \geq 0$  (see Example 5.6. If  $t/\tau$  is irrational, these eigenvalues form a dense subset of  $\Gamma$ . Since the spectrum is closed, we obtain  $\sigma(T(t)) = \Gamma$  for these  $t$ . Therefore in this example the spectral mapping theorem is valid only in the following “weak” form

$$\sigma(T(t)) = \overline{\exp(t\sigma(A))}, \quad t \geq 0.$$

(iii) By Example 1.3 there exists a semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  with generator  $A$  such that  $s(A) = -1$  and  $\omega_0(\mathcal{T}) = 0$ . This implies that for preassigned real numbers  $\alpha < \beta$  there exists a semigroup  $\mathcal{S} = (S(t))_{t \geq 0}$  with generator  $B$  such that  $s(B) = \alpha$  and  $\omega_0(\mathcal{S}) = \beta$ . Indeed, take  $S(t) = e^{\beta t} T((\beta - \alpha)t)$  and observe that  $B = (\beta - \alpha)A + \beta \text{Id}$ . In that case  $\exp(t\sigma(B))$  is contained in the circle about 0 with radius  $e^{\alpha t}$  while  $\sigma(S(t))$  has spectral values satisfying  $|\lambda| = r(S(t)) = e^{\beta t} > e^{\alpha t}$ .

(iv) The Example 1.3 can be strengthened in order to yield a semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  with generator  $A$  such that  $\sigma(A) = \emptyset$ , but  $\|T(t)\| = r(T(t)) = 1$  for  $t \geq 0$ , i.e.,  $s(A) = -\infty$ ,  $\omega_0 = 0$  and  $s(A) < \omega_0$  take the translation semigroup on the Banach space

$$E := C_0(\mathbb{R}_+) \cap L^1(\mathbb{R}_+, e^{x^2} dx)$$

with  $\|f\| := \sup\{|f(x)| : x \in \mathbb{R}_+\} + \int_0^\infty |f(x)|e^{x^2} dx$  (see Greiner et al. [11]).

(v) Another modification of Example 1.3 yields a group  $\mathcal{T} = (T(t))_{t \in \mathbb{R}}$  satisfying  $s(A) < \omega_0$ . Therefore the spectral mapping theorem does not hold in the setting of groups (see Wolff (1981)).

The next few theorems form the core of this chapter. We show that only one part of the spectrum and one inclusion is responsible for the failure of the spectral mapping theorem. The usefulness of this detailed analysis will become clear in the subsequent chapters on stability and asymptotics.



**Proposition 6.2 (Spectral Inclusion)**

Let  $A$  be the generator of a strongly continuous semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  on some Banach space  $E$ . Then

$$\exp(t\sigma(A)) \subset \sigma(T(t)) \text{ for } t \geq 0.$$

More precisely we have the following inclusions.

$$\exp(t \cdot P\sigma(A)) \subset P\sigma(T(t)), \quad (6.1)$$

$$\exp(t \cdot A\sigma(A)) \subset A\sigma(T(t)), \quad (6.2)$$

$$\exp(t \cdot R\sigma(A)) \subset R\sigma(T(t)). \quad (6.3)$$

**Proof** Since  $e^{\lambda t} - T(t) = (\lambda - A) \int_0^t e^{\lambda(t-s)} T(s) \, ds$  (see A-I,(3.1)), it follows that  $(e^{\lambda t} - T(t))$  is not bijective if  $(\lambda - A)$  fails to be bijective proving the main inclusion.

The inclusion (6.1) becomes evident from the following proof of (6.2): Take  $\lambda \in A\sigma(A)$  and an associated approximate eigenvector  $(f_n) \subset D(A)$ . Then

$$g_n := e^{\lambda t} f_n - T(t) f_n = \int_0^t e^{\lambda(t-s)} T(s) (\lambda - A) f_n \, ds$$

converges to zero as  $n \rightarrow \infty$ . Consequently,  $e^{\lambda t} \in A\sigma(T(t))$  and, in fact, the same approximate eigenvector  $(f_n)$  does the job for all  $t \geq 0$ .

For the proof of (6.3) we take  $\lambda \in R\sigma(A)$  and observe that  $(e^{\lambda t} - T(t))f = (\lambda - A) \left( \int_0^t e^{\lambda(t-s)} T(s) f \, ds \right) \in (\lambda - A)D(A)$  for every  $f \in E$ .  $\square$

As we know from the Examples 6.1, the converse inclusions do not hold in general, i.e., not every spectral value of a semigroup operator  $T(t)$  comes - via the exponential map - from a spectral value of the generator. But at least this is true for some important parts of the spectrum.

**Theorem 6.3 (Spectral Mapping Theorem for Point and Residual Spectrum)**

Let  $A$  be the generator of a strongly continuous semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$ . Then

$$\exp(t \cdot P\sigma(A)) = P\sigma(T(t)) \setminus \{0\}, \quad (6.4)$$

$$\exp(t \cdot R\sigma(A)) = R\sigma(T(t)) \setminus \{0\} \text{ for } t \geq 0. \quad (6.5)$$

**Proof** For the proof of (6.4) take  $t_0 > 0$  and  $0 \neq \lambda \in P\sigma(T(t_0))$ .

After rescaling the semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  to the semigroup

$$(\exp(-t \cdot \log \lambda / t_0) T(t))_{t \geq 0},$$

we may assume  $\lambda = 1$ . Then the closed,  $\mathcal{T}$ -invariant subspace

$$G := \{g \in E : T(t_0)g = g\}$$

is non trivial. The restricted semigroup  $T|_I$  is periodic with period  $\tau \leq t_0$  and the spectrum of its generator  $A|_I$  contains at least one eigenvalue  $\mu = 2\pi in/t_0$  for some  $n \in \mathbb{Z}$  (see Lemma 5.3). Since every eigenvalue of  $A|_I$  is an eigenvalue of  $A$ , we obtain that  $1 \in \exp(t_0 \cdot P\sigma(A))$ . The converse inclusion has been proved in (6.1). In fact, even more can be said: Let  $g \in G$  be an eigenvector of  $T(t_0)$  corresponding to the eigenvalue  $\lambda = 1$ . For each  $n \in \mathbb{Z}$  define

$$g_n := P_n g = 1/t_0 \cdot \int_0^{t_0} \exp(-2\pi in s/t_0) T(s) g \, ds \in G$$

as in Section 5. If  $g_n \neq 0$ , then  $G_n$  is an eigenvector of  $A|_I$ , hence of  $A$  with eigenvalue  $2\pi in/t_0$  as soon as  $g_n$  is distinct from zero. Since  $D(A|_I)$  is dense in  $G$  it follows from Theorem 5.4 that this holds for at least one  $n \in \mathbb{Z}$ . And from the proof of (6.1) we know that this  $g_n$  is in fact an eigenvector for each  $T(t)$ ,  $t \geq 0$ . Since  $R\sigma(A) = P\sigma(A^*)$  and  $R\sigma(T(t)) = P\sigma(T(t)^*)$  (see Proposition 4.4) the assertion (6.5) follows from (6.4).  $\square$

Note that the proof is essentially an application of the structure theorem for periodic semigroups as given in Theorem 5.4. The information gained there can be reformulated into statements on the eigenspaces of  $A$  and  $T(t)$ .

**Corollary 6.4** *For the eigenspaces of the generator  $A$ , resp. of the semigroup operators  $T(t)$ ,  $t > 0$ , the following holds for  $\mu \in \mathbb{C}$ .*

- (i)  $\ker(\mu - A) = \bigcap_{s \geq 0} \ker(e^{\mu s} - T(s))$ ,
- (ii)  $\ker(e^{\mu t} - T(t)) = \overline{\text{span}_{n \in \mathbb{Z}} \{\ker(\mu + 2\pi in/t - A)\}}$ .

We note that an analogous statements is valid for  $\ker(\mu - A')$  and  $\ker(e^{\mu t} - T(t)')$  if we take in (ii) the  $\sigma(E', E)$ -closure.

Without proof (see Greiner [9, Proposition 1.10]) we add another corollary showing that poles of the resolvent of  $T(t)$  correspond necessarily to poles of the resolvent of the generator. Again the converse is not true as shown by Example 5.6.

**Corollary 6.5** *Assume that  $e^{\mu t}$  is a pole of order  $k$  of  $R(\cdot, T(t))$  with residue  $P$  and  $Q$  as the  $k$ -th coefficient of the Laurent series. Then*

- (i)  $\mu + 2\pi in/t$  is a pole of  $R(\cdot, A)$  of order  $\leq k$  for every  $n \in \mathbb{Z}$ ,
- (ii) the residues  $P_n$  in  $\mu + 2\pi in/t$  yield  $PE = \overline{\text{span}_{n \in \mathbb{Z}} \{P_n E\}}$ ,
- (iii) the  $k$ -th coefficient of the Laurent series of  $R(\cdot, A)$  at  $\mu + 2\pi in/t$  is

$$Q_n = (t \cdot e^{\mu t})^{1-k} \cdot Q \circ (1/t) \int_0^t e^{-(\mu + 2\pi in/t)s} T(s) \, ds.$$

From Proposition 6.2 and Theorem 6.3 it follows that the approximate point spectrum is the trouble maker in the sense that not every approximate eigenvalue of  $T(t)$  corresponds to an approximate eigenvalue of the generator  $A$ . Since nothing more can be said in general, we now look for additional hypotheses on the semigroup implying the spectral mapping theorem.

As a simple example we assume  $T(t_0)$  to be compact for some  $t_0 > 0$ . Then  $\sigma(T(t)) \setminus \{0\} = P\sigma(T(t)) \setminus \{0\}$  for  $t \geq t_0$  and the spectral mapping theorem is valid by (6.4). A different class of semigroups verifying the spectral mapping theorem is given by the uniformly continuous semigroups (compare Corollary 1.2). Both cases, and many more, are included in the following result.

**Theorem 6.6 (Spectral Mapping Theorem for Eventually Continuous Semigroups)** *Let  $\mathcal{T} = (T(t))_{t \geq 0}$  be an eventually norm continuous semigroup with generator  $A$ . Then the spectral mapping theorem is valid, i.e.,*

$$\sigma(T(t)) \setminus \{0\} = e^{t \cdot \sigma(A)} \text{ for every } t \geq 0. \quad (6.6)$$

**Proof** By the previous considerations it suffices to show that  $A\sigma(T(t)) \setminus \{0\} \subset e^{t \cdot \sigma(A)}$  for  $t > 0$ . This will be done by converting approximate eigenvectors into eigenvectors in the semigroup  $\mathcal{F}$ -product (see subsection 4.2). The assertion then follows from (6.4) and Proposition 4.4.(ii).

Assume  $t \mapsto T(t)$  to be norm continuous for  $t \geq t_0$ . Moreover it suffices to consider  $1 \in A\sigma(T(t_1))$  for some  $t_1 > 0$ , i.e., we have a normalized sequence  $(f_n)_{n \in \mathbb{N}} \subset E$  such that

$$\lim_{n \rightarrow \infty} \|T(t_1)f_n - f_n\| = 0.$$

Choose  $k \in \mathbb{N}$  such that  $kt_1 > t_0$  and define  $g_n := T(kt_1)f_n$ . Then

$$\lim_{n \rightarrow \infty} \|g_n\| = \lim_{n \rightarrow \infty} \|T(t_1)^k f_n\| = \lim_{n \rightarrow \infty} \|f_n\| = 1$$

and

$$\lim_{n \rightarrow \infty} \|T(t_1)g_n - g_n\| = 0,$$

i.e.,  $(g_n)_{n \in \mathbb{N}}$  yields an approximate eigenvector of  $T(t_1)$  with approximate eigenvalue 1. But the semigroup  $\mathcal{T}$  is uniformly continuous on sets of the form  $T(t_0)V$ ,  $V$  bounded in  $E$ . In particular, it is uniformly continuous on the sequence  $(g_n)_{n \in \mathbb{N}}$ , which therefore defines an element  $g$  in the semigroup  $\mathcal{F}$ -product  $E_{\mathcal{F}}$ .

Obviously,  $g$  is an eigenvector of  $T_{\mathcal{F}}(t_1)$  with eigenvalue 1 and by (6.4) we obtain an eigenvalue  $2\pi i n / t_1$  of  $A_{\mathcal{F}}$  for some  $n \in \mathbb{Z}$ . The coincidence of  $\sigma(A)$  and  $\sigma(A_{\mathcal{F}})$  proves the assertion.  $\square$

We point out that the above spectral mapping theorem implies the coincidence of spectral bound and growth bound for eventually norm continuous semigroups, hence we have generalized the Liapunov Stability Theorem (see 1.2) to a much larger class of semigroups. As mentioned before, this will be of great use in many applications. Therefore we state explicitly the spectral mapping theorem for several important classes of semigroups all of which are eventually norm continuous (cf. the diagram preceding A-II, Example 1.27).

**Corollary 6.7** *The spectral mapping theorem 6.6 holds for each of the following classes of strongly continuous semigroups.*

- (i) eventually compact semigroups,

- (ii) eventually differentiable semigroups,
- (iii) holomorphic semigroups,
- (iv) uniformly continuous semigroups.

Another application of the above spectral mapping theorem can be made to tensor product semigroups (see A-I,3.7). Let  $\mathcal{T}_1 = (T_1(t))_{t \geq 0}$ ,  $\mathcal{T}_2 = (T_2(t))_{t \geq 0}$  be strongly continuous semigroups on Banach spaces  $E_1, E_2$  with generator  $A_1, A_2$ . The tensor product semigroup  $\mathcal{T} = \mathcal{T}_1 \otimes \mathcal{T}_2$  on some (appropriate) tensor product  $E := E_1 \otimes E_2$  has the generator  $A = A_1 \otimes \text{Id} + \text{Id} \otimes A_2$ , but in general the spectrum of  $A$  is not determined by the spectra of  $A_1, A_2$ . But with an additional hypothesis the following can be proved.

**Corollary 6.8** *If  $\mathcal{T}_1$  and  $\mathcal{T}_2$  are eventually norm continuous, then*

$$\sigma(A) = \sigma(A_1) + \sigma(A_2),$$

where  $A$  is the generator of the tensor product semigroup

$$\mathcal{T}_1 \otimes \mathcal{T}_2 = (T_1(t) \otimes T_2(t))_{t \geq 0}.$$

**Proof** Clearly, the tensor product semigroup is eventually norm continuous and hence the Spectral Mapping Theorem 6.6 is valid for all three semigroups  $\mathcal{T}_1, \mathcal{T}_2$  and  $\mathcal{T}$ . Moreover the spectrum of the tensor product of bounded operators is the product of the spectra Reed and Simon [23, XIII.9]. Therefore

$$\sigma(T_1(t) \otimes T_2(t)) = \sigma(T_1(t)) \cdot \sigma(T_2(t)), \quad t \geq 0.$$

Consequently we have the following identity for every  $t \geq 0$

$$\begin{aligned} e^{t \cdot \sigma(A)} &= \sigma(T_1(t) \otimes T_2(t)) \setminus \{0\} \\ &= \sigma(T_1(t)) \cdot \sigma(T_2(t)) \setminus \{0\} \\ &= e^{t \cdot \sigma(A_1)} \cdot e^{t \cdot \sigma(A_2)} \\ &= e^{t(\sigma(A_1) + \sigma(A_2))}. \end{aligned}$$

From this identity we want to deduce  $\sigma(A) = \sigma(A_1) + \sigma(A_2)$ .

“ $\subset$ ” Take  $\xi \in \sigma(A)$ . Then for every  $t > 0$  there exist  $\mu_t \in \sigma(A_1)$ ,  $\lambda_t \in \sigma(A_2)$  and  $n_t \in \mathbb{Z}$  such that  $\xi = \mu_t + \lambda_t + 2\pi i n_t / t$ .

Since the real parts of  $\mu_t, \lambda_t$  are bounded above, they lie in some interval  $[a, b]$ .

But  $\sigma(A_i) \cap ([a, b] + i\mathbb{R})$  is compact for  $i = 1, 2$  since  $A_i$  is the generator of an eventually norm continuous semigroup (see A-II, Theorem 1.20). By taking  $t$  sufficiently small, we conclude that  $n_{t'} = 0$  for some  $t' > 0$ , i.e.,  $\xi = \mu_{t'} + \lambda_{t'}$ .

“ $\supset$ ” Choose  $\mu \in \sigma(A_1), \lambda \in \sigma(A_2)$ . For every  $t > 0$  there exist  $\eta_t \in \sigma(A)$ ,  $m_t \in \mathbb{Z}$  such that  $\mu + \lambda = \eta_t + 2\pi i m_t / t$ . Since  $\text{Re } \mu + \text{Re } \lambda = \text{Re } \eta_t$  and  $\{\text{Im } \eta_t : t > 0\}$  is bounded -  $\mathcal{T} = (T_1(t) \otimes T_2(t))_{t \geq 0}$  is eventually norm continuous - it follows that  $m_{t'} = 0$  for some  $t' > 0$ .  $\square$

## 7 Weak Spectral Mapping Theorems

In the previous section we showed under which hypotheses a spectral mapping theorem of the form

$$\sigma(T(t)) \setminus \{0\} = e^{t \cdot \sigma(A)}, \quad t \geq 0, \quad (7.1)$$

is valid for the generator  $A$  of a strongly continuous semigroup  $(T(t))_{t \geq 0}$ .

Among the various examples showing that (7.1) does not hold in general we recall the following. Take the Banach space  $E = c_0$ , the multiplication operator  $A(x_n)_{n \in \mathbb{N}} = (inx_n)_{n \in \mathbb{N}}$  with maximal domain and the corresponding semigroup  $T(t)(x_n)_{n \in \mathbb{N}} = (e^{int}x_n)_{n \in \mathbb{N}}$ . Then  $\sigma(A) = \{in : n \in \mathbb{N}\}$  and the spectral mapping theorem is valid only in the following weak form

$$\sigma(T(t)) = \overline{\exp(t \cdot \sigma(A))}, \quad t \geq 0. \quad (7.2)$$

In this section we prove similar weak spectral mapping theorems. We start with a generalization of the above example.

Consider the Banach space  $E = C_0(X, \mathbb{C}^n)$  of all continuous  $\mathbb{C}^n$ -valued functions vanishing at infinity on some locally compact space  $X$ . In analogy to A-I,2.3 we associate to every continuous function  $q : X \rightarrow M(n)$ , where  $M(n)$  denotes the space of all complex  $n \times n$ -matrices, a "multiplication operator"  $M_q : f \rightarrow q \cdot f$  such that  $(q \cdot f)(x) = q(x) \cdot f(x)$ ,  $x \in X$ , on the maximal domain  $D(M_q) = \{f \in E : q \cdot f \in E\}$ . If  $\|e^{tq(x)}\|$  is uniformly bounded for  $0 \leq t \leq 1$  and  $x \in X$ , it follows that  $M_q$  generates the multiplication semigroup

$$(T(t)f)(x) = e^{tq(x)}(f(x)), \quad f \in E, \quad x \in X, \quad t \geq 0.$$

Since  $M_q$  has a bounded inverse if and only if  $q(x)^{-1}$  exists and is uniformly bounded for  $x \in X$ , it follows that the eigenvalues of each matrix  $q(x)$  are always contained in  $\sigma(M_q)$ . In fact, much more can be said in case the function is bounded.

**Lemma 7.1** *The spectrum of the matrix valued multiplication operator  $M_q$ , where  $q : X \rightarrow M(n)$ , is bounded is given by  $\sigma(M_q) = \overline{\bigcup_{x \in X} \sigma(q(x))}$ .*

**Proof** It remains to show that  $0 \notin \overline{\bigcup_{x \in X} \sigma(q(x))}$  implies  $0 \notin \sigma(M_q)$ . Since  $\det q(x)$  is the product of  $n$  eigenvalues (according to their multiplicity) of  $q(x)$ , the hypothesis implies that  $d := \inf\{|\det q(x)| : x \in X\} > 0$ . By Formula 4.12 in Chapter I of Kato [16] we obtain

$$\|q(x)^{-1}\| \leq \gamma \cdot \|q(x)\|^{n-1} \cdot |\det q(x)|^{-1} \leq \gamma/d \cdot \|M_q\|^{n-1}$$

for every  $x \in X$  and a constant  $\gamma$  depending only on the norm chosen on  $\mathbb{C}^n$ . Therefore  $x \mapsto q(x)^{-1}$  defines a bounded continuous function on  $X$  which obviously yields the inverse of  $M_q$ , i.e.,  $0 \notin \sigma(M_q)$ .  $\square$

**Theorem 7.2** Let  $A = M_q$  be a matrix multiplication operator on  $C_0(X, \mathbb{C}^n)$  generating a strongly continuous semigroup  $(T(t))_{t \geq 0}$ ,  $T(t) = M_{e^{tq}}$  for  $t \geq 0$ . Then the Weak Spectral Mapping Theorem (7.2) holds true, i.e.,

$$\sigma(T(t)) = \overline{\exp(t \cdot \sigma(A))}.$$

**Proof** By the Spectral Inclusion Proposition 6.2 we always have  $\exp(t\sigma(A)) \subset \sigma(T(t))$ . Since  $T(t)$  is a matrix multiplication operator with a bounded function, we obtain from Lemma 7.1

$$\sigma(T(t)) = \overline{\bigcup_{x \in X} \sigma(\exp(tq(x)))} = \overline{\bigcup_{x \in X} \exp(t\sigma(q(x)))} \subset \overline{\exp(t\sigma(A))}$$

which proves the assertion.  $\square$

**Corollary 7.3** The growth bound  $\omega_0(A)$  and the spectral bound  $s(A)$  coincide for matrix multiplication semigroups.

The above results remain valid for other Banach spaces of  $\mathbb{C}^n$ -valued functions such as  $L^p(X, \mathbb{C}^n)$ ,  $1 \leq p < \infty$ .

The example given at the beginning of this section can be generalized in a different way. In fact,  $A(x_n) := (inx_n)$  on  $E = c_0$  generates a bounded group, and we will show that this property too ensures that the Weak Spectral Mapping Theorem 7.2 holds. Without any boundedness assumption on  $(T(t))_{t \in \mathbb{R}}$  this result cannot be true (see Hille and Phillips [14, Sec.23.16] or [Wolff(1981)]).

**Theorem 7.4** Let  $\mathcal{T} = (T(t))_{t \in \mathbb{R}}$  be a strongly continuous group on some Banach space  $E$  such that  $\|T(t)\| \leq p(t)$  for some polynomial  $p$  and all  $t \in \mathbb{R}$ . Then the Weak Spectral Mapping Theorem 7.2 holds, i.e.,

$$\sigma(T(t)) = \overline{\exp(t \cdot \sigma(A))} \text{ for all } t \in \mathbb{R}.$$

From the proof we isolate a series of lemmas for which we always assume the hypothesis made in Theorem 7.4. Moreover we recall from Fourier analysis that the Fourier transformation  $\varphi \mapsto \hat{\varphi}$ ,

$$\hat{\varphi}(\alpha) := \int_{-\infty}^{\infty} \varphi(x) e^{-i\alpha x} dx$$

and its inverse  $\Psi \mapsto \check{\Psi}$ ,

$$\check{\Psi}(x) := \frac{1}{2\pi} \int_{-\infty}^{\infty} \Psi(\alpha) e^{i\alpha x} d\alpha$$

are topological isomorphisms of the Schwartz space  $\mathcal{S}(= \mathcal{S}(\mathbb{R}))$ . Since the subspace  $\mathcal{D}$  of all functions having compact support is dense in  $\mathcal{S}$ , it follows that  $\{\varphi \in \mathcal{S}: \check{\varphi} \in \mathcal{D}\}$  is also dense in  $\mathcal{S}$ .

**Lemma 7.5** For every function  $\varphi \in \mathcal{S}$  we obtain an operator  $T(\varphi) \in \mathcal{L}(E)$  by

$$T(\varphi)f := \int_{-\infty}^{\infty} \varphi(s)T(s)f \, ds, \quad f \in E.$$

This operator can be represented as

$$T(\varphi)f = \lim_{\varepsilon \rightarrow 0} \frac{1}{2\pi} \int_{-\infty}^{\infty} \check{\varphi}(\alpha) [R(\varepsilon - i\alpha, A)f - R(-\varepsilon - i\alpha, A)f] d\alpha, \quad f \in E. \quad (7.3)$$

**Proof** That  $T(\varphi)$  is well-defined follows from the polynomial boundedness of  $(T(t))_{t \in \mathbb{R}}$ . In fact,  $\varphi \rightarrow T(\varphi)$  is continuous from  $\mathcal{S}$  into  $(\mathcal{L}(E), \|\cdot\|)$ . We obtain

$$\begin{aligned} T(\varphi)f &= \lim_{\varepsilon \rightarrow 0} \int_{-\infty}^{\infty} \varphi(s) e^{-\varepsilon|s|} T(s)f \, ds \\ &= \lim_{\varepsilon \rightarrow 0} \int_{-\infty}^{\infty} \frac{1}{2\pi} \int_{-\infty}^{\infty} \check{\varphi}(\alpha) e^{i\alpha s} e^{-\varepsilon|s|} T(s)f \, d\alpha \, ds \\ &= \lim_{\varepsilon \rightarrow 0} \frac{1}{2\pi} \int_{-\infty}^{\infty} \check{\varphi}(\alpha) \int_{-\infty}^{\infty} e^{i\alpha s} e^{-\varepsilon|s|} T(s)f \, ds \, d\alpha \\ &= \lim_{\varepsilon \rightarrow 0} \frac{1}{2\pi} \int_{-\infty}^{\infty} \check{\varphi}(\alpha) [R(\varepsilon - i\alpha, A)f - R(-\varepsilon - i\alpha, A)f] d\alpha. \end{aligned}$$

Here we used that polynomially bounded groups have growth bound 0, hence  $\omega_0(A) = \omega_0(-A) = 0$ . Therefore the integral representation of  $R(\varepsilon - i\alpha, A)$  (cf. A-I, Proposition 1.11) exists for  $\varepsilon \neq 0$ .  $\square$

**Lemma 7.6** *If  $E \neq \{0\}$ , then  $\sigma(A) \neq \emptyset$ .*

**Proof** If  $\sigma(A) = \emptyset$ , then (7.3) implies  $T(\varphi) = 0$  whenever  $\check{\varphi}$  has compact support. Since these functions form a dense subspace of  $\mathcal{S}$ , we conclude that  $T(\varphi) = 0$  for all  $\varphi \in \mathcal{S}$ . Choosing an approximate identity  $(\psi_n)_{n \in \mathbb{N}} \subset \mathcal{D}$ , we obtain

$$f = T(0)f = \lim_{n \rightarrow \infty} T(\psi_n)f = 0$$

for every  $f \in E$ .  $\square$

**Proof (Proof of Theorem 7.4 (1st part))** By the Spectral Inclusion (see Proposition 6.2), we have to show that every spectral value of  $T(t)$  can be approximated by exponentials of spectral values of  $A$ . In view of the rescaling procedure it suffices to prove this when  $-1 \in \varrho(T(\pi))$ , provided that the following condition is satisfied.

$$\text{There exists } \varepsilon > 0 \text{ such that } \bigcup_{k \in \mathbb{Z}} i[2k + 1 - 2\varepsilon, 2k + 1 + 2\varepsilon] \subset \varrho(A). \quad (7.4)$$

Assume now that (7.4) holds. Then each of the sets

$$\sigma_k := \{i\alpha \in \sigma(A) : \alpha \in [2k - 1, 2k + 1]\}$$

is a spectral set of  $A$  with corresponding spectral projection  $P_k$ . If we choose  $\varphi_0 \in \mathcal{D}$  such that

$\text{supp}(\varphi_0) \subset [-1 + \varepsilon, 1 - \varepsilon]$  and  $\varphi_0(x) = 1$  for  $x \in [-1 + 2\varepsilon, 1 - 2\varepsilon]$ ,

it follows from (7.3) and the integral representation of  $P_k$  (cf. (3.1)) that  $P_0 = T(\check{\varphi}_0)$ . More generally, since  $(e^{i2k\cdot}\check{\varphi}_0)^\wedge(\alpha) = \varphi_0(\alpha - 2k)$ , the assertions (7.3) and (7.4) imply

$$P_k = \int_{-\infty}^{\infty} e^{i2ks} \check{\varphi}_0(s) T(s) ds \text{ for } k \in \mathbb{Z}. \quad (7.5)$$

At this point we isolate another lemma.

**Lemma 7.7**  $\text{span} \bigcup_{k \in \mathbb{Z}} P_k E$  is dense in  $E$ .

**Proof** The closure of  $\text{span} \bigcup_{k \in \mathbb{Z}} P_k E$  is a  $\mathcal{T}$ -invariant subspace  $G$  of  $E$ . Consider the quotient group  $(T(t))_{t \in \mathbb{R}}$  induced on  $E/G$ . The spectrum of its generator  $A_{/}$  is contained in  $\sigma(A)$  by Proposition 4.2(ii). Moreover, the spectral projection corresponding to  $\sigma(A_{/}) \cap \sigma_k$  is the quotient operator  $P_{k/}$ . Obviously  $P_{k/} = 0$ , hence  $\sigma(A_{/}) \cap \sigma_k = \emptyset$  for every  $k \in \mathbb{Z}$  and  $\sigma(A_{/}) = \emptyset$ . By Lemma 7.6 this implies  $E/G = \{0\}$ , i.e.,  $G = E$ .  $\square$

**Proof (Proof of Theorem 7.4 (2nd part))** We return to the situation of the first part of the proof. Using (7.5) the spectral projection  $P_k$  can be transformed into

$$\begin{aligned} P_k &= \int_{-\infty}^{\infty} e^{i2ks} \check{\varphi}_0(s) T(s) ds \\ &= \sum_{m \in \mathbb{Z}} \int_{(m-1/2)\pi}^{(m+1/2)\pi} e^{i2ks} \check{\varphi}_0(s) T(s) ds \\ &= \int_{-\pi/2}^{\pi/2} e^{i2ks} \sum_{m \in \mathbb{Z}} \check{\varphi}_0(s + m\pi) T(s + m\pi) ds, \end{aligned}$$

i.e.,  $P_k f$  is the  $k$ -th Fourier coefficient of the  $\pi$ -periodic, continuous function  $\xi_f: s \mapsto \sum_{m \in \mathbb{Z}} \check{\varphi}_0(s + m\pi) T(s + m\pi) f$ ,  $f \in E$ . Since the projections  $P_k$  are mutually orthogonal, i.e.,  $P_k P_m = 0$  for  $k \neq m$ , it follows that  $g = \sum_{n \in \mathbb{Z}} P_n g$  for every  $g \in \text{span} \bigcup_{k \in \mathbb{Z}} P_k E$ . In particular, the Fourier coefficients of the function  $\xi_g$  are absolutely summable, hence the Fourier series of  $\xi_g$  converges to  $\xi$ .

For  $s = 0$  we obtain

$$g = \sum_{n \in \mathbb{Z}} P_n g \cdot e^{-in0} = \sum_{m \in \mathbb{Z}} \check{\varphi}_0(0 + m\pi) T(0 + m\pi) g \quad \left( g \in \text{span} \bigcup_{k \in \mathbb{Z}} P_k E \right).$$

Since  $\text{span} \bigcup_{k \in \mathbb{Z}} P_k E$  is dense (Lemma 7.7), we conclude that

$$\sum_{m \in \mathbb{Z}} \varphi_0(m\pi) T(m\pi) = \text{Id}. \quad (7.6)$$

As the final step we construct the inverse operator of  $\text{Id} + T(\pi)$  showing that  $-1 \in \rho(T(\pi))$ . We define  $\psi_0(\alpha) := \varphi_0(\alpha) \cdot (1 + e^{i\pi\alpha})^{-1}$ ,  $\alpha \in \mathbb{R}$ . Then we have  $\psi_0 \in \mathcal{S}$



and  $\psi_0 \cdot (1 + e^{i\pi \cdot}) = \varphi_0$ , hence  $\check{\psi}_0(x) + \check{\psi}_0(x + \pi) = \check{\varphi}_0(x)$  for all  $x \in \mathbb{R}$ . Then (7.6) implies

$$\begin{aligned} \text{Id} &= \sum_{m \in \mathbb{Z}} \check{\varphi}_0(m\pi) T(m\pi) \\ &= \sum_{m \in \mathbb{Z}} (\check{\psi}_0(m\pi) + \check{\psi}_0((m+1)\pi)) T(m\pi) \\ &= \left[ \sum_{m \in \mathbb{Z}} \check{\psi}_0(m\pi) T(m\pi) \right] (\text{Id} + T(\pi)). \end{aligned}$$

In the rest of this section we discuss the behavior of the single spectral values  $\lambda$  of  $T(t)$ ,  $t > 0$ . The goal is a characterization of  $\sigma(T(t))$  involving only properties of the generator. By the rescaling procedure A-I,3.1 we may assume  $\lambda = 1$  and  $t = 2\pi$ .

From the Spectral Inclusion (see )Proposition 6.2) we know that  $1 \in \varrho(T(2\pi))$  implies  $i\mathbb{Z} \subset \varrho(A)$ . As seen in many examples the converse does not hold and we are now looking for additional conditions. Henceforth we assume  $i\mathbb{Z} \subset \varrho(A)$  and define for  $k \in \mathbb{Z}$

$$Q_k := \frac{1}{2\pi} \int_0^{2\pi} e^{-iks} T(s) ds = \frac{1}{2\pi} (1 - T(2\pi)) R(ik, A) \quad (7.7)$$

(cf. Formula A-I, (3.1)).

Our approach is based on Fejér's Theorem (for Banach space valued functions).

Let us recall this result. Suppose  $\xi: [0, 2\pi] \rightarrow E$  is a continuous function and let

$\xi_k := \frac{1}{2\pi} \int_0^{2\pi} e^{-iks} \xi(s) ds$  be its  $k$ -th Fourier coefficient. Then the Fourier series is Césaro summable to  $\xi$  in every point  $t \in (0, 2\pi)$ . Moreover one has

$$\frac{1}{2} (\xi(0) + \xi(2\pi)) = C_1 - \sum_{k \in \mathbb{Z}} \xi_k := \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{n=0}^{N-1} \left( \sum_{k=-n}^n \xi_k \right). \quad (7.8)$$

This result enables us to prove the following proposition.

**Proposition 7.8** *Let  $(T(t))_{t \geq 0}$  be a semigroup on a Banach space  $E$  and denote its generator by  $A$ . Then the following conditions are equivalent*

- (a)  $1 \in \varrho(T(2\pi))$ ,
- (b)  $i\mathbb{Z} \subset \varrho(A)$  and the series  $\sum_{k \in \mathbb{Z}} R(ik, A)f$  is Césaro-summable for every  $f \in E$ ,
- (c)  $i\mathbb{Z} \subset \varrho(A)$  and the series  $\sum_{k \in \mathbb{Z}} R(ik, A)Q_k f$  is Césaro-summable for every  $f \in E$ .

**Proof** (a)  $\Rightarrow$  (b) The Spectral Inclusion (see )Proposition 6.2) implies  $i\mathbb{Z} \subset \varrho(A)$ . By (7.7) we have  $R(ik, A) = 2\pi \cdot (1 - T(2\pi))^{-1} Q_k$ . Since  $\sum_{k \in \mathbb{Z}} Q_k f$  is Césaro-summable (towards  $\frac{1}{2}(f + T(2\pi)f)$ ) (see (7.8)), it follows that  $\sum_{k \in \mathbb{Z}} R(ik, A)f$  is Césaro-summable as well.

(b)  $\Leftrightarrow$  (c) If we use A-I,(3.1) and integrate by parts, we obtain

$$\begin{aligned}
R(ik, A)Q_k f &= \frac{1}{2\pi} \int_0^{2\pi} e^{-iks} T(s) R(ik, A) f \, ds \\
&= \frac{1}{2\pi} \int_0^{2\pi} \left[ R(ik, A) f - \int_0^s e^{-ikt} T(t) f \, dt \right] ds \\
&= R(ik, A) f - \frac{1}{2\pi} \int_0^{2\pi} e^{-ikt} (2\pi - t) T(t) f \, dt.
\end{aligned}$$

Fejér's theorem ensures that  $\sum_{k \in \mathbb{Z}} (1/2\pi) \int_0^{2\pi} e^{-ikt} (2\pi - t) T(t) f \, dt$  is Césaro summable. Hence  $\sum_{k \in \mathbb{Z}} R(ik, A)Q_k f$  is Césaro-summable if and only if  $\sum_{k \in \mathbb{Z}} R(ik, A) f$  is.

(b)  $\Rightarrow$  (a) We have  $Q_k = \frac{1}{2\pi} (1 - T(2\pi)) R(ik, A)$ . Furthermore we know by (7.7) and (7.8) that  $\sum_{k \in \mathbb{Z}} Q_k f$  is Césaro-summable towards  $\frac{1}{2} (f + T(2\pi) f)$ . If we define  $S: E \rightarrow E$  by  $Sf := \frac{1}{2} f + \frac{1}{2\pi} \cdot C_1 \cdot \sum_k R(ik, A) f$ , then we have

$$\begin{aligned}
(1 - T(2\pi)) Sf &= \frac{1}{2} (f - T(2\pi) f) + \frac{1}{2\pi} \cdot C_1 \cdot \sum_k (1 - T(2\pi)) R(ik, A) f \\
&= \frac{1}{2} (f - T(2\pi) f) + \frac{1}{2} (f + T(2\pi) f) = f.
\end{aligned}$$

Since  $S$  commutes with  $T(2\pi)$ , it follows that  $S$  is the inverse of  $(1 - T(2\pi))$  thus  $1 \in \varrho(T(2\pi))$ .  $\square$

Based on the equivalence of (a) and (b), one can state a characterization of the spectrum of  $T(t)$  in terms of the generator and its resolvent only. However, in general it is difficult to verify the summability condition stated in (b). In Hilbert spaces the boundedness of the resolvents will suffice (see Theorem 7.10 below).

**Lemma 7.9** *Let  $(T(t))_{t \geq 0}$  be a semigroup on some Hilbert space  $H$  and assume  $i\mathbb{Z} \subset \varrho(A)$  for the generator  $A$ . Then we have*

- (i)  $(Q_k f)_{k \in \mathbb{Z}} \subset \ell^2(H)$  for every  $f \in H$ , and
- (ii) if  $\sup_{k \in \mathbb{Z}} \|R(ik, A)\| < \infty$ , then  $\sum_{k \in \mathbb{Z}} R(ik, A) f_k$  is summable whenever  $(f_k)_{k \in \mathbb{Z}} \in \ell^2(H)$ .

**Proof** (i) We consider the Hilbert space  $L^2([0, 2\pi], H)$  and obtain

$$\begin{aligned}
0 &\leq \left\| T(\cdot)f - \sum_{k=-n}^n Q_k f \cdot e^{ik\cdot} \right\|^2 \\
&= \int_0^{2\pi} \|T(s)f\|^2 ds - \int_0^{2\pi} \sum_{k=-n}^n (T(s)f | e^{iks} Q_k f) ds - \\
&\quad \int_0^{2\pi} \sum_{k=-n}^n (e^{iks} Q_k f | T(s)f) ds + \int_0^{2\pi} \left( \sum_{k=-n}^n e^{iks} Q_k f | \sum_{\ell=-n}^n e^{i\ell s} Q_\ell f \right) ds \\
&= \int_0^{2\pi} \|T(s)f\|^2 ds - 2\pi \sum_{k=-n}^n \|Q_k f\|^2 \text{ (use (7.5))}.
\end{aligned}$$

It follows that  $\sum_{k \in \mathbb{Z}} \|Q_k f\|^2 \leq \frac{1}{2\pi} \int_0^{2\pi} \|T(s)f\|^2 ds < \infty$ .  
(ii) Fix  $\lambda > 0$  sufficiently large and set

$$g_k := (1 + \lambda R(ik, A)) f_k, k \in \mathbb{Z}.$$

Using the resolvent equation and then (A-I,(3.1)), we obtain

$$R(ik, A) f_k = R(\lambda + ik, A) g_k = [1 - e^{-2\pi\lambda} T(2\pi)]^{-1} \int_0^{2\pi} e^{-\lambda s} e^{-iks} T(s) g_k ds.$$

This yields for every finite subset  $N$  of  $\mathbb{Z}$  that

$$\begin{aligned}
\left\| \sum_{k \in N} R(ik, A) f_k \right\| &\leq \|(1 - e^{-2\pi\lambda} T(2\pi))^{-1}\| \cdot \int_0^{2\pi} \|T(s)\| \left\| \sum_{k \in N} e^{-iks} g_k \right\| ds \\
&\leq \|(1 - e^{-2\pi\lambda} T(2\pi))^{-1}\| \cdot \left( \int_0^{2\pi} \|T(s)\|^2 ds \right)^{1/2} \cdot \left( \int_0^{2\pi} \left\| \sum_{k \in N} e^{-iks} g_k \right\|^2 dx \right)^{1/2} \\
&= c \left( \sum_{k \in N} \|g_k\|^2 \right)^{1/2} \leq c(1 + \lambda M) \left( \sum_{k \in N} \|f_k\|^2 \right)^{1/2}.
\end{aligned}$$

Here  $c := \|(1 - e^{-2\pi\lambda} T(2\pi))^{-1}\| \cdot \left( \int_0^{2\pi} \|T(s)\|^2 ds \right)^{1/2}$  and  $M := \sup_{k \in \mathbb{Z}} \|R(ik, A)\|$ .  $\square$

**Theorem 7.10** *Let  $A$  be the generator of a semigroup  $(T(t))_{t \geq 0}$  on some Hilbert space  $H$ . Then the following form of the spectral mapping theorem is valid.*

$$\begin{aligned}
\sigma(T(t)) \setminus \{0\} &= \{e^{\lambda t} : \text{either } \mu_k := \lambda + 2\pi i k / t \in \sigma(A) \text{ for some } k \in \mathbb{Z} \\
&\quad \text{or } (\|R(\mu_k, A)\|)_{k \in \mathbb{Z}} \text{ is unbounded}\}.
\end{aligned}$$

**Proof** If  $e^{\lambda t} \notin \sigma(T(t))$ , it follows from the spectral inclusion theorem that  $\mu_k \notin \sigma(A)$  for every  $k \in \mathbb{Z}$  and from Formula (3.1) in A-I, that  $\|R(\mu_k, A)\|$  is bounded. For the converse inclusion it suffices to assume  $t = 2\pi$  and  $\lambda = 0$  (use the rescaling

procedure A-I,3.1). Assuming that  $i\mathbb{Z} \subset \varrho(A)$  and  $\|R(ik, A)\|$  is bounded, then  $\sum_{k \in \mathbb{Z}} R(ik, A)Q_k f$  is summable by Lemma 7.9. Since every summable series is Cesàro-summable, condition (c) of Proposition 7.8 is satisfied and we conclude  $1 \in \varrho(T(2\pi))$ .  $\square$

As an immediate consequence we obtain an interesting characterization of the growth bound  $\omega_0$  of semigroups on Hilbert spaces.

**Corollary 7.11** *The growth bound of a semigroup  $(T(t))_{t \geq 0}$  on a Hilbert space  $H$  satisfies*

$$\omega_0 = \inf \{ \lambda \in \mathbb{R} : \lambda + i\mathbb{R} \subset \varrho(A) \text{ and } \|R(\lambda + i\mu, A)\| \text{ is bounded for } \mu \in \mathbb{R} \}. \quad (7.9)$$

The Example 1.3 above in combination with C-III, Corollary 1.3 shows that (7.9) is not valid in arbitrary Banach spaces.

## NOTES

*Section 1:* It was already known to Hille and Phillips [14] that for strongly continuous semigroups  $(T(t))_{t \geq 0}$  with generator  $A$  the spectral mapping theorem “ $\sigma(T(t)) = \exp(t\sigma(A))$ ” may be violated in various ways [l.c., Sec.23.16]. The simple Examples 1.3 and 1.4 are due to Wolff (see Greiner et al. [11]) and Zabczyk [27]. A more sophisticated example of a positive group with “ $s(A) < \omega_0(A)$ ” is given in Wolff [25].

*Section 2:* In Definition 2.1 we define the residual spectrum of  $A$  in such a way that it coincides with the point spectrum of the adjoint  $A'$  (see Proposition 2.2.(ii)). It therefore differs slightly from the one used, e.g., by Schaefer [24]. The spectral mapping theorem for the resolvent (Theorem ??) is well known and can, e.g., be deduced from Lemma 9.2 and Theorem 3.11 of Chap.VII in Dunford and Schwartz [5].

*Section 3:* The general theory of spectral decompositions can be found in Kato [16], Chap.III, § 6.4]. Applications to isolated singularities like 3.6 are discussed extensively in [l.c., Chap. III, §6.5] and Yosida [26, Chap.VIII, Sec.8]. There are many ways to introduce an “essential spectrum” (see the footnote on page 243 of Kato [16]). However each one yields the same “essential spectral radius”.

*Section 4:* These results are taken from Derndinger [4] and Greiner [9].

*Section 5:* Periodic semigroups are studied explicitly in Bart [1], but most of the results of this section seem to be well known.

*Section 6:* The Spectral Inclusion (see Proposition 6.2) and the Spectral Mapping Theorem 6.6 for eventually norm continuous semigroups date back to Hille and Phillips [14]. Davies [3] gives an elegant proof using Banach algebra techniques. Tensor products of operators and their spectral theory have been studied by Ichinose and others (see Chap. XIII.9 of Reed and Simon [23]). The spectral mapping theorem in Corollary 6.8 generalizes Theorem XIII.35 of Reed and Simon [23] (see also Herbst [12]).

*Section 7:* Matrix valued multiplication semigroups appear as solution, via Fourier transformation, of systems of partial differential equations. Kreiss initiated a systematic investigation (see, e.g., Kreiss [17], Kreiss [18], Miller and Strang [20]) and the Weak Spectral Mapping Theorem 7.2 must have been known to him. The direct proof of the Weak Spectral Mapping Theorem 7.4 for polynomially bounded groups seems to be new. The result can also be deduced from the theory of spectral subspaces of group representations (see, e.g., Combes and Delaroche [2]), since the Arveson spectrum of a strongly continuous one-parameter group can be identified with the spectrum of the generator (see Evans [6]). The final part of this section is taken from Greiner [10] and yields a new approach to Gearhart's characterization of the spectrum of semigroups on Hilbert spaces Gearhart [7]. Different proofs can be found in Herbst [13], Howland [15] and Prüss [22].



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**Chapter A-IV**  
**Asymptotics of Semigroups on Banach Spaces**



**Part B**  
**Positive Semigroups on Spaces  $C_0(X)$**



## Chapter B-I

### Basic Results on $C_0(X)$

This part of the book is devoted to one-parameter semigroups of operators on spaces of continuous functions of type  $C_0(X)$ . Such spaces are Banach lattices of a very special kind. We treat this case separately since we feel that an intermingling with the abstract Banach lattice situation considered in Part C would have made it difficult to appreciate the easy accessibility and the pilot function of methods and results available here. In this chapter we want to fix the notation we are going to use and to collect some basic facts about the spaces we are considering.

If  $X$  is a locally compact topological space, then  $C_0(X)$  denotes the space of all continuous complex-valued functions on  $X$  which vanish at infinity, endowed with the supremum-norm. If  $X$  is compact, then any continuous function on  $X$  “vanishes at infinity” and  $C_0(X)$  is the space of all continuous functions on  $X$ . We often write  $C(X)$  instead of  $C_0(X)$  in this situation.

We sometimes study real-valued functions and write the corresponding real spaces as  $C_0(X, \mathbb{R})$  and  $C(X, \mathbb{R})$ , and the notations  $C_0(X, \mathbb{C})$  and  $C(X, \mathbb{C})$  are used if there might be confusion between both cases.

#### 1 Algebraic and Order-Structure: Ideals and Quotients

Any space  $C_0(X)$  is a commutative  $C^*$ -algebra under the sup-norm and the point-wise multiplication, and by the *Gelfand Representation Theorem* any commutative  $C^*$ -algebra can, on the other hand, be canonically represented as an algebra  $C_0(X)$  on a suitable locally compact space  $X$ . The algebraic notions of ideal, quotient, homomorphism are well known and need not be explained further.

Another natural and important structure of  $C_0(X)$  is the *pointwise* ordering, under which  $C_0(X, \mathbb{R})$  is a (real) Banach lattice and  $C_0(X, \mathbb{C})$  a complex Banach lattice in the sense explained in Chapter C-I. Concerning the order structure of  $C_0(X)$  we use the following notations. For a function  $f$  in  $C_0(X, \mathbb{R})$

1. A function  $f$  is called *positive*,  $f \geq 0$ , if  $f(t) \geq 0$  for all  $t \in X$ ,
2. We write  $f > 0$  if  $f$  is positive but does not vanish identically,

3. We call  $f$  *strictly positive* if  $f(t) > 0$  for all  $t \in X$ .

The notion of an order ideal explained in Chapter C-I applies of course to the Banach lattices  $C_0(X)$  and might give rise to confusion with the corresponding algebraic notion.

However, since we are mainly considering closed ideals and since a closed linear subspace  $I$  of  $C_0(X)$  is a lattice ideal if and only if  $I$  is an algebraic ideal, we may and will simply speak of closed ideals without specifying whether we think of the algebraic or the order theoretic meaning of this word.

An important and frequently used characterization of these objects is the following: A subspace  $I$  of  $C_0(X)$  is a closed ideal if and only if there exists a closed subset  $A$  of  $X$  such that a function  $f$  belongs to  $I$  if and only if  $f$  vanishes on  $A$ . The set  $A$  is of course uniquely determined by  $I$  and is called the *support* of  $I$ . If  $I = I_A$  is a closed ideal with support  $A$ , then  $I_A$  is naturally isomorphic to  $C_0(X \setminus A)$  and the quotient  $C_0(X)/I$  (under the natural quotient structure) is again a Banach algebra and a Banach lattice that can be identified canonically (via the map  $f + I \rightarrow f|_A$ ) with  $C_0(A)$ .

## 2 Linear Forms and Duality

The *Riesz Representation Theorem* asserts that the dual of  $C_0(X)$  can be identified in a natural way with the space of bounded regular Borel measures on  $X$ . While there is no natural algebra structure on this dual, the dual ordering (see Chapter C-I) makes  $C_0(X)'$  into a Banach lattice. We will occasionally make use of the order structure of  $C_0(X)'$ , but since at least its measure theoretic interpretation is supposed to be well-known, it may suffice here to refer to Chapter C-I, Sections 3 and 7, for a more detailed discussion and to recall only some basic notations here. If  $\mu$  is a linear form on  $C_0(X, \mathbb{R})$ , then

- $\mu \geq 0$  means  $\mu(f) \geq 0$  for all  $f \geq 0$ ;  $\mu$  is then called *positive*,
- $\mu > 0$  means that  $\mu$  is positive but does not vanish identically,
- $\mu \gg 0$  means that  $\mu(f) > 0$  for any  $f > 0$ ;  $\mu$  is then called *strictly positive*.

If  $\mu$  is a linear form on  $C_0(X, \mathbb{C})$ , then  $\mu$  can be written uniquely as  $\mu = \mu_1 + i\mu_2$  where  $\mu_1$  and  $\mu_2$  map  $C_0(X, \mathbb{R})$  into  $\mathbb{R}$  (decomposition into *real* and *imaginary parts*). We call  $\mu$  positive (strictly positive) and use the above notations if  $\mu_2 = 0$  and  $\mu_1$  is positive (strictly positive). We point out that strictly positive linear forms need not exist on  $C_0(X)$ , but if  $X$  is separable, then a strictly positive linear form is obtained by summing a suitable sequence of point measures.

The coincidence of the notions of a closed algebraic and a closed lattice ideal in  $C_0(X)$  has of course its effect on the algebraic and the lattice theoretic notions of a homomorphism. The case of a homomorphism into another space  $C_0(Y)$  will be discussed below.

As for homomorphisms into the scalar field, we have essentially coincidence between the algebraic and the order theoretic meaning of this word, more exactly:

A linear form  $\mu \neq 0$  on  $C_0(X)$  is a lattice homomorphism if and only if  $\mu$  is, up to normalization, an algebra homomorphism (algebra homomorphisms  $\neq 0$  must necessarily have norm 1). Since the algebra homomorphisms  $\neq 0$  on  $C_0(X)$  are known to be the point measures (denoted by  $\delta_t$ ) on  $X$  and since on the other hand  $\mu$  is a lattice homomorphism if and only if  $|\mu(f)|$  equals  $\mu(|f|)$  for all  $f$ , it follows that this latter condition on  $\mu$  is equivalent to  $\mu = \alpha\delta_t$  for a suitable  $t$  in  $X$  and a positive real number  $\alpha$ .

This can be summarized by saying that  $X$  can be canonically identified, via the map  $t \rightarrow \delta_t$ , with the subset of the dual  $C_0(X)'$  consisting of the non-zero algebra homomorphisms, which is also the set of all normalized lattice homomorphisms. This identification is a topological isomorphism with respect to the weak\*-topology of  $C_0(X)'$ .

### 3 Linear Operators

A linear mapping  $T$  from  $C_0(X, \mathbb{R})$  into  $C_0(Y, \mathbb{R})$  is called

*positive* (notation:  $T \geq 0$ ) if  $Tf$  is positive whenever  $f$  is positive,

*lattice homomorphism* if  $|Tf| = T|f|$  all  $f$ ,

*Markov-operator* if  $X$  and  $Y$  are compact and  $T$  is a positive operator mapping  $1_X$  to  $1_Y$ .

In the case of complex scalars,  $T$  can be decomposed into real and imaginary parts. We call  $T$  positive in this situation if the imaginary part of  $T$  is  $= 0$  and the real part is positive. The terms *Markov operator* and *lattice homomorphism* are defined as above. Note that a complex lattice homomorphism is necessarily positive, and that the *complexification* of a real lattice homomorphism is a complex lattice homomorphism. Positive Operators are always continuous.

Note that the adjoint of a Markov operator  $T$  maps positive normalized measures into positive normalized measures while the adjoint of an algebra homomorphism (lattice homomorphism) maps point measures into (multiples of) point measures. Therefore the adjoint of a Markov lattice homomorphism as well as the adjoint of an algebra homomorphism induces a continuous map  $\varphi$  from  $Y$  (viewed as a subset of the weak dual  $C(Y)'$ ) into  $X$  (viewed as a subset of  $C(X)'$ ).

This mapping  $\varphi$  determines  $T$  in a natural and unique way, so that the following are equivalent assertions on a linear mapping  $T$  from a space  $C(X)$  into a space  $C(Y)$ .

- (a)  $T$  is a Markov lattice homomorphism.
- (b)  $T$  is a Markov algebra homomorphism.
- (c) There exists a continuous map  $\varphi$  from  $Y$  into  $X$  such that  $Tf = f \circ \varphi$  for all  $f \in C(X)$ .

If  $T$  is, in addition, bijective, then the mapping  $\varphi$  in (c) is a homeomorphism from  $Y$  onto  $X$ . This characterization of homomorphisms carries over *mutatis mutandis* to situations where the conditions on  $X$ ,  $Y$  or  $T$  are less restrictive. For later reference we explicitly state the following.

- (i) Let  $K$  be compact. Then  $T \in LC(K)$  is a lattice homomorphism if and only if there is a mapping  $\varphi$  from  $K$  into  $K$  and a function  $h \in C(K)$  such that  $Tf(s) = h(s)f(\varphi(s))$  holds for all  $s \in K$ . The mapping  $\varphi$  is continuous in every point  $t$  with  $h(t) \neq 0$ .
- (ii) Let  $X$  be locally compact and  $T \in LC_0(X)$ . Then  $T$  is a lattice isomorphism if and only if there is a homeomorphism  $\varphi$  from  $X$  onto  $X$  and a bounded continuous function  $h$  on  $X$  such that  $h(s) \geq \delta > 0$  for all  $s$  and  $Tf(s) = h(s)f(\varphi(s))$  ( $s \in X$ ). Moreover,  $T$  is an algebraic  $*$ -isomorphism if and only if  $T$  is a lattice isomorphism and the function  $h$  above is  $\equiv 1$ .

## Notes

For the representation theory of commutative  $C^*$ -algebras we refer to Takesaki [2]. This and the other mentioned properties like algebraic ideals, their connections with closed sets, the representation of lattice or algebraic homomorphism etc. we refer to the excellent book Semadeni [1].



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**Chapter B-II**  
**Characterization of Positive Semigroups on**  
 **$C_0(X)$**



## Chapter B-III

# Spectral Theory of Positive Semigroups on $C_0(X)$

It is known that for a single operator  $T \in LC_0(X)$  the positivity of  $T$  has influence on the spectrum of  $T$ , mainly on the peripheral spectrum, i.e., the part of the spectrum containing all spectral values of maximal absolute value. This part of the spectrum is of interest because it determines the asymptotic behavior of the iterates  $T^n$  for large  $n \in \mathbb{N}$ . The spectral properties indicated above were first proved by Perron [16] and Frobenius [11] for positive square matrices, i.e., for positive operators on the Banach lattice  $\mathbb{C}^n$ . Later these results were extended to the infinite dimensional setting; important contributions are due to Jentzsch, Karlin, Krein, Krasnoselski'i, Lotz, Rota, Rutman, Schaefer and others (see Chapt. V of Schaefer [22]).

In this chapter we investigate the spectrum  $\sigma(A)$  of the generator  $A$  of a positive semigroup  $\mathcal{T} = (T(t))_{t \geq 0}$  on the Banach space  $C_0(X)$ . Throughout this chapter we assume that  $C_0(X)$  is the space of all *complex-valued* functions on the locally compact space  $X$ . In case we restrict to compact spaces we write  $K$  instead of  $X$ .

## 1 The Spectral Bound

One of the basic results on the spectrum of a positive operator is the fact that its spectral radius is an element of the spectrum (Schaefer [22, V.Proposition 4.1]). We begin the investigation of the spectrum of positive semigroups with the analogous result. To that purpose we recall that the spectral bound  $s(A)$  of a generator  $A$  is defined as the least upper bound of the real parts of all spectral values (cf. A-III,(1.2)).

**Theorem 1.1** *If  $A$  is the generator of a positive semigroup on  $E = C_0(X)$ , then  $s(A) \in \sigma(A)$  unless  $s(A) = -\infty$ . In case  $X$  is compact, we always have  $s(A) > -\infty$ .*

**Proof** We suppose  $\sigma(A) \neq \emptyset$  (i.e.,  $s(A) > -\infty$ ) and assume  $s(A) \notin \sigma(A)$ . Then there exist  $\varepsilon > 0$  and  $\alpha_0, \beta_0 \in \mathbb{R}$  such that

$$[s(A) - \varepsilon, \infty) \subset \varrho(A), \quad \mu_0 := \alpha_0 + i\beta_0 \in \sigma(A) \quad \text{and} \quad \alpha_0 > s(A) - \varepsilon. \quad (1.1)$$

Now we choose  $\lambda_0 \in \mathbb{R}$  large enough such that

$$|\lambda_0 - \mu_0| < \lambda_0 - (s(A) - \varepsilon) \quad (1.2)$$

and, in addition, such that  $\lambda_0 > \omega_0(A)$ . Then the resolvent  $R(\lambda_0, A)$  is a positive bounded operator, hence its spectral radius  $r(R(\lambda_0, A))$  is a spectral value. From A-III, Proposition 2.5 it follows that

$$\lambda_0 - r(R(\lambda_0, A))^{-1} \in \sigma(A) \quad \text{and} \quad r(R(\lambda_0, A)) \geq |\lambda_0 - \mu_0|^{-1} \quad (1.3)$$

This and (1.2) implies that  $\lambda_0 - r(R(\lambda_0, A))^{-1}$  is a real spectral value which is greater than  $s(A) - \varepsilon$ . We have derived a contradiction to (1.1) and thus have proved the first statement of the theorem.

To establish the second statement we recall that  $\lim_{\lambda \rightarrow \infty} \lambda R(\lambda, A)f = f$  for every  $f \in E$ . In particular, for  $f = \mathbb{1}_X$  we find a (large)  $\lambda_0 \in \mathbb{R}$  such that

$$\lambda_0 R(\lambda_0, A)\mathbb{1}_X \geq 1/2 \cdot \mathbb{1}_X \quad \text{hence} \quad R(\lambda_0, A)\mathbb{1}_X \geq (2\lambda_0)^{-1} \cdot \mathbb{1}_X \quad (1.4)$$

We may assume  $\lambda_0 > \omega_0(A)$  then  $R(\lambda_0, A) \geq 0$ , and iterating (1.4) we obtain

$$R(\lambda_0, A)^n \mathbb{1}_X \geq (2\lambda_0)^{-n} \cdot \mathbb{1}_X > 0 \quad \text{for every } n \in \mathbb{N}. \quad (1.5)$$

It follows that  $\|R(\lambda_0, A)^n\| \geq (2\lambda_0)^{-n}$  and therefore

$$r(R(\lambda_0, A)) = \lim_{n \rightarrow \infty} \|R(\lambda_0, A)^n\|^{1/n} \geq (2\lambda_0)^{-1} > 0. \quad (1.6)$$

Thus  $\sigma(R(\lambda_0, A))$  contains non-zero spectral values which in view of A-III, Proposition 2.5 is equivalent to  $\sigma(A) \neq \emptyset$ .  $\square$

The following examples show that the spectrum may be empty in case  $X$  is not compact or if the semigroup is not positive.

**Examples 1.2** (i) Consider  $X = [0, 1)$  and  $(T(t))$  on  $C_0(X)$  given by

$$(T(t)f)(x) := \begin{cases} f(x+t) & \text{if } x+t < 1, \\ 0 & \text{if } x+t \geq 1. \end{cases} \quad (1.7)$$

Then  $(T(t))_{t \geq 0}$  is nilpotent (we have  $T(t) = 0$  for  $t \geq 1$ ). It follows that  $\sigma(T(t)) = \{0\}$  for all  $t > 0$  and by A-III, Theorem 6.2 we have  $\sigma(A) = \emptyset$ .

(ii) The operator  $A$  on  $E := C_0[0, \infty)$  given by

$$(Af)(x) = f'(x) - xf(x), \quad D(A) = \{f \in E : f \in C^1, Af \in E\} \quad (1.8)$$

has empty spectrum. It is the generator of a positive non-nilpotent semigroup which is given by

$$(T(t)f)(x) = \exp(-(t^2/2) - xt) \cdot f(x+t). \quad (1.9)$$

(iii) Taking into account that  $C_0([0, 1])$  as well as  $C_0([0, \infty])$  both are topologically (but not isometrically) isomorphic to  $C([0, 1])$  (see Semadeni [23, Section 21.5]), one obtains from (i) and (ii) (non-positive) semigroups on  $C([0, 1])$  whose generators have empty spectrum.

The proof of Theorem 1.1 given above is based on the fact that the spectral radius of a bounded positive operator is an element of the spectrum. A direct proof not using this fact is given in C-III, Corollary 1.4.

**Corollary 1.3** *Suppose  $\lambda_0 \in \varrho(A)$ . Then  $R(\lambda_0, A)$  is a positive operator if and only if  $\lambda_0 > s(A)$ . For  $\lambda > s(A)$  we have  $r(R(\lambda, A)) = (\lambda - s(A))^{-1}$ .*

**Proof** The second statement is an immediate consequence of Theorem 1.1 and A-III, Proposition 2.5.

Given  $\lambda_0 > s(A)$  we choose  $\lambda_1 > \max\{\lambda_0, \omega_0(A)\}$ . Since

$$|\lambda_1 - \lambda_0| < |\lambda_1 - s(A)| = r(R(\lambda_1, A))^{-1}$$

we have

$$R(\lambda_0, A) = \sum_{n=0}^{\infty} (\lambda_1 - \lambda_0)^n \cdot R(\lambda_1, A)^{n+1}. \quad (1.10)$$

Since  $R(\lambda_1, A)$  is positive, it follows that  $R(\lambda_0, A)$  is positive as well. On the other hand, assuming that  $R(\lambda_0, A)$  is a positive operator, then  $\lambda_0$  has to be a real number (note that for  $g \geq 0$  we have  $f := R(\lambda_0, A)g \geq 0$  hence  $\lambda_0 f - Af = g = \bar{g} = (\lambda_0 - A)f = \bar{\lambda}_0 f - Af$ ). As we have shown above,  $R(\lambda, A)$  is positive for  $\lambda > \max\{\lambda_0, s(A)\}$  hence an application of the resolvent equation yields

$$R(\lambda_0, A) = R(\lambda, A) + (\lambda - \lambda_0)R(\lambda, A)R(\lambda_0, A) \geq R(\lambda, A) \geq 0 \quad (1.11)$$

It follows that for all  $\lambda > \max\{\lambda_0, s(A)\}$  we have

$$(\lambda - s(A))^{-1} = r(R(\lambda, A)) \leq \|R(\lambda, A)\| \leq \|R(\lambda_0, A)\| \quad (1.12)$$

which can be true only if  $\lambda_0$  is greater than  $s(A)$ .  $\square$

**Corollary 1.4** *Suppose  $X$  is compact and  $A$  has compact resolvent. Then there exists a real eigenvalue  $\lambda_0$  admitting a positive eigenfunction such that  $\operatorname{Re} \lambda \leq \lambda_0$  for every  $\lambda \in \sigma(A)$ .*

**Proof** From Theorem 1.1 we conclude that  $\lambda_0 := s(A)$  is a real number, contained in the spectrum and obviously  $\operatorname{Re} \lambda \leq \lambda_0$  for every  $\lambda \in \sigma(A)$ . Since  $A$  has compact resolvent it follows that  $\lambda_0$  is a pole of the resolvent. Let  $k$  be its order, then the highest coefficient in the Laurent series is given by

$$Q := \lim_{\lambda \rightarrow s(A)} (\lambda - s(A))^k R(\lambda, A). \quad (1.13)$$

It follows from Corollary 1.3 that  $Q$  is a positive operator. Since  $Q \neq 0$ , there exists  $g \geq 0$  such that  $h := Qg > 0$ . Moreover, by A-III,3.6., we have

$$(\lambda_0 - A)h = (\lambda_0 - A)Qg = 0.$$

The example of the rotation semigroup (A-III, Example 5.6) shows that the assumptions in Corollary 1.4 do not imply that  $s(A)$  is dominant. Additional hypotheses ensuring this stronger property will be given below (see Corollary 2.11 and 2.12). The following result is elementary. However, positivity is the crucial point in its proof. Note that it is not just a consequence of the spectral mapping theorem for the point spectrum.

**Proposition 1.5** *Suppose  $A$  is the generator of the positive semigroup  $(T(t))_{t \geq 0}$ . Take  $\tau > 0$ ,  $r > 0$  and let  $\alpha := \tau^{-1} \log(r)$ .*

- (i) *If  $r$  is an eigenvalue of  $T(\tau)$  with positive eigenfunction  $h_0$ , then there is a positive  $h \in D(A)$  such that  $Ah = \alpha h$  and  $\{x \in X : h_0(x) > 0\} \subset \{x \in X : h(x) > 0\}$ .*
- (ii) *If  $r$  is an eigenvalue of  $T(\tau)'$  with positive eigenvector  $\varphi_0$ , then there is a positive  $\varphi \in D(A^*)$  such that  $A^*\varphi = \alpha\varphi$  and  $\text{supp } \varphi_0 \subset \text{supp } \varphi$ .*

**Proof** Without loss of generality we may assume  $r = 1$ , i.e.,  $\alpha = 0$  and  $T(\tau)h_0 = h_0$ .

(i) Defining

$$h := \int_0^\tau T(s)h_0 \, ds, \tag{1.14}$$

then for  $0 \leq t \leq \tau$  we have

$$\begin{aligned} T(t)h &= \int_0^\tau T(s+t)h_0 \, ds = \int_t^\tau T(s)h_0 \, ds + \int_\tau^{\tau+t} T(s-\tau)T(\tau)h_0 \, ds \\ &= \int_t^\tau T(s)h_0 \, ds + \int_0^t T(s)T(\tau)h_0 \, ds = h \end{aligned}$$

It follows that  $Ah = \lim_{t \rightarrow 0} t^{-1}(T(t)h - h) = 0$ . So far, positivity was not used. The point is that in general,  $h$  may be zero. But if  $(T(t))$  is positive and  $h_0 \geq 0$ , then  $s \mapsto (T(s)h_0)(x)$  is a continuous positive function, hence  $0 < h_0(x_0) = (T(0)h_0)(x_0)$  implies  $h(x_0) = \int_0^\tau (T(s)h_0)(x_0) \, ds > 0$ .

(ii) Defining  $\varphi := \int_0^\tau T(s)'\varphi_0 \, ds$ , one can proceed as in (i) to obtain the desired result.  $\square$

We use Proposition 1.5 to prove an analogue of the famous Krein-Rutman result. For the sake of completeness we include the proof of this classical result, stating that the spectral radius of a positive operator  $T$  on  $C(K)$  (or more generally on an order unit space) is an eigenvalue of the adjoint  $T'$  (see the Corollary of Theorem 2.6 in the appendix of Schaefer [20]).



**Theorem 1.6** *Suppose  $K$  is compact and  $(T(t))_{t \geq 0}$  is a positive semigroup on  $C(K)$  with generator  $A$ . Then there exists a positive probability measure  $\varphi \in D(A')$  such that  $A'\varphi = \omega_0(A)\varphi$ .*

**Proof** Consider  $T := T(1)$ ,  $r := r(T) = e^{\omega_0(A)}$ . In view of Proposition 1.5 it is enough to show that  $r$  is an eigenvalue of  $T'$  with a positive eigenvector. Given  $\lambda \in \mathbb{C}$ ,  $|\lambda| > r$  and  $f \in C(K)$  we have

$$|R(\lambda, T)f| = \left| \sum_{n=0}^{\infty} \lambda^{-n-1} T^n f \right| \leq \sum_{n=0}^{\infty} |\lambda|^{-n-1} T^n |f| = R(|\lambda|, T)|f|.$$

It follows that  $\|R(\lambda, T)\| \leq \|R(|\lambda|, T)\|$  and therefore

$$\lim_{\lambda \downarrow r} \|R(\lambda, T)\| = \infty. \quad (1.15)$$

By the uniform boundedness principle there exist a sequence  $(\lambda_n)$ ,  $\lambda_n \downarrow r$  and a positive  $\psi \in M(K)$  such that  $\|R(\lambda_n, T)'\psi\| \rightarrow \infty$ . Defining  $\psi_n := \|R(\lambda_n, T)'\psi\|^{-1} R(\lambda_n, T)'\psi$  we have

$$\begin{aligned} (r - T')\psi_n &= \|R(\lambda_n, T)'\psi\|^{-1} \cdot ((r - \lambda_n) + (\lambda_n - T'))R(\lambda_n, T)'\psi \\ &= (r - \lambda_n)\psi_n + \|R(\lambda_n, T)'\psi\|^{-1}\psi \rightarrow 0. \end{aligned} \quad (1.16)$$

Since  $(r - T')$  is  $\sigma(M(K), C(K))$ -continuous, (1.16) implies that every  $\sigma(M(K), C(K))$  cluster point of  $(\psi_n)$  is a positive eigenvector, provided that it is non-zero. Because  $K$  is compact we have

$$\{\varphi \in M(K) : \varphi \geq 0, \|\varphi\| = 1\} = \{\varphi \in M(K) : \varphi \geq 0, \langle \varphi, 1 \rangle = 1\},$$

which shows that the set of probability measures is  $\sigma(M(K), C(K))$ -compact. Therefore the sequence  $(\psi_n)$  has non-zero cluster points.  $\square$

This theorem implies that for positive semigroups on  $C(K)$  the growth and spectral bounds coincide (cf. A-III, 4.4). Actually, this is true for locally compact spaces as well and can be proved directly (see B-IV, Theorem 1.4). Using this result one can prove Theorem 1.6 by applying the classical Krein-Rutman theorem to any resolvent operator  $R(\lambda, A)$  for  $\lambda \in \mathbb{R}$  sufficiently large.

The theorem ensures that  $A'$  always has eigenvalues, but the generator itself may have no eigenvalue at all. Multiplication operators have no eigenvalues unless the multiplier is constant on an open subset. Theorem 1.6 fails to be true for locally compact spaces as the following example shows.

**Example 1.7** Consider  $E = C_0(\mathbb{R}^n)$  and the semigroup  $(T(t))_{t \geq 0}$  generated by the Laplacian (cf. A-I, 2.8). From the explicit representation of  $T(t)$ ,

$$(T(t)f)(x) = (4\pi t)^{-n/2} \int_{\mathbb{R}^n} \exp(-(x-y)^2/4t) \cdot f(y) \, dy, \quad (1.17)$$

it follows that  $\lim_{t \rightarrow \infty} T(t)f = 0$  for every  $f \in C_0(\mathbb{R}^n)$  (Note that  $\|T(t)f\| \leq (4\pi t)^{-n/2} \int_{\mathbb{R}^n} |f(y)| dy \rightarrow 0$  provided that  $f$  has compact support and that  $\|T(t)\| = 1$  for all  $t \geq 0$ ).

If  $\varphi$  is an eigenvector of  $A'$  corresponding to  $s(A) = \omega_0(A) = 0$ , we have  $T(t)' \varphi = \varphi$  for all  $t \geq 0$ , hence  $\langle \varphi, f \rangle = \lim_{t \rightarrow \infty} \langle T(t)f, \varphi \rangle = 0$  for every  $f$ , i.e.,  $\varphi = 0$ .

## 2 The Boundary Spectrum

In this section we restrict our attention to the *boundary spectrum*  $\sigma_b(A)$  of a generator  $A$ , which, by definition, is the intersection of  $\sigma(A)$  with the line  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda = s(A)\}$ . Thus  $\sigma_b(A)$  contains all spectral values of  $A$  which have maximal real part. Note that in general the boundary spectrum is a proper subset of the topological boundary of  $\sigma(A)$ . Our aim is to prove results ensuring that  $\sigma_b(A)$  is a cyclic set (see Definition 2.5).

While most of the results of the preceding section were obtained by transforming the problem to a resolvent operator  $R(\lambda, A)$  ( $\lambda \in \mathbb{R}$  large enough), this procedure fails here. The reason is that there is no one-to-one correspondence between the boundary spectrum of  $A$  and the peripheral spectrum of  $R(\lambda, A)$ . Actually, from Theorem 1.1 and A-III, Proposition ?? it follows that the peripheral spectrum of  $R(\lambda, A)$  (i.e., the set of spectral values having maximal absolute value) is trivial, since it only contains the spectral radius  $r(R(\lambda, A)) = (\lambda - s(A))^{-1}$ .

We begin our discussion with two lemmas.

**Lemma 2.1** *Suppose  $K, L$  are compact and  $T: C(K) \rightarrow C(L)$  is a linear operator satisfying  $T\mathbb{1}_K = \mathbb{1}_L$ . Then we have  $T \geq 0$  if and only if  $\|T\| \leq 1$ .*

**Proof** If  $T$  is positive, then

$$|Tf| \leq T|f| \leq T(\|f\| \cdot \mathbb{1}_K) = \|f\| \cdot T(\mathbb{1}_K), \quad f \in C(K), \quad (2.1)$$

hence  $\|T\| = \|T\mathbb{1}_K\|$  whenever  $T$  is positive. This shows that  $T \geq 0$  implies  $\|T\| \leq 1$  whenever  $T\mathbb{1}_K = \mathbb{1}_L$ .

To prove the reverse direction, we first observe that for complex numbers and hence for complex-valued functions the following equivalence holds.

$$-1 \leq f \leq 1 \text{ if and only if } \|f - i \cdot r \cdot 1\| \leq \varrho_r := (1 + r^2)^{1/2} \text{ for every } r \in \mathbb{R}. \quad (2.2)$$

Now suppose  $f \in C(K)$ ,  $0 \leq f \leq 2 \cdot \mathbb{1}_K$ . Then we have  $-\mathbb{1}_K \leq f - \mathbb{1}_K \leq \mathbb{1}_K$  hence by (2.2)  $\|f - \mathbb{1}_K - i \cdot r \cdot \mathbb{1}_K\| \leq \varrho_r$  for every  $r \in \mathbb{R}$ . From  $T\mathbb{1}_K = \mathbb{1}_L$  and  $\|T\| \leq 1$  it follows that  $\|Tf - \mathbb{1}_L - i \cdot r \cdot \mathbb{1}_L\| \leq \varrho_r$  for every  $r \in \mathbb{R}$ . Using (2.2) once again, we obtain  $-\mathbb{1}_L \leq Tf - \mathbb{1}_L \leq \mathbb{1}_L$  or  $0 \leq Tf \leq 2 \cdot \mathbb{1}_L$ .  $\square$

Before we can formulate the second lemma we have to fix some notation.

**Definition 2.2** (i) Given  $h \in C_0(X)$  such that  $h(x) \neq 0$  for all  $x \in X$  then the operator  $S_h$  is defined to be the multiplication operator with sign  $h$ , i.e.,

$$S_h f = h|h|^{-1}f \quad (f \in C_0(X)). \quad (2.3)$$

(ii) For  $f \in C_0(X)$ ,  $n \in \mathbb{Z}$  we define  $f^{[n]} \in C_0(X)$  by

$$f^{[n]}(x) = \begin{cases} (f(x)/|f(x)|)^{n-1} \cdot f(x) & \text{if } f(x) \neq 0, \\ 0 & \text{if } f(x) = 0. \end{cases} \quad (2.4)$$

The following assertions are immediate consequences of the definition. They will be used frequently in the following.

$$S_h \text{ is a linear isometry satisfying } |S_h f| = |f|, \quad (2.5)$$

its inverse being  $S_{\bar{h}}$  where  $\bar{h}$  is the complex conjugate of  $h$ ,

$$f^{[1]} = f, f^{[0]} = |f|, f^{[-1]} = \bar{f}, |f^{[n]}| = |f| \text{ for every } n \in \mathbb{Z}, \quad (2.6)$$

$$\text{If } h(x) \neq 0 \text{ for all } x \in X, \text{ then } h^{[n]} = S_h^n |h| = S_h^{n-1} h \text{ for every } n \in \mathbb{Z}. \quad (2.7)$$

**Lemma 2.3** *Let  $T$  and  $R$  be bounded linear operators on  $C_0(X)$  and assume that  $h \in C_0(X)$  has no zeros. Suppose we have*

$$Rh = h, T|h| = |h| \text{ and } |Rf| \leq T|f| \text{ for every } f \in C_0(X). \quad (2.8)$$

*Then  $R$  and  $T$  are similar, more precisely,  $T = S_h^{-1}RS_h$ . In particular, the spectra (and point spectra, resp.) of  $T$  and  $R$  coincide.*

**Proof** We first note that the assertion  $|Rf| \leq T|f|$  ( $f \in E$ ) implies that  $T$  is a positive operator. Therefore  $T|h| = |h|$  implies that the principal ideal  $E_h = \{f \in C_0(X) : |f| \leq n|h| \text{ for some } n \in \mathbb{N}\}$  is an invariant subspace for  $T$  and for  $R$  as well.  $E_h$  is isomorphic to  $C^b(X) \cong C(\beta X)$  ( $\beta X$  denotes the Stone-Čech compactification of  $X$ ), an isomorphism is given by  $f \mapsto f|h|$ . Considering the restrictions  $T|_{E_h}$  and  $R|_{E_h}$  as operators on  $C(\beta X)$  and denoting them  $\tilde{T}$  and  $\tilde{R}$  respectively, we have

$$\tilde{R}\tilde{h} = \tilde{h}, \quad \tilde{T}\mathbb{1} = \mathbb{1}, \quad \tilde{T} \geq 0, \quad |\tilde{R}f| \leq \tilde{T}|f| \text{ for all } f. \quad (2.9)$$

Here  $\tilde{h}$  denotes the continuous extension of  $h/|h|$  to  $\beta X$ .

Defining  $T_1 := M_h^{-1}\tilde{R}M_{\tilde{h}}$  we have by (2.9)

$$T_1 \mathbb{1} = M_h^{-1}\tilde{R}\tilde{h} = \mathbb{1} \text{ and} \quad (2.10)$$

$$|T_1 f| = |M_h^{-1}\tilde{R}M_{\tilde{h}}f| = |\tilde{R}M_{\tilde{h}}f| \leq \tilde{T}|M_{\tilde{h}}f| = \tilde{T}|f| \text{ for all } f. \quad (2.11)$$

Hence we have  $\|T_1\| \leq \|\tilde{T}\| = 1$  (by (2.11), (2.9), (2.1)). Then it follows from Lemma 2.1 that  $T_1$  is a positive operator. Thus (2.11) implies that  $0 \leq T_1 \leq \tilde{T}$  and therefore  $\|\tilde{T} - T_1\| = \|(\tilde{T} - T_1)\mathbb{1}\| = 0$  (by (2.10), (2.9), (2.1)).  $\square$

We are now able to prove a result which in some sense is the key to cyclicity results for the spectrum. These general results will be proved by reducing the problem in such a way that the following theorem can be applied.

**Theorem 2.4** (i) Let  $T$  be a positive linear operator on  $C_0(X)$ , let  $h \in C_0(X)$  and  $\lambda \in \mathbb{C}$ ,  $|\lambda| = 1$ . If  $Th = \lambda h$  and  $T|h| = |h|$ , then we have  $Th^{[n]} = \lambda^n h^{[n]}$  for every  $n \in \mathbb{Z}$  (cf. (2.4)). If  $h$  does not have zeros in  $X$ , then

$$\lambda T = S_h^{-1} T S_h.$$

(ii) Suppose  $A$  is the generator of a positive semigroup,  $h \in C_0(X)$ ,  $\alpha, \beta \in \mathbb{R}$  such that  $Ah = (\alpha + i\beta)h$  and  $A|h| = \alpha|h|$ . Then we have  $Ah^{[n]} = (\alpha + in\beta)h^{[n]}$  for every  $n \in \mathbb{Z}$ . If  $h$  does not have zeros, then

$$S_h D(A) = D(A) \text{ and } i\beta + A = S_h^{-1} A S_h.$$

**Proof** (i) The closed principal ideal  $\overline{E_h}$ , which is canonically isomorphic to  $C_0(X_1)$  with  $X_1 = \{x \in X : h(x) \neq 0\}$ , is  $T$ -invariant. We give an object a tilde when we consider it as an element of  $\overline{E_h} \cong C_0(X_1)$ . Defining  $\tilde{R} := \lambda \tilde{T}$ , then  $\tilde{T}, \tilde{R}, \tilde{h}$  satisfy (2.8), hence we have

$$\tilde{T} = S_{\tilde{h}}^{-1} \circ \tilde{R} \circ S_{\tilde{h}} = \bar{\lambda} \cdot S_{\tilde{h}}^{-1} \circ \tilde{T} \circ S_{\tilde{h}} \quad (2.12)$$

which by iteration yields

$$\tilde{T} = \bar{\lambda}^n \cdot S_{\tilde{h}}^n \circ \tilde{T} \circ S_{\tilde{h}}^n \text{ for all } n \in \mathbb{Z}. \quad (2.13)$$

It follows that

$$\tilde{T}\tilde{h}^{[n]} = \tilde{T} \circ S_{\tilde{h}}^n |\tilde{h}| = \lambda^n \cdot S_{\tilde{h}}^n \circ \tilde{T} |\tilde{h}| = \lambda^n \cdot S_{\tilde{h}}^n \tilde{h} = \lambda^n \cdot \tilde{h}^{[n]}$$

(see (2.7) and (2.12)), which is precisely  $Th^{[n]} = \lambda^n h^{[n]}$  for all  $n \in \mathbb{Z}$ .

If  $h$  does not have zeros, then  $\overline{E_h} = E$ , hence  $T = \tilde{T}$ ,  $h = \tilde{h}$  and the remaining assertion follows from (2.12). (ii) This can be deduced easily from (i) as follows. If  $Ah = (\alpha + i\beta)h$ ,  $A|h| = \alpha|h|$ , then we have by A-III, Corollary 6.4

$$e^{-\alpha t} T(t)h = e^{i\beta t} h \text{ and } e^{-\alpha t} T(t)|h| = |h| \text{ for every } t \geq 0.$$

Hence by (a)  $e^{-\alpha t} T(t)h^{[n]} = e^{in\beta t} h^{[n]}$  ( $t \geq 0, n \in \mathbb{Z}$ ) which is equivalent to  $Ah^{[n]} = (\alpha + in\beta)h^{[n]}$ . If  $h$  does not have zeros, then  $e^{-\alpha t} T(t) = e^{-\alpha t} e^{i\beta t} S_h^{-1} T(t) S_h$  for every  $t \geq 0$  which is equivalent to the final statement of (ii).  $\square$

Before we state a first cyclicity result we give the definition and illustrate it by some examples.

**Definition 2.5** A subset  $M \subset \mathbb{C}$  is called *imaginary additively cyclic* (or simply *cyclic*), if it satisfies the following condition.

$\alpha + i\beta \in M$ ,  $\alpha, \beta \in \mathbb{R}$  implies that  $\alpha + ik\beta \in M$  for every  $k \in \mathbb{Z}$ .

Every subset of  $\mathbb{R}$  is cyclic. On the other hand, if  $M$  is cyclic and  $M \not\subset \mathbb{R}$ , then  $M$  has to be unbounded.

For a subset  $M$  of  $i\mathbb{R}$  we give the following equivalent conditions.

- (i)  $M$  is imaginary additively cyclic,
- (ii)  $M$  is the union of (additive) subgroups of  $i\mathbb{R}$ ,
- (iii)  $M = \cup_{\alpha \in S} i\alpha\mathbb{Z}$  for some set  $S \subset \mathbb{R}$ .

Here are some concrete cyclic subsets of  $i\mathbb{R}$ .

$$\begin{aligned} M_1 &= \{0\}, \quad M_2 = i\mathbb{R}, \quad M_3 = i\alpha\mathbb{Z} \quad (\alpha > 0), \\ M_4 &= i\alpha\mathbb{Z} + i\beta\mathbb{Z} = \{i n\alpha + i m\beta : n, m \in \mathbb{Z}\} \quad (\alpha, \beta \in \mathbb{R}), \\ M_5 &= \{0\} \cup \{i\lambda : \lambda \in \mathbb{R}, |\lambda| \geq 1\}, \\ M_6 &= \cup_{n=0}^{\infty} \{i\lambda : \lambda \in \mathbb{R}, n\alpha \leq |\lambda| \leq n\beta\} \quad (0 < \alpha \leq \beta, \alpha, \beta \in \mathbb{R}) \end{aligned}$$

In the following we consider the boundary spectrum of several semigroups. The notation  $M_i$  refers to the sets just defined.

- Examples 2.6** (a) For the Laplacian  $\Delta$  on  $\mathbb{R}^n$  or the second derivative on  $[0, 1]$  with Neumann boundary conditions the boundary spectrum is  $M_1$ .  
 (b) The first derivative on  $\mathbb{R}$  or  $\mathbb{R}_+$  is an example where the boundary spectrum of the generator is  $M_2$ .  
 (c) The rotation semigroup on  $C(\Gamma)$  (see A-III, Example 5.6) with period  $2\pi/\alpha$  has boundary spectrum  $M_3$ .  
 (d) For the semigroup on  $C(\Gamma \times \Gamma)$  given by

$$(T(t)f)(z, w) = f(z \cdot e^{i\alpha t}, w \cdot e^{i\beta t}) \quad (f \in C(\Gamma \times \Gamma), (z, w) \in \Gamma \times \Gamma)$$

we have  $P\sigma(A) = M_4$ . If  $\alpha/\beta$  is irrational, then this is a dense subset of  $i\mathbb{R}$  and  $\sigma_b(A) = \sigma(A) = i\mathbb{R}$ .

- (e) Consider  $D := \{z \in \mathbb{C} : |z| \leq 1\} = \{r \cdot e^{i\omega} : r \in [0, 1], \omega \in \mathbb{R}\}$ , and a strictly positive function  $\kappa \in C[0, 1]$ . The flow on  $D$  governed by the differential equation  $\dot{r} = 0, \dot{\omega} = \kappa(r)$  induces a strongly continuous semigroup on  $C(D)$  (which is given by

$$(T(t)f)(z) = f(z \cdot e^{i\kappa(|z|)t}).$$

The boundary spectrum is  $M_6$  with  $\alpha := \inf \kappa(r), \beta := \sup \kappa(r)$ . In particular, for  $\kappa(r) = 1 + r$  we obtain as boundary spectrum the set  $M_5$ .

- (f) Suppose  $M$  is a closed cyclic subset of  $i\mathbb{R}$ ,  $M = \cup_{\alpha \in S} i\alpha\mathbb{Z}$  for a suitable  $S \subset \mathbb{R}$  (e.g.,  $S = M$ ).

The space  $E_1 := \{(f_\alpha)_{\alpha \in S} : f_\alpha \in C(\Gamma), \sup \|f_\alpha\| < \infty\}$  is a Banach space under the norm  $\|(f_\alpha)\| := \sup \|f_\alpha\|$ . The closure of the linear subspace  $E_0 := \{(f_\alpha) \in E_1 : f_\alpha \neq 0 \text{ only for finitely many } \alpha \in S\}$  is isomorphic to  $C_0(X)$  where  $X$  is the topological sum of  $|S|$  copies of  $\Gamma$ .

Let  $(T_\alpha(t))_{t \geq 0}$  denote the rotation semigroup on  $C(\Gamma)$  with period  $2\pi/\alpha$ , then we define a semigroup  $(T(t))_{t \geq 0}$  on  $E := C_0(X)$  as

$$(T(t)(f_\alpha)) := (T_\alpha(t)f_\alpha) \quad ((f_\alpha)_{\alpha \in S} \in E).$$

This is a positive semigroup on  $E = C_0(X)$  whose boundary spectrum is precisely the given closed cyclic set  $M$ . We leave the verification as an exercise.

Our first result concerns cyclicity of the eigenvalues contained in the boundary spectrum, i.e., of the set

$$P\sigma_b(A) := P\sigma(A) \cap \sigma_b(A) = \{\lambda \in P\sigma(A) : \operatorname{Re} \lambda = s(A)\}$$

It is an almost straightforward consequence of Theorem 2.4.

**Proposition 2.7** *Assume that for some  $t_0 > 0$  there is a strictly positive measure  $\varphi$  such that  $T(t_0)' \varphi = \exp(s(A)t_0) \cdot \varphi$ . Then  $P\sigma_b(A)$  is imaginary additively cyclic.*

**Proof** If  $P\sigma_b(A)$  is empty, there is nothing to prove. Otherwise we have  $s(A) > -\infty$ . In view of the rescaling procedure we may assume  $s(A) = 0$ . By Proposition 1.5(ii) there exists  $\Psi \gg 0$  such that  $T(t)' \Psi = \Psi$  for all  $t \geq 0$ . Given  $i\alpha \in P\sigma_b(A)$  then there is  $h \in C_0(X)$ ,  $h \neq 0$ , such that  $Ah = i\alpha h$  or  $T(t)h = e^{i\alpha t} h$  for all  $t$  (A-III, Corollary 6.4). Then we have

$$|h| = |e^{i\alpha t} h| = |T(t)h| \leq T(t)|h| \text{ or } T(t)|h| - |h| \geq 0 \quad (2.14)$$

$$\langle T(t)|h| - |h|, \Psi \rangle = \langle |h|, T(t)' \Psi \rangle - \langle |h|, \Psi \rangle = 0. \quad (2.15)$$

Since  $\Psi$  is strictly positive, (2.14) and (2.15) imply that  $T(t)|h| = |h|$  for  $t \geq 0$  or equivalently  $A|h| = 0$ .

Now Theorem 2.4 implies that  $Ah^{[n]} = i\alpha h^{[n]}$  ( $n \in \mathbb{Z}$ ).  $\square$

Concerning the hypothesis  $T(t_0)' \varphi = \exp(s(A)t_0) \cdot \varphi \gg 0$  we recall that in case  $X$  is compact there are always positive linear forms such that  $T(t)' \varphi = e^{s(A)t} \varphi$  (see Theorem 1.6). If the semigroup is irreducible, then one also has  $\varphi \gg 0$  (see Section 3 below).

In a second result we consider semigroups having compact resolvent. An important step of the proof is isolated as a lemma. Before stating it, we recall that given a closed ideal  $I \subset C_0(X)$ , then  $I$  as well as  $C_0(X)/I$  are spaces of continuous functions on a locally compact space vanishing at infinity. More precisely, if  $I = \{f \in C_0(X) : f|_M = 0\}$  for a suitable closed subset  $M \subset X$ , then  $I \cong C_0(X \setminus M)$  and  $C_0(X)/I \cong C_0(M)$  (cf. B-I). It follows that given another closed ideal  $J = \{f \in C_0(X) : f|_N = 0\}$  such that  $I \subset J$  i.e.,  $N \subset M$ , then  $J/I$  can be identified with  $C_0(M \setminus N)$ .

We do not use this concrete representation of  $J/I$ . However, this shows that we stay within our setting of Banach spaces of continuous functions on locally compact spaces.

**Lemma 2.8** *Suppose  $A$  is the generator of a positive semigroup  $\mathcal{T}$  such that the spectral bound  $s(A)$  is a pole of the resolvent of order  $k$ . Then there is a sequence*

$$I_{-1} := \{0\} \subset I_0 \subsetneq I_1 \subsetneq \dots \subsetneq I_k := E \quad (2.16)$$

of  $\mathcal{T}$ -invariant closed ideals with the following properties. Denoting by  $A_n$  ( $n = 0, 1, \dots, k$ ) the generator of the semigroup on  $I_n/I_{n-1}$  which is induced by  $(T(t))$  we have

- (i)  $s(A_0) < s(A)$ ,
- (ii) If  $n \geq 1$ , then  $s(A_n) = s(A)$  is a first order pole of the resolvent  $R(\cdot, A_n)$ . The corresponding residue is a strictly positive operator.

**Proof** We can assume that  $s(A) = 0$  and we will denote the negative coefficients of the Laurent series of  $R(\cdot, A)$  at 0 by  $Q_n$ . Thus the following relations hold (see A-III,3.6),

$$\begin{aligned} Q_n &= \frac{1}{2\pi i} \int_{\gamma} z^{n-1} R(z, A) dz \quad (n \in \mathbb{N}), \\ Q_n &\neq 0 \text{ if } n \leq k \text{ and } Q_n = 0 \text{ for } n > k, \\ Q_n &= A^{n-1} Q_1 \quad (n \in \mathbb{N}); \quad Q_k = \lim_{z \rightarrow 0} z^k \cdot R(z, A). \end{aligned} \quad (2.17)$$

We define  $I_n$  as follows ( $n = 0, 1, \dots, k-1$ ).

$$I_n := \{f \in E : Q_{n+1}|f| = Q_{n+2}|f| = \dots = Q_k|f| = 0\}$$

At first we restrict our attention to  $I_{k-1}$ .

Since  $R(\lambda, A)$  is positive if  $\lambda > 0$  (Corollary 1.3), it follows from (2.17) that  $Q_k$  is a positive bounded operator, hence  $I_{k-1} = \{f \in E : Q_k|f| = 0\}$  is a closed ideal. Since  $Q_k$  commutes with  $R(\lambda, A)$  (see (2.17)), it follows that  $I_{k-1}$  is a  $T$ -invariant ideal. By A-III, Corollary 4.3 the generators  $A|_{I_{k-1}}$  and  $A_k$  induced by  $A$  on  $I_{k-1}$  and  $E/I_{k-1}$ , respectively, have a pole at 0. The coefficients of the Laurent series are the operators induced by  $Q_n$  on  $E/I_{k-1}$  and  $I_{k-1}$ , respectively.

Suppose that the pole order of  $R(\cdot, A_k)$  is greater than 1, say  $m$ . Then  $Q_{m/} = \lim_{z \rightarrow 0} z^m R(z, A_k)$  is a positive non-zero operator, hence we find for every  $x \in E_+$  an element  $y \in I_{k-1}$  such that  $Q_m x + y \geq 0$ . Then we have

$$0 \leq Q_k |Q_m x + y| = Q_k Q_m x + Q_k y = Q_{k+m-1} x + Q_k y = 0 + Q_k y \leq Q_k |y| = 0$$

hence  $Q_m x = (Q_m x + y) - y \in I_{k-1}$  ( $x \in E_+$ ). It follows that  $Q_{m/} = 0$  which is a contradiction.

So far we know that the resolvent of  $A_k$  has a pole of order  $\leq 1$ . Moreover, since  $Q_k|_{I_{k-1}} = 0$ , the resolvent of  $A|_{I_{k-1}}$  has a pole of order  $\leq k-1$ . From A-III, Corollary 4.3 it follows that the pole order of  $A_k$  and  $A|_{I_{k-1}}$  is precisely 1 and  $k-1$ , respectively. The residue  $Q_1|_{I_{k-1}} = \lim_{z \rightarrow 0} z R(z, A_k)$  is positive since  $R(z, A_k) \geq 0$  for  $z > 0$  (see Corollary 1.3). To prove that it is strictly positive we assume  $Q_1|_{I_{k-1}}(|x + I_{k-1}|) = 0$  which means  $Q_1|x| \in I_{k-1}$  hence  $Q_k|x| = A^{k-1} Q_1|x| = 0$ , that is,  $x \in I_{k-1}$  or  $x + I_{k-1} = 0$ .

Applying what we have proved so far to  $I_{k-1}$  and  $A|_{I_{k-1}}$  we obtain  $I_{k-2}$ ,  $A_{k-1}$ , and so on. After  $k$  steps ( $n = 1$ ) we conclude that  $I_0$  is  $T$ -invariant and that the order of the pole of  $R(\cdot, A|_{I_0})$  is 0, implying that  $0 \in \varrho(A|_{I_0})$ . Since  $A|_{I_0}$  generates a

positive semigroup and  $R(\lambda, A|_{I_0}) = R(\lambda, A)|_{I_0}$  is positive for  $\lambda > 0$ , it follows from Corollary 1.3 that  $s(A_0) = s(A|_{I_0}) < 0$ .  $\square$

One can check the different steps of the proof by studying the following example. Consider this matrix as generator on  $\mathbb{C}^4$

$$\begin{pmatrix} -1 & a & b & c \\ 0 & 0 & d & e \\ 0 & 0 & 0 & f \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \text{where } a, b, c, d, e, f \geq 0.$$

The result is summarized in the following table ( $e_j := (\delta_{jk})$ ).

	pole order	$I_0$	$I_2$	$I_2$	$I_3$
$d > 0, f > 0, e \geq 0$	3	$\langle e_1 \rangle$	$\langle e_1, e_2 \rangle$	$\langle e_1, e_2, e_3 \rangle$	$\mathbb{C}^4$
$d = 0, f > 0, e \geq 0$	2	$\langle e_1 \rangle$	$\langle e_1, e_2, e_3 \rangle$	$\mathbb{C}^4$	
$d = 0, f = 0, e > 0$	2	$\langle e_1 \rangle$	$\langle e_1, e_2, e_3 \rangle$	$\mathbb{C}^4$	
$d > 0, f = 0, e > 0$	2	$\langle e_1 \rangle$	$\langle e_1, e_2 \rangle$	$\mathbb{C}^4$	
$d > 0, f = 0, e = 0$	2	$\langle e_1 \rangle$	$\langle e_1, e_2, e_4 \rangle$	$\mathbb{C}^4$	

This example also shows that the operators  $Q_{k-1}, \dots, Q_1$  are not necessarily positive (e.g.,  $a > 0, b = c = 0, d = e = f = 2$ ).

A more general (and more interesting) example is the following. Suppose that  $A_i$  ( $i = 1, \dots, n$ ) are generators of positive semigroups on  $C_0(X)$  such that  $s(A_i) = 0$  is a first order pole of the resolvent. And let  $A_{ij}$  ( $1 \leq i < j \leq n$ ) be positive bounded operators on  $C_0(X)$ . Then

$$A := \begin{pmatrix} A_1 & A_{12} & \cdots & A_{1n} \\ 0 & A_2 & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & A_n \end{pmatrix}$$

is the generator of a positive semigroup on

$$C_0(X, \mathbb{C}^n) \cong C_0(X) \times C_0(X) \times \cdots \times C_0(X),$$

and  $s(A) = 0$  is a pole of the resolvent of order  $k$  where  $1 \leq k \leq n$ .

**Theorem 2.9** *Suppose  $A$  is the generator of a positive semigroup on  $C_0(X)$  such that every point of  $\sigma_b(A)$  is a pole of the resolvent. Then  $P\sigma_b(A) = \sigma_b(A)$  is cyclic.*

**Proof** If  $\sigma(A) = \emptyset$ , there is nothing to prove, thus we can assume that  $s(A) = 0$ . In view of the lemma and A-III, Proposition 4.3(i) we can assume that  $s(A)$  is a first order pole with strictly positive residue, which we call  $Q$ . We have  $AQ = QA = s(A)A = 0$  (see A-III, 3.6), hence



$$QT(t) = T(t)Q = Q \text{ for all } t \geq 0. \quad (2.18)$$

If  $Ah = i\alpha h$  for some  $\alpha \in \mathbb{R}$ ,  $h \neq 0$ , then  $T(t)h = e^{i\alpha t}h$  (by A-III, Corollary 6.4). Hence  $|h| = |e^{i\alpha t}h| = |T(t)h| \leq T(t)|h|$ , or equivalently,  $T(t)|h| - |h| \geq 0$ . By (2.18) we have  $Q(T(t)|h| - |h|) = 0$ . Since  $Q$  is strictly positive, it follows that  $T(t)|h| = |h|$  or  $A|h| = 0$ . Now we can apply Theorem 2.4 and obtain  $Ah^{[n]} = i\alpha h^{[n]}$  for every  $n \in \mathbb{Z}$ . This shows that  $P\sigma_b(A) = \sigma(A) \cap i\mathbb{R}$  is cyclic.  $\square$

If  $A$  has compact resolvent then every point of  $\sigma(A)$  is a pole of the resolvent (see A-III,3.6) hence we have

**Corollary 2.10** *If  $A$  has compact resolvent, then  $P\sigma_b(A) = \sigma_b(A)$  is cyclic.*

If it is known that the boundary spectrum of a generator is cyclic and nonvoid, the following alternative holds.

$$\text{Either } \sigma_b(A) = s(A) \text{ or else } \sigma_b(A) \text{ is an infinite unbounded set.} \quad (2.19)$$

If one can exclude the second alternative, then there is a unique spectral value having maximal real part. A real spectral value  $\lambda_0$  of a generator  $A$  is called a *dominant* provided that  $\operatorname{Re} \lambda < \lambda_0$  for every  $\lambda \in \sigma(A)$ , it is called *strictly dominant* if for some  $\delta > 0$  one has  $\operatorname{Re} \lambda \leq \lambda_0 - \delta$  for every  $\lambda \in \sigma(A)$ ,  $\lambda \neq \lambda_0$ .

The assumptions of Corollary 2.10 do not imply that  $s(A)$  is dominant, the rotation semigroup (A-III, Example 5.6) is a counterexample.

**Corollary 2.11** *Assume that for some  $t_0 > 0$  (hence for all  $t > 0$ ) one has  $r_{\text{ess}}(T(t_0)) < r(T(t_0))$ , e.g., that  $T(t_0)$  is compact and  $r(T(t_0)) > 0$  (see A-III,3.7). Then  $s(A)$  is a strictly dominant eigenvalue.*

**Proof** If  $s(A)$  is not strictly dominant, then we have by Theorem 2.9 and A-III, Corollary 6.5 that  $\{\lambda \in \sigma(A) : \operatorname{Re} \lambda > s(A) - r\}$  contains infinitely many eigenvalues for every  $r > 0$ . From A-III, Corollary 6.4 it follows that  $\{\lambda \in \sigma(T(t)) : |\lambda| > r\}$  contains infinitely many eigenvalues (counted according to their multiplicities) for every  $r < \exp(s(A)t) = r(T(t))$ . This contradicts the assumption  $r_{\text{ess}}(T(t)) < r(T(t))$  (see A-III,3.7).  $\square$

**Corollary 2.12** *Suppose  $A$  has compact resolvent and non-empty spectrum. If the corresponding semigroup is eventually norm continuous (e.g., if it is holomorphic or differentiable), then there is a strictly dominant eigenvalue admitting a positive eigenfunction.*

**Proof** Since  $(T(t))_{t \geq 0}$  is eventually norm continuous,  $\{\lambda \in \sigma(A) : \operatorname{Re} \lambda \geq s(A) - r\}$  is compact for every  $r > 0$  (see A-II, Theorem 1.20) and this set does not have accumulation points because  $A$  has compact resolvent. In other words, it is a finite set. The assertion now follows from Theorem 2.9 and Corollary 1.4.  $\square$

We now consider some examples. The first one shows that there are positive semigroups with  $P\sigma_b(A)$  being not cyclic. It is unknown whether there are positive semigroups where  $\sigma_b(A)$  is not cyclic.

*Example 2.13* Consider  $E = C(\Gamma) \times C_0(\mathbb{R}) (\cong C_0(\Gamma \dot{\cup} \mathbb{R}))$ . We fix a positive function  $k \in C_0(\mathbb{R})$  with compact support. The operator  $A$  given by

$$\begin{aligned} A(f, g) &:= (f', g' + \frac{1}{2\pi} \int_0^{2\pi} f(\vartheta) \, d\vartheta \cdot k) \\ D(A) &:= \{(f, g) \in E : f, g \in C^1, g' \in C_0(\mathbb{R})\} \end{aligned} \quad (2.20)$$

generates a semigroup  $(T(t))_{t \geq 0}$  which is given by

$$\begin{aligned} T(t)(f, g) &:= (f_t, g_t) \text{ with} \\ f_t(\vartheta) &:= f(\vartheta + t), \\ g_t(x) &:= g(x + t) + \frac{1}{2\pi} \int_0^{2\pi} f(\vartheta) \, d\vartheta \cdot \int_x^{x+t} k(u) \, du. \end{aligned} \quad (2.21)$$

Then  $(T(t))_{t \geq 0}$  is a positive semigroup and  $\|T(t)\| \leq (1 + \|k\|_1)$ . In particular,  $s(A) \leq \omega_0(A) \leq 0$ . It is easy to see that 0 is not an eigenvalue of  $A$ , while all  $ik$ ,  $k \in \mathbb{Z}$ ,  $k \neq 0$  are eigenvalues, the corresponding eigenfunctions being  $(e_k, 0)$  with  $e_k(\vartheta) = e^{ik\vartheta}$ .

*Example 2.14* (i) *One-dimensional Schrödinger operator.*

Let  $X = \mathbb{R}$ ,  $E = C_0(X)$  and  $V: \mathbb{R} \rightarrow \mathbb{R}$  be a continuous function such that  $\inf_x V(x) > -\infty$ .

If we define

$$\begin{aligned} (Af)(x) &:= f''(x) - V(x)f(x), \\ D(A) &:= \{f \in C_0(X) : f \in C^2, Af \in C_0(X)\}. \end{aligned} \quad (2.22)$$

then  $A$  is the generator of a positive semigroup.

In case  $\lim_{|x| \rightarrow \infty} V(x) = \infty$ ,  $A$  has compact resolvent. Then, by Corollary 2.10, there exists a dominant real eigenvalue with corresponding positive eigenfunction. Actually, the eigenfunction  $f$  is strictly positive. (In fact, if  $f \in C^2$ ,  $f \geq 0$  and  $f(x_0) = 0$  for some  $x_0$ , then  $f'(x_0) = 0$ . Therefore the uniqueness theorem for ordinary differential equations implies that  $f$  is identically zero).

(ii) *A retarded linear differential equation.*

Consider  $E = C[-1, 0]$  and define  $A_m$  and  $A_0$  as follows,

$$A_m f := f', \quad f \in D(A_m) = C^1[-1, 0], \quad (2.23)$$

$$A_0 f := f', \quad f \in D(A_0) = \{f \in C^1[-1, 0] : f'(0) = 0\}. \quad (2.24)$$

$A_0$  generates a contraction semigroup  $(T_0(t))_{t \geq 0}$  which is given by

$$(T_0(t)f)(x) = \begin{cases} f(x+t) & \text{if } x+t \leq 0, \\ f(0) & \text{if } x+t \geq 0. \end{cases} \quad (2.25)$$

This semigroup is positive, eventually norm continuous ( $T_0(t) = \delta_0 \otimes \mathbb{1}$  for  $t \geq 1$ ) and has compact resolvent. Given a linear functional  $\Psi$  on  $C[-1, 0]$ , we consider

$$A_\Psi := A_m|_{D(A_\Psi)} \text{ with } D(A_\Psi) := \{f \in C^1[-1, 0] : f'(0) = \langle f, \Psi \rangle\}. \quad (2.26)$$

Denoting the exponential function  $x \mapsto e^{\lambda x}$  by  $e_\lambda$ , we have for real  $\lambda$  and  $\lambda > \|\Psi\|$ .

$$\begin{aligned} \text{Id} - 1/\lambda \cdot \Psi \otimes e_\lambda &\text{ is a bijection of } D(A_\Psi) \text{ onto } D(A_0) \\ \text{and } \lambda - A_\Psi &= (\lambda - A_0)(\text{Id} - 1/\lambda \cdot \Psi \otimes e_\lambda). \end{aligned} \quad (2.27)$$

Using the Neumann series expansion of  $(\text{Id} - 1/\lambda \cdot \Psi \otimes e_\lambda)^{-1}$  one obtains the following estimate.

$$\|(\text{Id} - 1/\lambda \cdot \Psi \otimes e_\lambda)^{-1}\| \leq \lambda/(\lambda - \|\Psi\|) \quad \text{if } \lambda > \|\Psi\|. \quad (2.28)$$

It follows from (2.25) and (2.26) that for  $\lambda > \|\Psi\|$ , the resolvent  $R(\lambda, A_\Psi)$  exists and satisfies  $\|R(\lambda, A_\Psi)\| \leq \lambda/(\lambda - \|\Psi\|) \cdot 1/\lambda = 1/(\lambda - \|\Psi\|)$ . Then the Hille-Yosida Theorem (A-II, Theorem 1.7) implies that  $A_\Psi$  generates a semigroup  $(T(t))$  satisfying  $\|T(t)\| \leq \exp(\|\Psi\|t)$ . Moreover, this semigroup is eventually norm continuous (see B-IV, Corollary 3.3).

By B-II, Example 1.22 we have the following equivalence.

$$A_\Psi \text{ generates a positive semigroup if and only if } \Psi + r\delta_0 \geq 0 \text{ for some } r \in \mathbb{R}. \quad (2.29)$$

Thus Corollary 2.12 is applicable if  $\Psi + r\delta_0 \geq 0$  for some  $r \in \mathbb{R}$ . Since every eigenvalue of  $A_\Psi$  is an eigenvalue of  $A_m$  and since  $\text{Ker}(\lambda - A_m) = \{ae_\lambda : a \in \mathbb{C}\}$ , the spectral bound  $s(A_\Psi)$  is determined by the (unique) real  $\lambda \in \mathbb{R}$  such that  $e_\lambda \in D(A_\Psi)$  or equivalently,  $\lambda$  is a solution of the so-called *characteristic equation*

$$\lambda = \Psi(e_\lambda), \quad \lambda \in \mathbb{R}. \quad (2.30)$$

(The assumption  $\Psi + r\delta_0 \geq 0$  implies that the function  $\lambda \mapsto \Psi(e_\lambda)$  is strictly decreasing and  $\lim_{\lambda \rightarrow \infty} \langle e_\lambda, \Psi \rangle > -\infty$ ,  $\lim_{\lambda \rightarrow -\infty} \langle e_\lambda, \Psi \rangle = \infty$  unless  $\Psi = r_0\delta_0$  for some  $r_0 \in \mathbb{R}$ .)

We conclude this section with some additional remarks related to Theorem 2.9 and its corollaries.

**Remarks 2.15** (i) If  $s(A)$  is a pole of the resolvent, then for generators of positive semigroups one has the following equivalences.

- (a)  $s(A)$  is a first order pole.
- (b) For every  $0 < f \in \text{Ker}(s(A) - A)$  there exists  $0 \leq \Psi \in \text{Ker}(s(A) - A')$  such that  $\langle f, \Psi \rangle > 0$ .
- (c) For every  $0 < \Psi \in \text{Ker}(s(A) - A')$  there exists  $0 \leq f \in \text{Ker}(s(A) - A)$  such that  $\langle f, \Psi \rangle > 0$ .

In particular, if  $\text{Ker}(s(A) - A)$  contains a strictly positive function or if  $\text{Ker}(s(A) - A')$  contains a strictly positive measure, then  $s(A)$  is a first order pole. We sketch the proof of (a)  $\Leftrightarrow$  (b) assuming that  $s(A) = 0$ . If 0 is a first order pole, then the residue  $P$  is a positive projection satisfying  $PE = \text{Ker}(A)$ ,  $P'E' = \text{Ker}(A)'$  (see

A-III,3.6). Thus given  $0 < f \in \text{Ker}(A)$  and any  $0 \leq \varphi \in E'$  such that  $\langle f, \varphi \rangle > 0$ , we have for  $\Psi := P'\varphi$ :  $\langle f, \Psi \rangle = \langle f, P'\varphi \rangle = \langle Pf, \varphi \rangle = \langle f, \varphi \rangle > 0$ . To prove the reverse direction, we first observe that the highest coefficient  $Q_k$  of the Laurent expansion is a positive operator. Thus if 0 is a pole of order  $k \geq 2$ , we choose  $0 < h \in E$  such that  $f := Q_k h > 0$ . Then  $Af = AQ_k h = 0$  and for every  $\Psi \in \text{Ker}(A)'$  we have  $\langle f, \Psi \rangle = \langle Q_k h, \Psi \rangle = \langle h, Q'_k \Psi \rangle = \langle h, Q'_{k-1} A' \Psi \rangle = 0$ .

(ii) If a linear operator  $S$  on  $C_0(X)$  is weakly compact, then  $S^2$  is compact (see B-IV, Proposition 2.4(b)). Therefore every non-zero spectral value of a weakly compact operator is a pole of the resolvent. This shows that Theorem 2.9 is applicable if either  $T(t_0)$  is weakly compact for some  $t_0$  or  $R(\lambda, A)$  is weakly compact for some  $\lambda \in \varrho(A)$ . We quote two criteria for weak compactness.

If  $T \in L(C(K))$ ,  $K$  compact, is positive, then it is weakly compact  
if and only if its biadjoint  $T''$  maps bounded Borel functions  
into  $C(K)$  (see B-IV, Proposition 2.4) (2.31)

A positive operator  $T$  on  $C_0(X)$  which is dominated by a finite rank  
operator, is weakly compact. (2.32)

Actually, its adjoint  $T'$  is dominated by a finite rank operator as well, hence it maps the unit ball in an order interval. It follows that  $T'$  is weakly compact hence so is  $T$ .

(iii) Stronger results than Theorem 2.9 will be proved in Chapter C-III. Actually, assuming only that  $s(A)$  is a pole of finite algebraic multiplicity one can show that  $\sigma_b(A)$  contains only poles of finite multiplicity (C-III, Theorem 3.13). In C-III, Corollary 2.12 we will show that  $\sigma_b(A)$  is cyclic whenever  $s(A)$  is a pole of the resolvent.

(iv) Example 2.14(ii) can be extended to systems of functional differential equations even the infinite dimensional case. For details we refer to Section 3 of Chapter B-IV.

### 3 Irreducible Semigroups

In the case of matrices it is well known that considerably stronger results are available if one considers positive matrices which are irreducible. The concept of irreducibility can be extended to our setting and in many cases one can check easily whether a given semigroup has this property (see Example 3.4). We will show that irreducible semigroups have many interesting properties. For example, the spectrum  $\sigma(A)$  is always non-empty, positive eigenfunctions are strictly positive and if  $s(A)$  is a pole, it is algebraically (and geometrically) simple (see Proposition 3.5). Moreover, in certain cases irreducibility ensures that  $\sigma_b(A)$  and  $P\sigma_b(A)$  are not only cyclic subsets but *subgroups* (see Theorem 3.6 and Theorem 3.11 for details). We start the discussion with several, mutually equivalent, definitions of irreducibility.

**Definition 3.1** A positive semigroup  $\mathcal{T} = (T(t))$  on  $E = C_0(X)$ ,  $X$  locally compact, with generator  $A$  is called *irreducible* if one of the following mutually equivalent conditions is satisfied.

- (a) There is no  $T$ -invariant closed ideal except  $\{0\}$  and  $E$ .
- (b) Given  $0 < f \in E$ ,  $0 < \varphi \in E'$ , then  $\langle T(t_0)f, \varphi \rangle > 0$  for some  $t_0 \geq 0$ .
- (c) For every  $f > 0$  we have  $\bigcup_{t \geq 0} \{x \in X : (T(t)f)(x) > 0\} = X$ .
- (d) For some (every)  $\lambda > s(A)$  there exists no closed ideal which is invariant under  $R(\lambda, A)$  except  $\{0\}$  and  $E$ .
- (e) For some (every)  $\lambda > s(A)$ , we have  $R(\lambda, A)f$  is strictly positive whenever  $f > 0$ .
- (f)  $\bigcup_{t \geq 0} \text{supp } T(t)' \delta_x$  is dense in  $X$  for every  $x \in X$ .

That these six conditions are actually equivalent can be seen as follows.

(a)  $\implies$  (b): Suppose there are  $0 < f \in E$ ,  $0 < \varphi \in E'$  such that  $\langle T(t)f, \varphi \rangle = 0$  for every  $t \geq 0$ . Then the ideal  $I$  generated by  $\{T(t)f : t \geq 0\}$  satisfies  $\{0\} \neq I \subset \{g \in E : \varphi(|g|) = 0\} \neq E$ . Obviously  $I$  is  $\mathcal{T}$ -invariant.

(b)  $\implies$  (c): Given  $0 < f \in E$ ,  $x \in X$ . By (b) there exists  $t_0$  such that  $(T(t_0)f)(x) = \langle T(t_0)f, \delta_x \rangle > 0$ .

(c)  $\implies$  (d): Suppose that  $\bigcup_{t \geq 0} \text{supp } T(t)' \delta_y$  is not dense for some  $y \in X$ . Then there exists  $f_0 \in E$ ,  $f_0 > 0$  such that  $\text{supp } f_0 \cap \text{supp } T(t)' \delta_y = \emptyset$  for every  $t \geq 0$ . Hence  $(T(t)f_0)(y) = \langle f_0, T(t)' \delta_y \rangle > 0$ , that is,  $y \notin \bigcup_{t \geq 0} \{x \in X : (T(t)f_0)(x) > 0\}$ .

(d)  $\implies$  (e): Given  $0 < f \in E$ ,  $\lambda > \omega_0(A)$ ,  $y \in X$ , there exists  $t_0 \geq 0$  such that  $\{x : f(x) > 0\} \cap \text{supp } T(t_0)' \delta_y \neq \emptyset$ . Hence,  $(T(t_0)(f))(y) = \langle f, T(t_0)' \delta_y \rangle > 0$  and therefore

$$(R(\lambda, A)f)(y) = \int_0^\infty e^{-\lambda t} (T(t)f)(y) dt > 0.$$

Since  $\lambda \mapsto R(\lambda, A)f$  is decreasing in the interval  $(s(A), \infty)$  (use the resolvent equation and the fact that  $R(\lambda, A)$  is positive) we have  $R(\lambda, A)f \gg 0$  for all  $\lambda > s(A)$ .

(e)  $\implies$  (f): If  $I$  is a  $R(\lambda, A)$ -invariant ideal and  $0 < f \in I$ , then  $g := R(\lambda, A)f \in I$ . By (e),  $g$  is strictly positive, thus  $I$  has to be dense (it contains all functions of compact support).

(f)  $\implies$  (a): At first we recall that a closed linear subspace which is invariant for  $R(\lambda_0, A)$  ( $\lambda_0 \in \varrho(A)$ ), is invariant for  $R(\lambda, A)$  whenever  $\lambda$  and  $\lambda_0$  belong to the same component of  $\varrho(A)$ . Hence by A-I.3.2 every  $R(\lambda_0, A)$ -invariant subspace where  $\lambda_0 \in \varrho_+(A)$  is  $\mathcal{T}$ -invariant and vice versa.

**Remark 3.2** Obviously, irreducibility of a semigroup  $(T(t))_{t \geq 0}$  is implied by the following condition.

- (g)  $T(t)f \gg 0$  whenever  $f > 0$  and  $t > 0$ .

The rotation semigroup (see A-I.2.5) is irreducible but it does not satisfy condition (g). However, assuming that the semigroup  $(T(t))$  is holomorphic, then (g) is equivalent to irreducibility. We will give a proof of this result in the more general situation of Banach lattices (see C-III, Theorem 3.2(b)).

A semigroup  $(T(t))_{t \geq 0}$  is irreducible if and only if  $(e^{-\alpha t} T(t))_{t \geq 0}$ ,  $\alpha \in \mathbb{R}$  is. More generally, irreducibility is invariant under perturbations by multiplication operators. In fact, we have the following result.

**Proposition 3.3** *Suppose  $A$  generates a positive semigroup  $\mathcal{T}$  on  $C_0(X)$  and let  $h$  be a continuous, bounded real-valued function on  $X$ . Then the semigroup  $\mathcal{S}$  generated by  $B := A + M_h$  is irreducible if and only if  $\mathcal{T}$  has this property.*

**Proof** Since every closed ideal is of the form  $\{f \in E : f|_M = 0\}$  where  $M \subset X$  is a closed subset (cf. Section 1 of B-I), it is clear that all closed ideals are invariant under the multiplication operator  $M_h$  and  $M_{-h}$ , respectively. Thus the assertion follows from the expansions which are true for  $\lambda$  sufficiently large

$$R(\lambda, B) = (1 - R(\lambda, A)M_h)^{-1}R(\lambda, A) = \sum_{n=0}^{\infty} (R(\lambda, A)M_h)^n R(\lambda, A)$$

$$R(\lambda, A) = (1 - R(\lambda, B)M_{-h})^{-1}R(\lambda, B) = \sum_{n=0}^{\infty} (R(\lambda, B)M_{-h})^n R(\lambda, B)$$

**Examples 3.4** (a) (cf. B-II, Section 3). Suppose  $(T(t))_{t \geq 0}$  is governed by a continuous semiflow  $\varphi : \mathbb{R}_+ \times X \rightarrow X$ , i.e.,  $T(t)f = f \circ \varphi_t$  ( $f \in C_0(X)$ ). Then the following assertions are equivalent.

- (i)  $(T(t))_{t \geq 0}$  is irreducible.
- (ii) There is no closed subset of  $X$  which is  $\varphi$ -invariant except  $\emptyset$  and  $X$ .
- (iii) Every orbit  $\{\varphi(t, x) : t \in \mathbb{R}_+\}$  is dense in  $X$ .

More generally, these equivalences still hold if the semigroup  $(T(t))$  is given by  $T(t)f = h_t \cdot (f \circ \varphi_t)$  where  $h_t$  are suitable continuous, strictly positive, bounded functions on  $X$ .

(b) Suppose that the semigroup  $(T(t))_{t \geq 0}$  has the following form. There exist a positive measure  $\mu$  on  $X$  and a positive continuous function  $k : (0, \infty) \times X \times X \rightarrow \mathbb{R}$  such that

$$(T(t)f)(x) = \int_X k(t, x, y)f(y) d\mu(y) \quad (t > 0, f \in C_0(X), x \in X). \quad (3.1)$$

Then  $(T(t))_{t \geq 0}$  is irreducible if and only if  $\bigcup_{t > 0} \text{supp}\{k(t, x, \cdot)\}$  is dense in  $X$  for every  $x \in X$ .

(c) We consider the first derivative  $Af = f'$  (cf. A-I, 2.4). If  $E = C_0(\mathbb{R})$ , then the corresponding semigroup  $(T(t))$  is not irreducible. Note however, that there is no closed invariant ideal  $I$  with  $\{0\} \neq I \neq E$  which is invariant under the group  $(T(t))_{t \in \mathbb{R}}$  generated by  $A$ . For  $E = C_0[0, \infty)$  and  $E = C_0(-\infty, 0)$  the corresponding semigroups are reducible (i.e., not irreducible) as well. If  $E = C_{2\pi}(\mathbb{R})$  (i.e., the  $2\pi$ -periodic functions), then  $Af = f'$  generates an irreducible semigroup on  $E$ . It is (isomorphic to) the semigroup of rotations on the unit circle.

(d) (cf. Example 2.14(ii)) Consider  $Af = f'$  on  $E = C[-1, 0]$  with  $D(A\psi) = \{f \in C^1 : f'(0) = \Psi(f)\}$  where the linear functional  $\Psi$  satisfies  $\Psi + \alpha\delta_0 \geq 0$  for some

$\alpha \in \mathbb{R}$  (see B-II, Example 1.22). The corresponding semigroup is irreducible if and only if  $-1 \in \text{supp } \Psi$ .

(e) The second derivative  $Af = f''$  generates an irreducible semigroup on  $C_0(\mathbb{R})$  and on  $C_0(0, 1)$  (cf. A-I, 2.7). With Neumann boundary conditions (or more generally,  $f'(0) = \alpha_0 f(0)$ ,  $f'(1) = \alpha_1 f(1)$  where  $\alpha_0, \alpha_1 \in \mathbb{R}$ ) the second derivative generates an irreducible semigroup on  $C[0, 1]$  (cf. A-I, 2.7).

The operator  $Af = f'' - Vf$  on  $C_0(\mathbb{R})$ , where  $V$  is continuous, real-valued with  $\inf V(x) > -\infty$  (see Example 2.14(i)) also generates an irreducible semigroup.

This can be derived from the maximum principle as follows. For  $\lambda > -\inf V(x)$ ,  $f \in C_0(\mathbb{R})$ ,  $g := R(\lambda, A)f$  we have  $g \in C^2$  and  $g'' - (\lambda + V)g = -f$ . If  $f > 0$ , then  $g > 0$ , hence Protter and Weinberger [17, Chap. I, Theorem 3] implies that  $g$  is strictly positive.

(f) The Laplacian  $\Delta$  generates an irreducible semigroup on  $C_0(\mathbb{R}^n)$  as can be seen easily from A-I, 2.8. More general elliptic operators will be discussed below (see Example 3.10(ii)).

We now return to the general situation and show that irreducible semigroups possess several interesting properties.

**Proposition 3.5** *Suppose  $A$  is the generator of a strongly continuous semigroup on  $C_0(X)$  which is irreducible. Then the following assertions are true.*

- (i)  $\sigma(A) \neq \emptyset$ .
- (ii) Every positive eigenfunction of  $A$  is strictly positive.
- (iii) Every positive eigenvector of  $A'$  is strictly positive.
- (iv) If  $\text{Ker}(s(A) - A')$  contains a positive element (e.g., if  $X$  is compact (cf. Theorem 1.6), then  $\dim(\text{Ker}(s(A) - A)) \leq 1$ .
- (v) if  $s(A)$  is a pole of the resolvent, then it is algebraically simple. The residue has the form  $P = \varphi \otimes u$  where  $\varphi \in E'$  and  $u \in E$  are strictly positive eigenvectors of  $A'$  and  $A$ , respectively, satisfying  $\langle u, \varphi \rangle = 1$ .

**Proof** (i) Take any  $f_0 \in C_0(X)$  which is positive and has compact support. If  $\lambda > s(A)$ , then  $R(\lambda, A)f_0$  is strictly positive (by Definition 3.1(e)), hence there exists  $\varepsilon > 0$  such that  $R(\lambda, A)f_0 \geq \varepsilon f_0$ . It follows that  $R(\lambda, A)^n f_0 \geq \varepsilon^n f_0 \geq 0$  for all  $n \in \mathbb{N}$  and therefore  $r(R(\lambda, A)) = \lim_{n \rightarrow \infty} \|R(\lambda, A)^n\|^{1/n} \geq \varepsilon > 0$ . The assertion now follows from A-III, Proposition 2.5.

(ii) Suppose  $Ah = rh$  where  $h \neq 0$  is positive. Then  $r$  has to be real and we have  $T(t)h = e^{rt}h$  (A-III, Corollary 6.4). For  $|f| \leq n \cdot h$  ( $n \in \mathbb{N}$ ) we have

$$|T(t)f| \leq T(t)|f| \leq n \cdot T(t)h = n \cdot e^{rt}h. \quad (3.2)$$

This shows that the ideal generated by  $h$  is invariant, hence dense by irreducibility. This is true if and only if  $h$  is strictly positive.

(iii) Suppose  $A'\varphi = r\varphi$  for some  $0 < \varphi \in E'$ . Again  $r$  has to be real and  $T(t)'\varphi = e^{rt}\varphi$  ( $t \geq 0$ ). From

$$\langle |T(t)f|, \varphi \rangle \leq \langle T(t)|f|, \varphi \rangle = \langle |f|, e^{rt}\varphi \rangle, f \in E \quad (3.3)$$

it follows that  $I := \{f \in E : \varphi(|f|) = 0\}$  is an invariant ideal. We have  $I \neq E$  (because  $\varphi \neq 0$ ), hence the irreducibility implies  $I = \{0\}$ , i.e.,  $\varphi$  is strictly positive. (iv) By (i) we know that  $s(A) > -\infty$  hence we can assume without loss of generality that  $s(A) = 0$ . By (iii) there exists a strictly positive  $\Psi \in E'$  such that  $A'\Psi = 0$ . It follows from (2.14) and (2.15) that

$$h \in \text{Ker}(A) \text{ implies } |h| \in \text{Ker}(A) \quad (3.4)$$

Assuming  $\dim(\text{Ker}(A)) \geq 2$ , then there is an eigenfunction  $h \in \text{Ker}(A)$ ,  $h \neq 0$  which has at least one zero in  $X$  ( $h := h_1(x_0) \cdot h_2 - h_2(x_0) \cdot h_1$ , where  $h_1, h_2$  are linearly independent,  $x_0 \in X$ ). By (3.4)  $|h|$  is a positive eigenfunction but not strictly positive. This is a contradiction with (ii).

(v) If  $s(A)$  is a pole, then there exists a corresponding positive eigenfunction (see the proof of Corollary 1.4). By (ii) it is even strictly positive, thus  $s(A)$  is a first order pole by Rem.2.15(a). The residue  $P$  is a positive operator satisfying  $PE = \text{Ker}(s(A) - A)$  and  $P'E' = \text{Ker}(s(A) - A')$ , therefore the remaining assertion follows from (ii) and (iv).  $\square$

In the remainder of this section we focus our interest on the boundary spectrum of irreducible semigroups, more precisely, on the eigenvalues and the corresponding eigenfunctions of the boundary spectrum. In view of assertion (a) of Proposition 3.5 the assumption “ $s(A) = 0$ ” is not crucial in the following theorem. However, it allows a simpler formulation.

**Theorem 3.6** *Suppose  $\mathcal{T} = (T(t))$  is an irreducible semigroup with generator  $A$  and spectral bound  $s(A) = 0$ . Assume that there exists a positive linear form  $\Psi \neq 0$  such that  $A'\Psi = 0$ . (This is automatically satisfied whenever  $X$  is compact (see Theorem 1.6).) If  $P\sigma(A) \cap i\mathbb{R}$  is non-empty, then the following assertions are true.*

- (i)  $P\sigma(A) \cap i\mathbb{R}$  is a (additive) subgroup of  $i\mathbb{R}$ .
- (ii) The eigenspaces corresponding to  $\lambda \in P\sigma(A) \cap i\mathbb{R}$  are one-dimensional.
- (iii) If  $Ah = i\alpha h$  ( $h \neq 0, \alpha \in \mathbb{R}$ ), then  $h$  has no zeros in  $X$ . In case  $\alpha = 0$  then  $h(x)/|h(x)|$  is constant; otherwise,  $\{h(x)/|h(x)| : x \in X\}$  is a dense subset of  $\Gamma$ .
- (iv) If  $Ah = i\alpha h$  ( $h \neq 0, \alpha \in \mathbb{R}$ ), then

$$S_h(D(A)) = D(A) \text{ and } S_h^{-1} \circ A \circ S_h = (A + i\alpha). \quad (3.5)$$

*In particular, spectrum and point spectrum of  $A$  are invariant under translations by  $i\alpha$ .*

- (v)  $0$  is the only eigenvalue admitting a positive eigenfunction.

**Proof** By Proposition 3.5(iii) the invariant linear form  $\Psi$  is strictly positive and it satisfies  $T(t)'\Psi = \Psi$  ( $t \geq 0$ ).

- (iv) Supposing  $Ah = i\alpha h$  ( $h \neq 0, \alpha \in \mathbb{R}$ ) then  $A|h| = 0$  by (2.14) and (2.15). By Proposition 3.5(ii)  $|h|$  is strictly positive, thus Theorem 2.4(b) implies (3.5).



(ii) Assertion (iv) implies that  $S_h$  maps  $\text{Ker}(m + A)$  onto  $\text{Ker}(A)$  whenever  $i\alpha \in P\sigma(A) \cap i\mathbb{R}$ . Moreover, we have seen in the proof of (iv) that  $\text{Ker}(A) \neq \{0\}$  hence it is one-dimensional by Proposition 3.5(iv).

(i) Assume that  $Ah = i\alpha h$ ,  $Ag = i\beta g$  ( $\alpha, \beta \in \mathbb{R}$ ,  $h \neq 0$ ,  $g \neq 0$ ). By (3.5) we have  $S_{\bar{g}}AS_g = A + i\beta$  and  $S_hAS_{\bar{h}} = A - i\alpha$ , therefore

$$A + i(\beta - \alpha) = S_h(A + i\beta)S_{\bar{h}} = S_hS_{\bar{g}}AS_gS_h^{-1}. \quad (3.6)$$

It follows that  $\text{Ker}(A + i(\beta - \alpha)) = S_hS_{\bar{g}}(\text{Ker}(A)) \neq \{0\}$ , hence  $i(\beta - \alpha) \in P\sigma(A)$ .

(v) If  $Af = \lambda f$  where  $f > 0$ , then

$$\lambda \langle f, \Psi \rangle = \langle Af, \Psi \rangle = \langle f, A'\Psi \rangle = 0. \quad (3.7)$$

Since  $\Psi$  is strictly positive we have  $\langle f, \Psi \rangle > 0$  hence  $\lambda = 0$ .

(iii) We already know that  $Ah = i\alpha h$  implies that  $A|h| = 0$ . It follows from Proposition 3.5(ii) that  $h$  is strictly positive; i.e.,  $h$  has no zeros in  $X$ . By Proposition 3.5(iv)  $\text{Ker}(A)$  is one-dimensional hence every eigenfunction corresponding to 0 is the scalar multiple of a strictly positive function. If  $Ah = i\alpha h$ ,  $h \neq 0$ ,  $\alpha \neq 0$ , we consider  $\tilde{h}(x) := h(x)/|h(x)|$ . Assuming that  $\tilde{h}(X)$  is not dense in  $\Gamma$ , there exists a sequence of polynomials  $(p_n)_{n \in \mathbb{N}}$  such that

$$p_n(z) \rightarrow 1/z \text{ uniformly in } z \in \tilde{h}(X). \quad (3.8)$$

It follows that  $h(x) \cdot p_n(\tilde{h}(x)) \rightarrow |h|(x)$  uniformly in  $x \in X$ . Obviously,  $h \cdot p_n(h)$  is a linear combination of  $h^{[1]}, h^{[2]}, h^{[3]}, \dots$ , that is, it is an element of

$$\text{span} \{ \text{Ker}(ik\alpha - A) : k = 0, 1, 2, \dots \}, \text{ (cf. Theorem 2.4).}$$

By (3.7) the linear form  $\Psi$  vanishes on  $\text{Ker}(\lambda - A)$  whenever  $\lambda \neq 0$ . Therefore  $\langle h \cdot p_n(h), \Psi \rangle = 0$  and we have  $0 < \langle |h|, \Psi \rangle = \lim_{n \rightarrow \infty} \langle h \cdot p_n(h), \Psi \rangle = 0$  which is a contradiction.  $\square$

The group  $P\sigma(A) \cap i\mathbb{R}$  need not be discrete. For example, the semigroup described in Example 2.6(d) satisfies the assumptions of Theorem 3.6 if  $\frac{\alpha}{\beta}$  is irrational. In this case  $P\sigma(A) = i\alpha\mathbb{Z} + i\beta\mathbb{Z}$  is a dense subgroup of  $i\mathbb{R}$ . Actually one can show that for every subgroup  $H$  of  $i\mathbb{R}$  there is an irreducible semigroup on  $C(G)$ ,  $G := (H_d)^\sim$ , such that  $P\sigma(A) = H$ . Here  $(H_d)^\sim$  denotes the dual of the abelian group  $H$  equipped with the discrete topology. For details see Greiner [13, p.62]. An immediate consequence of assertion (iv) of Theorem 3.6 is the following corollary.

**Corollary 3.7** *Suppose  $\mathcal{T}$  satisfies the hypotheses of Theorem 3.6 and let  $A$  be its generator. If  $k$  is a bounded continuous real-valued function,  $M_k$  the corresponding multiplication operator, then for  $B := A + M_k$  we have  $\sigma(B) + P\sigma(A) \cap i\mathbb{R} = \sigma(B)$ . In particular,  $s(B) + P\sigma(A) \cap i\mathbb{R} \subset \sigma(B)$ .*

The next two corollaries are essentially consequences of assertion (iii) of Theorem 3.6. The statement of the first one can be summarized as follows. In case there

are non-real eigenvalues in the boundary spectrum, then the semigroup *contains* the semigroup of rotations on  $\Gamma$ .

**Corollary 3.8** *Suppose that the hypotheses of Theorem 3.6 are satisfied and that there is an eigenvalue  $i\alpha$  of  $A$  with  $\alpha > 0$ . Let  $\tau := 2\pi/\alpha$ . Then there exists a continuous injective lattice homomorphism  $j : C(\Gamma) \rightarrow C_0(X)$  such that the diagram commutes.*

$$\begin{array}{ccc} C(\Gamma) & \xrightarrow{R_\tau(t)} & C(\Gamma) \\ j \downarrow & & \downarrow j \\ C_0(X) & \xrightarrow{T(t)} & C_0(X) \end{array}$$

Here,  $(R_\tau(t))$  denotes the rotation semigroup of period  $\tau$  (see A-I,2.5). If  $X$  is compact, then  $j$  is a topological embedding.

**Proof** Assume that  $Ah = i\alpha h$ ,  $\alpha > 0$ , and let  $\tilde{h}(x) := h(x)/|h(x)|$ . Then we define  $j$  by

$$j(f) := |h| \cdot f \circ \tilde{h} \quad (\text{i.e., } (j(f))(x) = |h(x)| \cdot f(\tilde{h}(x))). \quad (3.9)$$

Obviously,  $j$  is a lattice homomorphism and because  $h$  has no zeros and  $\tilde{h}$  has a dense image in  $\Gamma$  (Theorem 3.6(c)), it follows that  $j$  is injective. For the functions  $e_n \in C(\Gamma)$  given by  $e_n(z) = z^n$  ( $n \in \mathbb{Z}$ ) one has  $j(e_n) = |h|^{[n]}$  ( $n \in \mathbb{Z}$ ) and therefore  $T(t) \circ j(e_n) = T(t)|h|^{[n]} = e^{i\alpha t} \cdot |h|^{[n]}$  (cf. Theorem 2.4) and  $j \circ R_\tau(t)(e_n) = j(e^{i\alpha t} e_n) = e^{i\alpha t} \cdot |h|^{[n]}$ . Since  $\{e_n : n \in \mathbb{Z}\}$  is a total subset of  $C(\Gamma)$ , we have  $T(t) \circ j = j \circ R_\tau(t)$  for every  $t > 0$ .

If  $X$  is compact, then  $\tilde{h}(X)$  is closed, hence  $\tilde{h}$  is onto, moreover,  $|h| \geq \varepsilon$  for some  $\varepsilon > 0$ , thus the definition of  $j$  implies that  $\|j(f)\| > \varepsilon\|f\|$  for every  $f \in C(\Gamma)$ .  $\square$

A consequence of Corollary 3.8 is the following. If  $s(A) \notin P\sigma(A) \cap i\mathbb{R}$ , then for every  $\varepsilon > 0$  there exists  $g > 0$  such that  $T(t)g$  and  $T(s)g$  have disjoint support whenever  $|s - t| = \varepsilon$ . Another consequence is that there exist positive functions  $f_1$  and  $f_2$  such that  $T(t)f_1$  and  $T(t)f_2$  have disjoint support for every  $t \geq 0$  (consider the images under  $j$  of two disjoint functions on  $C(\Gamma)$ ). This observation proves the following corollary.

**Corollary 3.9** *Suppose that the hypotheses of Theorem 3.6 are satisfied and that for some  $t_0 > 0$  we have  $T(t_0)f \gg 0$  whenever  $f > 0$ . Then  $P\sigma(A) \cap i\mathbb{R} = \{0\}$ .*

Corollary 3.9 can be applied if  $T(t_0)$  is a kernel operator with strictly positive kernel. We give some examples.

**Examples 3.10** (a) We assume that the semigroup  $(T(t))$  satisfies the hypotheses of Theorem 3.6 and that it is given by

$$(T(t)f)(x) = \int_X k(t, x, y) f(y) d\mu(y),$$

where  $\mu$  is a positive measure and  $k$  is a positive continuous function (see Example 3.4(ii)). We will show that  $P\sigma(A) \cap (s(A) + i\mathbb{R}) = \{s(A)\}$ .

Assuming the contrary, by Theorem 3.6(d) there exist  $\alpha \neq 0$ ,  $h \in C_0(X)$  such that

$$S_h^{-1}T(t) \circ S_h = e^{i\alpha t} \cdot T(t) \text{ for all } t \geq 0. \quad (3.10)$$

This implies that  $k$  satisfies

$$\frac{\overline{h(x)}}{|h(x)|} \cdot \frac{h(y)}{|h(y)|} \cdot k(t, x, y) = e^{i\alpha t} k(t, x, y) \quad (t > 0, x, y \in X). \quad (3.11)$$

It follows that for  $0 < |s - t| < 2\pi/\alpha$  the kernel functions  $k(t, \cdot, \cdot)$  and  $k(s, \cdot, \cdot)$  have disjoint support. This is impossible if  $k$  is continuous.

(b) Let  $\Omega$  be a domain in  $\mathbb{R}^n$  and define  $L_0$  as

$$L_0 f := \sum_{i,j=1}^n a_{ij} f'_{ij} + \sum_{i=1}^n b_i f'_i + c f,$$

with domain  $D(L_0) := \{f \in C_0(\Omega) : f \text{ is } C^\infty, L_0 f \in C_0(\Omega)\}$ . (Here  $f'_i$  stands for  $\partial f / \partial x_i$ , and  $f'_{ij} = \partial^2 f / \partial x_i \partial x_j$ ).

Suppose that  $L_0$  is elliptic,  $a_{ij}, b_i, c$  are real-valued  $C^\infty$ -functions with  $\lambda_0 := \sup c < \infty$ , assume further that the closure  $L$  of  $L_0$  is the generator of a positive semigroup on  $C_0(\Omega)$  which has compact resolvent. For example, this is true if  $\partial\Omega$  is  $C^\infty$  and  $a_{ij} \in C^\infty(\overline{\Omega})$  (cf. Theorem 4.8.3 of Fattorini [10]). We will show that  $P\sigma(A) \cap (s(A) + i\mathbb{R}) = \{s(A)\}$ .

In order to apply Theorem 3.6, we have to show that the corresponding semigroup  $(T(t))$  is irreducible. Given  $0 < f \in E$ , then there is  $g \in D(L_0)$  such that  $0 < g \leq f$ .  $h := R(\lambda, L)g$  is  $C^\infty$  (Weyl's Lemma) and satisfies  $L_0 h - \lambda h = -g < 0$ . Assuming that  $\lambda > \lambda_0$ , then  $h$  is positive, even strictly positive by the maximum principle Protter and Weinberger [17, Chap.2, Theorem 6]. It follows from  $R(\lambda, L)f \geq R(\lambda, L)g = h \gg 0$  that  $(T(t))$  is irreducible.

Next we apply Theorem 3.6(d) in order to show that the spectral bound is a dominant eigenvalue. We can assume that  $s(L) = 0$ . If  $s(L)$  is not dominant, then by Theorem 3.6(d) we have

$$L_0 h = i\alpha h, L_0 |h| = 0, L_0 \bar{h} = -i\alpha \bar{h} \text{ for some } h \neq 0, \alpha > 0. \quad (3.12)$$

If we define  $u := |h|$  and  $w := h/|h|$ , then (3.12) reads

$$L_0(uw) = i\alpha uw, \quad L_0(u) = 0, \quad L_0(u/w) = -i\alpha \cdot u/w. \quad (3.13)$$

Explicit calculation of  $L_0(uw)$  and  $L_0(u/w)$  using the product formula yields

$$\begin{aligned}
L_0(uw) &= wL_0(u) + u \sum_{i,j} a_{ij}w'_{ij} + \sum_i \left( ub_i + \sum_j a_{ij}u'_j \right) w'_i, \\
L_0(u/w) &= \frac{1}{w}L_0(u) + u \sum_{i,j} a_{ij}(1/w)'_{ij} + \sum_i \left( ub_i + \sum_j a_{ij}u'_j \right) (1/w)'_i.
\end{aligned} \tag{3.14}$$

Observing that  $(1/w)'_i = -w^{-2} \cdot w'_i$  and  $(1/w)'_{ij} = w^{-3} \cdot (2w'_i w'_j - ww'_{ij})$ , we obtain

$$L_0(uw) + w^2 L_0(u/w) = 2wL_0(u) + 2u/w \cdot \sum_{ij} a_{ij}w'_i w'_j. \tag{3.15}$$

This identity and (3.13) implies that  $2u/w \cdot \sum_{ij} a_{ij}w'_i w'_j = 0$ . Since  $u$  has no zeros and  $(a_{ij})$  is positive definite, we have  $\text{grad } w = (w'_i) = 0$  in  $\Omega$ , hence  $w = \text{const}$ . Then, by (3.13), we have  $i\alpha uw = L_0(uw) = wL_0(u) = 0$ , a contradiction.

The assumption that  $L_0$  is elliptic, i.e., that  $(a_{ij})$  is positive definite, is essential in order to show that there is only one eigenvalue in the boundary spectrum. In the following example  $(a_{ij})$  is positive semi-definite and  $P\sigma_b(A) = s(A) + i\alpha\mathbb{Z}$ .

(c) We consider  $\Omega = \{(x, y) \in \mathbb{R}^2 : 1 < (x^2 + y^2)^{1/2} < 2\}$ , and the second order differential operator  $L_0$  given by

$$(L_0 f)(x, y) = 1/(x^2 + y^2) \cdot (x^2 f_{xx} + 2xy f_{xy} + y^2 f_{yy}) + (x f_y - y f_x).$$

The assertion concerning the boundary spectrum can be verified easily by using polar coordinates,  $x = r \cdot \cos \omega$ ,  $y = r \cdot \sin \omega$ . Then  $L_0$  becomes  $L_0 f = f_{rr} + f_\omega$  on the space  $C_0(1, 2) \otimes C_{2\pi}(\mathbb{R})$ .

In this section we have seen that the eigenvalues in the boundary spectrum of an irreducible semigroup form a subgroup of  $i\mathbb{R}$  (provided that  $s(A) = 0$ ). We conclude this section mentioning an analogous statement for the whole boundary spectrum of Markov semigroups on  $C(K)$ ,  $K$  compact. It seems to be unknown if this is true for irreducible semigroups in general. To prove this result one uses the proof of the analogous result for a single operator (cf. Schaefer [21, Theorem 7]) as a guideline.

**Theorem 3.11** *Suppose that  $\mathcal{T}$  is an irreducible semigroup of Markov operators on  $C(K)$ ,  $K$  compact. Then  $\sigma_b(A)$  is a (closed) subgroup of  $i\mathbb{R}$ . Hence either  $\sigma_b(A) = \{0\}$  or  $= i\mathbb{R}$  or  $= i\alpha\mathbb{Z}$  for some  $\alpha > 0$ .*

## 4 Semigroups of Lattice Homomorphisms

As we have seen in Section 2 the boundary spectrum of a many positive semigroups is a cyclic set. However, there are hardly any restrictions on the set

$$\lambda \in \sigma(A) : \text{Re } \lambda < s(A)\},$$

except that it is symmetric with respect to the real axis. For semigroups of lattice homomorphisms the situation is quite different. We will show that the whole spectrum is an imaginary additively cyclic subset of  $\mathbb{C}$  (see Definition 2.5). A complete proof of this results requires some facts of the theory of Banach lattices, therefore, we postpone it to Part C (see C-III, Theorem 4.2).

**Theorem 4.1** *If  $A$  is the generator of a semigroup of lattice homomorphisms, then  $\sigma(A)$ ,  $A\sigma(A)$  and  $P\sigma(A)$  are cyclic subsets of  $\mathbb{C}$ .*

**Proof (1<sup>st</sup> part of the proof)** We prove the assertion concerning  $A\sigma(A)$  and  $P\sigma(A)$ . Assume that  $Ah = (\alpha + i\beta)h$ ,  $\alpha, \beta \in \mathbb{R}$ ,  $h \neq 0$ , then  $T(t)h = e^{\alpha t} e^{i\beta t} h$  for all  $t \geq 0$  (A-III, Corollary 6.4). Since  $T(t)$  is a lattice homomorphism we have  $T(t)|h| = |T(t)h| = e^{\alpha t} |h|$  ( $t \geq 0$ ) or  $A|h| = \alpha|h|$ , hence  $Ah^{[n]} = (\alpha + i\beta)h^{[n]}$  for all  $n \in \mathbb{Z}$  by Theorem 2.4(ii). We have shown that  $P\sigma(A)$  is cyclic.

To prove that  $A\sigma(A)$  is cyclic as well, one considers a semigroup  $\mathcal{F}$ -product  $E_{\mathcal{F}}^T$  of  $E$  (see A-III, 4.5). It is easy to see that  $E_{\mathcal{F}}^T$  is a Banach lattice and  $(T_{\mathcal{F}}(t))$  is a semigroup of lattice homomorphisms. The proposition in A-III, 3.5 implies  $A\sigma(A) = P\sigma(A_{\mathcal{F}})$ . Thus the assertion follows from the cyclicity of point spectrum.  $\square$

Performing a similar construction as in Example 2.6(f) one can show that every closed cyclic subset of  $\mathbb{C}$  which is contained in a left halfplane is the spectrum of a suitable semigroup of lattice homomorphisms. For details see Derndinger and Nagel [8]. In the following we restrict ourselves to the case of compact spaces. Then a semigroup of lattice homomorphisms can be described explicitly by a semi-flow  $\varphi$ , and real-valued functions  $h$  and  $p$  (see B-II, Thms. 3.5 & 3.6). The function  $p$  has no influence on spectral properties (cf. B-II, (3.7)). Therefore we will assume that  $(T(t))$  has the following form (cf. B-II, Theorem 3.5).

$$T(t)f = h_t \cdot f \circ \varphi_t \quad (t \geq 0, f \in C(K)) \quad (4.1)$$

where  $\varphi = (\varphi_t) : \mathbb{R}_+ \times K \rightarrow K$  is a continuous semiflow and  $h_t(x) = \exp \int_0^t h(\varphi(s, x)) ds$  ( $t \geq 0, x \in K$ ) for some continuous function  $h : K \rightarrow \mathbb{R}$ . In the following we will describe the spectrum of the semigroup given by (4.1) in terms of  $\varphi$  and  $h$ . At first we have to fix some notation. Let  $K$ ,  $\varphi$ ,  $h$  be as in (4.1). Then

$$K_t := \varphi_t(K) \quad (t < \infty), \quad K_\infty := \bigcap_{t < \infty} K_t. \quad (4.2)$$

Some properties of the sets  $K_t$  are listed in the following lemma. The proof is not difficult and is left as an exercise.

**Lemma 4.2** *Every  $K_t$  ( $0 \leq t \leq \infty$ ) is a non-empty closed subset of  $K$  which is invariant under the semiflow  $\varphi$ . Moreover, the following assertions are true.*

- (i) *For  $s > t$  we have  $K_s \subset K_t$ . In case that  $K_s = K_t$  then  $K_t = K_\infty$ .*
- (ii)  *$\varphi_t(K_\infty) = K_\infty$  for all  $t \geq 0$ .*
- (iii) *If one partial mapping  $\varphi_t$ ,  $t > 0$ , is injective (surjective), then all mappings  $\varphi_s$  are injective (surjective).*

We call a *semiflow*  $\varphi$  *injective* (*surjective*) if one and hence all of the partial mappings  $\varphi_t$  are injective (surjective). Studying the spectrum of the semigroup given by (4.1) we divide the complex plane into these three sets

$$\begin{aligned} \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < \underline{c}(h, \varphi)\}, \\ \{\lambda \in \mathbb{C} : \underline{c}(h, \varphi) \leq \operatorname{Re} \lambda \leq \bar{c}(h, \varphi)\}, \\ \{\lambda \in \mathbb{C} : \bar{c}(h, \varphi) < \operatorname{Re} \lambda\}. \end{aligned} \quad (4.3)$$

The quantities  $\underline{c}(h, \varphi)$  and  $\bar{c}(h, \varphi)$  are defined as follows.

$$\begin{aligned} \bar{c}(h, \varphi) &:= \lim_{t \rightarrow \infty} \bar{c}_t(h, \varphi) = \inf_{t > 0} \bar{c}_t(h, \varphi) \text{ where } \bar{c}_t(h, \varphi) := \sup_{x \in K} \left\{ \frac{1}{t} \int_0^t h(\varphi(s, x)) \, ds \right\}, \\ \underline{c}(h, \varphi) &:= \lim_{t \rightarrow \infty} \underline{c}_t(h, \varphi) = \sup_{t > 0} \underline{c}_t(h, \varphi) \text{ where } \underline{c}_t(h, \varphi) := \inf_{x \in K} \left\{ \frac{1}{t} \int_0^t h(\varphi(s, x)) \, ds \right\}. \end{aligned} \quad (4.4)$$

It is easy to see that  $\bar{c}_t(h, \varphi) = 1/t \cdot \log \|T(t)\|$ , hence in the definition of  $\bar{c}(h, \varphi)$ , both the limit and the infimum exist and coincide with the growth bound (see A-I.(1.1)). Furthermore,  $\underline{c}_t(h, \varphi) = -\bar{c}_t(-h, \varphi)$ . Therefore,  $\underline{c}(h, \varphi)$  is well defined too.

First we will describe the part of  $\sigma(A)$  which is contained in the left half-plane determined by  $\underline{c}(h, \varphi)$ . It turns out that either the whole half-plane is contained in  $\sigma(A)$  or it has empty intersection with  $\sigma(A)$ . This depends only on properties of  $\varphi$ . Essentially there

are three different cases. Before we state the general result (see Theorem 4.4) we give some typical examples.

**Examples 4.3** (a) Consider on  $K = [0, \infty]$  the semiflow defined by  $\varphi(t, x) := x + t$  ( $\infty + t = \infty$ ). Then  $K_t = [t, \infty]$  and  $K_\infty = \{\infty\}$ . The spectrum of the corresponding semigroup  $T(t)f = f \circ \varphi_t$  is  $\sigma(A) = A\sigma(A) = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda \leq 0\}$ .  
 (b) Consider again  $K = [0, \infty]$  and define a semiflow by

$$\varphi(t, x) := \begin{cases} x - t & \text{if } x \geq t, \\ 0 & \text{if } x < t. \end{cases} \quad (\infty - t = \infty)$$

Then  $K_t = K$  for all  $t$ , hence  $K_\infty = K$  and  $\sigma(A) = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda \leq 0\}$ ,  $R\sigma(A) = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < 0\} \cup \{0\}$ .

(c) Consider on  $K_1 := [-1, \infty)$  the equivalence relation  $\sim$  defined by “ $x \sim y$  if and only if  $x, y \geq 0$  and  $x - y \in \mathbb{Z}$ ”. The semiflow  $\varphi_1$  on  $K_1$  given by  $\varphi_1(t, x) = x + t$  induces a semiflow  $\varphi$  on  $K := K_1/\sim$ . For  $0 < t < 1$  we have  $K \neq K_t \neq K_\infty$  ( $K_\infty = [0, 1]/\sim \cong \Gamma$ ). The spectrum is  $\sigma(A) = 2\pi i\mathbb{Z}$ .

(d) Consider on  $K = [-1, 1]$  the flow  $\varphi$  given by

$$\varphi(t, x) := \begin{cases} -1 & \text{if } x < 0 \text{ and } t > -\frac{x+1}{x}, \\ \frac{x}{1+tx} & \text{otherwise.} \end{cases}$$

Then  $K_t = [-1, \frac{1}{1+t}]$ ,  $K_\infty = [-1, 0]$  and

$$\sigma(A) = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda \leq 0\}, \quad \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < 0\} \subseteq A\sigma(A) \cap R\sigma(A).$$

**Theorem 4.4** Suppose  $\mathcal{T}$  is a semigroup of lattice homomorphisms given by (4.1) with generator  $A$ . Considering  $H := \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < \underline{c}(h, \varphi)\}$ , where  $\underline{c}(h, \varphi)$  is given by (4.4), then we have.

- (i) If  $K_t \neq K_\infty$  for every  $t < \infty$ , then  $H \subseteq A\sigma(A)$ .
- (ii) If  $\varphi|_{K_\infty}$  is not injective, then  $H \subseteq R\sigma(A)$ .
- (iii) If  $K_s = K_\infty$  for some  $s < \infty$  and  $\varphi|_{K_\infty}$  is injective, then  $H \cap \sigma(A) = \emptyset$ .

**Proof** For  $\varepsilon > 0$  we define  $H_\varepsilon = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < \underline{c}(h, \varphi) - \varepsilon\}$ . Obviously it is enough to prove assertion (a), (b) and (c) respectively for  $H_{2\varepsilon}$ ,  $\varepsilon > 0$  arbitrary, instead of  $H$ . (i) By the definition given in (4.4) there exists a  $\tau > 0$  such that  $\underline{c}_t(h, \varphi) \geq \underline{c}(h, \varphi) - \varepsilon$  for all  $t \geq \tau$ . It follows that

$$h_t(x) \geq e^{(\alpha+\varepsilon)t} \text{ whenever } t \geq \tau, x \in K, \alpha < \underline{c}(h, \varphi) - 2\varepsilon. \quad (4.5)$$

Now we fix  $\lambda = a + i\beta \in H_{2\varepsilon}$  ( $a, \beta \in \mathbb{R}$ ) and construct an approximate eigenvector  $(g_n)$  of  $A$  corresponding to  $\lambda$ . For  $n \leq \tau + 1$  we choose an arbitrary function  $g_n \neq 0$ . Now suppose  $n > \tau + 1$ . We choose  $x_n \in K_{n+1/2} \setminus K_{n+1}$  (cf. Lemma 4.2(i)), then there exists  $y_n \in K$  such that  $\varphi(n + 1/2, y_n) = x_n$ . We have  $\varphi([0, n + 1/2], y_n) \cap K_{n+1} = \emptyset$  and the mapping  $t \mapsto \varphi(t, y_n)$  is a continuous injection, hence a homeomorphism from  $[0, n + 1/2]$  into  $K$  (this is true because  $\varphi(n + 1/2, y_n) \notin K_{n+1}$ ). By Tietze's Theorem there is  $f_n \in C(K)$  such that

$$\begin{aligned} \|f_n\| &\leq 1, \quad f_n|_{K_{n+1}} = 0, \\ f_n(\varphi(t, y_n)) &= 0 \text{ for } 0 \leq t \leq n - (1 + \delta) \text{ and } n + \delta \leq t \leq n + 1, \\ f_n(\varphi(t, y_n)) &= e^{i\beta t} \text{ for } n - 1 \leq t \leq n. \end{aligned} \quad (4.6)$$

The constant  $\delta \in (0, 1/2)$  will be determined later.

Considering  $g_n := \int_0^{n+1} e^{-\lambda t} T(t) f_n t dt$ , then  $g_n \in D(A)$  and

$$(A - \lambda)g_n = (1 - e^{-\lambda(n+1)} T(n+1)) f_n = f_n - e^{-\lambda(n+1)} \cdot h_{n+1} \cdot f_n \circ \varphi_{n+1} = f_n. \quad (4.7)$$

Moreover,

$$\begin{aligned} \|g_n\| &\geq \left| g_n(y_n) \right| = \left| \int_0^{n+1} e^{-\lambda t} h_t(y_n) f_n(\varphi(t, y_n)) t dt \right| \geq \\ &\left| \int_{n-1}^n e^{-\lambda t} h_t(y_n) e^{i\beta t} dt \right| - \left[ \int_{n-(1+\delta)}^{n-1} + \int_n^{n+\delta} \right] |e^{-\lambda t} h_t(y_n) f_n(\varphi(t, y_n))| dt \Bigg| \\ &\geq \int_{n-1}^n e^{-at} e^{(a+\varepsilon)t} dt - \left[ \int_{n-(1+\delta)}^{n-1} + \int_n^{n+\delta} e^{-at} |h_t(y_n)| dt \right] \end{aligned}$$

$$= 1/\varepsilon \cdot \left( e^{\varepsilon n} - e^{\varepsilon(n-1)} \right) - \left[ \int_{n-(1+\delta)}^{n-1} + \int_n^{n+\delta} e^{-at} |h_t(y_n)| dt \right].$$

The constant  $\delta$  can be chosen such that

$$\|g_n\| \geq 1/2\varepsilon \cdot \left( e^{\varepsilon n} - e^{\varepsilon(n-1)} \right) \rightarrow \infty \text{ for } n \rightarrow \infty. \quad (4.8)$$

It follows from (4.8) and (4.7) that  $g_n/\|g_n\|$  is an approximate eigenvector of  $A$  corresponding to  $\lambda$ . Thus (a) is proved.

The proofs of (ii) and (iii) will be handled simultaneously. First we show that we can restrict attention to the case where  $K = K_\infty$ .

Indeed,  $K_\infty$  is a  $\varphi$ -invariant subset, hence  $I_\infty := \{f \in C(K) : f|_{K_\infty} = 0\}$  is a  $T$ -invariant ideal. Identifying  $C(K)/I_\infty$  with  $C(K_\infty)$  (cf. B-I, Section 1), then  $(T(t)/I_\infty)$  is the semigroup governed by  $\varphi|_{K_\infty}$  and  $h|_{K_\infty}$ . Since one always has  $R\sigma(A|_{I_\infty}) \subseteq R\sigma(A)$ , assertion (ii) is proved, when we can show that  $H_{2\varepsilon} \subseteq R\sigma(A|_{I_\infty})$ . In case (iii) one has  $K_s = K_\infty$  for some  $s < \infty$ , which implies  $T(s)|_{I_\infty} = 0$ . Hence we have  $\sigma(A|_{I_\infty}) = \emptyset$  and therefore  $\sigma(A) = \sigma(A|_{I_\infty})$  by A-III, Proposition 4.2.

Henceforth we will assume that  $K = K_\infty$ , that is,  $\varphi$  is surjective (cf. Lemma 4.2(ii)). We choose  $\tau > 0$  such that (4.5) is true. Since  $\varphi$  is surjective, for every  $f \in C(K)$  there is a  $x_f \in K$  such that  $\|f\| = \|f(\varphi(\tau, x_f))\|$  and we obtain for  $\lambda \in H_{2\varepsilon}$ ,  $\lambda = a + i\beta$ ,  $\alpha, \beta \in \mathbb{R}$

$$\begin{aligned} \|(e^{\lambda\tau} - T(\tau))f\| &\geq |h_\tau(x_f)f(\varphi(\tau, x_f)) - e^{\lambda\tau}f(x_f)| \\ &\geq h_\tau(x_f)\|f\| - e^{\alpha\tau}|f(x_f)| \\ &\geq e^{(a+\varepsilon)\tau}\|f\| - e^{\alpha\tau}\|f\| \\ &= e^{\alpha\tau}(e^{\varepsilon\tau} - 1)\|f\|. \end{aligned} \quad (4.9)$$

It follows that the disc  $D := \{\lambda \in \mathbb{C} : |\lambda| < \exp(\underline{c}(h, \varphi) - 2\varepsilon)\}$  has an empty intersection with  $A\sigma(T(\tau))$  and therefore  $H_{2\varepsilon} \cap A\sigma(A) = \emptyset$  by A-III, 6.2. Since every boundary point of the spectrum is an approximate eigenvalue (by A-III, Proposition 2.2(i)) we have the following alternative.

$$\begin{aligned} \text{Either } D &\subseteq \varrho(T(\tau)) \text{ and } H_{2\varepsilon} \subseteq \varrho(A) \\ \text{or } D &\subseteq R\sigma(T(\tau)) \text{ and } H_{2\varepsilon} \subseteq R\sigma(A). \end{aligned} \quad (4.10)$$

It is not difficult to see that  $0 \in \varrho(T(\tau))$  whenever  $\varphi_t$  is bijective and that 0 is an eigenvalue of  $T(\tau)'$  if  $\varphi_\tau$  is not injective. Since we assumed that  $\varphi$  is surjective, assertions (ii) and (iii) of the theorem are immediate consequences of (4.10).  $\square$

The Examples 4.3(a), (b) and (c) respectively are prototypes of the three different cases considered in Theorem 4.4. Example 4.34.3(c) also shows that there are semigroups whose spectrum is contained in a right half-plane, although they cannot be embedded in a group (compare Corollary 4.5 below). Example 4.3(d) shows that (a) and (b) do not exclude each other.



**Corollary 4.5** *If  $\varphi$  is injective or surjective, then the following assertions are equivalent.*

- (a) *A is the generator of a strongly continuous group.*
- (b)  *$\sigma(A)$  is contained in a right half-plane.*

**Proof** (a)  $\implies$  (b): holds true because  $-A$  is a generator of a semigroup.

(b)  $\implies$  (a): We have to show that one (hence each) operator  $T(t)$ ,  $t > 0$  is invertible. Obviously this is true if  $\varphi$  is bijective. At first we assume that  $\varphi$  is surjective, that is,  $K = K_\infty$ . By Theorem 4.4 we have that  $\varphi|_{K_\infty}$  is injective if (b) is true. Thus  $\varphi$  is bijective. Now we assume that  $\varphi$  is injective. We have to show that  $K = K_\infty$ . By Theorem 4.4 we have  $K_\infty = K_s$  for some  $s$ , whenever (b) is true. Given  $x \in K$  then by Lemma 4.2(ii) there exists  $y \in K_\infty$  such that  $\varphi(s, x) = \varphi(s, y)$ . If  $\varphi$  is injective we have  $x = y \in K_\infty$ .  $\square$

**Example 4.6** Suppose  $F: \mathbb{R}^n \rightarrow \mathbb{R}^n$  is continuously differentiable. We denote the maximal flow corresponding to the differential equation  $y' = F(y)$  by  $\varphi_0$ . In general,  $\varphi_0$  is only defined on an open subset of  $\mathbb{R} \times \mathbb{R}^n$  which contains  $\{0\} \times \mathbb{R}^n$ . For  $x \in \mathbb{R}^n$  there exist  $\underline{t}_x$  and  $\bar{t}_x$  such that

$$\begin{aligned} -\infty &\leq \underline{t}_x < 0 < \bar{t}_x \leq \infty, \\ \varphi_0(t, x) &\text{ is defined if } \underline{t}_x < t < \bar{t}_x, \\ \text{if } \bar{t}_x < \infty \text{ (} \underline{t}_x > -\infty \text{) then } |\varphi_0(t, x)| &\rightarrow \infty \text{ as } t \uparrow \bar{t}_x \text{ (} t \downarrow \underline{t}_x \text{).} \end{aligned} \quad (4.11)$$

For details see Sect.18.2 of Dieudonné [9].

(a) If  $\varphi_0$  is a global flow, i.e., if  $\varphi_0$  is defined on  $\mathbb{R} \times \mathbb{R}^n$ , then one has a corresponding (semi-)group on  $C_0(\mathbb{R}^n)$ . If  $F$  is differentiable, its generator is the closure of  $A_1$  which is defined as follows (cf. B-II, Example 3.15).

$$\begin{aligned} A_1 f &= (F|_{\text{grad}} f) := \sum F_i \cdot \partial_i f, \\ D(A_1) &:= \{f \in C^1 : \text{supp } f \text{ is compact}\}. \end{aligned} \quad (4.12)$$

Then  $\varphi_0$  can be uniquely extended to a flow  $\tilde{\varphi}_0$  on  $\mathbb{R}^n \cup \{\infty\}$  by defining  $\tilde{\varphi}_0(t, \infty) := \infty$  for all  $t \in \mathbb{R}$ .  $\varphi_0$  and  $\tilde{\varphi}_0$  satisfy condition (c) of Theorem 4.4. A global flow exists if  $F$  is globally Lipschitz continuous or uniformly bounded. For  $\{x \in \mathbb{R}^n : (x|F(x)) > 0\}$  bounded in  $\mathbb{R}^n$ , a global semiflow always exists (cf. Deimling [5, Section 5.2]).

(b) We do not assume that  $\varphi_0$  is globally defined. Instead we consider a bounded domain  $\Omega \subset \mathbb{R}^n$  with smooth boundary  $\partial\Omega$  such that  $(F(x)|\nu(x)) > 0$  for every  $x \in \partial\Omega$ , where  $\nu(x)$  denotes the outward normal vector.

Then for  $x \in \bar{\Omega}$  we have  $\underline{t}_x = -\infty$ . Moreover, either  $\varphi_0(t, x) \in \Omega$  for all  $t \geq 0$  or else there exists a unique  $s_x$  with  $0 \leq s_x < \bar{t}_x$  such that  $\varphi_0(s_x, x) \in \partial\Omega$ . In the first case we write  $s_x := \infty$ . Then we define  $\varphi: \mathbb{R}_+ \times \bar{\Omega} \rightarrow \bar{\Omega}$  as

$$\varphi(t, x) := \begin{cases} \varphi_0(t, x) & \text{if } 0 \leq t < s_x, \\ \varphi_0(s_x, x) & \text{if } t \geq s_x. \end{cases}$$

Then  $\varphi$  is a continuous semiflow on the compact set  $K := \overline{\Omega}$ . We have  $K_\infty = K$  and  $\varphi|_{K_\infty}$  is not injective.

In case  $F$  is differentiable, the generator of the corresponding semigroup is the closure of the operator  $A_2$  defined by

$$A_2 f := (F|_{\text{grad } f}), \quad D(A_2) := \{f \in C^1(\overline{\Omega}) : (F|_{\text{grad } f}) = 0 \text{ on } \partial\Omega\}.$$

(c) We consider  $\Omega$  as in (b) and assume that  $(F(x)|_{\nu(x)}) \leq 0$  for every  $x \in \partial\Omega$ . Then for every  $x \in \overline{\Omega}$  we have  $\bar{t}_x = \infty$ . Thus  $\varphi := \varphi_{0|\mathbb{R}_+ \times \overline{\Omega}}$  is a continuous semiflow on  $K := \overline{\Omega}$ .

If  $(F(x)|_{\nu(x)}) < 0$  for some  $x \in \partial\Omega$ , we have  $K_t \subsetneq K_s$  whenever  $t > s$  and  $\varphi|_{K_\infty}$  is injective. For a differentiable vector field  $F$ , the generator of the corresponding semigroup is the closure of  $A_3$  defined as

$$A_3 f := (F|_{\text{grad } f}), \quad D(A_3) := C^1(\overline{\Omega}).$$

We conclude the discussion of semi-flows associated with ordinary differential equations by remarking that the ideas of (b) and (c) can be combined to obtain semigroups for more general subsets  $\Omega$ .

We continue the discussion of the spectrum of semigroups of lattice homomorphisms on  $C(K)$  given by (4.1). Theorem 4.4 gives a good description of the part contained in  $\{\lambda \in \mathbb{C} : \text{Re } \lambda < \underline{c}(h, \varphi)\}$ .

The half-plane  $\{\lambda \in \mathbb{C} : \text{Re } \lambda > \bar{c}(h, \varphi)\}$  is always a subset of the resolvent set (see Proposition 4.8(a) below). The description of the remaining part  $\{\lambda \in \sigma(A) : \underline{c}(h, \varphi) \leq \text{Re } \lambda \leq \bar{c}(h, \varphi)\}$  is more difficult. First we discuss some examples and then give a partial answer to this problem (see Proposition 4.8(ii)-(v)).

*Example 4.7* (a) Consider the flow on  $[-\frac{\pi}{2}, \frac{\pi}{2}]$  defined by

$$\varphi(t, x) := \arctan(\tan x - t), x \in [-\pi/2, \pi/2], t \in \mathbb{R}.$$

It belongs to the differential equation  $y' = -\cos^2 y$ , and a continuous function  $h : [-\frac{\pi}{2}, \frac{\pi}{2}] \rightarrow \mathbb{R}$  with  $h(-\frac{\pi}{2}) \leq h(\frac{\pi}{2})$ . Then we have  $\underline{c}(h, \varphi) = h(-\frac{\pi}{2})$  and  $\bar{c}(h, \varphi) = h(\frac{\pi}{2})$ . The spectrum of the corresponding semigroup is given by

$$\sigma(A) = \{\lambda \in \mathbb{C} : h(-\pi/2) \leq \text{Re } \lambda \leq h(\pi/2)\}.$$

(b) Consider  $K = \{z \in \mathbb{C} : 1 \leq |z| \leq 2\} = \{r \cdot e^{i\omega} : \omega \in \mathbb{R}, 1 \leq r \leq 2\}$  and a continuous function  $\kappa : [1, 2] \rightarrow \mathbb{R}_+$ .

Let  $\tilde{\varphi}$  be the flow on  $K$  governed by the differential equation  $\dot{\omega} = \kappa(r)$ ,  $\dot{r} = 0$  (hence  $\tilde{\varphi}(t, r \cdot e^{i\omega}) = r \cdot e^{i(\omega + \kappa(r)t)}$ ).

For a continuous function  $h : K \rightarrow \mathbb{R}$  let  $\hat{h}(r) := \frac{1}{2\pi} \int_0^{2\pi} h(r \cdot e^{it}) dt$  ( $1 \leq r \leq 2$ ). The spectrum of the semigroup corresponding to  $\tilde{\varphi}$  and  $h$  (cf. (4.1)) is given by

$$\sigma(A) = \{\hat{h}(r) + ik\kappa(r) : k \in \mathbb{Z}, 1 \leq r \leq 2\} \cup \{h(z) : \kappa(|z|) = 0\}.$$

**Proposition 4.8** *Suppose the semigroup  $(T(t))_{t \geq 0}$  on  $C(K)$  is given by (4.1) and let  $\underline{c}(h, \varphi)$ ,  $\bar{c}(h, \varphi)$  be defined as in (4.4). Then the following assertions hold.*

- (i)  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda > \bar{c}(h, \varphi)\} \subset \varrho(A)$ ,
- (ii)  $\bar{c}(h, \varphi)$  and  $\underline{c}(h, \varphi)$  are spectral values,
- (iii) If  $\varphi(t, x_0) = x_0$  for every  $t \geq 0$ , then  $h(x_0) \in R\sigma(A)$ ,
- (iv) Assume  $x_0$  has a finite orbit (i.e.,  $\varphi(\mathbb{R}_+, x_0) = \varphi([0, T], x_0)$  for some  $T < \infty$ ) and  $\tau := \inf\{t > 0 : \varphi(T+t, x_0) = \varphi(T, x_0)\} > 0$ , then  $\hat{h}(x_0) + \frac{2\pi}{\tau}i\mathbb{Z} \subset R\sigma(A)$  where  $\hat{h}(x_0) := \frac{1}{\tau} \int_T^{T+\tau} h(\varphi(s, x_0)) ds$ ,
- (v) If  $x_0$  has an infinite orbit and  $\hat{h} := \lim_{t \rightarrow \infty} h(\varphi(t, x_0))$  exists, then  $\hat{h} + i\mathbb{R} \subset \sigma(A)$ .

**Proof** (i) and (ii): A look at (4.4) shows that  $\bar{c}_t(h, \varphi) = 1/t \cdot \log \|T(t)\|$  hence  $\bar{c}(h, \varphi) = \omega_0(A)$  (cf. A-I, (1.1)). Consequently, we have  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda > \bar{c}(h, \varphi)\} \subset \varrho(A)$  and  $\bar{c}(h, \varphi) \in \sigma(A)$  by Theorem 1.6.

To prove  $\underline{c}(h, \varphi) \in \sigma(A)$ , we can assume by Theorem 4.4 that  $K_\infty = K_s$  for some  $s$  and that  $\varphi|_{K_\infty}$  is injective. It is easy to see that  $\underline{c}(h, \varphi) = \underline{c}(h|_{K_\infty}, \varphi|_{K_\infty})$ , moreover, we have  $\sigma(A|_{I_\infty}) = \emptyset$  hence  $\sigma(A) = \sigma(A|_{I_\infty})$  by A-III, Proposition 4.2. This shows that we also can assume that  $K = K_\infty$ , i.e.,  $\varphi$  is bijective or  $A$  is the generator of a group. Now the assertion follows from  $\underline{c}(h, \varphi) = \underline{c}(h, \varphi^{-1}) = -\bar{c}(-h, \varphi^{-1}) = -s(-A)$ .

(iii) and (iv): One can check easily that in case of (iii) the Dirac functional  $\delta_{x_0}$  is an eigenvector of  $A'$  corresponding to  $h(x_0)$ . A little bit more calculation is necessary to check that in case of (iv) the functional  $\Psi_k$  defined by

$$\Psi_k(f) := \int_T^{T+\tau} \exp\left(-i \cdot \frac{2\pi k}{\tau} \cdot t\right) \cdot h_t(x_0) \cdot f(\varphi(t, x_0)) dt \quad (k \in \mathbb{Z}, f \in C(K))$$

is an eigenvector of  $A'$  corresponding to  $\hat{h}(x_0) + i \cdot \frac{2\pi k}{\tau}$ .

(v) Given  $\beta \in \mathbb{R}$  we will show that  $\hat{h} + i\beta \in A_\sigma(A') \subseteq \sigma(A)$ . For  $n, m \in \mathbb{N}$  we define a linear functional  $\Psi_{nm}$  as

$$\Psi_{nm}(f) := \frac{1}{n} \int_0^n \exp(-(h^* + i\beta)t) \cdot h_t(\varphi(m, x_0)) \cdot f(\varphi(m+t, x_0)) dt, \quad f \in C(K).$$

For  $f \in D(A)$  we have

$$\begin{aligned} \langle (\hat{h} + i\beta - A)f, \Psi_{nm} \rangle &= \\ \frac{1}{n} \cdot \left( f(\varphi(m, x_0)) - e^{-i\beta n} \cdot \exp\left(\int_m^{m+n} (h(\varphi(s, x_0)) - \hat{h}) ds\right) f(\varphi(m+n, x_0)) \right). \end{aligned}$$

It follows that  $\varphi_{nm} \in D(A')$  and, since  $\lim_{t \rightarrow \infty} h(\varphi(t, x_0)) = \hat{h}$ ,

$$\limsup_{m \rightarrow \infty} \|(\hat{h} + i\beta - A')\Psi_{nm}\| \leq 1/n \text{ for every } n \in \mathbb{N}. \quad (4.13)$$

Because the orbit is infinite we have

$$\begin{aligned}\|\Psi_{nm}\| &= \frac{1}{n} \int_0^n \left| e^{-(\hat{h} + i\beta)t} h_t(\varphi(m, x_0)) \right| dt \\ &= \frac{1}{n} \int_0^n \exp \left( \int_m^{m+t} (h(\varphi(s, x_0)) - \hat{h}) ds \right) dt\end{aligned}$$

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which shows that

$$\lim_{m \rightarrow \infty} \|\Psi_{nm}\| = 1 \text{ for every } n \in \mathbb{N}. \quad (4.14)$$

In view of (4.13) and (4.14) it is not difficult to find a subsequence  $k(n)$  of  $\mathbb{N}$  such that  $(\Psi_{n, k(n)})$  is an approximate eigenvector of  $A'$  corresponding to  $\hat{h} + i\beta$ .  $\square$

We are now going to apply the results obtained so far to the special case where  $h = 0$ , i.e., we consider semigroups of lattice homomorphisms which are Markov operators.

**Theorem 4.9** *Suppose  $\mathcal{T}$  is a semigroup of Markov lattice homomorphisms on  $C(K)$  governed by the semiflow  $\varphi$ .*

- (i) *If  $\varphi|_{K_\infty}$  is not injective or if  $K_t \neq K_\infty$  for every  $t < \infty$ , then  $\sigma(A) = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda \leq 0\}$ .*
- (ii) *If  $K_\infty = K_s$  for some  $s$  and  $\varphi|_{K_\infty}$  is injective, then  $\sigma(A)$  is a cyclic closed subset of  $i\mathbb{R}$ . Moreover, we have  $\sigma(A) \neq i\mathbb{R}$  if and only if there is a  $T < \infty$  such that every orbit of  $\varphi$  has length less than  $T$  (i.e.,  $\varphi(\mathbb{R}_+, x) = \varphi([0, T], x)$  for every  $x \in K$ ).*

**Proof** (i) This is an immediate consequence of Theorem 4.4 and Proposition 4.8.

(ii) The first assertion follows from Theorem 4.4 and Theorem 4.1. Moreover, as in the proof of Theorem 4.4(ii) and (iii) we can assume without loss of generality that  $K = K_\infty$ , hence  $\varphi$  is bijective. If there is no upper bound for the length of the orbits, then  $\sigma(A) = i\mathbb{R}$  by assertions (iv) and (v) of Proposition 4.8.

Now we assume that the lengths of the orbits are bounded by  $T$ . Because  $\varphi$  is bijective, for every  $x \in K$  there exists a  $r = r_x$  with  $T/2 \leq r \leq T$  such that

$$\varphi(t, x) = \varphi(t + r, x) = \varphi(t + 2r, x) = \cdots = \varphi(t + kr, x) \quad (t \in \mathbb{R}_+, k \in \mathbb{N}).$$

Therefore we have for  $\lambda \in \mathbb{C}$ ,  $\operatorname{Re} \lambda > 0$ ,  $f \in C(K)$ ,  $x \in K$

$$\begin{aligned}(R(\lambda, A)f)(x) &= \int_0^\infty e^{-\lambda t} f(\varphi(t, x)) dt = \\ &= \sum_{k=0}^\infty e^{-\lambda kr} \int_{kr}^{(k+1)r} e^{-\lambda(t-kr)} f(\varphi(t-kr, x)) dt = \\ &= (1 - e^{-\lambda r})^{-1} \cdot \int_0^r e^{-\lambda t} f(\varphi(t, x)) dt.\end{aligned} \quad (4.15)$$

If  $0 < \beta < 2\pi/T$ , then the assumption  $T/2 \leq r \leq T$  implies that there exists a neighborhood  $U$  of  $\lambda_0 := i\beta$  such that the functions  $\lambda \mapsto (1 - \exp(-\lambda r_x))^{-1}$

are uniformly bounded on  $U$ , by  $M$  say. Then (4.15) implies that  $\|R(\lambda, A)f\| \leq M \left( \int_0^r |e^{-\lambda t}| dt \right) \|f\|$  for  $\lambda \in U$ ,  $\operatorname{Re} \lambda > 0$ , therefore  $\lambda_0 = i\beta \in \varrho(A)$ .  $\square$

*Remark 4.10* In case  $\sigma(A) \neq i\mathbb{R}$ , then  $\varphi|_{K_\infty}$  is bijective and has only finite orbits. Therefore every point  $x \in K_\infty$  has a well-defined period  $\tau_x := \inf\{\tau > 0 : \varphi(\tau, x) = x\}$ . A more detailed analysis yields the following description

$$\sigma(A) = \overline{\{i \cdot 2\pi k / \tau_x : k \in \mathbb{Z}, x \in K_\infty, \tau_x > 0\}} \cup \{0\}. \quad (4.16)$$

The inclusion “ $\subseteq$ ” can be derived from Theorem 4.11 which is stated below. The reverse inclusion follows from Proposition 4.8(d).

In our detailed discussion of the spectrum of lattice homomorphisms we restricted ourselves to the case where the space  $K$  is compact. The main reason is that there is no description as given in (4.1) of the semigroups for locally compact spaces  $X$ . In general, it is difficult to define a semiflow on  $X$  because points may tend to infinity in a finite time. But even if one can find a flow on a suitable compactification of  $C$ , it may be impossible to find a multiplier. This can be seen by studying the following example.

Suppose  $\varphi_1$  is a semiflow on a compact space  $K_1$  and  $K_0$  is a closed  $\varphi_1$ -invariant subset,  $h$  a continuous function on  $K_1$ . The semigroup  $(T_1(t))$  on  $C(K_1)$  corresponding to  $\varphi_1$  and  $h$  leaves the ideal  $I := \{f \in C(K_1) : f|_{K_0} = 0\}$  invariant and induces via restriction a semigroup  $(T(t))$  on  $I = C_0(X)$ , where  $X = K_1 \setminus K_0$ . In this case one can construct semi-flows associated with  $(T(t))$  on  $X \cup \{\infty\}$  or on  $\bar{X}$  (closure in  $K_1$ ), but in general one cannot find a corresponding multiplier which is defined on one of these compactifications.

The situation is much nicer when groups of lattice homomorphisms instead of semigroups are considered. In this case there is an analogue of (4.1) (cf. B-II, Theorem 3.14) and the spectrum can be described completely. For more details and the proof of the following result we refer to Arendt and Greiner [1].

**Theorem 4.11** *Suppose  $X$  is a locally compact space and  $(T(t))_{t \in \mathbb{R}}$  is a group of lattice homomorphisms governed by the flow  $\varphi$  and the multiplier  $h$ . Then we have*

(i)  $\sigma(A) = \sigma_1 \cup \sigma_2 \cup \sigma_3$  where the sets  $\sigma_i$  are defined as follows.

$$\begin{aligned} \sigma_1 &:= \overline{\{\hat{h}(x) + i \cdot 2\pi k / \tau_x : x \in X, 0 < \tau_x < \infty\}}, \\ \sigma_2 &:= \overline{\{h(x) : x \in X, \tau_x = 0\}}, \\ \sigma_3 &:= \{\lambda \in \mathbb{C} : \lambda + i\mathbb{R} \subseteq \sigma(A)\} \end{aligned}$$

(ii)  $\sigma(T(t)) = \overline{\exp(it\sigma(A))}$  for every  $t \geq 0$ .

(iii) Every isolated point of  $\sigma(A)$  is a first order pole of the resolvent.

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## Notes

Spectral theory for a single positive operator is an essential cornerstone for spectral theory of positive one-parameter semigroups. Many of the results we have presented in this chapter have analogues in the discrete case (i.e., for a single operator). This relation may serve as a guide. However, only in few cases can the continuous version be deduced directly from its discrete analogue. Therefore we will not try to trace back the roots of every result to the discrete version. Instead we refer to Schaefer [22] and the notes and references given there.

Many of the results we have presented in this chapter can be extended (more or less easily) to the more general setting of Banach lattices, which include the very important examples of  $L^p$ -spaces. Others are typical for  $C_0(X)$  and allow no extension. We will discuss this fact in more detail in Chapter C-III. The more general setting considered there also allows us to prove results for  $C_0(X)$  which we could not obtain staying within the framework of spaces of continuous functions.

*Section 1:* Theorem 1.1 was stated by Karlin [14], but a complete proof is given in Derndinger [6]. Proposition 1.5 is taken from Greiner [13] and Theorem 1.6 is (implicitly) contained in Derndinger and Nagel [8]. A generalization to (non-lattice) ordered Banach spaces can be found in Section 2.4 of Batty and Robinson [2].

*Section 2:* Lemma 2.3 dates back to Rota (see Schaefer [22]). Our approach follows Greiner [12]. The notion “(imaginary) additively cyclic” was introduced by Derndinger [6] (and Schaefer (1980) respectively). Derndinger proves some cyclicity results for the boundary spectrum. A result similar to Proposition 2.7 is given in Section 7.4 of Davies [4]. Lemma 2.8 in combination with C-III, Lemma 3.13 can be used to characterize semigroups whose spectral bound is a pole of finite algebraic multiplicity (see C-III, (3.19)). The hypothesis of Theorem 2.9 can be weakened, one only needs that  $s(A)$  is a pole of the resolvent (see C-III, Corollary 2.12). Further results on the cyclicity of the boundary spectrum will be given in Chapter C-III. In particular we refer to C-III, Theorems 2.10, 3.11 and 3.13. The dichotomy stated in (2.19) is probably the most interesting consequence of cyclicity results. It has far reaching consequences on the asymptotic behavior of positive semigroups. Example 2.13 is due to Davies (unpublished note). Example 3.4(ii) will be discussed in more detail and more generality in Section 3 of Chapter B-IV. We return to Remark 2.15(b) in Section 2 of B-IV.

*Section 3:* The concept of irreducibility as defined in 3.1 closely related to various other notions: In topological dynamics flows inducing irreducible semigroups are called “minimal flows” (cf. Example 3.4(i)). Moreover, “ergodicity” and “unique ergodicity” are closely related to irreducibility (see [?] or Krengel [15]). Irreducible semigroups are discussed to some extent in Davies [4]. E.g. he proves a special case of Theorem 3.6. Proposition 3.3 will be generalized in C-III, Proposition 3.3. Assertion (a) of Proposition 3.5 was proven by [?] while Theorem 3.6 is taken from Greiner [13]. Elliptic operators (more general than Example 3.4(ii)) as gener-

ators on spaces of continuous functions, were investigated by many people, e.g., [?], [?], [Roth (1976) & (1978)] and Stewart [24].

*Section 4:* Theorem 4.1 is due to Derndinger [7]. The spectrum of semigroups of Markov lattice homomorphisms is investigated by Derndinger and Nagel [8]. In particular they prove Theorem 4.4 for Markov semigroups. Earlier results are due to Scarpellini [19]. We indicated briefly in Example 4.6 that there is a relationship between spectral properties of lattice semigroups and differentiable dynamics. For more details we refer to Chicone and Swanson [3] and Sacker and Sell [18]. E.g., the “annular hull theorem” is a special case of Theorem 4.11(b). The general result 4.11 was proven by Arendt and Greiner [1].





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## **Chapter B-IV**

### **Asymptotics of Positive Semigroups on $C_0(X)$**



**Part C**  
**Positive Semigroups on Banach Lattices**



# Chapter C-I

## Basic Results on Banach Lattices and Positive Operators

This introductory chapter is intended to give a brief exposition of those results on Banach lattices and ordered Banach spaces which are indispensable for an understanding of the subsequent chapters. We do not give proofs of the results, since these can easily be found in the literature (e.g., in Schaefer [1]). We rather want to give the reader, who is unfamiliar with the results or the terminology used in this book, the necessary information for an intelligent reading of the main discussions. Since relatively few general results on ordered Banach spaces are needed, we will primarily talk about Banach lattices. The scalar field will be  $\mathbb{R}$  except for the last three sections, where complex Banach lattices will be discussed.

The notion of a Banach lattice was devised to obtain a common abstract setting within which one could talk about phenomena related to positivity. This has previously been studied in various types of spaces of real-valued functions, such as the spaces  $C(K)$  of continuous functions on a compact topological space  $K$ , the Lebesgue spaces  $L^1(\mu)$  or more generally the spaces  $L^p(\mu)$  constructed over a measure space  $(X, \Sigma, \mu)$  for  $1 \leq p \leq \infty$ . Thus it is a good idea to think of such spaces first in order to get a feeling for the concrete meaning of the abstract notions we introduce. Later we will see that the connections between *abstract* Banach lattices and the *concrete* function lattices  $C(K)$  and  $L^1(\mu)$  are closer than one might think at first. We will use without further explanation the terms *order relation* (ordering), *ordered set*, *majorant*, *minorant*, *supremum*, *infimum*.

By definition, a Banach lattice is a Banach space  $(E, \|\cdot\|)$  which is endowed with an order relation, usually written  $\leq$ , such that  $(E, \leq)$  is a lattice and the ordering is compatible with the Banach space structure of  $E$ . We elaborate this in more detail now. The axioms of compatibility between the linear structure of  $E$  and the order are

$$f \leq g \text{ implies } f + h \leq g + h \text{ for all } f, g, h \text{ in } E, \quad (\text{LO1})$$

$$f \geq 0 \text{ implies } \lambda f \geq 0 \text{ for all } f \text{ in } E \text{ and } \lambda \geq 0. \quad (\text{LO2})$$

Any (real) vector space with an ordering satisfying (LO<sub>1</sub>) and (LO<sub>2</sub>) is called an *ordered vector space*. The property expressed in (LO<sub>1</sub>) is sometimes called *trans-*

*lattice invariance* and implies that the ordering of an ordered vector space  $E$  is completely determined by the positive part  $E_+ = \{f \in E : f \geq 0\}$  of  $E$ . In fact, one has  $f \leq g$  if and only if  $g - f \in E_+$ .  $(LO_1)$  together with  $(LO_2)$  furthermore imply that the positive part of  $E$  is a convex set and a cone with vertex 0 (often called the *positive cone* of  $E$ ). It is easily verified that conversely any proper convex cone  $C$  with vertex 0 in  $E$  is the positive part of  $E$  with respect to a uniquely determined compatible ordering.

An ordered vector space  $E$  is called a *vector lattice* if any two elements  $f, g$  in  $E$  have a supremum, which is denoted by  $\sup(f, g)$  or by  $f \vee g$ , and an infimum, denoted by  $\inf(f, g)$  or by  $f \wedge g$ . It is obvious that the existence of, e.g., the supremum of any two elements in an ordered vector space implies the existence of the supremum of any finite number of elements in  $E$  and, since  $f \leq g$  is equivalent to  $-g \leq -f$  this automatically implies the existence of finite infima. However, suprema (infima) of infinite majorized subsets need not exist in a vector lattice. If they do, then the vector lattice is called *order complete* (*countably order complete* or  *$\sigma$ -order complete* if suprema of countable majorized subsets exist). At any rate, the binary relations *sup* and *inf* in a vector lattice automatically satisfy the (infinite) distributive laws

$$\begin{aligned}\inf(\sup_{\alpha} f_{\alpha}, h) &= \sup(\inf_{\alpha}(f_{\alpha}, h)), \\ \sup(\inf_{\alpha} f_{\alpha}, h) &= \inf(\sup_{\alpha}(f_{\alpha}, h)),\end{aligned}$$

whenever one side exists. This gives rise to the following definitions.

$$\begin{aligned}\sup(f, -f) &= |f| \text{ is called the } \textit{absolute value} \text{ of } f, \\ \sup(f, 0) &= f^+ \text{ is called the } \textit{positive part} \text{ of } f, \\ \sup(-f, 0) &= f^- \text{ is called the } \textit{negative part} \text{ of } f.\end{aligned}$$

Note that the negative part of  $f$  is positive. We call two elements  $f, g$  of a vector lattice *orthogonal* or *lattice disjoint* and write  $f \perp g$  if  $\inf(|f|, |g|) = 0$ .

Apart from this, the above definitions allow us to formulate the axiom of compatibility between norm and order requested in a Banach lattice in the following short way.

$$|f| \leq |g| \text{ implies } \|f\| \leq \|g\|. \quad (LN)$$

A norm on a vector lattice is called a *lattice norm* if it satisfies (LN). With these notations we can now give the definition of a Banach lattice as follows.

*A Banach lattice is a Banach space  $E$  endowed with an ordering  $\leq$  such that  $(E, \leq)$  is a vector lattice and the norm on  $E$  is a lattice norm. By a normed vector lattice we understand a vector lattice endowed with a lattice norm.*

There is a number of elementary, but very important formulas valid in any vector lattice, such as



$$\begin{aligned}
f &= f^+ - f^- & |f + g| &\leq |f| + |g| \\
|f| &= f^+ + f^- & f + g &= \sup(f, g) + \inf(f, g)
\end{aligned}$$

(see, e.g., Schaefer [1]). Let us note in passing the following consequences.

- (i) The lattice operations  $(f, g) \mapsto \sup(f, g)$  and  $(f, g) \mapsto \inf(f, g)$  and the mappings  $f \mapsto f^+$ ,  $f \mapsto f^-$ ,  $f \mapsto |f|$  are uniformly continuous.
- (ii) The positive cone is closed.
- (iii) *Order intervals*, i.e., sets of the form

$$[f, g] = \{h \in E : f \leq h \leq g\}$$

are closed and bounded.

Instead of dwelling upon a detailed discussion of the above equalities and inequalities let us rather formulate the following principle, which allows us to verify any of them and to invent, prove or disprove new ones whenever necessary.

*Any general formula relating a finite number of variables to each other by means of lattice operations and/or linear operations is valid in any Banach lattice as soon as it is valid in the real number system.*

In fact, we see below that any Banach lattice  $E$  is, as a vector lattice, *locally* of type  $C(X)$ , more exactly: Given any finite number  $x_1, \dots, x_n$  of elements in  $E$ , there is a compact topological space  $X$  and a vector sublattice  $J$  of  $E$  which is isomorphic to  $C(X)$  and contains  $x_1, \dots, x_n$  (see Section. 4). The above principle is an easy consequence of the following: In a space  $C(X)$  it is clear that a formula of the type considered need only be verified pointwise, i.e., in  $\mathbb{R}$ .

The reader may now be prepared to follow a concise presentation of the most basic facts on Banach lattices.

## 1 Sublattices, Ideals, Bands

The notion of a *vector sublattice* of a vector lattice  $E$  is self-explanatory, but it should be pointed out that a vector subspace  $F$  of  $E$  which is a vector lattice for the ordering induced by  $E$  need not be a vector sublattice of  $E$  (formation of suprema may differ in  $E$  and in  $F$ ), and that a vector sublattice need not contain (or may lead to different) infinite suprema and infima. The following are necessary and sufficient conditions on a vector subspace  $G$  of  $E$  to be a vector sublattice.

- (a)  $|h| \in G$  for all  $h \in G$ ,
- (b)  $h^+ \in G$  for all  $h \in G$ ,
- (c)  $h^- \in G$  for all  $h \in G$ .

A subset  $B$  of a vector lattice is called *solid* if  $f \in B$ ,  $|g| \leq |f|$  implies  $g \in B$ . Thus a norm on a vector lattice is a lattice norm if and only if its unit ball is solid. A solid linear subspace is called an *ideal*. Ideals are automatically vector sublattices

since  $|\sup(f, g)| \leq |f| + |g|$ . On the other hand, a vector sublattice  $F$  is an ideal in  $E$  if  $g \in F$  and  $0 \leq f \leq g$  imply  $f \in F$ . A *band* in a vector lattice  $E$  is an ideal which contains arbitrary suprema, or more exactly:

*$B$  is a band in  $E$  if  $B$  is an ideal in  $E$  and  $\sup M$  is contained in  $B$  whenever  $M$  is contained in  $B$  and has a supremum in  $E$ .*

Since the notions of sublattice, ideal, band are invariant under the formation of arbitrary intersections there exists, for any subset  $B$  of  $E$ , a uniquely determined smallest sublattice (ideal, band) of  $E$  containing  $B$ , i.e., the *sublattice (ideal, band) generated by  $B$* .

If we denote by  $B^d$  the set  $\{h \in E : \inf(|h|, |f|) = 0 \text{ for all } f \in B\}$ , then  $B^d$  is a band for any subset  $B$  of  $E$ , and  $(B^d)^d = B^{dd}$  is a band containing  $B$ . If  $E$  is a normed vector lattice (more generally, if  $E$  is archimedean ordered, see e.g., Schaefer [1]), then  $B^{dd}$  is the band generated by  $B$ .

If two ideals  $I, J$  of a vector lattice  $E$  have trivial intersection  $\{0\}$ , then  $I$  and  $J$  are *lattice disjoint*, i.e.,  $I \subset J^d$ . Thus if  $E$  is the direct sum of two ideals  $I, J$ , then one has automatically  $I = J^d$  and  $J = I^d$ , hence  $I = I^{dd}$  and  $J = J^{dd}$  must be bands in this situation. In general, an ideal  $I$  need not have a complementary ideal  $J$  even if  $I = I^{dd}$  is a band. This amounts to the same as saying that even if  $I = I^{dd}$  (which is always true if  $I$  is a band in a normed vector lattice) one need not necessarily have  $E = I + I^d$ .

An ideal  $I$  is called a *projection band* if it does have a complementary ideal, and in this case the projection of  $E$  onto  $I$  with kernel  $I^d$  is called the *band projection* belonging to  $I$ . An example of a band which is not a projection band is furnished by the subspace of  $C([0, 1])$  consisting of the functions vanishing on  $[0, 1/2]$ .

The *Riesz Decomposition Theorem* asserts that in an order complete vector lattice every band is a projection band. As a consequence, if  $E$  is order complete and  $B$  is an arbitrary subset of  $E$ , then  $E$  is the direct sum of the complementary bands  $B^d$  and  $B^{dd}$ .

This theorem, which is quite easy to prove, is widely used in analysis and gives an abstract background to, e.g., the decomposition of a measure into atomic and diffuse parts (the atomic measures being those contained in the band generated by the point measures, the diffuse measures those disjoint to the latter). Or, more specifically, to the well-known decomposition of a measure on  $[a, b]$  into an atomic part and a diffuse part, which latter can in turn be decomposed into the sum of a measure which is *absolutely continuous* (which means, contained in the band generated by Lebesgue measure) and a *singular measure* (which means, a diffuse measure disjoint to Lebesgue measure).

A band in a normed vector lattice is necessarily closed. By contrast, an ideal need not be closed, but the closure of an ideal is again an ideal. The situation, where every closed ideal is a band, will be briefly discussed in Section 5.

## 2 Order Units, Weak Order Units, Quasi-Interior Points

An element  $u$  in the positive cone of a vector lattice  $E$  is called an *order unit* if the ideal generated by  $u$  is all of  $E$ . If the band generated by  $u$  is all of  $E$  (which is equivalent to  $\{u\}^d = 0$  whenever  $E$  is archimedean, hence in particular if  $E$  is a normed vector lattice), then  $u$  is called a *weak order unit* of  $E$ . If  $E$  is a Banach lattice, then any order unit in  $E$  is an interior point of the positive cone  $E_+$ , and conversely any interior point of  $E_+$  must be an order unit of  $E$ . Every space  $C(K)$  has order units (namely, the strictly positive functions), and conversely by the Kakutani-Krein Representation Theorem (see Section 4), every Banach lattice with an order unit is isomorphic to a space  $C(K)$ .

If an element  $u$  in the positive cone of a Banach lattice  $E$  has the property that the closed ideal generated by  $u$  is all of  $E$ , then  $u$  is called a *quasi-interior point* of  $E_+$ . Quasi-interior points of the positive cone exist, e.g., in any separable Banach lattice. If  $E = C(K)$ , then the quasi-interior points and the interior points of  $E_+$  coincide, while the weak order units of  $E$  are the (positive) functions vanishing on a nowhere dense subset of  $K$ . If  $E$  is a space  $L^p(\mu)$  with  $\sigma$ -finite  $\mu$  and  $1 \leq p < \infty$ , then the weak order units and the quasi-interior points of  $E_+$  coincide with the functions strictly positive  $\mu$ -a.e., while  $E_+$  does not contain any interior point.

## 3 Linear Forms and Duality

A linear functional  $\varphi$  on a vector lattice  $E$  is called

- order-bounded* if  $\varphi$  is bounded on order intervals of  $E$ ,
- positive* if  $\varphi(f) \geq 0$  for all  $f \geq 0$ ,
- strictly positive* if  $\varphi(f) > 0$  for all  $f > 0$ .

Any positive linear functional is order bounded, and the positive functionals form a proper convex cone with vertex 0 in the linear space  $E^\#$  of all order bounded functionals, thus defining a natural ordering (given by  $\varphi \leq \psi$  if and only if  $\varphi(f) \leq \psi(f)$  for all  $f \in E_+$ ) under which  $E^\#$  is an order complete vector lattice. In particular, positive part, negative part and absolute value exist for any order bounded functional on  $E$ , the absolute value of  $\varphi \in E^\#$  being given by

$$|\varphi|(f) = \sup\{\varphi(h) : |h| \leq f \text{ for } f \in E_+ \}.$$

As a consequence, one has  $|\varphi(f)| \leq |\varphi|(|f|)$  for all  $f$  in  $E$  whenever  $\varphi$  is order bounded, and  $|\varphi(f)| \leq \varphi(|f|)$  if and only if  $\varphi$  is positive. An order bounded linear functional  $\varphi$  is called *order-continuous* ( $\sigma$ -order-continuous) if both positive and negative part of  $\varphi$  have the property that they transform any decreasing net (any decreasing sequence) with infimum 0 into a net (sequence) converging to 0 in  $\mathbb{R}$ . The order-continuous ( $\sigma$ -order-continuous) functionals form a band in  $E^\#$ .

In general, a vector lattice  $E$  need not admit any non-zero order-bounded linear functional. However, if  $E$  is a normed lattice, then any continuous functional is order-bounded, and if  $E$  is a Banach lattice, then one has coincidence between  $E^\#$  and  $E'$ . Still, order-continuous functionals  $\neq 0$  need not exist on a Banach lattice. Situations where every order-bounded functional is order-continuous will be briefly discussed in Section 5.

If  $E$  is a Banach lattice, then the dual norm on  $E' = E^\#$  is a lattice norm, hence  $E'$  is an order-complete Banach lattice under the natural norm and order. The evaluation map from  $E$  into the second dual  $E''$  is a lattice homomorphism (for the definition see Section 6) into the band of order-continuous functionals on  $E'$ . In particular, every dual Banach lattice  $E$  admits sufficiently many order-continuous functionals to separate the points of  $E$ .

## 4 AM- and AL-Spaces

If the norm on a Banach lattice  $E$  satisfies

$$\|\sup(f, g)\| = \sup(\|f\|, \|g\|) \text{ for } f, g \in E_+, \quad (\text{M})$$

then  $E$  is called an abstract M-space or an *AM-space*. If, in addition, the unit ball of  $E$  contains a largest element  $u$ , then  $u$  must be an order unit of  $E$  and  $E$  is then called an *(AM)-space with unit*. Condition (M) in  $E$  implies that in the dual of  $E$  one has

$$\|f + g\| = \|f\| + \|g\| \text{ for } f, g \in E'_+. \quad (\text{L})$$

Any Banach lattice satisfying (L) is called an abstract L-space or an *AL-space*. Thus the dual of an AM-space is an AL-space.

It is quite easy to verify that, on the other hand, the dual of an AL-space is an AM-space with unit, the unit being the uniquely determined linear functional that coincides with the norm on the positive cone. Putting this together, one gets that the second dual of an AM-space  $E$  is an AM-space with unit. If  $E$  already has a unit  $u$ , then  $u$  is also the unit of  $E''$ , so that the ideal of  $E''$  generated by  $E$  is all of  $E''$ . By contrast, if  $E$  is an AL-space, then  $E$  is an ideal (even a band) in  $E''$ . Infinite-dimensional AL- or AM-spaces are never reflexive.

The importance of AL- and AM-spaces in the general theory of Banach lattices is due to the fact that these spaces have very special concrete representations as function lattices and that, on the other hand, any general Banach lattice  $E$  is in a very intimate way connected to certain families of AL- and AM-spaces canonically associated with  $E$ . Let us first discuss the natural representations of AM- and AL-spaces.

If  $E$  is an AM-space with unit  $u$ , then the set  $K$  of lattice homomorphisms from  $E$  into  $\mathbb{R}$  taking the value 1 on  $u$  is a non-empty,  $\sigma(E', E)$ -compact subset of  $E'$  and the natural evaluation map from  $E$  into  $\mathbb{R}^K$  maps  $E$  isometrically onto the continuous real-valued functions on  $K$  (cf. Section 6). This is the *Kakutani-Krein Repre-*

*sentation Theorem*, which is an order-theoretic counterpart to the Gelfand Representation Theorem in the theory of commutative  $C^*$ -algebras. If  $E$  is an AM-space without unit, then the second dual of  $E$  has a unit and thus gives a representation of  $E$  as a closed sublattice of a space  $C(K)$ .

If  $E$  is an AL-space, then the representation of the dual of  $E$  as a space  $C(K)$  leads to an interpretation of the elements of the bidual of  $E$  as Radon measures on  $K$ .

If  $E_+$  has a quasi-interior point  $h$ , then in this interpretation  $E$  consists exactly of the measures absolutely continuous with respect to (the measure corresponding to)  $h$ , thus by the *Radon-Nikodym-Theorem*,  $E = L^1(K, h)$ . In general, a similar argument leads to a representation of  $E$  as a space  $L^1(X, \mu)$  constructed over a locally compact space  $X$ .

If  $E$  is an arbitrary Banach lattice and  $f \in E_+$ , then the ideal  $I$  generated by  $f$  in  $E$  (which is the union of the positive multiples of the interval  $[-f, f]$ ) can be made into an AM-space with unit  $f$  by endowing it with the gauge function  $p_f$  of  $[-f, f]$ . We denote  $(I, p_f)$  by  $E_f$ . On the other hand, if  $f'$  is a positive linear functional on  $E$ , then the mapping  $q_{f'}: f \mapsto \langle |f|, f' \rangle$  is a semi-norm on  $E$ . The kernel  $J$  of  $q_{f'}$  is an ideal in  $E$ , and the completion of  $E/J$  with respect to the norm canonically derived from  $q_{f'}$  becomes an AL-space which we denote by  $(E, x')$ . A good illustration for these constructions is the following.

If  $E = C(K)$  and if  $\mu$  is a positive linear form (Radon measure) on  $E$ , then  $(E, \mu)$  is just  $L^1(K, \mu)$ ; if  $E = L^p(\mu)$  ( $1 \leq p < \infty$ ,  $\mu$  finite), then  $E_{1_X} = L^\infty(\mu)$ .

## 5 Special Connections Between Norm and Order

If an increasing net  $(x_\alpha)_{\alpha \in A}$  in a normed vector lattice is convergent, then its limit must be the supremum as a consequence of the closedness of the positive cone. On the other hand, if  $\{x_\alpha: \alpha \in A\}$  has a supremum, the net  $(x_\alpha)_{\alpha \in A}$  need not converge. A Banach lattice is said to have *order-continuous norm* ( $\sigma$ -*order-continuous norm*) if any increasing net (sequence) which has a supremum is automatically convergent. This is of course equivalent to saying that any decreasing net (sequence) with an infimum is convergent. Since infimum and limit must coincide, the order continuity ( $\sigma$ -order continuity) of the norm in a Banach lattice is also equivalent to the property that any decreasing net (sequence) with infimum 0 converges to 0.

A Banach lattice with order-continuous norm must be order complete, but  $\sigma$ -order-continuity of the norm need not imply order completeness. At any rate, one has the following characterization.

A Banach lattice  $E$  has order-continuous norm if and only if any one of the following equivalent assertions holds.

- (a)  $E$  is  $\sigma$ -order complete and has  $\sigma$ -order-continuous norm.
- (b) Every order interval in  $E$  is weakly compact.
- (c)  $E$  is (under evaluation) an ideal in  $E''$ .
- (d) Every continuous linear form on  $E$  is order continuous.

(e) Every closed ideal in  $E$  is a projection band.

An even more stringent condition than order-continuity of the norm is that any increasing norm-bounded net be convergent. This condition is satisfied if and only if any one of the following equivalent assertions holds.

- (a)  $E$  is (under evaluation) a band in  $E''$ .
- (b)  $E$  is weakly sequentially complete.
- (c) Every order-continuous linear form on  $E'$  belongs to  $E$ .
- (d) No closed sublattice of  $E$  is isomorphic to  $c_0$ .

The most important examples of non-reflexive Banach lattices with this property are the AL-spaces.

## 6 Positive Operators, Lattice Homomorphisms

A linear mapping  $T$  from an ordered Banach space  $E$  into an ordered Banach space  $F$  is called *positive* (notation:  $T \geq 0$ ) if  $Tf \in F_+$  for all  $f \in E_+$ ;  $T$  is called *strictly positive* if  $T \geq 0$  and  $\{f \in E: T|f| = 0\} = \{0\}$ . The set of all positive linear mappings is a convex cone in the space  $LE, F$  of all linear mappings from  $E$  into  $F$  defining the *natural ordering* of  $LE, F$ . The linear subspace of  $LE, F$  generated by the positive maps (i.e. the space of linear maps that can be written as differences of positive maps) is denoted by  $\mathcal{L}^r(E; F)$  and its elements are called *regular mappings*. If  $E$  and  $F$  are Banach lattices, then any regular mapping from  $E$  into  $F$  is continuous, but  $\mathcal{L}^r(E; F)$  is in general a proper subspace of the space  $LE, F$  of all continuous linear mappings. One has coincidence of  $\mathcal{L}^r(E; F)$  and  $LE, F$ , e.g., when  $E = F$  is an order complete AM-space with unit or an AL-space. At any rate, if  $F$  is order complete, then  $\mathcal{L}^r(E; F)$  under the natural ordering is an order-complete vector lattice, and a Banach lattice under the norm

$$T \mapsto \|T\|_r = \||T|\|,$$

the right hand side denoting the operator norm of the absolute value of  $T$ . The absolute value of  $T \in \mathcal{L}^r(E; F)$ , if it exists, is given by

$$|T|(f) := \sup\{Th: |h| \leq f, f \in E_+\}.$$

Thus  $T$  is positive if and only if  $|Tf| \leq T|f|$  holds for any  $f$  in  $E$ .

An operator  $T \in LE, F$  is called a *lattice homomorphism* if  $|Tf| = T|f|$  holds for all  $f \in E$ . Lattice homomorphisms are alternatively characterized by any one of the following conditions holding for all  $f$ , and  $g \in E$ .

- (i)  $(Tf)^+ = T(f^+)$ ,
- (ii)  $(Tf)^- = T(f^-)$ ,
- (iii)  $T(f \vee g) = Tf \vee Tg$ ,
- (iv)  $T(f \wedge g) = Tf \wedge Tg$ ,

$$(v) \quad T(f^+) \wedge T(f^-) = 0.$$

The kernel of a lattice homomorphism is an ideal. If  $T$  is bijective, then  $T$  is a lattice homomorphism if and only if  $T$  and  $T^{-1}$  are positive.

## 7 Complex Banach Lattices

Although the notion of a Banach lattice is intrinsically related to the real number system, it is possible and often desirable to extend discussions to complexifications of Banach lattices in such a way that the order-related terms introduced in the real situation essentially retain their meaning. Thus we define a *complex Banach lattice*  $E$  to be the complexification of a real Banach lattice  $E_{\mathbb{R}}$  in the sense that

$$E = E_{\mathbb{R}} \oplus iE_{\mathbb{R}}$$

which means more exactly  $E = E_{\mathbb{R}} \times E_{\mathbb{R}}$  with scalar multiplication

$$(\alpha + i\beta)(x, y) = (\alpha x - \beta y, \beta x + \alpha y).$$

The space  $E_{\mathbb{R}}$  will sometimes be called the *underlying real Banach lattice* or the *real part* of  $E$ . The classical complex Banach spaces  $C(X)$ ,  $L^p(\mu)$  are complex Banach lattices in this sense, the underlying real Banach lattices being the corresponding (real) subspaces of real-valued functions. We want to extend the formation of absolute values, which is a priori defined only in the real part of  $E$ , in such a way that in the classical situation  $E = C(X)$  or  $E = L^p(\mu)$  the usual absolute value of a function is obtained. This is in fact possible by putting, for  $h = f + ig$  in  $E$ ,

$$|h| = \sup\{\operatorname{Re}(e^{i\vartheta} h) : 0 \leq \vartheta \leq 2\pi\}.$$

The only problem with this definition being the existence of the right hand side without the assumption of order-completeness on  $E_{\mathbb{R}}$ . But for this we just have to observe that the set  $M = \{\operatorname{Re}(e^{i\vartheta} h) : 0 \leq \vartheta \leq 2\pi\}$  is contained and order bounded in the ideal generated in  $E_{\mathbb{R}}$  by  $|f| + |g|$ , which in turn is by the Kakutani-Krein Representation Theorem isomorphic to a space  $C_{\mathbb{R}}(X)$  under the pointwise ordering. Now the pointwise supremum of  $M$  in  $\mathbb{R}^X$  is readily seen to be a continuous function (namely, the modulus of the complex valued continuous function corresponding to  $f + ig$ ), so that  $M$  has a supremum in  $C_{\mathbb{R}}(X) = (E_{\mathbb{R}})_{|f|+|g|}$ . Since the mapping  $f \mapsto |f|$  now has a meaning in  $E$ , the definition of an ideal can be extended formally unchanged to the complex situation. We observe that  $|f + ig| = |f - ig| \leq |f| + |g|$  implies that any ideal  $J$  in a complex Banach lattice is conjugation invariant and itself the complexification of the ideal  $J \cap E_{\mathbb{R}}$  of the real part of  $E$ .

Suffice it now to say that the meaning of most of the terms introduced for real Banach lattices can be extended to the complex situation under retention (*mutatis*

mutandis) of the corresponding results valid in the real case by either using the complex modulus or else, if the formation of suprema or infima is involved, by relating them to real parts. For example  $f \in E$  is called *positive* if  $f = |f|$  which means that  $f$  is a positive element of  $E_{\mathbb{R}}$ ,  $E$  is called order complete if  $E_{\mathbb{R}}$  is order complete, and an ideal  $J$  is called a band if the real part of  $J$  is a band. We refer to Chapter II, Section 11 of Schaefer [1] for a detailed discussion of this and restrict ourselves to a short discussion of linear mappings.

Let  $E$  and  $F$  be complex Banach lattices with real parts  $E_{\mathbb{R}}$  and  $F_{\mathbb{R}}$ . Then a linear mapping  $T$  from  $E$  into  $F$  is determined by its restriction  $T_0$  to  $E_{\mathbb{R}}$ , and  $T_0$  can be written in the form  $T_0 = T_1 + iT_2$  with real-linear mappings  $T_j$  from  $E_{\mathbb{R}}$  into  $F_{\mathbb{R}}$ . Thus  $L(E, F)$  is the complexification of the real linear space  $L(E_{\mathbb{R}}, F_{\mathbb{R}})$ . With the above notation,  $T$  is called *real* if  $T_2 = 0$ , *positive* if  $T$  is real and  $T_1$  is positive, and a *lattice homomorphism* if  $T$  is real and  $T_1$  is a lattice homomorphism. Lattice homomorphisms are characterized by the equality  $|Th| = T|h|$  as in the real case.

## 8 The Signum Operator

We discuss in some detail how a mapping of the form

$$g \mapsto (\text{sign } f)g$$

which has an obvious meaning, depending on  $f$ , in spaces  $C(K)$ , can be defined in an abstract complex Banach lattice. We prove the following

Let  $E$  be a complex Banach lattice and let  $f \in E$ . If either  $E$  is order-complete or  $|f|$  is a quasi-interior point in  $E_+$ , then there exists a unique linear mapping  $S_f$ , called the *signum operator* with respect to  $f$ , with the following properties.

- (i)  $S_f \bar{f} = |f|$ , where  $\bar{f} = \text{Re}(f) - i \cdot \text{Im}(f)$ ,
- (ii)  $|S_f g| \leq |g|$  for every  $g$  in  $E$ ,
- (iii)  $S_f g = 0$  for every  $g$  in  $E$  orthogonal to  $f$ .

In fact, if  $E = C(K)$  and if  $|f|$  is a quasi-interior point in  $E$ , then  $|f|$  is a strictly positive function and multiplication with the function  $\text{sign } f = f \cdot |f|^{-1}$  has the desired properties. Uniqueness follows from Zaanen [2, Chap. 20]. We reduce the general situation to the case just considered in the following way.

- If  $|f|$  is quasi-interior to  $E_+$ , then  $E_{|f|}$  is a dense subspace of  $E$  isomorphic to a space  $C(K)$ , and with the above arguments one gets a uniquely determined operator  $S_0$  on  $E_{|f|}$  with the desired properties. Since (ii) implies the continuity of  $S_0$  for the norm induced by  $E$ ,  $S_0$  can be extended to  $E$ .
- If  $f$  is arbitrary, then, as above, one gets an operator  $S_0$  on  $E_{|f|}$  with (i) and (ii). If  $E$  is order complete, an extension  $S_f$  of  $S_0$  to  $E$  satisfying (i)–(iii) is possible as soon as  $S_0$  can be extended to the band  $\{x\}^{dd}$  of  $E$ .
  - On the complementary band  $\{x\}^d$  one has necessarily the values  $= 0$  for  $S_f$ .



- The extension to  $\{x\}^{dd}$  is obtained as follows: If  $S_0$  is positive (which means  $f \geq 0$ ), then

$$S_f h = \sup\{S_f g : g \in [0, h] \cap E_{|f|} \text{ for } h \geq 0\}$$

will do.

In general, the problem can be reduced to this situation by decomposing  $S_0$  into a sum of the form  $S_0 = (S_1 - S_2) + i(S_3 - S_4)$  with positive operators  $S_j$ . Such a decomposition of  $S_0$  exists since the order completeness of  $E$  implies the order completeness of  $E_{|f|} = C(K)$  and since every continuous linear operator on a space  $C(K)$  is necessarily order-bounded.

## 9 The Center of $\mathcal{L}(E)$

We give a short description of a special, but important class of operators. Let  $E$  be a (complex) Banach lattice. For  $T \in \mathcal{L}(E)$  the following conditions are equivalent.

- (a)  $f \perp g$  implies  $Tf \perp g$  ( $f, g \in E$ ),
- (b)  $\pm T \leq \|T\|\text{Id}$ ,
- (c)  $TJ \subseteq J$  for every ideal  $J$  in  $E$ .

If  $E$  is countably order complete, then this is equivalent to:

- (d)  $TJ \subseteq J$  for every projection band  $J$  in  $E$ .

The last assertion also means that  $T$  commutes with every band projection.

The set of all  $T \in \mathcal{L}(E)$  satisfying the above conditions is called the *center* of  $\mathcal{L}(E)$  and denoted  $\mathcal{Z}(E)$ . Under its natural ordering, the operator norm and the composition product is  $\mathcal{Z}(E)$  isomorphic to a Banach lattice algebra  $C(K)$  with  $K$  compact. The following examples may illustrate the situation and explain why the term *multiplication operator* is often used for operators in  $\mathcal{Z}(E)$ .

- (i) If  $E = L^p(X, \Sigma, \mu)$  ( $1 \leq p \leq \infty$ ) with  $\sigma$ -finite  $\mu$ , then  $\mathcal{Z}(E)$  is isomorphic to  $L^\infty(\mu)$  via the natural identification of a function  $f \in L^\infty(\mu)$  with the multiplication operator  $g \mapsto f \cdot g$  on  $E$ .
- (ii) If  $X$  is locally compact,  $E = C_0(X)$ , then similarly  $\mathcal{Z}(E) \cong C^b(X)$  via the identification of  $f \in C^b(X)$  with the mapping  $g \mapsto f \cdot g$  ( $g \in C_0(X)$ ).



## References

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**Chapter C-II**  
**Characterization of Positive Semigroups on**  
**Banach Lattices and Positive Operators**



## Chapter C-III

# Spectral Theory of Positive Semigroups on Banach Lattices

In Chapter B-III we have shown that positive semigroups on spaces  $C_0(X)$  possess several interesting spectral properties. Now we are going to extend many of these results to the more general setting of Banach lattices. We will improve some of them considerably and give the complete proof of B-III, Theorem 4.1. Throughout this chapter we will assume that  $E \neq \{0\}$  is a complex Banach lattice.

### 1 The Spectral Bound

The fact that the spectral bound of a positive semigroup is always contained in the spectrum (provided that the spectrum is non-empty) is also true in the general setting of Banach lattices. The proof given in B-III, Theorem 1.1 for spaces  $C_0(X)$  works in the general case too. Another proof is given below (cf. Corollary 1.4). Furthermore, Corollary 1.3 and Proposition 1.5 of B-III are true in the setting of Banach lattices and their proofs can be carried over to the general case. For the sake of completeness we summarize these results in the following theorem.

**Theorem 1.1** *Let  $A$  be the generator of a positive semigroup  $(T(t))_{t \geq 0}$  on a Banach lattice  $E$ .*

- (i)  $s(A) \in \sigma(A)$  unless  $\sigma(A) = \emptyset$ .
- (ii) For  $\lambda_0 \in \rho(A)$  we have  $R(\lambda_0, A)$  is positive if and only if  $\lambda_0 > s(A)$ . In this case  $r(R(\lambda_0, A)) = (\lambda_0 - s(A))^{-1}$ .
- (iii) If  $T(1)$  has a positive fixed vector  $h_0$ , then  $\ker(A)$  contains a positive element  $h$  such that  $h_0 \in E_{|h|}$ .
- (iv) If  $T(1)' \varphi_0 = \varphi_0$  for some  $\varphi_0 \in E'_+$ , then there exists  $\varphi \in D(A^*)_+$  with  $\{f \in E : \langle |f|, \varphi \rangle = 0\} \subseteq \{f \in E : \langle |f|, \varphi_0 \rangle = 0\}$  such that  $A^* \varphi = 0$ .

The fact that  $s(A)$  is always an eigenvalue of the adjoint (cf. B-III Theorem 1.6) is characteristic for spaces  $C(K)$ ,  $K$  compact, as can be seen by considering the Laplacian on  $L^p(\mathbb{R}^n)$ , where  $1 < p < \infty$ , or on  $C_0(\mathbb{R}^n)$  (see B-III, Example 1.7).

Another result which cannot be extended to arbitrary Banach lattices is that spectral bound and growth bound coincide (cf. B-IV, Theorem 1.4); an example is given in A-III, Example 1.3. Despite of this the resolvent  $R(\lambda, A)$  of a positive semigroup is given as the Laplace transform of the semigroup in the half-plane  $\{z \in \mathbb{C} : \operatorname{Re} z > s(A)\}$  (even in case that  $\omega_0(A) > s(A)$ ). Note however that the integral exists only as an improper Riemann integral. By Datko's Theorem (A-IV, Theorem 1.11) the function  $t \mapsto e^{-\lambda t} T(t)f$  cannot be Bochner integrable for all  $f \in E$  in the case  $\operatorname{Re} \lambda \leq \omega_0(A)$ .

**Theorem 1.2** *Suppose  $A$  is the generator of a positive semigroup  $(T(t))_{t \geq 0}$ . For  $\operatorname{Re} \lambda > s(A)$  we have*

$$R(\lambda, A)f = \lim_{t \rightarrow \infty} \int_0^t e^{-\lambda s} T(s)f \, ds \text{ for all } f \in E. \quad (1.1)$$

Moreover, the operators  $\int_0^t e^{-\lambda s} T(s) \, ds$  tend to  $R(\lambda, A)$  with respect to the operator norm as  $t \rightarrow \infty$ .

**Proof** We fix  $\lambda_0 > \omega_0(A)$ . Then, by A-I, Proposition 1.11,

$$R(\lambda_0, A)^{n+1} f = \frac{1}{n!} \int_0^\infty s^n \exp(-\lambda_0 s) T(s)f \, ds \quad (n \in \mathbb{N}_0, f \in E). \quad (1.2)$$

Given  $\mu$  such that  $s(A) < \mu < \lambda_0$ ,  $f \in E_+$ ,  $\varphi \in E'_+$ , then

$$\begin{aligned} \langle R(\mu, A)f, \varphi \rangle &= \sum_{n=0}^{\infty} (\lambda_0 - \mu)^n \langle R(\lambda_0, A)^{n+1} f, \varphi \rangle = \\ &= \sum_{n=0}^{\infty} \int_0^\infty \frac{1}{n!} (\lambda_0 - \mu)^n \exp(-\lambda_0 s) \langle T(s)f, \varphi \rangle \, ds = \\ &= \int_0^\infty \sum_{n=0}^{\infty} \frac{1}{n!} (\lambda_0 - \mu)^n \exp(-\lambda_0 s) \langle T(s)f, \varphi \rangle \, ds = \\ &= \int_0^\infty \exp((\lambda_0 - \mu)s) \exp(-\lambda_0 s) \langle T(s)f, \varphi \rangle \, ds = \\ &= \int_0^\infty \exp(-\mu s) \langle T(s)f, \varphi \rangle \, ds = \\ &= \lim_{t \rightarrow \infty} \left\langle \int_0^t \exp(-\mu s) T(s)f \, ds, \varphi \right\rangle. \end{aligned} \quad (1.3)$$

Note that one can interchange summation and integration because all the integrands are positive functions.

It follows from (1.3) that the net  $(\int_0^t \exp(-\mu s) T(s)f \, ds)_{t \geq 0}$  converges weakly to  $R(\mu, A)f$  for  $t \rightarrow \infty$ . Because it is monotone increasing ( $f \geq 0$ ), we have strong convergence (see the corollary to II. Theorem 5.9 in Schaefer [23]). If  $\lambda = \mu + i\nu$  with  $\mu, \nu$  real and  $\mu > s(A)$ , we have for arbitrary  $f \in E$ ,  $\varphi \in E'$



$$\left| \left\langle \int_r^t e^{-\lambda s} T(s) f \, ds, \varphi \right\rangle \right| \leq \int_r^t e^{-\mu s} \langle T(s) |f|, |\varphi| \rangle \, ds$$

$$\text{hence } \left\| \int_r^t e^{-\lambda s} T(s) f \, ds \right\| \leq \left\| \int_r^t e^{-\mu s} T(s) |f| \, ds \right\|$$

which shows that  $\lim_{t \rightarrow \infty} \int_0^t e^{-\lambda s} T(s) f \, ds$  exists. Thus  $R(\lambda, A)f = \int_0^\infty e^{-\lambda s} T(s) f \, ds$  by A-I, Proposition 1.11.

It remains to prove that the net  $\left( \int_0^t \exp(-\mu s) T(s) \, ds \right)_{t \geq 0}$  converges with respect to the operator norm. We fix  $\mu$  such that  $s(A) < \mu < \operatorname{Re} \lambda$ . As we have seen above, the map  $s \mapsto e^{-\mu s} \langle T(s) f, \varphi \rangle$  is Lebesgue integrable for every  $(f, \varphi) \in E \times E'$ , thus defining a bilinear map  $b: E \times E' \rightarrow L^1(\mathbb{R}_+)$ . Using the closed graph theorem, it is easy to see that  $b$  is separately continuous, hence jointly continuous by Schaefer [22, III. Theorem 5.1]. Thus there is a constant  $M$  such that

$$\int_0^\infty e^{-\mu s} |\langle T(s) f, \varphi \rangle| \, ds = \|b(f, \varphi)\| \leq M \|f\| \|\varphi\| \quad (f \in E, \varphi \in E'). \quad (1.4)$$

Given  $0 \leq t < r$  and setting  $\varepsilon := \operatorname{Re} \lambda - \mu$  we have

$$\begin{aligned} \left| \int_t^r e^{-\lambda s} \langle T(s) f, \varphi \rangle \, ds \right| &\leq \int_t^r \exp(-(\operatorname{Re} \lambda - \mu)s) e^{-\lambda s} |\langle T(s) f, \varphi \rangle| \, ds \\ &\leq e^{-\varepsilon t} \int_t^r e^{-\lambda s} |\langle T(s) f, \varphi \rangle| \, ds \leq e^{-\varepsilon t} M \|f\| \|\varphi\|. \end{aligned}$$

It follows that  $\left\| \int_t^r e^{-\lambda s} T(s) \, ds \right\| \leq M e^{-\varepsilon t}$ , hence  $\left( \int_0^t e^{-\lambda s} T(s) \, ds \right)_{t \geq 0}$  is a Cauchy net with respect to the operator norm.  $\square$

Theorem 1.2 has many consequences. In particular, we can conclude that  $s(A) \in \sigma(A)$  whenever  $s(A) > -\infty$  (without using the analogous result for bounded operators, cf. Corollary 1.4 below).

In each of the following corollaries we assume that  $A$  is the generator of a positive semigroup on a Banach lattice  $E$ .

**Corollary 1.3** *If  $\operatorname{Re} \lambda > s(A)$ , then we have*

$$|R(\lambda, A)f| \leq R(\operatorname{Re} \lambda, A)|f| \quad (f \in E). \quad (1.5)$$

The proof is an immediate consequence of Theorem 1.2.

**Corollary 1.4** *We have  $s(A) \in \sigma(A)$  unless  $s(A) = -\infty$ .*

**Proof** Assume that  $s(A) > -\infty$  and  $s(A) \notin \sigma(A)$ , then it follows from (1.5) that  $\{R(\lambda, A) : \operatorname{Re} \lambda > s(A)\}$  is uniformly bounded in  $\mathcal{L}(E)$ , by  $M$  say. Then  $\{z \in \mathbb{C} : \operatorname{Re} z = s(A)\} \subseteq \varrho(A)$  and  $\|R(z, A)\| \leq M$  for  $z$  with  $\operatorname{Re} z = s(A)$ . It follows that  $\{z \in \mathbb{C} : |\operatorname{Re} z - s(A)| < M^{-1}\} \subseteq \varrho(A)$ , which is absurd by the definition of  $s(A)$ .  $\square$

**Corollary 1.5** *Suppose that  $s(A)$  is a pole of order  $m$  of the resolvent  $R(\lambda, A)$ . Then  $m$  is a majorant for the order of any other pole on the line  $s(A) + i\mathbb{R}$ .*

**Proof** Without loss of generality we may assume that  $s(A) = 0$ . By (1.5) we have  $\|R(\varepsilon + i\beta, A)\| \leq \|R(\varepsilon, A)\|$  for every  $\beta \in \mathbb{R}$ ,  $\varepsilon > 0$ . Therefore  $\lim_{\varepsilon \rightarrow 0} \|\varepsilon^k R(\varepsilon + i\beta, A)\| \leq \lim_{\varepsilon \rightarrow 0} \|\varepsilon^k R(\varepsilon, A)\| = 0$  for  $k > m$ .  $\square$

The spectrum of a positive semigroup may be empty (see B-III, Example 1.2(a)) and the spectrum of a general group may be empty as well (see Hille and Phillips [12, Section 23.16]). However, for positive groups this cannot occur. More precisely, we have the following result

**Corollary 1.6** *If  $A$  is the generator of a positive group, then  $\sigma(A) \cap \mathbb{R} \neq \emptyset$ .*

**Proof** Both  $A$  and  $-A$  are generators of positive semigroups, hence if  $\sigma(A) = \emptyset$ , then  $s(A) = s(-A) = -\infty$  and (1.5) implies that

$$\{R(\lambda, A) : \operatorname{Re} \lambda \geq 0\} \cup \{R(\lambda, -A) : \operatorname{Re} \lambda \geq 0\}$$

is bounded in  $\mathcal{L}(E)$ , i.e.,  $\{R(\lambda, A) : \lambda \in \mathbb{C}\}$  is bounded. By Liouville's Theorem the function  $\lambda \mapsto R(\lambda, A)$  is constant, hence identically zero because  $\lim_{\lambda \rightarrow \infty} R(\lambda, A) = 0$ . Thus we arrive at a contradiction.  $\square$

We conclude this section by indicating possible extensions and further consequences of the results stated above.

**Remarks 1.7** (i) Many of the results of this section remain true for positive semigroups on ordered Banach spaces more general than Banach lattices. The interested reader is referred to Greiner et al. [11].

(ii) From Theorem 1.2 one can easily deduce that for positive semigroups on  $L^1$ -spaces spectral bound and growth bound coincide. To prove the analogous result for  $L^2$ -spaces one makes use of Corollary 1.3. For details we refer to C-IV, Theorem 1.1.

## 2 The Boundary Spectrum

In Chapter B-III we have seen that under suitable assumptions the boundary spectrum  $\sigma_b(A)$ , consisting of all spectral values with maximal real part is a cyclic set (cf. B-III, Definition 2.5). In the main theorem of this section we prove a result which is more general and which is true for arbitrary Banach lattices.

We first want to extend some of the notions used in B-III to the more general setting considered here. If  $E$  is a Banach lattice and  $f, g \in E$  such that  $g \in E_{|f|}$ , then  $(\operatorname{sign} f)g$  is well-defined (cf. Section 8 of C-I). Thus the following definition makes sense

**Definition 2.1** If  $E$  is a Banach lattice then for  $f \in E$ ,  $n \in \mathbb{Z}$  we define  $f^{[n]}$  recursively as follows

$$\begin{aligned} f^{[0]} &:= |f|, \\ f^{[n]} &:= (\operatorname{sign} f) f^{[n-1]} \text{ if } n > 0, \\ f^{[n]} &:= (\operatorname{sign} \bar{f}) f^{[n+1]} \text{ if } n < 0. \end{aligned} \quad (2.1)$$

Obviously, for  $E = C_0(X)$  this amounts to the same as B-III, Definition 2.2. Moreover, in case  $E$  is an  $L^p$ -space, then  $f^{[n]}$  is the function given by

$$f^{[n]}(x) = \begin{cases} (f(x)/|f(x)|)^{n-1} f(x) & \text{if } f(x) \neq 0, \\ 0 & \text{otherwise.} \end{cases} \quad (2.2)$$

The following properties are immediate consequences Definition 2.1

$$f^{[0]} = |f|, f^{[1]} = f, f^{[-1]} = \bar{f}, |f^{[n]}| = |f| \quad (n \in \mathbb{Z}) \quad (2.3)$$

$$f^{[n]} = (\operatorname{sign} f) f^{[n-1]} = (\operatorname{sign} \bar{f}) f^{[n+1]} \text{ for all } n \in \mathbb{Z}; \quad (2.4)$$

$$(\alpha f)^{[n]} = \alpha(\alpha/|\alpha|)^{n-1} f^{[n]} \text{ for } n \in \mathbb{Z}, \alpha \in \mathbb{C}, \alpha \neq 0. \quad (2.5)$$

Next we show that B-III, Theorem 2.4 is true for arbitrary Banach lattices. For definition and simple properties of the signum operator  $S_h$  see C-I, Section 8.

**Theorem 2.2** Let  $(T(t))_{t \geq 0}$  be a positive semigroup on a Banach lattice  $E$  with generator  $A$  and suppose that for  $h \in E$ ,  $\alpha, \beta \in \mathbb{R}$  we have

$$Ah = (\alpha + i\beta)h, \quad A|h| = \alpha|h|. \quad (2.6)$$

Then the following holds true

$$Ah^{[n]} = (\alpha + i n \beta) h^{[n]} \text{ for all } n \in \mathbb{Z}. \quad (2.7)$$

In case  $|h|$  is a quasi-interior point of  $E_+$ , then

$$S_h D(A) = D(A) \text{ and } A + i\beta \operatorname{Id} = S_h^{-1} A S_h.$$

**Proof** Without loss of generality we may assume that  $\alpha = 0$ . Then the assumption (2.6) implies that  $T(t)|h| = |h|$  and  $T(t)h = e^{i\beta t} h$  for  $t \geq 0$  (see A-III, Corollary 6.4). In particular, the principal ideal  $E_{|h|}$  is invariant under every operator  $T(t)$ . By the Kakutani-Krein Theorem (C-I, Section 4) we can identify  $E_{|h|}$  with a space  $C(K)$ ,  $K$  compact. Then the restrictions  $\bar{T}(t) := T(t)|_{E_{|h|}}$  are positive operators on  $C(K)$  satisfying  $\bar{T}(t)|\bar{h}| = |\bar{h}|$  and  $\bar{T}(t)\bar{h} = e^{i\beta t} \bar{h}$ .

From B-III, Theorem 2.4(a) we conclude  $\bar{T}(t)\bar{h}^{[n]} = e^{i\beta t} \bar{h}^{[n]}$  for all  $t \geq 0$ ,  $n \in \mathbb{Z}$ . Translating this back to  $T(t)$  and  $E$  this means precisely  $T(t)h^{[n]} = e^{in\beta} h^{[n]}$ , hence  $h^{[n]} \in D(A)$  and  $Ah^{[n]} = in\beta h^{[n]}$ .

Moreover, by B-III, Theorem 2.4(a) we have  $e^{i\beta t}\bar{T}(t) = S_h^{-1}\bar{T}(t)S_h$ . If  $|h|$  is a quasi-interior point, this relation extends by continuity from the dense subspace  $E_{|h|}$  to the whole space  $E$ , i.e., we have  $e^{i\beta t}T(t) = S_h^{-1}T(t)S_h$  for all  $t \geq 0$ .  $\square$

In the proof above we could not apply assertion (b) of B-III, Theorem 2.4 because the semigroup  $(\bar{T}(t))$  on  $E_{|h|} \cong C(K)$  need not be strongly continuous with respect to the sup-norm.

As a first application of Theorem 2.2 we prove a cyclicity result for the point spectrum of contraction semigroups on a class of Banach lattices which includes the  $L^p$ -spaces.

**Corollary 2.3** *Suppose  $E$  is a Banach lattice such that the norm is strictly monotone on  $E_+$  (i.e.,  $0 \leq f < g \Rightarrow \|f\| < \|g\|$ ). If  $(T(t))$  is a positive contraction semigroup on  $E$  with  $s(A) = 0$ , then  $P\sigma_b(A) = P\sigma(A) \cap i\mathbb{R}$  is imaginarily additively cyclic.*

**Proof** Suppose that  $Ah = i\beta h$  ( $\beta \in \mathbb{R}, h \in E$ ). Then we have  $T(t)h = e^{i\beta t}h$  ( $t \geq 0$ ) and  $|h| = |T(t)h| \leq T(t)|h|$  since  $T(t)$  is positive. Moreover,  $\|h\| \leq \|T(t)h\| \leq \|h\|$  since  $\|T(t)\| \leq 1$ . The assumption on the norm of  $E$  implies that  $T(t)|h| = |h|$  for all  $t \geq 0$ , equivalently  $A|h| = 0$ . Now we can apply Theorem 2.2 in order to obtain the desired result.  $\square$

A more general result on cyclicity of the eigenvalues in the boundary spectrum will be proved in Corollary 4.3. In the remaining part of this section we focus our interest on the entire boundary spectrum. We will prove that it is cyclic provided that the resolvent  $R(\lambda, A)$  does not grow too fast as  $\lambda \rightarrow s(A)$ . We start with some preparations. An important tool in the proof are pseudo-resolvents.

**Definition 2.4** Let  $D$  be an open (non-empty) subset of  $\mathbb{C}$  and let  $G$  be a Banach space. A mapping  $R: D \rightarrow \mathcal{L}(G)$  which satisfies

$$R(\lambda) - R(\mu) = -(\lambda - \mu)R(\lambda)R(\mu) \quad (\lambda, \mu \in D) \quad (2.8)$$

is called a *pseudo-resolvent* on  $G$ .

An equivalent (often quite useful) version of (2.8) is the following

$$(1 - (\lambda - \mu)R(\lambda))(1 - (\mu - \lambda)R(\mu)) = 1 \quad (\lambda, \mu \in D) \quad (2.9)$$

Obviously, the resolvent of a closed linear operator  $A$  on  $G$  is a pseudo-resolvent on  $D = \varrho(A)$ . In general a pseudo-resolvent need not be the resolvent of an operator. Further information can be found in Hille and Phillips [12], Pazy [19] or [?]. For our purposes the following examples are of particular interest

**Example 2.5** (a) Suppose  $A$  is a densely defined linear operator on  $G$  with  $\varrho(A) \neq \emptyset$  and let  $G_{\mathcal{F}}$  be an F-product of  $G$  (cf. A-I, 3.6). Then the canonical extensions  $R(\lambda, A)_{\mathcal{F}}$  of  $R(\lambda, A)$  form a pseudo-resolvent  $R_{\mathcal{F}}$  on  $G_{\mathcal{F}}$  with  $\varrho(A)$  as domain of definition. If  $A$  is unbounded, then  $0 \in A\sigma(R(\lambda, A))$  hence  $0 \in P\sigma(R_{\mathcal{F}}(\lambda, A))$  (cf. A-III, 4.5). It follows that  $R_{\mathcal{F}}$  is not the resolvent of an operator on  $G$ .

(b) If  $\{R(\lambda)\}_{\lambda \in D}$  is a pseudo-resolvent on  $G$ , then  $\{R(\lambda)'\}_{\lambda \in D}$  is a pseudo-resolvent on  $G'$ . Moreover, if  $H$  is a closed linear subspace of  $G$  which is  $\{R(\lambda)\}_{\lambda \in D}$ -invariant ( $R(\lambda)H \subset H$  for all  $\lambda \in D$ ), then the operators on  $H$  and  $G/H$  induced by  $R(\lambda)$  in the canonical way form a pseudo-resolvent on  $H$  and  $G/H$ , respectively.

In the following we list several simple properties. We assume that  $R: D \rightarrow \mathcal{L}(G)$  is a pseudo-resolvent on a Banach space  $G$

$$\begin{aligned} &\text{Given } \lambda_0 \in D, \mu \in \mathbb{C} \text{ there exists at most one operator } S \in \mathcal{L}(G) \\ &\text{such that } R(\lambda_0) - S = -(\lambda_0 - \mu)R(\lambda_0)S = -(\lambda_0 - \mu)SR(\lambda_0). \end{aligned} \quad (2.10)$$

In case such an operator exists we have

$$R(\lambda) - S = -(\lambda - \mu)R(\lambda)S = -(\lambda - \mu)SR(\lambda) \text{ for all } \lambda \in D.$$

$$\begin{aligned} &\text{Given } \lambda_0 \in D, \text{ then for } \mu \in D \text{ with } |\mu - \lambda_0| < \|R(\lambda_0)\|^{-1} \\ &\text{we have } R(\mu) = \sum_{n=0}^{\infty} (\lambda_0 - \mu)^n R(\lambda_0)^{n+1}. \end{aligned} \quad (2.11)$$

$$\begin{aligned} &\text{The map } \lambda \mapsto R(\lambda) \text{ is a locally holomorphic function defined on } D \subseteq \mathbb{C} \\ &\text{with values in } \mathcal{L}(G). \end{aligned} \quad (2.12)$$

We only sketch the proof of these assertions. (2.12) follows from (2.11) and the latter is a consequence of (2.10). The identity stated in (2.10) can be rewritten as follows  $(1 - (\lambda_0 - \mu)R(\lambda_0))(1 - (\mu - \lambda_0)S) = 1 = (1 - (\mu - \lambda_0)S)(1 - (\lambda_0 - \mu)R(\lambda_0))$ . Thus  $S = (\mu - \lambda_0)^{-1}(1 - (1 - (\lambda_0 - \mu)R(\lambda_0))^{-1})$  has to be unique. It follows from (2.11) and (2.12) that every pseudo-resolvent has a unique maximal extension. Further properties of pseudo-resolvents are given in the following two propositions.

**Proposition 2.6** *Suppose  $G$  is a Banach space,  $D \subseteq \mathbb{C}$  and  $R: D \rightarrow \mathcal{L}(G)$  is a pseudo-resolvent.*

- (i) *Given  $\alpha \in \mathbb{C}$ ,  $x \in G$  one has  $(\lambda - \alpha)R(\lambda)x = x$  either for all  $\lambda \in D$  or for none.*
- (ii) *Suppose  $\mu \in \overline{D} \setminus D$ . Then  $R$  can be extended to an open set containing  $\mu$  if and only if there exists a sequence  $(\lambda_n) \subset D$  converging to  $\mu$  such that  $\|R(\lambda_n)\|$  is bounded.*

**Proof** (i) Suppose that  $(\lambda - \alpha)R(\lambda)x = x$  for some fixed  $\lambda \in D$ ,  $x \in G$ . Then using (2.8) we have for  $\mu \in D$   $(\mu - \alpha)(\mu - \lambda)R(\mu)R(\lambda)x = (\lambda - \alpha)(R(\lambda)x - R(\mu)x) = x - (\lambda - \alpha)R(\mu)x$ . It follows that  $(\mu - \alpha)R(\mu)x = x$  for all  $\mu \in D$ .

(ii) If there exists an extension, then  $\|R(\lambda_n)\|$  is bounded for every sequence  $(\lambda_n)$  converging to  $\mu$  by (2.12). On the other hand assuming that  $\|R(\lambda_n)\|$  is bounded by  $M$  for a fixed sequence  $(\lambda_n) \subset D$  with  $\lambda_n \rightarrow \mu$  ( $M \geq 0$ ), we have  $\|R(\lambda_n) - R(\lambda_m)\| = |\lambda_n - \lambda_m| \|R(\lambda_n)R(\lambda_m)\| \leq M^2 |\lambda_n - \lambda_m|$  which shows that  $(R(\lambda_n))$  is a Cauchy sequence in  $\mathcal{L}(G)$ , hence  $S := \lim_{n \rightarrow \infty} R(\lambda_n)$  exists. The assertion now follows from (2.10) and (2.11).  $\square$

In the next proposition we consider a positive pseudo-resolvent  $R$  on a Banach lattice  $E$ , i.e., we assume that the domain  $D$  of  $R$  contains the positive real axis and that  $R(\mu)$  is a positive operator for every  $\mu > 0$ . Applying Pringsheim's Theorem (see Theorem 2.1 in the appendix of Schaefer [22]) to the expansion given in (2.11) one can conclude that  $R$  has an extension to the halfplane  $\{z \in \mathbb{C} : \operatorname{Re} z > 0\}$ . This shows that without loss of generality one can assume that the domain of a positive pseudo-resolvent contains the halfplane  $\{z \in \mathbb{C} : \operatorname{Re} z > 0\}$ .

**Proposition 2.7** *Suppose  $R : \Delta \rightarrow \mathcal{L}(E)$  is a positive pseudo-resolvent on a Banach lattice  $E$  and  $\Delta := \{z \in \mathbb{C} : \operatorname{Re} z > 0\}$ .*

*If for some  $\beta \in \mathbb{R}$ ,  $h \in E$  we have  $\lambda R(\lambda + i\beta)h = h$  and  $\lambda R(\lambda)|h| = |h|$  ( $\lambda \in \Delta$ ), then*

$$\lambda R(\lambda + in\beta)h^{[n]} = h^{[n]} \text{ for all } n \in \mathbb{Z}, \lambda \in \Delta.$$

**Proof** At first we prove the following domination property which is the extension of (1.5) to pseudo-resolvents

$$|R(\lambda)f| \leq R(\operatorname{Re} \lambda)|f| \text{ for every } \lambda \in \Delta, f \in E. \quad (2.13)$$

To do this we fix  $\lambda \in \Delta$ . Then there exists  $r_0 > 0$  such that  $|r - \lambda| < r$  whenever  $r > r_0$ . Therefore  $R(\lambda) = \sum_{n=0}^{\infty} (r - \lambda)^n R(r)^{n+1}$  for  $r > r_0$ , which implies for  $f \in E$

$$\begin{aligned} |R(\lambda)f| &\leq \sum_{n=0}^{\infty} |r - \lambda|^n R(r)^{n+1}|f| = \\ &= \sum_{n=0}^{\infty} (r - (r - |r - \lambda|))^n R(r)^{n+1}|f| = R(r - |\lambda - r|)|f|. \end{aligned}$$

Since  $\lim_{r \rightarrow \infty} (r - |\lambda - r|) = \operatorname{Re} \lambda$ , we obtain (2.13).

As a consequence of (2.13) and the assumption  $rR(r)|h| = |h|$  we have that the principal ideal  $E_{|h|}$  is  $\{R(\lambda)\}_{\lambda \in \Delta}$ -invariant. Identifying, according to the Kakutani-Krein Theorem,  $E_{|h|}$  with a space  $C(K)$ ,  $K$  compact, and by restricting the operators  $R(\lambda)$  to  $E_{|h|} \cong C(K)$ , we obtain a positive pseudo-resolvent  $\tilde{R} : \Delta \rightarrow L(C(K))$ . Then we have for every  $\alpha > 0$  and  $f \in E$

$$\alpha \tilde{R}(\alpha + i\beta)h = h, \alpha \tilde{R}(\alpha)|h| = |h| = \mathbb{1}_K, \alpha |\tilde{R}(\alpha + i\beta)f| \leq \alpha \tilde{R}(\alpha)|f|.$$

Applying B-III, Lemma 2.3 we obtain  $\tilde{R}(\alpha) = S_h^{-1} \tilde{R}(\alpha + i\beta) S_h$  for every  $\alpha > 0$  and using the uniqueness theorem for holomorphic functions we obtain

$$\tilde{R}(z) = S_h^{-n} \tilde{R}(z + in\beta) S_h^n \text{ for all } z \in \Delta, n \in \mathbb{Z}. \quad (2.14)$$

In particular,  $S_h^n |h| = S_h^{-n} z \tilde{R}(z) |h| = z \tilde{R}(z + in\beta) S_h^n |h|$ .

In terms of the initial space this means precisely  $h^{[n]} = z R(z + in\beta) h^{[n]}$ , and the proposition is proved.  $\square$

We will prove cyclicity of the boundary spectrum under a *growth condition* which is stated in the following definition.

**Definition 2.8** Let  $A$  be the generator of a positive semigroup  $(T(t))_{t \geq 0}$  with spectral bound  $s(A) > -\infty$ . The resolvent is said to *grow slowly* if one of the following (equivalent) conditions is satisfied.

- (i)  $\{(\lambda - s(A))R(\lambda, A) : \lambda > s(A)\}$  is bounded in  $\mathcal{L}(E)$ .
  - (ii)  $\left\{\frac{1}{t} \int_0^t \exp(-\tau s(A))T(\tau) d\tau : t > 0\right\}$  is bounded in  $\mathcal{L}(E)$ .
- (2.15)

Before proving the equivalence of the two assertions we make some remarks.

(a) Since one always has  $\lambda R(\lambda, A) \rightarrow \text{Id}$  for  $\lambda \rightarrow \infty$ ,  $\{(\lambda - s(A))R(\lambda, A) : \lambda > s(A) + \varepsilon\}$  is bounded for every  $\varepsilon > 0$ . Thus in (2.15)(i) the essential fact is boundedness near  $s(A)$ . On the other hand,  $\{\frac{1}{t} \int_0^t \exp(-\tau s(A))T(\tau) d\tau : 0 \leq t \leq T\}$  is bounded for every  $T \geq 0$ , hence in (2.15)(ii) the boundedness for  $t \rightarrow \infty$  is important.

(b) By Corollary 1.4 we have  $\|R(\lambda, A)\| \geq r(R(\lambda, A)) = (\lambda - s(A))^{-1}$ . Hence  $\|R(\lambda, A)\|$  grows at least as fast as  $(\lambda - s(A))^{-1}$ . Thus if (2.15)(i) is satisfied, the resolvent grows as slowly as it possibly can for  $\lambda \rightarrow s(A)$ .

(c) We do not assume in Definition 2.8 that spectral bound and growth bound coincide. A slight modification of A-III, Example 1.3 shows that there are semigroups with slowly growing resolvent and  $s(A) < \omega_0(A)$ .

**Proof** To prove equivalence of (2.15)(i) and (2.15)(ii), we assume  $s(A) = 0$  and write  $C(t) := \frac{1}{t} \int_0^t T(\tau) d\tau$ .

(2.15)(i)  $\Rightarrow$  (2.15)(ii) Consider  $\lambda > 0$ ,  $t > 0$  such that  $\lambda t = 1$ . Then we have

$$\lambda \cdot e^{-\lambda s} \geq \begin{cases} (et)^{-1} & \text{if } s \leq t, \\ 0 & \text{if } s > t. \end{cases}$$

Now (1.1) implies

$$\lambda R(\lambda, A) = \int_0^\infty \lambda \exp(-\lambda s)T(s) ds \geq e^{-1}C(t) = e^{-1} \cdot C\left(\frac{1}{\lambda}\right) \geq 0.$$

Thus  $C(t)$  is bounded for  $t \rightarrow \infty$  whenever  $\lambda R(\lambda, A)$  is bounded for  $\lambda \downarrow 0$ .

(2.15)(ii)  $\Rightarrow$  (2.15)(i) Let  $M := \sup\{\|C(t)\| : t > 0\}$ . Given  $f \in E$ ,  $\lambda > 0$  and  $r > 0$  then integration by parts yields

$$\begin{aligned} \lambda \int_0^r e^{-\lambda s} T(s)f ds &= \lambda e^{-\lambda r} \int_0^r T(\sigma)f d\sigma + \lambda^2 \int_0^r s e^{-\lambda s} \left( \frac{1}{s} \int_0^s T(\sigma)f d\sigma \right) ds \\ \left\| \lambda \int_0^r e^{-\lambda s} T(s)f ds \right\| &\leq \left( r\lambda e^{-\lambda r} + \lambda^2 \int_0^r s e^{-\lambda s} ds \right) M\|f\| \\ &= (1 - e^{-\lambda r})M\|f\|. \end{aligned}$$

Letting  $r \rightarrow \infty$ , we obtain by (1.1)  $\|\lambda R(\lambda, A)f\| \leq M\|f\|$  ( $f \in E, \lambda > 0$ ) hence  $\|\lambda R(\lambda, A)\| \leq M$  □

Two sufficient conditions for a resolvent to grow slowly are stated in the following proposition. Its simple proof is omitted.

**Proposition 2.9** *Suppose  $(T(t))_{t \geq 0}$  is a positive semigroup with generator  $A$ . Each of the following conditions guarantees that the resolvent grows slowly.*

- (i)  $(T(t))_{t \geq 0}$  is bounded and  $s(A) = 0$ ;
- (ii)  $s(A)$  is a first order pole of the resolvent.

In case  $s(A)$  is a pole of order greater than 1, the resolvent does not grow slowly. We will treat this case in Corollary 2.12

**Theorem 2.10** *The boundary spectrum of a positive semigroup with slowly growing resolvent is cyclic.*

**Proof** Without loss of generality we can assume that  $s(A) = 0$ .

Given  $i\beta \in \sigma(A)$  ( $\beta \in \mathbb{R}$ ), then  $i\beta \in A\sigma(A)$  (A-III, Proposition 2.2) and  $(\lambda - i\beta)^{-1} \in A\sigma(R(\lambda, A))$  (A-III, Proposition 2.5). We consider an  $\mathcal{F}$ -product  $E_{\mathcal{F}}$  of  $E$  and for convenience write  $E_1$  instead of  $E_{\mathcal{F}}$ . The canonical extensions of  $R(\lambda, A)$  to  $E_1$  form a positive pseudo-resolvent  $\{(R_1(\lambda))_{\operatorname{Re} \lambda > 0}$  on  $E_1$ . By Proposition 2.6(i) and A-III, 4.5 there exists  $h_1 \in E_1$ ,  $h_1 \neq 0$  such that

$$\lambda R_1(\lambda + i\beta)h_1 = h_1 \text{ for } \operatorname{Re} \lambda > 0. \quad (2.16)$$

By (2.13) we have

$$|h_1| = |\tau R_1(\tau + i\beta)h_1| \leq \tau R_1(\tau)|h_1| \quad (r > 0). \quad (2.17)$$

Next we choose any  $\varphi \in E'_1$  such that  $\langle h_1, \varphi \rangle \neq 0$ . Since  $\|R_1(\lambda)'\| = \|R_1(\lambda)\| = \|R(\lambda, A)\|$ , the assumption of slow growth implies that  $\{\lambda R_1(\lambda)'\varphi : \lambda > 0\}$  is bounded in  $E'_1$ , hence  $\sigma(E'_1, E_1)$ -relatively compact by Alaoglu's Theorem. Thus there exist  $\varphi_1 \in \cap_{\varepsilon > 0} \{\tau R_1(\tau)'\varphi : 0 < \tau < \varepsilon\}^{-\sigma(E'_1, E_1)}$ .

Using the resolvent equation (2.8) we obtain for  $r > 0$ ,  $\varepsilon > 0$

$$(1 - \tau R_1(\tau)')\varepsilon R_1(\varepsilon)'\varphi = \varepsilon(\tau - \varepsilon)^{-1}(\tau R_1(\tau)'\varphi - \varepsilon R_1(\varepsilon)'\varphi).$$

Since the right hand side tends to 0 as  $\varepsilon \rightarrow 0$ , we have  $(1 - \tau R_1(\tau)')\varphi_1 = 0$  or

$$\lambda R_1(\lambda)'\varphi_1 = \varphi_1 \text{ for } \operatorname{Re} \lambda > 0. \quad (2.18)$$

Moreover, from

$$0 < |\langle h_1, \varphi \rangle| \leq \langle |h_1|, |\varphi| \rangle \leq \langle R_1(\tau)|h_1|, |\varphi| \rangle = \langle |h_1|, \tau R_1(\tau)'\varphi \rangle$$

it follows that

$$\langle |h_1|, \varphi_1 \rangle > 0. \quad (2.19)$$

for arbitrary  $f_1 \in E_1$ ,  $\operatorname{Re} \lambda > 0$  we have  $\langle |R_1(\lambda)f_1|, \varphi_1 \rangle \leq \langle R_1(\operatorname{Re} \lambda)|f_1|, \varphi_1 \rangle = \langle |f_1|, R_1(\operatorname{Re} \lambda)'\varphi_1 \rangle = (\operatorname{Re} \lambda)^{-1} \langle |f_1|, \varphi_1 \rangle$ .



Therefore the ideal  $I := \{f_1 \in E_1 : \langle |f_1|, \varphi_1 \rangle = 0\}$  is invariant under  $\{(R_1(\lambda))_{\operatorname{Re} \lambda > 0}\}$ . Furthermore we have (see (2.17), (2.18))

$$\begin{aligned} \langle |rR_1(r)|h_1| - |h_1|, \varphi_1 \rangle &= \langle rR_1(r)|h_1| - |h_1|, \varphi_1 \rangle = \\ &= \langle |h_1|, rR_1(r)' \varphi_1 - \varphi_1 \rangle = 0 \end{aligned}$$

which implies

$$rR_1(r)|h_1| - |h_1| \in I \text{ for } r > 0. \quad (2.20)$$

Denote by  $E_2$  the quotient space  $E_1/I$  and by  $\{(R_2(\lambda))_{\operatorname{Re} \lambda > 0}\}$  the pseudo-resolvent on  $E_2$  induced by  $\{(R_1(\lambda))_{\operatorname{Re} \lambda > 0}\}$  in the canonical way. Then  $h_2 := h_1 + I \neq 0$  (by (2.19)). Moreover,  $\lambda R_2(\lambda + i\beta)h_2 = h_2$  (by (2.16)) and  $\lambda R_2(\lambda)|h_2| = |h_2|$  (by (2.20) and Proposition 2.6(i)).

Now we apply Proposition 2.7(b) and obtain

$$\lambda R_2(\lambda + in\beta)h_2^{[n]} = h_2^{[n]} \text{ for } \operatorname{Re} \lambda > 0, n \in \mathbb{Z}. \quad (2.21)$$

In particular, we have  $\|R_2(r + in\beta)\| \geq \frac{1}{r}$ , thus

$$\|R(r + in\beta, A)\| = \|R_1(r + in\beta)\| \geq \|R_2(r + in\beta)\| \geq \frac{1}{r} \text{ for } r > 0.$$

This finally implies that  $in\beta \in \sigma(A)$  for  $n \in \mathbb{Z}$ . □

To prove cyclicity of the boundary spectrum in case  $s(A)$  is a pole (of arbitrary order), one applies B-III, Lemma 2.8 to reduce the problem to the case of first order poles. Actually, B-III, Lemma 2.8 is true for arbitrary Banach lattices and the proof given in chapter B-III works in the general case as well. For completeness we recall this result.

**Proposition 2.11** *Let  $A$  be the generator of a positive semigroup  $\mathcal{T}$  on a Banach lattice  $E$  and suppose that the spectral bound  $s(A)$  is a pole of the resolvent of order  $k$ . Then there is a sequence*

$$I_{-1} := \{0\} \subset I_0 \subsetneq I_1 \subsetneq \dots \subsetneq I_k := E \quad (2.22)$$

*of  $\mathcal{T}$ -invariant closed ideals with the following properties. If  $A_n$  is the generator of the semigroup induced by  $\mathcal{T}$  on the quotient  $I_n/I_{n-1}$ , then we have*

- (i)  $s(A_0) < s(A)$ ,
- (ii) *If  $n \geq 1$ , then  $s(A_n) = s(A)$  is a first order pole of the resolvent  $R(\cdot, A_n)$ . The corresponding residue is a strictly positive operator.*

Combining Theorem 2.10 and Proposition 2.11 one obtains the following generalization of B-III, Theorem 2.9. In contrast with the former result we do not assume that every point of  $\sigma_b(A)$  is a pole.

**Corollary 2.12** *If  $A$  is the generator of a positive semigroup such that  $s(A)$  is a pole of the resolvent, then  $\sigma_b(A)$  is cyclic.*

**Proof** Considering the sequence of ideals as described in Proposition 2.11 and the corresponding generators  $A_n$  ( $0 \leq n \leq k$ ), then we have by A-III, Proposition 4.2 that  $\sigma_b(A) = \bigcup_{n=1}^k \sigma_b(A_n)$ . By Theorem 2.10 each set  $\sigma_b(A_n)$  is cyclic, hence so is  $\sigma_b(A)$ .  $\square$

The proof of the preceding corollary indicates a possible generalization of Theorem 2.10. Instead of assuming that the resolvent grows slowly one merely needs that there exist a finite chain of closed  $\mathcal{T}$ -invariant ideals as described in (2.22) such that the semigroups induced on the corresponding quotient spaces have slowly growing resolvents.

In case that  $\sigma_b(A)$  is cyclic one has the alternative (cf. B-III, (2.19))

Either  $\sigma_b(A) = \{s(A)\}$  or else  $\sigma_b(A)$  is an unbounded set.

Obviously one can use this fact to prove the existence of a dominant spectral value (cf. the explanation preceding B-III, Corollary 2.11). We give a typical example.

**Corollary 2.13** *Let  $A$  be the generator of a positive, eventually norm-continuous semigroup. Suppose either that the resolvent grows slowly or that  $s(A)$  is a pole of the resolvent. Then  $s(A)$  is a dominant spectral value.*

**Proof** The boundary spectrum  $\sigma_b(A)$  is cyclic (Theorem 2.10 and Corollary 2.12 resp.) and compact (A-II, Theorem 1.20). Hence  $\sigma_b(A) = \{s(A)\}$ .  $\square$

A situation in which Corollary 2.13 can be applied is described in the following example. For more details and proofs we refer to Amann [1].

*Example 2.14* Let  $\Omega$  be a bounded domain in  $\mathbb{R}^n$  of class  $C^2$ .

Assume that  $\partial\Omega = \Gamma_0 \cup \Gamma_1$  where  $\Gamma_0$  and  $\Gamma_1$  are disjoint open and closed subsets of  $\partial\Omega$ . On  $E = L^p(\Omega)$  ( $1 \leq p < \infty$ ) we consider a differential operator  $L_{p,0}$  which is defined as follows

$$\begin{aligned} L_{p,0}f &:= \sum_{i,j=1}^n a_{ij} f_{ij}'' + \sum_{i=1}^n b_i f_i' + cf, \text{ with domain} \\ D(L_{p,0}) &:= \{f \in C^2(\bar{\Omega}) : f(x) = 0 \text{ for } x \in \Gamma_0 \\ &\quad \text{and } \partial f / \partial \nu(x) + \gamma(x)f(x) = 0 \text{ for } x \in \Gamma_1\} \end{aligned} \tag{2.23}$$

Here  $f_i'$  stands for  $\partial f / \partial x_i$ , thus  $f_{ij}'' = \partial^2 f / \partial x_i \partial x_j$ . We assume that  $L_{p,0}$  is elliptic and that all coefficients are real-valued satisfying  $a_{ij} \in C^2(\bar{\Omega})$ ,  $b_i \in C^1(\bar{\Omega})$ ,  $\gamma \in C^1(\bar{\Omega})$ ,  $c \in C^1(\bar{\Omega})$ .

Then  $L_{p,0}$  is closable and its closure  $L_p$  is the generator of a holomorphic semigroup of positive operators. Moreover, the resolvent is compact. Thus Corollary 2.13 is applicable and one obtains that  $s(A)$  is strictly dominant provided that  $\sigma(A) \neq \emptyset$ . Using the results of Section 3 one can show that  $\sigma(A) \neq \emptyset$  and that  $s(A)$  is an algebraically simple eigenvalue (see Theorem 3.7 and Proposition 3.5).

We conclude with some remarks.

**Remarks 2.15** (a) In the proof of Theorem 2.10 we did not use the assumption that  $R$  is the resolvent of a semigroup. In fact one can state this theorem for closed operators having positive resolvent. In this case one has to assume that  $\{(\lambda - s(A))R(\lambda, A) : s(A) < \lambda < s(A) + 1\}$  is bounded in  $\mathcal{L}(E)$ . One can go even further and consider positive pseudo-resolvents  $\{R(\lambda)\}_{\lambda \in D}$ . This is also possible with respect to Corollary 2.12.

(b) If  $s(A)$  is a pole, then the criteria stated in B-III, Remark 2.15(a) for  $s(A)$  to be a first order pole are valid in the setting of arbitrary Banach lattices as well. In particular, one has a first order pole provided that  $\ker(s(A) - A)$  contains a quasi-interior point or in case that  $\ker(s(A) - A')$  contains a strictly positive linear form.

(c) It is not difficult to give examples of semigroups whose resolvent do not grow slowly or cannot be reduced by a finite chain of invariant ideals as described after Corollary 2.12. E.g., one can take a bounded positive operator  $A$  which is not nilpotent and satisfies  $\sigma(A) = \{0\}$ . However, the following question is still unanswered.

*Does every positive semigroup have cyclic boundary spectrum?*

### 3 Irreducible Semigroups

The concept of irreducibility is very natural in the general setting of Banach lattices. However, some of the (equivalent) assertions stated in B-III, Definition 3.1 do not make sense here, others need a slightly different formulation.

**Definition 3.1** A positive semigroup  $(T(t))_{t \geq 0}$  on a Banach lattice  $E$  with generator  $A$  is called *irreducible* if one of the following (mutually equivalent) conditions is satisfied

- (a) There is no  $(T(t))$ -invariant closed ideal except  $\{0\}$  and  $E$ .
- (b) Given  $f \in E$ ,  $\varphi \in E'$  such that  $f > 0$ ,  $\varphi > 0$  then  $\langle T(t_0)f, \varphi \rangle > 0$  for some  $t_0 \geq 0$ .
- (c) For arbitrary  $f, g \in E_+$ ,  $f > 0$ ,  $g > 0$  there exists  $t_0$  such that  $\inf\{T(t_0)f, g\} > 0$ .
- (d) For some (every)  $\lambda > s(A)$  there is no closed ideal other than  $\{0\}$  or  $E$  which is invariant under  $R(\lambda, A)$ .
- (e) For some (every)  $\lambda > s(A)$  we have  $R(\lambda, A)f$  is a quasi-interior point of  $E_+$  whenever  $f > 0$ .

Equivalence of the five conditions above is obtained by a slight modification of the arguments given in B-III, Definition 3.1. Since there are no difficulties we omit a detailed proof. Obviously, a semigroup is irreducible if one single operator  $T(t_0)$  is irreducible. In general the converse does not hold (see p.65 in Greiner [10]). The situation is different when holomorphic semigroups are considered. Then an even stronger assertion holds. In fact irreducibility of a holomorphic semigroup implies

that every single operator maps the positive elements onto quasi-interior points. This is the second statement of the following theorem (see also B-III, Remark 3.2).

**Theorem 3.2** (i) *If  $(T(t))$  is an irreducible semigroup then every operator  $T(t)$  is strictly positive, i.e., given  $f > 0$ ,  $t \geq 0$ , then  $T(t)f > 0$ .*  
(ii) *Suppose  $(T(t))_{t \geq 0}$  is a holomorphic positive semigroup. If  $(T(t))$  is irreducible, then  $T(t)f$  is a quasi-interior point of  $E_+$  whenever  $f > 0$  and  $t > 0$ . Equivalently, given  $f \in E$ ,  $\varphi \in E'$  such that  $f > 0$ ,  $\varphi > 0$ , then  $\langle T(t)f, \varphi \rangle > 0$  for all  $t > 0$ .*

**Proof** (i) Given  $t > 0$  and  $f > 0$  such that  $T(t)f = 0$  and  $\lambda > s(A)$ , then we have  $T(t)(R(\lambda, A)f) = R(\lambda, A)T(t)f = 0$ . Since  $R(\lambda, A)f$  is a quasi-interior point, it follows that  $T(t) = 0$ . Thus for fixed  $t \in \mathbb{R}_+$  we have either  $T(t)$  is strictly positive or else  $T(t) = 0$ . Then strong continuity and  $T(0) = \text{Id} \neq 0$  implies that there exists  $\tau > 0$  such that  $T(t)$  is strictly positive for  $0 \leq t \leq \tau$ . For arbitrary  $t \in \mathbb{R}_+$  we find  $n \in \mathbb{N}$  such that  $\frac{t}{n} \leq \tau$ . Then  $T(t) = T(\frac{t}{n})^n$  is also strictly positive.

(ii) We prove that for an arbitrary holomorphic positive semigroup  $(T(t))_{t \geq 0}$  the following holds

Given  $f > 0$ ,  $\varphi > 0$  then either  $\langle T(t)f, \varphi \rangle = 0$  for all  $t \geq 0$  or  $\langle T(t)f, \varphi \rangle > 0$  for all  $t > 0$ .

Then it follows from Definition 3.1(b) that for irreducible semigroups always the second case occurs.

Assume that  $\langle T(t_0)f, \varphi \rangle = 0$  for some  $t_0 > 0$ .

We consider a null sequence  $(t_n)$ ,  $0 < t_n < t_0$ , such that  $\|T(t_n)f - f\| \leq 2^{-n}$  and define  $f_n := T(t_n)f$ ,  $g_n := f - \sum_{k=n}^{\infty} (f - f_k)^+$ .

Then for  $g_n \leq f$ ,  $f = \lim_{n \rightarrow \infty} g_n$  and  $m \geq n$ , we have

$$g_n \leq f - (f - f_m)^+ = \inf\{f, f_m\} \leq f_m.$$

For  $n \in \mathbb{N}$  fixed and  $m \geq n$  we obtain

$$0 \leq \langle T(t_0 - t_m)g_n^+, \varphi \rangle \leq \langle T(t_0 - t_m)f_m, \varphi \rangle = \langle T(t_0)f, \varphi \rangle = 0.$$

Thus the function  $t \mapsto \langle T(t)g_n^+, \varphi \rangle$  is identically zero by the uniqueness theorem for analytic functions. Since  $f = \lim_{n \rightarrow \infty} g_n^+$ , we have  $\langle T(t)h, \varphi \rangle = 0$  for all  $t \in \mathbb{R}_+$ .

□

The next result can be used to check irreducibility for a semigroup whose generator is a bounded perturbation of a known semigroup. It is a generalization (and an extension to Banach lattices) of B-III, Proposition 3.3.

**Proposition 3.3** *Suppose that  $A$  is the generator of a positive semigroup  $\mathcal{T}$ , further assume that  $K$  is a bounded positive operator and  $M$  is a bounded real multiplier (cf. C-I, Section 8). Let  $\mathcal{S}$  be the semigroup generated by  $B := A + K + M$ . For a closed ideal  $I \subset E$  the following assertions are equivalent.*

- (a)  $I$  is  $\mathcal{S}$ -invariant.
- (b)  $I$  is invariant both under  $\mathcal{T}$  and  $K$ .

**Proof** We recall that a closed subspace  $I \subset E$  is invariant for a semigroup generated by  $C$  if and only if  $C(D(C) \cap I) \subset I$  and the restriction  $C|_I$  of  $C$  with domain  $D|_I := D(C) \cap I$  generates a semigroup on  $I$  (see A-I, 3.2). Now let  $I$  be a

closed ideal of  $E$ . (b) $\Rightarrow$ (a). If  $I$  is  $\mathcal{T}$ -invariant then  $A|_I$  generates a semigroup on  $I$ . The restrictions  $K|_I$  and  $M|_I$  of  $K$  and  $M$  respectively are bounded linear operators on  $I$ . Note that each closed ideal is invariant for  $M$ , cf. C-I, Section 8. Thus  $B|_I = A|_I + M|_I + K|_I$  with domain  $D(A|_I) = D(A) \cap I = D(B) \cap I$  is the generator of a semigroup on  $I$ . It follows that  $I$  is invariant for the semigroup generated by  $B$ . (a) $\Rightarrow$ (b). Without loss of generality we assume  $M \geq 0$ . Then we have  $0 \leq T(t) \leq S(t)$  for all  $t \geq 0$ . It follows that  $I$  is  $T$ -invariant. Thus for  $x \in D(A) \cap I = D(B) \cap I$ , we have  $Kx = Bx - Ax - Mx$ . This shows that  $K(D(B) \cap I) \subset I$ . Since  $B|_I$  is a generator  $D(B) \cap I$  is dense in  $I$ . Then, by continuity, we have  $KI \subset I$ , i.e.,  $I$  is  $K$ -invariant.  $\square$

Next we consider some concrete examples.

**Examples 3.4** (a) Suppose that on  $E = L^p(\mu)$  ( $1 \leq p < \infty$ ) the semigroup  $(T(t))$  is given by

$$(T(t)f)(x) = \int_X k(t, x, y) f(y) \, d\mu(y) \quad (x \in X, t > 0) \quad (3.1)$$

for some measurable function  $k: \mathbb{R}_+ \times X \times X \rightarrow \mathbb{R}_+$ . Then  $(T(t))$  is irreducible if and only if for any two measurable sets  $M$  and  $N$  with  $0 < \mu(M) < \infty$ ,  $0 < \mu(N) < \infty$ ,  $\mu(M \cap N) = 0$  there exist  $t_0 > 0$  such that  $\int_M \int_N k(t_0, x, y) \, d\mu(x) \, d\mu(y) > 0$ .

(b) Consider the first derivative on  $\mathbb{R}$ ,  $\mathbb{R}_+$  or  $\mathbb{R}_{2\pi} = \Gamma$  as operator on the corresponding  $L^p$ -space (with respect to the Lebesgue measure.) Then the statements made in B-III, Example 3.4(c) are true. The same is true for B-III, Example 3.5(e) and (f) (second order differential operator) when the corresponding  $L^p$ -spaces are considered.

B-III, Ex 3.5(e)  
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(c) Let  $E = L^1[-1, 0]$  and for  $g \in L^\infty$  consider the operator  $A_g$  given by

$$A_g f := f', \quad D(A_g) := \{f \in W^1[-1, 0] : f(0) = \int_{-1}^0 f(x)g(x) \, dx\} \quad (3.2)$$

If  $g \geq 0$  then  $A_g$  generates a positive semigroup. In case there exist  $\varepsilon > 0$  such that  $g$  vanishes a.e. on  $[-1, -1 + \varepsilon]$ , then  $I := \{f \in L^1 : f|_{[-1+\varepsilon, 0]} = 0\}$  is a non-trivial closed ideal which is invariant under the semigroup. It is not difficult to see that the condition on  $g$  stated above is also necessary for  $(T(t))$  to be reducible (i.e., not irreducible.)

(d) Let  $E = L^1([0, 1] \times [-1, 1])$  and consider the semigroup  $(T(t))_{t \geq 0}$  defined as follows

$$(T(t)f)(x, v) := \begin{cases} f(x - vt, v) & \text{for } 0 \leq x - vt \leq 1, \\ 0 & \text{otherwise.} \end{cases} \quad (3.3)$$

$(T(t))_{t \geq 0}$  is a positive semigroup on  $E$  and

$$D_0 := \{f \in C^1([0, 1] \times [-1, 1]) : f(0, v) = f_x(0, v) = 0 \text{ if } v \geq 0, \\ f(1, v) = f_x(1, v) = 0 \text{ if } v \leq 0\}$$

is a core for its generator  $A$  (cf. A-I, Corollary 1.34). We have

$$(Af)(x, v) = -v \frac{\partial f}{\partial x}(x, v) \quad (f \in D_0). \quad (3.4)$$

The Laplace transform of  $(T(t))$  is the resolvent of  $A$ . An explicit calculation yields

$$(R(\lambda, A)f)(x, v) = \int_0^1 r_\lambda(x, x', v) f(x', v) \, dx' \quad (\lambda > 0) \quad (3.5)$$

where  $r_\lambda: [0, 1] \times [0, 1] \times [-1, 1] \rightarrow \mathbb{R}$  is given by

$$r_\lambda(x, x', v) = \begin{cases} |v|^{-1} \exp(-\lambda(x - x')v^{-1}) & \begin{cases} \text{if either } v > 0 \text{ and } x' \leq x \\ \text{or } v < 0 \text{ and } x' \geq x, \end{cases} \\ 0 & \text{otherwise.} \end{cases}$$

Let  $\sigma: [0, 1] \times [-1, 1] \rightarrow \mathbb{R}_+$  and  $\kappa: [0, 1] \times [-1, 1] \times [-1, 1] \rightarrow \mathbb{R}_+$  be measurable functions and consider the operators  $M$  and  $K$  given by

$$Mf := \sigma f, \quad Kf := \int_{-1}^1 \kappa(\cdot, \cdot, v') f(\cdot, v') \, dv'. \quad (3.6)$$

Then  $B := A - M + K$  with domain  $D(B) := D(A)$  is the generator of a positive semigroup.

Using Proposition 3.3 we can prove the following irreducibility criterion for the semigroup  $(S(t))_{t \geq 0}$  generated by  $B$ .

$$\text{If } \kappa \text{ is strictly positive, then } (S(t))_{t \geq 0} \text{ is irreducible.} \quad (3.7)$$

Actually, in view of Proposition 3.3, we have to show that a closed ideal which is invariant under  $R(\lambda, A)$  and  $K$  has to be  $\{0\}$  or  $E$ .

We recall that closed ideals of  $E$  are uniquely determined (up to sets of measure zero) by measurable subsets  $Y$  of  $[0, 1] \times [-1, 1]$ , i.e., every closed ideal has the form

$$I_Y = \{f \in E: f \text{ vanishes (a.e.) on } [0, 1] \times [-1, 1] \setminus Y\}.$$

Since we assumed that  $\kappa$  is strictly positive,  $I_Y$  is  $K$ -invariant if and only if  $Y = X \times [-1, 1]$  for some measurable set  $X \subset [0, 1]$ . If we assume that  $X$  has positive measure and define

$$\alpha := \sup\{x \in [0, 1]: \int_0^x \mathbb{1}_X(s) \, ds = 0\}, \beta := \inf\{x \in [0, 1]: \int_x^1 \mathbb{1}_X(s) \, ds = 0\},$$

then we have  $\alpha < \beta$  and the support of the function  $h := R(\lambda, A)\mathbb{1}_Y$  ( $Y := X \times [-1, 1]$ ) is given by  $\text{supp } h = [\alpha, 1] \times [0, 1] \cup [0, \beta] \times [-1, 0]$ . Since we assumed that  $I_Y$  is  $R(\lambda, A)$ -invariant, we have  $h \in I_Y$ , i.e.,  $\text{supp } h \subset Y = X \times [-1, 1]$ . Obviously, this is true only if  $Y = [0, 1] \times [-1, 1]$  or  $I_Y = E$ .

A weaker condition than (3.7) entailing irreducibility is the following.

There exists  $\delta > 0$  such that  $\kappa$  is strictly positive  
on the sets  $[0, \delta] \times [-1, 1]$  and  $[1 - \delta, 1] \times [-1, 1]$ . (3.8)

For details we refer to [Greiner (1984d)].

In the following proposition we list some properties which are consequences of irreducibility. This extends B-III, Proposition 3.5 to the setting of Banach lattices. The first assertion of the latter proposition is no longer true in the general setting (see Example 3.6 and Theorem 3.7).

**Proposition 3.5** *Suppose  $A$  to be the generator of an irreducible, positive semigroup on a Banach lattice  $E$ . Then the following assertions are true.*

- (i) *Every positive eigenvector of  $A$  is a quasi-interior point.*
- (ii) *Every positive eigenvector of  $A'$  is strictly positive.*
- (iii)  *$\ker(s(A) - A')$  contains a positive element, then  $\dim(\ker(s(A) - A)) \leq 1$ .*
- (iv) *If  $s(A)$  is a pole of the resolvent, then it has algebraic (and geometric) multiplicity 1. The corresponding residue has the form  $P = \varphi \otimes u$ , where  $\varphi \in E'$  is a positive eigenvector of  $A'$ ,  $u \in E$  is a positive eigenvector of  $A$  and  $\langle u, \varphi \rangle = 1$ .*

**Proof** To prove (i), (ii) and (iv) one can proceed as in the case  $C_0(X)$  (see B-III, Proposition 3.5). We only prove (iii) and assume  $s(A) = 0$ . By assumption and by assertion (i) there exists  $\varphi \gg 0$  such that  $T(t)' \varphi = \varphi$  ( $t \geq 0$ ). Given  $f \in \ker A$ , then  $T(t)f = f$  hence  $|f| = |T(t)f| \leq T(t)|f|$ . Since  $\varphi$  is strictly positive and  $\langle |f|, \varphi \rangle \leq \langle T(t)|f|, \varphi \rangle = \langle |f|, \varphi \rangle$ , it follows that  $|f| = T(t)|f|$ . We have shown that  $\ker A$  is a sublattice. Then for  $f \in \ker A$ ,  $f$  real, i.e.,  $f = \bar{f}$ , we have that  $f^+$  and  $f^-$  are elements of  $\ker A$ . Hence the principal ideals generated by  $f^+$  and  $f^-$  are  $T$ -invariant. Since these ideals are orthogonal, the irreducibility of  $T$  implies that either  $f^+$  or  $f^-$  is zero. We have shown that  $\ker A \cap E_{\mathbb{R}}$  is totally ordered, hence at most one-dimensional (see Proposition 3.4 of Schaefer [23]).  $\square$

In arbitrary Banach lattices it is no longer true that an irreducible semigroup has necessarily nonvoid spectrum. We indicate how an irreducible semigroup having empty spectrum can be constructed.

**Example 3.6** Consider the Banach lattice  $E = L^p(\Gamma \times \Gamma)$ . For (fixed) positive numbers  $\alpha, \beta$  such that  $\frac{\alpha}{\beta}$  is irrational we define a positive semigroup  $(T_0(t))_{t \geq 0}$  as follows

$$(T_0(t)f)(z, w) := f(z \cdot e^{i\alpha t}, w \cdot e^{i\beta t}) \quad (z, w \in \Gamma = \{\xi \in \mathbb{C} : |\xi| = 1\}). \quad (3.9)$$

Next we define for a positive function  $m : \Gamma \times \Gamma \rightarrow \mathbb{R}$  which is continuous on  $\Gamma \times \Gamma \setminus (1, 1)$  functions  $m_t$ ,  $t \geq 0$ , as follows

$$m_t(z, w) := \exp\left(-\int_0^t m(z \cdot e^{i\alpha s}, w \cdot e^{i\beta s}) ds\right). \quad (3.10)$$

Then  $(T(t))_{t \geq 0}$  defined by

$$T(t)f := m_t \cdot (T_0(t)f) \quad (3.11)$$

is a strongly continuous semigroup of positive contractions on  $E$ . Since  $\frac{\alpha}{\beta}$  is irrational, the semigroup  $(T_0(t))$  is irreducible. Moreover, each  $m_t$  is strictly positive (i.e.,  $m_t > 0$  a.e.) thus  $(T(t))$  is irreducible as well. If one chooses  $m$  such that  $m(z, w)$  tends to  $+\infty$  sufficiently fast as  $(z, w) \rightarrow (1, 1)$ , one obtains  $\|T(t)\| = \|m_t\|_\infty \leq \exp(-t^2)$  for all  $t \geq 0$ . Obviously such an estimate of  $\|T(t)\|$  implies  $\omega_0(A) = -\infty$ , hence  $\sigma(A) = \emptyset$ .

**Theorem 3.7** *Suppose that  $(T(t))_{t \geq 0}$  is an irreducible, positive semigroup on the Banach lattice  $E$ . Each of the following conditions on  $E$  and  $(T(t))$ , respectively, implies that  $\sigma(A) \neq \emptyset$*

- (i)  $E = C_0(X)$  where  $X$  is locally compact.
- (ii)  $E = \ell^p$  ( $1 \leq p < \infty$ ) (more generally,  $E$  contains atoms).
- (iii) either  $T(t_0)$  is compact for some  $t_0$  or  $R(\lambda_0, A)$  is compact for some  $\lambda_0 \in \varrho(A)$ .
- (iv)  $E$  has order continuous norm and either  $T(t_0)$  or  $R(\lambda_0, A)$  is a kernel operator for some  $t_0 \geq 0$  ( $\lambda_0 \in \varrho(A)$ ).<sup>1</sup>
- (v)  $E$  is reflexive and there exist  $t_0 > 0$ ,  $h \in E_+$  such that  $T(t_0)E \subset E_h$ .

**Proof** (i) is proved in B-III, Proposition 3.5(a).

Assertion (ii)-(f) will be proved utilizing the analogous results for a single operator. In view of A-III, Proposition 2.5 we have to show that  $r(R(\lambda, A)) > 0$  for some  $\lambda \in \varrho(A)$ . Moreover, from A-I, (3.1) we deduce

$$T(t)R(\lambda, A) = e^{\lambda t} R(\lambda, A) - e^{\lambda t} \int_0^t e^{-\lambda s} T(s) \, ds \leq e^{\lambda t} R(\lambda, A) \quad (t \geq 0, \lambda > s(A)).$$

Since the spectral radius is an isotone function on the cone of positive operators, it is enough to show that

$$r(T(t)R(\lambda, A)) > 0 \text{ for some } t \geq 0, \lambda > s(A). \quad (3.12)$$

Using Theorem 3.2(i) it is easy to see that  $T(t)R(\lambda, A) = R(\lambda, A)T(t)$  is irreducible.

The assertions (ii),(iv) and (v) now follow from the corresponding results for a single operator as presented in Sect.V.6 of Schaefer [23] (see Proposition 6.1, Theorem 6.5 Corollary and Theorem 6.5 l.c.). (iii) follows from the recent result of de Pagter [6] which ensures that every positive operator on a Banach lattice which is compact and irreducible has positive spectral radius.  $\square$

The theorem can be used to prove that elliptic operators as described in Example 2.14 have non-empty spectrum. It is shown in Amann [1] that these operators

<sup>1</sup> For a precise definition of a kernel operator we refer to Section IV.9 of Schaefer [23] or Chapter 13 of Zaanen [29].



have compact resolvent and generate irreducible semigroups. Thus the assumption of (iii) is satisfied.

Concerning the eigenvalues of an irreducible semigroup which are contained in  $\sigma_b(A)$  all statements established for spaces  $C_0(X)$  in B-III, Theorem 3.6 are true in the setting of Banach lattices. The proof can be translated without difficulties and will be omitted (see also Greiner [10, Theorem 2.6]).

**Theorem 3.8** *Suppose  $\mathcal{T}$  is an irreducible semigroup on the Banach lattice  $E$  and let  $A$  be its generator. Assume that  $s(A) = 0$  and that there exists a positive linear form  $\psi \in D(A')$  with  $A'\psi \leq 0$ . If  $P\sigma(A) \cap i\mathbb{R}$  is non-empty, then the following assertions are true.*

- (i)  $P\sigma(A) \cap i\mathbb{R}$  is a (additive) subgroup of  $i\mathbb{R}$ .
- (ii) The eigenspaces corresponding to  $\lambda \in P\sigma(A) \cap i\mathbb{R}$  are one-dimensional.
- (iii) If  $Ah = i\alpha h$  ( $h \neq 0$ ,  $\alpha \in \mathbb{R}$ ) then  $|h|$  is a quasi-interior point and the following holds

$$S_h(D(A)) = D(A) \text{ and } S_h^{-1} \circ A \circ S_h = (A + i\alpha \text{Id}). \quad (3.13)$$

- (iv) 0 is the only eigenvalue of  $A$  admitting a positive eigenvector.

One can apply the theorem in order to prove that the rotation semigroup on  $\Gamma$  (cf. A-I,2.5) is the only positive periodic semigroup which is irreducible.

**Corollary 3.9** *Let  $(T(t))_{t \geq 0}$  be a positive irreducible semigroup on a Banach lattice  $E$  which is periodic of period  $\tau$ . Assume that  $\dim E > 1$ . Then there exist continuous lattice homomorphisms  $i: C(\Gamma) \rightarrow E$  and  $j: E \rightarrow L^1(\Gamma)$ , both injective with dense range, such that the diagram commutes for all  $t \geq 0$ . Hereby,  $j \circ i$  is the canonical inclusion of  $C(\Gamma)$  in  $L^1(\Gamma)$ .*

$$\begin{array}{ccccc} C(\Gamma) & \xrightarrow{i} & E & \xrightarrow{j} & L^1(\Gamma) \\ R_\tau(t) \downarrow & & T(t) \downarrow & & \downarrow R_\tau(t) \\ C(\Gamma) & \xrightarrow{i} & E & \xrightarrow{j} & L^1(\Gamma) \end{array}$$

**Proof** By Theorem 3.8 and A-III, Theorem 5.4 we have  $R\sigma(A) = P\sigma(A) = \sigma(A) = i\alpha\mathbb{Z}$  with  $\alpha := \frac{2\pi}{n\tau}$  for suitable  $n \in \mathbb{N}$ . We fix  $h \in \ker(i\alpha - A)$ ,  $h \neq 0$ . Then  $|h| \in \ker A$  and there exists  $\varphi \in \ker A'$  such that  $\langle |h|, \varphi \rangle = 1$ . According to the Kakutani-Krein Theorem we identify  $E_{|h|}$  with  $C(K)$ . Then  $h$  is a unimodular function onto  $\Gamma$  (use the argument given in the proof of B-III, Theorem 3.6(c)). We define  $i: C(\Gamma) \rightarrow E$  by  $i(f) := f \circ h \in C(K) \cong E_h \subset E$ , then  $i$  is injective. For the monomials  $e_n(z) := z^n$  ( $n \in \mathbb{Z}$ ) we have  $i(e_n) = h^{[n]}$  thus  $i$  has dense image in  $E$  (by A-III, Theorem 5.4). Moreover,

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$$2\pi \cdot \delta_{n0} = \langle h^{[n]}, \varphi \rangle = \langle i(e_n), \varphi \rangle = \int_0^{2\pi} e_n(e^{it}) \, dt \text{ for all } n \in \mathbb{Z},$$

hence  $\int_0^{2\pi} f(e^{it}) dt = \langle i(f), \varphi \rangle$  for all  $f \in C(\Gamma)$ . It follows that  $(E, \varphi) \cong L^1(\Gamma)$ , and we define  $j$  to be the canonical mapping from  $E$  into  $(E, \varphi) \cong L^1(\Gamma)$  (see C-I, Section 4). Then  $j$  has dense image and is injective since  $\varphi$  is strictly positive (cf. Proposition 3.5(ii)). One easily verifies that the diagram commutes.  $\square$

Now we are going to prove the main result of this section. As in the proof of Theorem 2.10 we will utilize pseudo-resolvents on a suitable  $\mathcal{F}$ -product of the Banach lattice. To simplify the proof we isolate two lemmas.

**Lemma 3.10** *Let  $\mathcal{F}$  be a filter on  $\mathbb{N}$  which is finer than the Frechet filter and let  $E_{\mathcal{F}}$  be the  $\mathcal{F}$ -product of the Banach lattice  $E$ . Given  $R \in \mathcal{L}(E)$  and denoting its canonical extension to  $E_{\mathcal{F}}$  by  $R_{\mathcal{F}}$  the following is true.  
If  $\alpha \in A\sigma(R) \setminus P\sigma(R)$ , then  $\ker(\alpha - R_{\mathcal{F}})$  is infinite dimensional.*

**Proof** Let  $(f_n)_{n \geq 1}$  be a normalized approximate eigenvector of  $R$  corresponding to  $\alpha$ . Since every accumulation point of  $(f_n)$  is an eigenvector of  $R$ , the assumption  $\alpha \notin P\sigma(R)$  implies that  $(f_n)$  does not have any accumulation points. Then there exist an  $\varepsilon > 0$  and a subsequence  $(g_n)$  of  $(f_n)$  such that

$$\|g_n - g_m\| \geq \varepsilon \text{ whenever } n \neq m. \quad (3.14)$$

Obviously,  $(g_n)$  is a normalized approximate eigenvector of  $R$  and so is every subsequence of  $(g_n)$ . In particular, for  $k \in \mathbb{N}$  the sequence  $(g_{n+k})_{n \geq 1}$  is a normalized approximate eigenvector of  $R$ . Then the elements  $\hat{g}^k \in E_{\mathcal{F}}$  given by  $\hat{g}^k := ((g_{n+k})_{n \geq 1} + c_{\mathcal{F}}(E))$  are normalized eigenvectors of  $R_{\mathcal{F}}$  corresponding to  $\alpha$ . As a consequence of (3.14) we obtain  $\|\hat{g}^k - \hat{g}^m\| = \mathcal{F}\text{-}\limsup \|g_{n+k} - g_{n+m}\| \geq \varepsilon$  provided that  $k \neq m$ . This shows that the unit ball in  $\ker(\alpha - R_{\mathcal{F}})$  is not relatively compact, hence  $\ker(\alpha - R_{\mathcal{F}})$  has to be infinite dimensional.  $\square$

**Lemma 3.11** *Let  $E$  be a Banach lattice and let  $M, L$  be two linear subspaces of  $E$ . Assume that  $f \in M$  implies  $|f| \in L$ , then  $\dim L \geq \dim M$ .*

**Proof** Let  $\{g_1, g_2, \dots, g_m\}$  ( $m \geq 1$ ) be any (finite) subset of  $M$  which is linearly independent. For  $u := \sum_{n=1}^m |g_n|$  all vectors  $g_n$  are contained in the principal ideal  $E_u$  which (by the Kakutani-Krein Theorem) is isomorphic to a space  $C(K)$ . Considering  $g_1, g_2, \dots, g_m$  as continuous functions on  $K$ , there exist points  $x_1, x_2, \dots, x_m \in K$  and functions  $h_1, h_2, \dots, h_m \in \text{span}\{g_1, g_2, \dots, g_m\}$  such that  $h_i(x_j) = \delta_{ij}$ . Then  $|h_i|(x_j) = \delta_{ij}$  hence  $\{|h_j| : 1 \leq j \leq m\}$  is a subset of  $m$  linearly independent vectors which (by assumption) is contained in  $L$ .  $\square$

The surprising fact in the following theorem is the conclusion that every point in the boundary spectrum is a simple algebraic pole if only  $s(A)$  is supposed to be a pole.

**Theorem 3.12** *Let  $T$  be an irreducible semigroup on a Banach lattice and let  $A$  be its generator. If  $s(A)$  is a pole of the resolvent, then there exists  $\alpha \geq 0$  such that  $\sigma_b(A) = s(A) + i\alpha\mathbb{Z}$ . Moreover,  $\sigma_b(A)$  contains only algebraically simple poles.*

**Proof** We will assume that  $s(A) = 0$ . Assuming first that every element of  $\sigma_b(A)$  is an eigenvalue of  $A$ , one can conclude the following. By Theorem 3.8(i) we know that  $\sigma_b(A)$  is an additive subgroup of  $i\mathbb{R}$ . Since it is a closed subset and 0 is an isolated point, it follows that  $\sigma_b(A) = i\alpha\mathbb{Z}$  for some  $\alpha \geq 0$ . Moreover, as a consequence of (3.13), for every  $k \in \mathbb{Z}$  we obtain

$$R(\lambda + ik\alpha, A) = S_h^{-k} \circ R(\lambda, A) \circ S_h^k \quad (\lambda \in \varrho(A), k \in \mathbb{Z}). \quad (3.15)$$

By Proposition 3.5(iv) 0 is an algebraically simple pole. Then (3.15) implies that every point  $ik\alpha$  has the same property.

We now show that every element  $i\beta$  is an eigenvalue of  $A$ . By Proposition 3.5(iv) the residue of  $R(\cdot, A)$  in  $\lambda = 0$  has the form  $P = \varphi \otimes u$  with  $\varphi(u) = 1$ . Given an ultrafilter  $\mathcal{U}$  on  $\mathbb{N}$  which is finer than the Frechet filter, then  $\lim_{\mathcal{U}} \varphi(f_n)$  exists for every bounded sequence  $(f_n) \subset E$ . Using this fact it is easy to see that the canonical extension  $P_{\mathcal{U}}$  of  $P$  to the  $\mathcal{U}$ -product  $E_{\mathcal{U}}$  of  $E$  has the following form.

$$P_{\mathcal{U}} = \hat{\varphi} \otimes \hat{u} \quad \text{where } \hat{u} := (u, u, u, \dots) + c_{\mathcal{U}}(E) \in E_{\mathcal{U}} \text{ and } \hat{\varphi} \in (E_{\mathcal{U}})' \\ \text{is given by } \hat{\varphi}((f_n) + c_{\mathcal{U}}(E)) := \lim_{\mathcal{U}} \varphi(f_n) \quad ((f_n) + c_{\mathcal{U}}(E) \in E_{\mathcal{U}}). \quad (3.16)$$

Given  $i\beta \in \sigma_b(A)$  then  $i\beta \in A\sigma(A)$  hence  $1 \in A\sigma(\lambda R(\lambda + i\beta, A))$ . Assuming  $i\beta \notin P\sigma(A)$ , then  $1 \notin P\sigma(\lambda R(\lambda + i\beta, A))$ . Then Lemma 3.10 implies that  $M := \ker(1 - \lambda R(\lambda + i\beta, A)_{\mathcal{U}})$  is infinite dimensional (and independent of  $\lambda$  by Proposition 2.6(i).) For  $\hat{f} \in M$  we have  $|\hat{f}| = \gamma R(\gamma + i\beta, A)_{\mathcal{U}}|\hat{f}| \leq \gamma R(\gamma, A)_{\mathcal{U}}|\hat{f}|$  for every  $\gamma > 0$ . It follows that  $\hat{\varphi}(|\hat{f}|) = P_{\mathcal{U}}|\hat{f}| = \lim_{\gamma \rightarrow 0} \gamma R(\gamma, A)_{\mathcal{U}}|\hat{f}| \geq |\hat{f}|$ . Thus considering the closed ideal  $I := \{\hat{f} \in E_{\mathcal{U}} : \hat{\varphi}(|\hat{f}|) = 0\}$  we have

$$\tilde{\varphi}(|\hat{f}|) - |\hat{f}| \in I \text{ for every } \hat{f} \in M. \quad (3.17)$$

This implies that  $M \cap I = \{0\}$ . Hence the canonical image  $M_I$  of  $M$  in the quotient space  $E_{\mathcal{U}/I}$  is infinite dimensional as well. By (3.16) and (3.17) the absolute value of an element  $\tilde{f} \in M_I$  is a scalar multiple of  $\tilde{u} := \hat{u} + I$ . This is a contradiction by Lemma 3.11.  $\square$

In view of A-III, Proposition 4.2 the result above has consequences for semigroups which can be reduced (by considering restrictions to invariant ideals or quotients) to semigroups which satisfy the hypothesis of Theorem 3.12. Semigroups having this property are precisely those for which  $s(A)$  is a pole of the resolvent of finite algebraic multiplicity. The latter claim is a consequence of Proposition 2.11 and the following lemma.

**Lemma 3.13** *Suppose that  $\mathcal{T} = (T(t))_{t \geq 0}$  is a positive semigroup such that  $s(A)$  is a first order pole of the resolvent. Moreover assume that the corresponding residue is a strictly positive operator of finite rank.*

*Then there are closed  $\mathcal{T}$ -invariant ideals  $J_1, J_2, \dots, J_m$  which are mutually orthogonal. For the restrictions  $\mathcal{T}_k$  of  $\mathcal{T}$  to  $J_k$  the following is true.*

- (i)  $\mathcal{T}_k$  is irreducible with spectral bound  $s(A_k) = s(A)$ .

(ii)  $s(A_{/J}) < s(A)$  where  $J := J_1 \oplus J_2 \oplus \dots \oplus J_m$ .

**Proof** We assume  $s(A) = 0$ . Since  $P$  is a strictly positive projection  $PE = \ker A$  is a sublattice of  $E$ . Actually, if  $x \in PE$  i.e.,  $Px = x$ , then  $P|x| \geq |Px| = |x|$ . Hence  $P(|P|x| - |x|) = P^2|x| - P|x| = 0$  which implies that  $P|x| - |x| = 0$  or  $|x| \in PE$ . Thus we know that  $\ker A$  is a finite dimensional sublattice of  $E$  hence it is isomorphic to a space  $\mathbb{C}^m$  for some  $m \in \mathbb{N}$  (see Section II.4 of Schaefer [23]). Then there exist vectors  $e_j \in E_+$  ( $1 \leq j \leq m$ ) such that the following holds.

$$\ker A = \text{span}\{e_1, e_2, \dots, e_m\} \text{ and } \inf\{e_i, e_j\} = 0 \text{ for } i \neq j. \quad (3.18)$$

We have  $T(t)e_k = e_k$  hence the closed ideal generated by  $e_k$  is  $\mathcal{T}$ -invariant. We denote this ideal  $J_k$  and define  $J := J_1 \oplus J_2 \oplus \dots \oplus J_m$ . The ideal  $J$  is closed (see [Schaefer (1974), III. Theorem 1.2]),  $\mathcal{T}$ -invariant and we have  $PE = \ker A \subset J$ . Then  $P_{/J} = 0$  hence the spectral bound  $s(A_{/J})$  is strictly less than zero (by Theorem 1.1(i)). Moreover, the residue corresponding to the resolvent of  $\mathcal{T}_k$ , we denote it  $P_k$ , is the restriction of  $P$  to  $J_k$ . Then  $P_k$  is strictly positive and  $P(J_k) = \text{span}\{e_k\}$ . To show that  $T_k$  is irreducible, we consider an invariant ideal  $I$ . Then we have  $R(\lambda, A_k)I \subset I$  for  $\lambda > 0$  hence  $P_k = \lim_{\lambda \rightarrow 0} \lambda R(\lambda, A_k)$  leaves  $I$  invariant. If  $I \neq \{0\}$ , then  $P_k I \neq \{0\}$  since  $P_k$  is strictly positive. Then  $e_k \in P_k I \subset I$  which implies that  $J_k \subset I$ .  $\square$

Combining the lemma with Proposition 2.11 one obtains the following.

If  $s(A)$  is a pole of finite algebraic multiplicity, then there exists a finite chain of  $\mathcal{T}$ -invariant ideals  $I_{-1} := \{0\} \subset I_0 \subset \dots \subset I_N := E$  ( $N \in \mathbb{N}$ ) such that the following is true.

For the semigroup  $\mathcal{T}_n$  on  $I_n/I_{n-1}$  ( $0 \leq n \leq N$ ) which is induced by  $\mathcal{T}$  we have either  $s(A_n) = s(A)$  and  $\mathcal{T}_n$  is irreducible or  $s(A_n) < s(A)$ . (3.19)

The following theorem is an immediate consequence of (3.19), Theorem 3.12 and A-III, Proposition 4.2.

**Theorem 3.14** Let  $\mathcal{T}$  be a positive semigroup on a Banach lattice with generator  $A$ . If  $s(A)$  is a pole of finite algebraic multiplicity, then  $\sigma_b(A)$  is a finite union of discrete subgroups (i.e.,  $\sigma_b(A) = s(A) + \cup_{k=1}^N i\alpha_k \mathbb{Z}$  with  $\alpha_k \in \mathbb{R}$ ). Moreover,  $\sigma_b$  contains only poles of finite algebraic multiplicity.

Here the assumption that the multiplicity of  $s(A)$  is finite is essential as can be seen from the following example.

**Example 3.15** Consider  $X := [0, 1] \times V$ ,  $V := \{v \in \mathbb{R} : v_1 < |v| < v_2\}$  ( $0 < v_1 < v_2 < \infty$ ). The flow in the phase space  $X$  which describes the free motion in the interval  $[0, 1]$  with velocities in  $V$  assuming that the particles are reflected at the endpoints generates a positive semigroup on  $L^p(X, \mu)$  ( $\mu$  the Lebesgue measure). For the spectrum of the generator  $A$  one obtains  $\sigma(A) = \{iy : v_1 \leq |y| \leq v_2 \text{ for some } n \in \mathbb{N}_0\}$  with  $y_1 := \pi v_1^{-1}$ ,  $y_2 := \pi v_2^{-1}$ . Moreover, 0 is a first order

pole of the resolvent, obviously the only pole in  $\sigma_b(A) = \sigma(A)$ . These statements can be verified by calculating the resolvent explicitly. This can be done using the integral representation. The semigroup is given as follows.

$$(T(t)f)(x, v) = \begin{cases} f(x - vt + k, v) & \text{if } k - 1 \leq vt - x \leq k \text{ and } k \text{ even,} \\ f(1 - (x - vt + k), -v) & \text{if } k - 1 \leq vt - x \leq k \text{ and } k \text{ odd.} \end{cases} \quad (3.20)$$

Obviously one can apply Theorem 3.12 and Theorem 3.14, respectively, in order to prove existence of strictly dominant eigenvalues. We consider two typical cases in the following corollaries. The meaning of  $r_{ess}(T(t))$  and  $\omega_{ess}(\mathcal{T})$  is explained in A-III, 3.7.

**Corollary 3.16** *Suppose that  $\mathcal{T}$  is a positive semigroup such that  $\omega_{ess}(\mathcal{T}) < \omega_0(\mathcal{T})$ . Then  $s(A) = \omega_0(\mathcal{T})$  is a strictly dominant eigenvalue. If, in addition, there exists an eigenfunction which is a quasi-interior point of  $E_+$  (e.g., if  $\mathcal{T}$  is irreducible), then  $s(A)$  is a first order pole of  $R(\cdot, A)$ .*

**Proof** There exist  $\varepsilon > 0$  such that for every  $t > 0$  the set  $\{\lambda \in \sigma(T(t)) : |\lambda| \geq \exp((s(A) - \varepsilon)t)\}$  contains only (finitely many) poles of  $R(\cdot, T(t))$  each being of finite algebraic multiplicity. In view of A-III, Corollary 6.5 the set  $\{\lambda \in \sigma(A) : \operatorname{Re} \lambda > s(A) - \varepsilon\}$  is finite and contains only poles of  $R(\cdot, A)$ . Thus we can apply Theorem 3.14. It follows that  $s(A)$  is strictly dominant. For the final assertion we refer to Remark 2.15(b).  $\square$

**Corollary 3.17** *Suppose that  $\mathcal{T}$  is an irreducible, eventually norm continuous semigroup having compact resolvent. Then  $s(A) = \omega_0(\mathcal{T})$  is an algebraically simple pole and a strictly dominant eigenvalue.*

**Proof** By Theorem 3.7(iii) we know that  $s(A) > -\infty$ . Theorem 3.12 is applicable since we assumed that  $T$  is irreducible and has compact resolvent. Thus  $s(A)$  is an algebraically simple pole and  $\sigma_b(A) = s(A) + i\alpha\mathbb{Z}$  for some  $\alpha \geq 0$ . In addition  $\{\lambda \in \sigma(A) : \operatorname{Re} \lambda \geq -1\}$  is compact since  $T$  is eventually norm-continuous (see A-II, Theorem 1.20). It follows that  $s(A)$  is strictly dominant. By A-III, Theorem 6.6 we have  $s(A) = \omega_0(\mathcal{T})$ .  $\square$

In the following proposition we give a condition which ensures that Theorem 3.14 can be applied to certain perturbations. Moreover, we state a criterion ensuring the existence of a dominant eigenvalue.

**Proposition 3.18** *Suppose that  $A$  is the generator of a positive semigroup and that  $K \in \mathcal{L}(E)$  is a positive linear operator. If  $K$  is  $A$ -compact (i.e., if  $KR(\lambda_o, A)$  is compact for some  $\lambda_o \in \varrho(A)$ ) and if  $s(A + K) > s(A)$ , then  $B := A + K$  satisfies the assumptions of Theorem 3.14.*

*If, in addition,  $K$  is irreducible, then  $s(B)$  is a dominant eigenvalue and the semigroup generated by  $B$  is irreducible.*

**Proof** The resolvent equation  $R(\lambda, A) = R(\lambda_0, A)(1 - (\lambda - \lambda_0)R(\lambda, A))$  implies that  $KR(\lambda, A)$  is a compact operator for every  $\lambda \in \varrho(A)$ . For  $\lambda > s(A)$  we have  $\lambda - B = (1 - KR(\lambda, A))(\lambda - A)$  and  $(1 - KR(\lambda, A))^{-1}$  exists for  $\lambda > s(B)$ . Therefore Theorem 1.2, XIII.13 of Reed and Simon [20] implies that  $R(\lambda, B) = R(\lambda, A)(1 - KR(\lambda, A))^{-1}$  has only poles of finite algebraic multiplicity in  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda > s(A)\}$ . This proves the first claim. In order to prove the second, we denote the semigroup corresponding to  $A$  and  $B$  by  $(T(t))$  and  $(S(t))$ , respectively. It follows from Proposition 3.3 that  $(S(t))$  is irreducible and we have  $S(t) = T(t) + \int_0^t T(t-s)KS(s) ds$  (see A-II, (1.9)). Iterating this identity we obtain for every  $m \in \mathbb{N}, t \geq 0$

$$\begin{aligned} S(t) &= \sum_{n=0}^{m-1} T_n(t) + R_m(t) \quad \text{where} \\ T_0(t) &:= T(t), \quad T_n(t) := \int_0^t T(t-s)KT_{n-1}(s) ds \quad \text{for } n \in \mathbb{N}, \\ R_m(t) &:= \int_0^t \int_0^{t_1} \dots \int_0^{t_{m-1}} T(t-t_1)KT(t_1-t_2)K \dots T(t_{m-1}-t_m)KS(t_m) dt_m \dots dt_1. \end{aligned} \quad (3.21)$$

We fix  $0 < f \in E, 0 < \varphi \in E', t > 0$ . By Theorem 3.2(i),  $S(t)f > 0$ . Since  $K$  is irreducible, there exists  $m \in \mathbb{N}$  such that  $\langle K^m S(t)f, \varphi \rangle > 0$ . Thus the integrand appearing in the representation (3.21) of  $\langle R_m(t)f, \varphi \rangle$  is non-zero at  $t_1 = t_2 = \dots = t_{m-1} = t, t_m = t$ .

Since the integrand is positive and continuous, we conclude

$$\langle S(t)f, \varphi \rangle \geq \langle R_m(t)f, \varphi \rangle > 0 \quad \text{for } 0 < f, 0 < \varphi, t > 0. \quad (3.22)$$

It follows that  $(e^{-ts(B)}S(t))_{t \geq 0}$  cannot contain the rotation semigroup on  $\Gamma$ . On the other hand, assuming that  $s(B)$  is not dominant, then  $\dim(\ker((e^{\tau \cdot s(B)} - S(\tau))) > 1$  for some  $\tau > 0$ . Hence, the restriction  $(e^{-ts(B)}S(t)|_F)_{t \geq 0}$  where  $F := \ker(e^{\tau \cdot s(B)} - S(\tau))$ , contains the rotation semigroup by Corollary 3.9.  $\square$

We conclude this section considering once again Example 3.4(d). The generator considered there is  $B = (A - M) + K$ , where  $K$  is positive linear. From (3.5) and (3.6) one deduces that

$$(KR(\lambda, A)f)(x, v) = \int_0^1 \int_{-1}^1 k(x, v, x', v')f(x', v') dx' dv'$$

where the kernel  $k$  is given by  $k(x, v, x', v') := \kappa(x, v, v')r_\lambda(x, x', v')$  (cf. (3.5), (3.7)). Using this representation of  $KR(\lambda, A)$  it follows that  $K$  is A-compact. Moreover for  $\lambda$  sufficiently large one has  $R(\lambda, A - M) = R(\lambda, A)(1 - MR(\lambda, A))^{-1}$  which shows that  $K$  is also  $(A - M)$ -compact. In order to apply Theorem 3.14 one needs  $s(B) > s(A - M)$  (see Proposition 3.18) which is difficult to verify. In case the function  $\sigma$  is continuous one can state a sufficient condition as follows. There exist  $r \in \mathbb{R}$  and  $g \in L^1([0, 1] \times [-1, 1])$ ,  $g > 0$  such that

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$r < \inf\{\sigma(x, 0) : x \in [0, 1]\}$  and  $Bg \geq -rg$ . The additional assumption made in the second part of Proposition 3.18 is not satisfied in this example. Nevertheless one can show that  $s(B)$  is strictly dominant in this situation (provided that  $s(B) > s(A)$ ). For details we refer to [Greiner (1984d)] or Voigt [26] where the linear transport equation in higher dimensional spaces is discussed.

## 4 Semigroups of Lattice Homomorphisms

In Section 2 we proved that the boundary spectrum of certain positive semigroups is a cyclic set. For semigroups of lattice homomorphisms much more can be said. The whole spectrum is an imaginary additively cyclic subset of  $\mathbb{C}$  (cf. Theorem 4.2). This result can be used to derive cyclicity results for the eigenvalues in the boundary spectrum of positive semigroups (cf. Corollary 4.3). In the last part of this section we discuss a spectral decomposition of positive groups (cf. Theorem 4.8).

**Lemma 4.1** *Suppose that  $(T(t))_{t \geq 0}$  is a semigroup of lattice homomorphisms on a Banach lattice  $E$  with generator  $A$ . In case  $i\alpha \in R\sigma(A)$ ,  $\alpha \in \mathbb{R}$ , then one of the following assertions are true*

- (a)  $i\alpha\mathbb{Z} \subset R\sigma(A)$ ;
- (b)  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < 0\} \subset R\sigma(A)$ .

**Proof** There exists  $\varphi \in E'$ ,  $\varphi \neq 0$  such that  $T(t)' \varphi = e^{i\alpha t} \varphi$  ( $t \geq 0$ ). Then we have  $|\varphi| = |T(t)' \varphi| \leq T(t)' |\varphi|$  ( $t \geq 0$ ). If we fix  $r > \omega_0(\mathcal{T})$  and define  $\psi := rR(r, A)' |\varphi|$ , we have

$$T(t)' \psi \leq e^{rt} \psi, T(t)' \psi \geq \psi \quad (t \geq 0) \quad \text{and} \quad |\varphi| \leq \psi. \quad (4.1)$$

In fact, A-I,(3.1) implies  $(e^{rt} - T(r))R(r, A) \geq 0$  hence  $T(t)' \psi = rR(r, A)' T(t)' |\varphi| \leq r \cdot e^{rt} R(r, A)' |\varphi| = e^{rt} \psi$ . Moreover, the inequality  $T(t)' |\varphi| \geq |\varphi|$  ( $t \geq 0$ ) implies  $T(t)' \psi = rR(r, A)' T(t)' |\varphi| \geq rR(r, A)' |\varphi| = \psi$  and  $\psi = rR(r, A)' |\varphi| = r \int_0^\infty e^{-rt} T(t)' |\varphi| dt \geq r \int_0^\infty e^{-rt} |\varphi| dt = |\varphi|$ .  $\square$

Now, considering the AL-space  $(E, \psi)$  (see C-I, Section 4) the first inequality of (4.1) implies that  $(T(t))_{t \geq 0}$  induces a strongly continuous semigroup  $(T_1(t))_{t \geq 0}$  on  $(E, \psi)$ . That is we have

$$\begin{array}{ccc} E & \xrightarrow{T(t)} & E \\ q_\psi \downarrow & & \downarrow q_\psi \\ (E, \psi) & \xrightarrow{T_1(t)} & (E, \psi) \end{array} \quad (4.2)$$

Denoting by  $A_1$  the generator of  $(T_1(t))$  we have  $R\sigma(A_1) \subset R\sigma(A)$ . Indeed,  $A_1^* x = \lambda x$  implies  $T_1(t)' x = e^{\lambda t} x$  hence by (4.2)  $T(t)' q'_\psi(x) = e^{\lambda t} q'_\psi(x)$  or equivalently  $A^*(q'_\psi(x)) = q'_\psi(x)$ . Thus it remains to show that either  $i\alpha\mathbb{Z}$  or  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < 0\}$  is contained in  $R\sigma(A_1)$ .

Obviously,  $(T_1(t))$  is a semigroup of lattice homomorphisms as well. The second inequality of (4.1) implies

$$\|T_1(t)f\|_\psi = \langle |T_1(t)f|, \psi \rangle = \langle |f|, T_1(t)' \psi \rangle \geq \langle |f|, \psi \rangle = \|f\|_\psi. \quad (4.3)$$

Then for  $\lambda \in \mathbb{C}$  with  $\operatorname{Re} \lambda < 0$  we have

$$\|(e^{\lambda t} - T_1(t))f\|_\psi \geq \|T_1(t)f\|_\psi - \|e^{\lambda t}f\|_\psi \geq (1 - |e^{\lambda t}|)\|f\|_\psi \quad (f \in (E, \psi))$$

and we obtain for the corresponding generator

$$\begin{aligned} \|(\lambda - A_1)f\|_\psi &= \lim_{t \rightarrow 0} \left\| \frac{1}{t} (e^{-\lambda t} T_1(t)f - f) \right\|_\psi \geq \lim_{t \rightarrow 0} \frac{1}{t} (e^{-t \operatorname{Re} \lambda} - 1) \|f\|_\psi \\ &= -\operatorname{Re} \lambda \cdot \|f\|_\psi \text{ for } \operatorname{Re} \lambda < 0 \text{ and } f \in (E, \psi). \end{aligned} \quad (4.4)$$

It follows from (4.3) and (4.4) that  $A\sigma(T_1(t)) \cap \{z \in \mathbb{C} : |z| < 1\} = \emptyset$  and  $A\sigma(A_1) \cap \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < 0\} = \emptyset$ . Since the topological boundary of the spectrum is always contained in the approximate point spectrum (see A-III, Proposition 2.2) and  $R\sigma(T(t)) \setminus \{0\} = \exp(tR\sigma(A))$  (see A-III, Theorem 6.3), precisely one of the following two cases occurs.

- (A)  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < 0\} \subset \varrho(A_1)$  and  $\{z \in \mathbb{C} : |z| < 1\} \subset \varrho(T_1(t))$ ;
- (B)  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < 0\} \subset R\sigma(A_1)$  and  $\{z \in \mathbb{C} : |z| < 1\} \subset R\sigma(T_1(t))$ .

We mentioned above that  $R\sigma(A_1) \subset R\sigma(A)$ . Thus we only have to analyze case (A). In this case each operator  $T_1(t)$  is an invertible lattice homomorphism hence a lattice isomorphism. It follows that  $T_1(t)'$  is a lattice isomorphism as well. The third inequality in (4.1) implies that  $\varphi$  can be considered as an element of  $(E, \psi)'$  and  $T(t)'\varphi = e^{i\alpha t}\varphi$  ( $t \geq 0$ ) implies  $T_1(t)'\varphi = e^{i\alpha t}\varphi$ . Furthermore, we have  $T_1(t)'|\varphi| = |T_1(t)'\varphi| = |e^{i\alpha t}\varphi|$  or equivalently  $A_1^*|\varphi| = 0$ . Now we can apply Theorem 2.2 and obtain  $i\alpha\mathbb{Z} \subset P\sigma(A_1^*) = R\sigma(A_1)$ .  $\square$

**Theorem 4.2** *Let  $A$  be the generator of a semigroup  $(T(t))_{t \geq 0}$  of lattice homomorphisms on a Banach lattice  $E$ . Then  $\sigma(A)$ ,  $A\sigma(A)$  and  $P\sigma(A)$  are imaginatively cyclic subsets of  $\mathbb{C}$ .*

**Proof** We first consider the point spectrum. If  $\lambda \in P\sigma(A)$ ,  $\lambda = \alpha + i\beta$  ( $\alpha, \beta \in \mathbb{R}$ ), then there exists  $f \in E$ ,  $f \neq 0$  such that  $Af = \lambda f$ . It follows that  $T(t)f = e^{\lambda t}f$  ( $t \geq 0$ ) hence  $T(t)|f| = |T(t)f| = e^{\alpha t}|f|$  ( $t \geq 0$ ), or equivalently,  $A|f| = \alpha|f|$ . Now Theorem 2.2 is applicable and we obtain  $A(f^{[n]}) = (\alpha + in\beta)f^{[n]}$  for all  $n \in \mathbb{Z}$ .

To prove the assertion for  $A\sigma(A)$  we consider an  $\mathcal{F}$ -product semigroup in order to reduce the problem to the point spectrum. We use the notation of A-I,3.6. Obviously the space  $m(E)$  is a Banach lattice and every operator  $\hat{T}(t)$  is a lattice homomorphism. We have  $|T(t)|f| - |f| = ||T(t)f| - |f|| \leq |T(t)f - f|$  ( $f \in E$ ), hence  $(|f_n|) \in m^{\mathcal{T}}(E)$  whenever  $(f_n) \in m^{\mathcal{T}}(E)$ . This proves that  $m^{\mathcal{T}}(E)$  is a sublattice, hence a Banach lattice as well. Obviously,  $c_{\mathcal{F}}(E) \cap m^{\mathcal{T}}(E)$  is an order ideal. Thus  $E_{\mathcal{F}}^{\mathcal{T}}$  is a Banach lattice and  $(T_{\mathcal{F}}(t))$  is a semigroup of lattice homomorphisms. It follows that  $P\sigma(A_{\mathcal{F}})$  is cyclic hence  $A\sigma(A)$  is cyclic by A-III,4.5.

Cyclicity of the entire spectrum now follows from the cyclicity of  $A\sigma(A)$  and Lemma 4.1.  $\square$



One can use Theorem 4.2 in order to prove cyclicity for the eigenvalues in the boundary spectrum of positive semigroups. We list some typical cases in the following corollary.

**Corollary 4.3** *Let  $\mathcal{T} = (T(t))_{t \geq 0}$  be a positive semigroup on a Banach lattice  $E$  which is bounded. Each of the following conditions implies that  $P\sigma(A) \cap i\mathbb{R}$  is imaginary additively cyclic.*

- (i)  *$E$  is weakly sequentially complete (e.g.  $E = L^p(\mu)$ ,  $1 \leq p < \infty$ );*
- (ii) *Every operator  $T(t)$  is mean ergodic (i.e., the Césaro means  $\frac{1}{n} \sum_{k=0}^{n-1} T(t)^k$  converge strongly as  $n \rightarrow \infty$ );*
- (iii) *There is a strictly positive linear form which is  $\mathcal{T}$ -invariant.*

**Proof** We will show that each of the conditions (i), (ii), (iii) implies that  $\ker(1 - T(s))$  is a Banach lattice (not necessarily a sublattice of  $E$ ) for every  $s \geq 0$ . Then one argues as follows. Given  $i\alpha \in P\sigma(A)$ ,  $\alpha \in \mathbb{R}$ , then  $T(t)g = e^{i\alpha t}g$  for suitable  $g \neq 0$ . For  $\tau := 2\pi|\alpha|^{-1}$  we have  $g \in F := \ker(1 - T(\tau))$ . Then the restriction  $(T(t)|_F)_{t \geq 0}$  is a  $\tau$ -periodic positive semigroup on  $F$ . Since  $(T(t)|_F)^{-1} = T(n\tau - t)|_F \geq 0$ , it follows that  $(T(t)|_F)$  is a semigroup of lattice isomorphisms. Since  $g \in F$ , we have  $i\alpha \in P\sigma(A|_F)$  hence  $i\alpha\mathbb{Z} \in P\sigma(A|_F) \subset P\sigma(A)$  by Theorem 4.2. Now we show that  $\ker(1 - T(s))$  is a vector lattice for the induced order and a Banach lattice for an equivalent norm.

In case (iii),  $\ker(1 - T(s))$  is even a sublattice of  $E$ . Indeed, assume  $T(t)' \varphi = \varphi$  and  $\varphi \gg 0$ , ( $t \geq 0$ ), then  $T(s)f = f$  implies  $T(s)|f| \geq |f|$ . Thus from  $\langle T(s)|f| - |f|, \varphi \rangle = \langle |f|, T(s)' \varphi - \varphi \rangle = 0$  it follows that  $T(s)|f| = |f|$ .

Now we assume that  $E$  is weakly sequentially complete, which is equivalent to (cf. Section 5 of C-I)

$$\text{Every increasing norm-bounded net of } E_+ \text{ converges.} \quad (4.5)$$

We fix  $s > 0$  and define  $F := \ker(1 - T(s))$ ,  $T := T(s)$ . Obviously  $f \in F$  implies  $\bar{f} \in F$  hence  $F = F \cap E_{\mathbb{R}} + iF \cap E_{\mathbb{R}}$ . Thus we have to show that  $F_{\mathbb{R}} = F \cap E_{\mathbb{R}}$  is a sublattice. Given  $f \in F_{\mathbb{R}}$ , then  $Tf = f$  hence  $|f| \leq T|f|$ . Iterating this inequality we obtain  $|f| \leq T|f| \leq T^2|f| \leq T^3|f| \leq \dots$ . By (4.5)  $|f|_o := \lim_{n \rightarrow \infty} T^n|f|$  exists and we have  $T|f|_o = \lim_{n \rightarrow \infty} T^{n+1}|f| = |f|_o$ , i.e.,  $|f|_o \in F_{\mathbb{R}}$ . And, for  $g \in F_{\mathbb{R}}$  satisfying  $\pm f \leq g$ , we have  $|f|_o \leq g$  thus  $|f|_o = \sup_F \{f, -f\}$ . Moreover,  $\|f\|_o := \| |f|_o \|$  ( $f \in F$ ) is an equivalent norm on  $F$  such that  $(F, \|\cdot\|_o)$  is a Banach lattice.

(ii) If  $T(s)$  is mean-ergodic, then we have  $\ker(1 - T(s)) = PE$  where  $P$  is the mean-ergodic projection, i.e.,  $Pf = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{k=0}^{n-1} T(s)^k f$ . Obviously  $P$  is positive, hence II.11.5 of Schaefer [23] implies that  $PE$  is a Banach lattice (for the induced order and an equivalent norm).  $\square$

The assumptions made in Corollary 4.3 can be weakened slightly (cf. Greiner [10]). However, one still cannot prove cyclicity of  $P\sigma_b(A)$  for arbitrary positive semigroups.

**Example 4.4** At first we recall Example 2.13 of Chapter B-III. There we constructed a bounded semigroup on the space  $C(\Gamma) \times C_0(\mathbb{R})$  such that  $P\sigma_b(A) = \{ik : k \in \mathbb{Z}, k \neq 0\}$ . Let us perform the same construction on the Hilbert space  $H := L^2(\Gamma) \times L^2(\mathbb{R})$ . For a fixed positive, non-zero function  $k \in C_c(\mathbb{R})$ , we define  $T(t)$  on  $H$  as follows.

$$\begin{aligned} T(t)([f, g]) &:= [f_t, g_t] \quad \text{with} \\ f_t(z) &:= f(z \cdot e^{it}) \quad (z \in \Gamma) \quad \text{and} \\ g_t(x) &:= g(x+t) + \frac{1}{2\pi} \int_0^{2\pi} f(z \cdot e^{is}) \, ds \cdot \int_x^{x+t} k(u) \, du. \end{aligned} \quad (4.6)$$

Then  $(T(t))_{t \geq 0}$  is a positive semigroup on  $H$  and for the spectrum of the generator we obtain  $\sigma(A) = i\mathbb{R}$ ,  $P\sigma(A) = i\mathbb{R} \setminus \{0\}$ . In view of Corollary 4.3(i) the semigroup cannot be bounded. (The explicit representation (4.6) only allows the estimate  $\|T(t)\| \leq \sqrt{2} + t \cdot \|k\|_2$  ( $t \geq 0$ ).)

In the next proposition we show that for semigroups of lattice homomorphisms on  $L^1$ -spaces, there is a spectral mapping theorem for the real part of the spectrum.

**Proposition 4.5** *Let  $(T(t))_{t \geq 0}$  be a strongly continuous semigroup of lattice homomorphisms on an  $L^1$ -space and denote by  $A$  its generator. Then we have*

$$\exp(t\sigma(A) \cap \mathbb{R}) = \sigma(T(t)) \cap (0, \infty) \quad \text{for every } t \geq 0. \quad (4.7)$$

**Proof** In view of A-III,6.2 it is enough to prove that the left hand side contains the set on the right.

Fix  $t > 0$  and assume  $r \in \sigma(T(t))$ ,  $r > 0$  and let  $\alpha := \frac{1}{t} \log r$ . At first we assume  $r \in R(\sigma(T(t)))$ . Then by A-III, Theorem 6.3 there exists  $\beta \in \mathbb{R}$  such that  $\alpha + i\beta \in R\sigma(A)$ . By Lemma 4.1 either  $\alpha + i\beta\mathbb{Z} \subset R\sigma(A)$  or  $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < \alpha\} \subset R\sigma(A)$ . In both cases we have  $\alpha \in \sigma(A)$ .

Now we assume  $r \in A\sigma(T(t))$ . Then there exists a normalized sequence  $(f_n) \subset E$  such that  $\lim_{n \rightarrow \infty} \|T(t)f_n - rf_n\| = 0$ . Since we have

$$|(T(t)|f| - r|f|)| = |(|T(t)f| - r|f|)| \leq |T(t)f - rf|, \quad (f \in E)$$

we may assume that  $(f_n)$  is a sequence in  $E_+$ .

Defining  $g_n := \int_0^t e^{-\alpha s} T(s)f_n \, ds$  we have  $g_n \in D(A)$  and

$$(A - \alpha)g_n = (A - \alpha) \int_0^t e^{-\alpha s} T(s)f_n \, ds = e^{-\alpha t} T(t)f_n - f_n = \frac{1}{t} (T(t)f_n - rf_n).$$

Therefore  $\lim_{n \rightarrow \infty} \|(A - \alpha)g_n\| = 0$ . It remains to prove  $\liminf_{n \rightarrow \infty} \|g_n\| > 0$ . The latter assertion is a consequence of the following facts.

- Since  $f_n$  is positive and the norm is additive on  $E_+$ , we have  $\|g_n\| = \int_0^t e^{-\alpha s} \|T(s)f_n\| \, ds$ .

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- The inequality  $\|T(t)f\| \leq \|T(t-s)\|\|T(s)f\|$  implies  $\|T(s)f\| \geq M^{-1}\|T(t)f\|$  for  $0 \leq s \leq t$ ,  $f \in E$  and  $M := \sup_{0 \leq s \leq t} \|T(s)\|$ .
- Since  $\lim_{n \rightarrow \infty} \|T(t)f_n - rf_n\| = 0$  and  $\|f_n\| = 1$ , we have  $\lim_{n \rightarrow \infty} \|T(t)f_n\| = r > 0$ .  $\square$

For semigroups satisfying the assumption of Proposition 4.5, the spectrum  $\sigma(A)$  is additively cyclic (by Theorem 4.2) and  $\sigma(T(t))$  is multiplicatively cyclic (by Schaefer [23, V.Theorem 4.4]). Then the relation (4.7) implies that decompositions of the spectrum by vertical lines allow a spectral decomposition of the semigroup (cf. A-III, Definition 3.1). (One simply performs a spectral decomposition of a single operator  $T(t)$ ). In the following we will show that for positive groups (on arbitrary Banach lattices) spectral decompositions of this type always exist. Moreover, it will turn out that the decomposition is compatible with the lattice structure. The proof of this result uses Kato's equality (see Section 5 of C-II). As a consequence of C-II, Corollary 5.8 we have the following.

Let  $E$  be a Banach lattice with order continuous norm and  $(T(t))_{t \in \mathbb{R}}$  be a group of positive operators on  $E$  with generator  $A$ . Then the domain  $D(A)$  is a sublattice of  $E$  and

$$A|f| = \operatorname{Re}[(\operatorname{sign} f)Af] \quad \text{for every } f \in D(A). \quad (4.8)$$

For real  $\mu$  one has  $\mu|f| = \operatorname{Re}[(\operatorname{sign} f)\mu f]$ , hence

$$(\mu - A)|f| = \operatorname{Re}[(\operatorname{sign} f)(\mu - A)f] \quad \text{for } \mu \in \mathbb{R}, f \in D(A).$$

The relations  $f^+ = \frac{1}{2}(|f| + f)$ ,  $f^- = \frac{1}{2}(|f| - f)$  yield

$$\begin{aligned} (\mu - A)f^+ &= \frac{1}{2}[(\operatorname{sign} f)(\mu - A)f + (\mu - A)f] \quad \text{and} \\ (\mu - A)f^- &= \frac{1}{2}[(\operatorname{sign} f)(\mu - A)f - (\mu - A)f], \end{aligned}$$

in case  $f$  is contained in the underlying real Banach lattice  $E_{\mathbb{R}}$ . For  $\mu \in \varrho(A) \cap \mathbb{R}$ , we can apply  $R(\mu, A)$  on both sides and the substitution  $f = R(\mu, A)g$  finally leads to

$$\begin{aligned} (R(\mu, A)g)^+ &= \frac{1}{2}R(\mu, A)[(\operatorname{sign} R(\mu, A)g)g + g] \\ (R(\mu, A)g)^- &= \frac{1}{2}R(\mu, A)[(\operatorname{sign} R(\mu, A)g)g - g] \end{aligned} \quad (4.9)$$

for all  $g \in E_{\mathbb{R}}$ . If we set

$$g_1 := \frac{1}{2} \cdot (g + (\operatorname{sign} R(\mu, A)g)g) \quad \text{and} \quad g_2 := \frac{1}{2} \cdot (g - (\operatorname{sign} R(\mu, A)g)g),$$

then obviously  $g = g_1 + g_2$ . Moreover,  $g$  is positive if and only if both,  $g_1$  and  $g_2$  are positive. We summarize these considerations in the following lemma.

**Lemma 4.6** *Let  $A$  be the generator of a positive group on a Banach lattice  $E$  which has order continuous norm. Given  $\mu \in \varrho(A) \cap \mathbb{R}$ , then every  $g \in E_{\mathbb{R}}$  is representable as sum of two elements  $g_1$  and  $g_2$  such that*

- (i)  $g \geq 0$  if and only if both  $g_1$  and  $g_2$  are positive,
- (ii)  $R(\mu, A)g_1 = (R(\mu, A)g)^+$ ,
- (iii)  $R(\mu, A)g_2 = -(R(\mu, A)g)^-$ .

We need another lemma. It can be formulated for arbitrary positive semigroups on Banach lattices.

**Lemma 4.7** *Let  $(T(t))_{t \geq 0}$  be a positive semigroup on a Banach lattice  $E$  with generator  $A$ . Given  $\mu \in \varrho(A) \cap \mathbb{R}$  and  $h \in E_+$ , then the following assertions are equivalent.*

- (a)  $R(\mu, A)h \geq 0$ ,
- (b)  $\left\{ \int_0^t e^{-\mu s} T(s)h \, ds : t \in \mathbb{R}_+ \right\}$  is bounded in  $E$ .

**Proof** (a)  $\Rightarrow$  (b): We have  $\int_0^t e^{-\mu s} T(s)h \, ds = (Id - e^{-\mu t} T(t))R(\mu, A)h$  (see A-I, (3.2)). Since  $R(\mu, A)h \geq 0$  and  $T(t)$  is a positive operator we obtain

$$\int_0^t e^{-\mu s} T(s)h \, ds = R(\mu, A)h - e^{-\mu t} T(t)R(\mu, A)h \leq R(\mu, A)h$$

which implies assertion (b).

(b)  $\Rightarrow$  (a): The assumption implies that

$$\int_0^\infty e^{-\nu s} T(s)h \, ds := \lim_{t \rightarrow \infty} \int_0^t e^{-\nu s} T(s)h \, ds \text{ exists for } \nu > \mu.$$

Using that  $A$  is a closed operator it follows that

$$(\nu - A) \left( \int_0^\infty e^{-\nu s} T(s)h \, ds \right) = h.$$

For  $\nu$  sufficiently close to  $\mu$  such that  $\nu \in \varrho(A) \cap \mathbb{R}$  we have

$$R(\nu, A)h = \int_0^\infty e^{-\nu s} T(s)h \, ds \geq 0.$$

By continuity we conclude  $R(\mu, A)h \geq 0$ . □

By now we are prepared to prove the spectral decomposition for positive groups. Before we formulate the theorem we recall the following consequence of Theorem 4.2. For any  $\mu \in \varrho(A) \cap \mathbb{R}$  the line  $\mu + i\mathbb{R}$  is a subset of the resolvent set and divides  $\sigma(A)$  into disjoint sets. Both sets will be unbounded in general.

**Theorem 4.8** *Let  $(T(t))_{t \in \mathbb{R}}$  be strongly continuous group of positive operators on a Banach lattice  $E$  with order continuous norm. If  $A$  is the generator and  $\mu \in$*

$\varrho(A) \cap \mathbb{R}$ , then  $I_\mu := \{f \in E : R(\mu, A)|f| \geq 0\}$  and  $J_\mu := \{f \in E : R(\mu, A)|f| \leq 0\}$  are  $(T(t))_{t \in \mathbb{R}}$ -invariant projection bands, the direct sum of them is  $E$ , and the spectra of the restrictions satisfy

$$\begin{aligned}\sigma(A|_{I_\mu}) &= \sigma(A) \cap \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < \mu\}, \\ \sigma(A|_{J_\mu}) &= \sigma(A) \cap \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda > \mu\}.\end{aligned}$$

**Proof** At first we consider  $I_\mu$ . Obviously it is a closed subset. From Lemma 4.7 we deduce that it is a lattice ideal. Moreover,  $I_\mu$  is  $R(\mu, A)$ -invariant and  $(T(t))_{t \in \mathbb{R}}$ -invariant as well (use Lemma 4.7 again).

Since  $-A$  is the generator of the positive group  $(T(-t))_{t \in \mathbb{R}}$  and  $J_\mu = \{f \in E : R(-\mu, -A)|f| \geq 0\}$ ,  $J_\mu$  has the same properties.

If  $f \in I_\mu \cap J_\mu$ , then  $R(\mu, A)|f| = 0$ , hence  $f = 0$  which shows that  $I_\mu \cap J_\mu = \{0\}$ . On the other hand, decomposing  $0 \leq h = h_1 + h_2 \in E_+$  according to Lemma 4.6, then assertion (ii) of this lemma implies that  $h_1 \in I_\mu$ , while assertion (iii) ensures that  $h_2 \in J_\mu$ . Since the positive cone  $E_+$  is generating, we have  $E = I_\mu \oplus J_\mu$  and the first part of the theorem is proved.

Since  $I_\mu$  is  $R(\mu, A)$ -invariant, we have  $\mu \in \varrho(A|_{I_\mu})$  and  $R(\mu, A|_{I_\mu}) = R(\mu, A)|_{I_\mu} \geq 0$ . Theorem 1.1(ii) then implies  $\sigma(A|_{I_\mu}) \subset \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda < \mu\}$ . The same argument applied to  $-A$  and  $-\mu$  yields  $\sigma(A|_{J_\mu}) \subset \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda > \mu\}$ . Now the assertion follows from A-III, Proposition 4.2.  $\square$

The spectral projections corresponding to the spectral decomposition described above have the expected representation as an integral 'around' the spectral sets (see Corollary 3 in [Greiner (1984c)]).

**Corollary 4.9** Assume that the assumptions of the theorem are satisfied,  $\mu \in \varrho(A) \cap \mathbb{R}$ ,  $\beta > s(A)$ ,  $\alpha < -s(-A)$ . If we denote the projections corresponding to the decomposition  $E = I_\mu \oplus J_\mu$  by  $P_\mu$  and  $Q_\mu$  (i.e.,  $P_\mu E = \ker Q_\mu = I_\mu$ ,  $Q_\mu E = \ker P_\mu = J_\mu$ ), then for  $f \in D(A^2)$  we have

$$\begin{aligned}P_\mu f &= \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} R(\mu + i\tau, A) f \, d\tau - \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} R(\alpha + i\tau, A) f \, d\tau, \\ Q_\mu f &= \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} R(\beta + i\tau, A) f \, d\tau - \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} R(\mu + i\tau, A) f \, d\tau.\end{aligned}\tag{4.10}$$

(The integrals appearing in (4.10) are improper Riemann integrals.)

We mention another consequence of Theorem 4.8. Just like Proposition 4.5 it is a spectral mapping theorem for the real part of the spectrum.

**Corollary 4.10** If  $(T(t))_{t \in \mathbb{R}}$  is a positive group on a space  $L^2$  or  $C_0(X)$  with generator  $A$ , then

$$\sigma(T(t)) \cap \mathbb{R}_+ = \exp(t\sigma(A) \cap \mathbb{R}) \quad \text{for every } t \geq 0.\tag{4.11}$$

**Proof** We borrow from the next chapter that for positive semigroups on spaces  $L^1$ ,  $L^2$  or  $C_0(X)$  spectral bound and growth bound coincide (see C-IV, Theorem 1.1).

We only have to show that  $\exp(t\varrho(A) \cap \mathbb{R}) \subset \varrho(T(t)) \cap \mathbb{R}_+$ .

If we consider a positive semigroup on an  $L^2$ -space, Theorem 4.8 can be applied directly. Given  $\mu \in \varrho(A) \cap \mathbb{R}$ , then  $E = I_\mu \oplus J_\mu$  according to Theorem 4.8. The result mentioned above implies  $r(T(t)|_{I_\mu}) < e^{\mu t}$  and  $r(T(-t)|_{J_\mu}) < e^{\mu t}$ . Hence  $\sigma(T(t)|_{I_\mu}) \subset \{\lambda \in \mathbb{C} : |\lambda| < e^{\mu t}\}$  and  $\sigma(T(t)|_{J_\mu}) = (\sigma(T(-t)|_{J_\mu}))^{-1} \subset \{\lambda \in \mathbb{C} : |\lambda| > e^{\mu t}\}$ . Thus  $\sigma(T(t)) = \sigma(T(t)|_{I_\mu}) \cup \sigma(T(t)|_{J_\mu})$  does not contain  $e^{\mu t}$ .

In case  $(T(t))$  is a positive group on  $C_0(X)$ , then the adjoint group  $(T(t)')$  is a group of lattice homomorphisms on  $E'$ . It follows that  $E^*$  is a sublattice of  $C_0(X)'$  which is isomorphic to  $M_b(X)$ , hence an  $L^1$ -space. The argument given for the  $L^2$ -space yields  $\sigma(T(t)*) \cap \mathbb{R}_+ = \exp(t\sigma(A^*) \cap \mathbb{R})$  for every  $t \geq 0$ . Thus the assertion follows from A-III,4.4.  $\square$

We conclude by describing a general situation of lattice semigroups. In Section 4 of B-III we constructed semigroups of lattice homomorphisms on  $C_0(X)$  starting with a continuous (semi-) flow on the locally compact space  $X$  and a multiplication operator. One can perform similar constructions on spaces  $L^p(\mu)$  for  $1 \leq p < \infty$  under certain conditions on the flow. We consider an example which shows where the problems are.

Define the semiflow  $\varphi$  on  $\mathbb{R}_+$  as follows.  $\varphi(t, x) := x - t$  for  $x \geq t$  and  $\varphi(t, x) := 0$  for  $x < t$ . For  $f \in L^p(\mu)$  one has difficulties to define  $f \circ \varphi_t$  properly since the preimage of the zero-set  $\{0\}$  does not have measure zero. This problem does not arise in case every transformation  $\varphi_t$  is measure preserving, i.e.  $\mu(\varphi_t^{-1}(C)) = \mu(C)$  for every Borel set  $C$ . A more general criterion is stated in the following proposition.

**Proposition 4.11** *Let  $X$  be a locally compact space and let  $\mu$  be a regular, positive Borel measure on  $X$ . Assume that the continuous semiflow  $\varphi : \mathbb{R}_+ \times X \rightarrow X$  satisfies the condition*

$$\varphi_t^{-1}(K) \text{ is compact for every compact set } K \subset X, t \geq 0. \quad (4.12)$$

(i) *For every  $p$ ,  $1 \leq p < \infty$  the following assertions are equivalent.*

- (a) *The operators  $T(t)$  defined by  $T(t)f := f \circ \varphi_t$  for  $f \in L^p(\mu)$ ,  $t \geq 0$ , are well-defined as bounded linear operator on  $L^p(\mu)$  and  $(T(t))_{t \geq 0}$  is a strongly continuous semigroup.*
- (b) *There exist constants  $t_0 > 0$ ,  $M > 0$  such that  $\mu(\varphi_t^{-1}(C)) \leq M \cdot \mu(C)$  for every open (compact) set  $C \subset X$  and every  $t \leq t_0$ .*

(ii) *In case the conditions (i) and (ii) are fulfilled, then  $(T(t))_{t \geq 0}$  is a semigroup of lattice homomorphisms on  $L^p(\mu)$  and  $C_c(X) \cap D(A)$  is a core of the generator.*

**Proof** (i) Since  $\mu$  is assumed to be regular, the inequality stated in (b) holds true for all Borel sets provided it is true for all open sets (compact sets, respectively).

(a)  $\Rightarrow$  (b): Assume that  $(T(t))$  is a strongly continuous semigroup on  $L^p(\mu)$ ,  $1 \leq p < \infty$ . For  $t_0 > 0$  we define  $M := (\sup\{\|T(t)\| : 0 \leq t \leq t_0\})^{1/p}$ . Given a

Borel set  $C \subset X$  we write  $C(t) := \varphi_t^{-1}(C)$ . Then we have  $T(t)\mathbb{1}_C = \mathbb{1}_{C(t)}$ , hence  $\mu(\varphi_t^{-1}(C)) = \|\mathbb{1}_{C(t)}\|_p^p = \|T(t)\mathbb{1}_C\|_p^p \leq M \cdot \|\mathbb{1}_C\|_p^p = M \cdot \mu(C)$ .

(b)  $\Rightarrow$  (a): Since the inequality in (b) holds for all Borel sets,  $\varphi_t^{-1}(C)$  is a  $\mu$ -null set whenever  $C$  is a  $\mu$ -null set. Thus given Borel functions  $f, g$  such that  $f = g$   $\mu$ -a.e., then  $f \circ \varphi_t = g \circ \varphi_t$   $\mu$ -a.e.. Moreover, for  $0 \leq f \in L^p(\mu)$ , there exists an increasing sequence  $(h_n)$  of simple functions converging pointwise to  $f$ . Then  $(h_n \circ \varphi_t)$  is a monotone sequence converging pointwise to  $f \circ \varphi_t$ . Using the fact that  $\mathbb{1}_C \circ \varphi_t = \mathbb{1}_{C(t)}$ ,  $C(t)$  as above, and the assumption  $\mu(C(t)) \leq M \cdot \mu(C)$ , it is easy to see that  $\|h_n \circ \varphi_t\|_p^p \leq M \cdot \|h_n\|_p^p \leq M \cdot \|f\|_p^p$ . Thus by the Monotone Convergence Theorem we have  $f \circ \varphi_t \in L^p(\mu)$  and  $\|f \circ \varphi_t\|_p \leq M^{1/p} \|f\|_p$ . It follows that  $T(t)$  is a bounded linear operator on  $L^p(\mu)$  and  $\|T(t)\| \leq M^{1/p}$  for  $0 \leq t \leq t_0$ . Since  $\varphi$  is a semiflow, we have  $T(0) = \text{Id}$  and  $T(t+s) = T(s)T(t)$  ( $0 \leq s, t < \infty$ ). It remains to prove strong continuity. Since  $\varphi$  is continuous and (4.12) holds, we know that  $T(t)(C_c(X)) \subset C_c(X)$  and that  $T(t)f$  tends to  $f$  uniformly as  $t \rightarrow 0$  provided that  $f \in C_c(X)$ . It follows that  $\lim_{t \rightarrow 0} \|T(t)f - f\|_p = 0$  for  $f \in C_c(X)$ . Since  $C_c(X)$  is dense in  $L^p(\mu)$  and  $\|T(t)\| \leq M^{1/p}$  for  $0 \leq t \leq t_0$ , the semigroup is strongly continuous.

(ii) Obviously every operator  $T(t)$  defined in assertion (a) of (i) is a lattice homomorphism. Above we pointed out that  $C_c(X)$  is invariant under  $(T(t))$ , then  $D(A) \cap C_c(X)$  is invariant as well. It is dense because the elements of the form  $\int_0^r T(s)f ds$ ,  $f \in C_c(X)$ ,  $r > 0$  belong to  $C_c(X)$  and to  $D(A)$ . Hence  $D(A) \cap C_c(X)$  is a core (by A-I, Corollary 1.34).  $\square$

Proposition 4.11 can be used to prove that flows corresponding to certain ordinary differential equations on  $\mathbb{R}^n$  generate strongly continuous semigroups on  $L^p(\mathbb{R}^n)$  (where  $\mathbb{R}^n$  is equipped with the Lebesgue measure). One has to impose conditions on the corresponding vector field. Note that for continuous flows condition (4.12) is automatically satisfied because for a compact  $K \subset X$  the set  $\varphi_t^{-1}(K) = \varphi_{-t}(K)$  is compact as the continuous image of a compact set.

*Example 4.12* Let  $F : \mathbb{R}^n \rightarrow \mathbb{R}^n$  be a  $C^1$ -vector field and assume that the derivative  $DF$  is uniformly bounded on  $\mathbb{R}^n$ . Then the ordinary differential equation  $y' = F(y)$  possesses a global flow  $\varphi : \mathbb{R} \times \mathbb{R}^n \rightarrow \mathbb{R}^n$  which is  $C^1$ . Moreover, we have

$$\|D\varphi_t(x)\| \leq e^{M|t|} \quad \text{for all } x \in \mathbb{R}^n, t \in \mathbb{R}, \text{ where } M := \sup\{\|DF(x)\| : x \in \mathbb{R}^n\}. \quad (4.13)$$

All these properties were proven in Example 3.15 of B-II. We will show that  $\varphi$  satisfies condition (ii) of Proposition 4.11(a). Hence it induces a strongly continuous (semi-)group of lattice homomorphisms on  $L^p(\mathbb{R}^n)$  ( $1 \leq p < \infty$ ) via  $T(t)f = f \circ \varphi_t$ . This is done using the change of variables formula as follows.

Let  $U$  be an open subset of  $\mathbb{R}^n$ , then  $\varphi_t^{-1}(U) = \varphi_{-t}(U) =: U(-t)$ . If  $\lambda$  denotes the Lebesgue measure, then

$$\begin{aligned}
\lambda(\varphi_t^{-1}(U)) &= \int_{U(-t)} 1 \, dx = \int_U 1 \circ \varphi_{-t}(x) \cdot |\det D\varphi_{-t}(x)| \, dx = \\
&\int_U |\det D\varphi_{-t}(x)| \, dx \leq \int_U e^{nM|t|} \, dx = e^{nM|t|} \cdot \lambda(U).
\end{aligned} \tag{4.14}$$

Here we used (4.13) and the fact that the determinant of an  $n \times n$ -matrix  $B$  satisfies  $|\det B| \leq \|B\|^n$ .

In general, existence of a global flow does not ensure that one can associate a semigroup of bounded linear operators on  $L^p(\mathbb{R}^n)$ , even if the vector field is  $C^\infty$ . For example the differential equation  $y' = \sin(y^2)$  does not induce a semigroup on  $L^p(\mathbb{R})$ . There is another important class of differential equations, “Hamiltonian differential equations”, which do induce semigroups of lattice homomorphisms on  $L^p$ -spaces. In fact, Liouville’s Theorem states that the flow corresponding to a Hamiltonian vector field preserves the volume (see [?], Section 3.3]). Thus assertion (b) of Proposition 4.11(i) is trivially satisfied. Further examples of flows which are measure preserving and therefore induce semigroups of lattice homomorphisms on  $L^p$ -spaces are billiard flows on compact convex subsets of  $\mathbb{R}^n$  and geodesic flows on Riemannian manifolds (see [?]).



## Notes

Spectral theory for a single positive operator as developed in Chapter V of Schaefer [23] is an essential tool for this chapter. Various results on the spectral theory of positive one-parameter semigroups can be found in Chapter 7 of Davies [5] and in the second part of Batty and Robinson [3].

*Section 1:* That the spectral bound is always an element of the spectrum was stated by Karlin [13], but a valid proof was given by Derndinger [7]. This assertion as well as assertion (b) of Theorem 1.1 allow generalizations in various directions. They are valid for ordered Banach spaces (see Greiner et al. [11] and Klein [16]) and one only needs that  $A$  has positive resolvent (see Kato [14] or Nussbaum [18]). Theorem 1.2 as well as its corollaries are also valid in ordered Banach spaces. For the analogue in the theory of the Laplace transform we refer to Section 10.5 in Widder [27] and Voigt [25].

*Section 2:* Theorem 2.2 is the basis for the subsequent cyclicity results. Pseudoresolvents are discussed e.g. in Hille and Phillips [12] or Yosida [28]. For nonpositive semigroups the two assertions stated in Definition 2.8 are no longer equivalent. A special case of Theorem 2.10 was proven by Derndinger [7] while the general result is due to Greiner [9]. Instead of pseudo-resolvents on the whole  $\mathcal{F}$ -product Derndinger works with the semigroup on the semigroup  $\mathcal{F}$ -product. Therefore he can only consider eigenvalues. Elliptic differential operators as generators of positive semigroups are discussed by many authors, e.g., Amann [1], Fattorini [8], ? ] or Pazy [19].

*Section 3:* There exist various notions which are (more or less closely) related to irreducibility, e.g. “positivity improving” in Reed and Simon [20], “ $u_0$ -positivity” in [Krasnosel’skii (1964)] or “quasi-strictly positive” in Karlin [13]. Sawashima [21] uses “non-support” instead of irreducible. She also discusses several modifications (“semi-non-support”, “strictly non-support”, “strongly positive”) and the interrelation between these notions. The notion of irreducibility can be extended to the (non-lattice) ordered setting (see Batty and Robinson [3]). Assertion (b) of Theorem 3.2 is due to Majewski and Robinson [17] while special cases can be found in Section XIII.12 of Reed and Simon [20] and in Kishimoto and Robinson [15]. Proposition 3.3 is due to ? ]. Retarded equations as discussed in Example 3.4(c) will be discussed in more detail in Section 3 of C-IV. Example 3.4(d) is a one-dimensional version of the linear transport equation. The higher dimensional equation is more delicate but can be treated similarly (see e.g. ? ], ? ], or [Voigt (1984b)]). A special case of Proposition 3.5 can be found in Davies [5]. Theorem 3.7 and Example 3.6 are taken from Schaefer [24]. The most interesting criterion of Theorem 3.7 seems to be condition (iii), since it gives a sufficient condition for the existence of eigenvalues for a sufficiently large class of semigroups. For semigroups induced by measure-preserving flows Theorem 3.8 and Corollary 3.9 are proven in ? ]. Corollary 3.9 is a special case of the Halmos-von Neumann Theorem which classifies irreducible semigroups having discrete spectrum (see ? ], Greiner [10] and Schaefer [23] for the general result).

Lemma 3.10 is taken from [Groh (1984b)] and Theorems 3.12 and 3.14 can be found (with slightly different proofs) in Greiner [9].

*Section 4:* It was Derndinger [7] who proved Theorem 4.2. In Corollary 4.3 one can replace boundedness of the semigroup by the assumption that the resolvent grows slowly (see Greiner [10]). Example 4.4 is due to Davies and Proposition 4.5 to H. Kellermann (both unpublished). The spectral decomposition for positive groups as described in Theorem 4.8 is valid in arbitrary Banach lattices (see Arendt [2] and [Greiner (1984c)]). This also holds for Corollaries 4.9 and 4.10. Proposition 4.11 and Example 4.12 indicate the relationship of positive groups to dynamical systems. For example, the “Annular Hull Theorem” (see Chicone and Swanson [4]) is closely related to the results of this section.

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**Chapter C-IV**  
**Asymptotics of Positive Semigroups on Banach**  
**Lattices**



**Part D**  
**Positive Semigroups on  $C^*$ - and**  
 **$W^*$ -Algebras**





## Chapter D-I

# Basic Results on Semigroups and Operator Algebras

This is not a systematic introduction to the theory of strongly continuous semigroups on  $C^*$ - and  $W^*$ -algebras. We only prepare for the following chapters on spectral and asymptotic theory by fixing the notations and introducing some standard constructions. For results on strongly continuous semigroups on Banach spaces, we refer to Chapter A-I.

### 1 Notations

1. Let  $M$  denote a  $C^*$ -algebra with unit  $\mathbb{1}$ , where  $M^{sa} := \{x \in M : x^* = x\}$  is the self-adjoint part of  $M$  and  $M_+ := \{x^*x : x \in M\}$  is the positive cone in  $M$ . If  $M'$  is the dual of  $M$ , then  $M'_+ := \{\varphi \in M' : \varphi(x) \geq 0, x \in M_+\}$  is a weak\*-closed generating cone in  $M'$  and  $S(M) := \{\varphi \in M'_+ : \varphi(\mathbb{1}) = 1\}$  is called the state space of  $M$ . For the theory of  $C^*$ -algebras and related notions see Pedersen [5].
2. We say that  $M$  is a  $W^*$ -algebra if there exists a Banach space  $M_*$  such that its dual  $(M_*)'$  is (isomorphic to)  $M$ . We call  $M_*$  the *predual* of  $M$  and  $\varphi \in M_*$  a *normal linear functional*. It is known that  $M_*$  is unique. For this and other properties of  $M_*$ , see Takesaki [6, Chapter III].
3. A map  $T \in LM$  is called *positive* (in symbols  $T \geq 0$ ) if  $T(M_+) \subseteq M_+$ . It is called *n-positive* ( $n \in \mathbb{N}$ ) if  $T \otimes \text{Id}_n$  is positive from  $M \otimes M_n$  in  $M \otimes M_n$ , where  $\text{Id}_n$  is the identity map on the  $C^*$ -algebra  $M_n$  of all  $n \times n$ -matrices. Obviously, every  $n$ -positive map is positive.

We call a contraction  $T \in LM$  a *Schwarz map* if  $T$  satisfies the so called *Schwarz-inequality*

$$T(x)T(x)^* \leq T(xx^*)$$

for all  $x \in M$ . It is well known that every  $n$ -positive contraction, for  $n \geq 2$  and every positive contraction on a commutative  $C^*$ -algebra is a Schwarz map. (Takesaki [6, Chapter IV]) As we shall see, the Schwarz inequality is crucial for our investigations.

4. If  $M$  is a  $C^*$ -algebra, we assume that  $\mathcal{T} = (T(t))_{t \geq 0}$  is a strongly continuous semigroup (abbreviated as semigroup), while for  $W^*$ -algebras we consider weak\*-semigroups, i.e. the mapping  $(t \mapsto T(t)x)$  is continuous from  $\mathbb{R}_+$  into  $(M, \sigma(M, M_*))$ , where  $M_*$  is the predual of  $M$ , and every  $T(t) \in \mathcal{T}$  is  $\sigma(M, M_*)$ -continuous. Note that the preadjoint semigroup

$$\mathcal{T}_* = \{T(t)_* : T(t) \in \mathcal{T}\}$$

is weakly, hence strongly continuous on  $M_*$ . (Chapter A-I, ??)

5. We call the semigroup  $\mathcal{T}$  *identity preserving* if  $T(t)\mathbb{1} = \mathbb{1}$  and of *Schwarz type* if every  $T(t)$  is a Schwarz map.

For the notations concerning one-parameter semigroups we refer to Part A. In addition, we recommend to compare the results of this section with the corresponding results for commutative  $C^*$ -algebras, i.e., for  $C_0(X)$ ,  $C(K)$  and  $L^\infty(\mu)$  in Part B.

## 2 A Fundamental Inequality for the Resolvent

If  $\mathcal{T} = (T(t))_{t \geq 0}$  is a strongly continuous semigroup of Schwarz maps on a  $C^*$ -algebra  $M$  (resp. a weak\*-semigroup of Schwarz type on a  $W^*$ -algebra  $M$ ) with generator  $A$ , then the spectral bound satisfies  $s(A) \leq 0$ . The resolvent  $R(\lambda, A)$  exists for  $\operatorname{Re}(\lambda) > 0$  and is positive for  $\lambda \in \mathbb{R}_+$ . There exists a representation for the resolvent  $R(\lambda, A)$  given by the formula

$$R(\lambda, A)x = \int_0^\infty e^{-\lambda t} T(t)x \, dt \quad (x \in M)$$

where the integral exists in the norm topology.

In Bratteli and Robinson [2, Theorem 5] it is shown, that  $\mathcal{T}$  is a semigroup of Schwarz type if and only if  $\mu R(\mu, A)$  is a Schwarz map for every  $\mu \in \mathbb{R}_+$ . Here we relate the domination of two semigroups to an inequality for the corresponding resolvent operators. This inequality will be needed later.

**Theorem 2.1** *Let  $\mathcal{T} = (T(t))_{t \geq 0}$  be a semigroup of Schwarz type with generator  $A$  and  $\mathcal{S} = (S(t))_{t \geq 0}$  a semigroup with generator  $B$  on a  $C^*$ -algebra  $M$ . If*

$$(S(t)x)(S(t)x)^* \leq T(t)(xx^*) \quad (*)$$

*for all  $x \in M$  and  $t \in \mathbb{R}_+$ . Then*

$$(\mu R(\mu, B)x)(\mu R(\mu, B)x)^* \leq \mu R(\mu, A)xx^*$$

*for all  $x \in M$  and  $\mu \in \mathbb{R}_+$ . The same result holds if  $\mathcal{T}$  is a weak\*-semigroup of Schwarz type and  $\mathcal{S}$  is a weak\*-semigroup on a  $W^*$ -algebra  $M$  such that  $(*)$  is fulfilled.*

**Proof** From the assumption (\*) it follows that

$$\begin{aligned}
 0 &\leq (S(r)x - S(t)x)(S(r)x - S(t)x)^* \\
 &= (S(r)x)(S(r)x)^* - (S(r)x)(S(t)x)^* \\
 &\quad - (S(t)x)(S(r)x)^* + (S(t)x)(S(t)x)^* \\
 &\leq T(r)xx^* + T(t)xx^* - (S(r)x)(S(t)x)^* - (S(t)x)(S(r)x)^*
 \end{aligned}$$

for every  $r, t \in \mathbb{R}_+$  and therefore

$$(S(r)x)(S(r)x)^* + (S(t)x)(S(t)x)^* \leq T(r)xx^* + T(t)xx^*.$$

Obviously,  $\|S(t)\| \leq 1$  for all  $t \in \mathbb{R}_+$ . Then for all  $\mu \in \mathbb{R}_+$  and  $x \in M$

$$\begin{aligned}
 (R(\mu, B)x)(R(\mu, B)x)^* &= \left( \int_0^\infty e^{-\mu r} S(r)x \, dr \right) \left( \int_0^\infty e^{-\mu t} S(t)x \, dt \right)^* \\
 &= \frac{1}{2} \left( \int_0^\infty \int_0^\infty e^{-\mu(r+t)} ((S(r)x)(S(t)x)^* + (S(t)x)(S(r)x)^*) \, dr \, dt \right) \\
 &\leq \frac{1}{2} \left( \int_0^\infty \int_0^\infty e^{-\mu(r+t)} (T(r)xx^* + T(t)xx^*) \, dr \, dt \right) \\
 &= \left( \int_0^\infty e^{-\mu s} \, ds \right) \left( \int_0^\infty e^{-\mu t} T(t)xx^* \, dt \right) = \mu^{-1} R(\mu, A)xx^*
 \end{aligned}$$

where the handling of the integral is justified by Bourbaki [1, Chap. V, §8, n° 4, Proposition 9]. The claim is obtained by multiplying both sides by  $\mu^2$ .  $\square$

**Corollary 2.2** *Let  $\mathcal{T}$  be a semigroup of Schwarz maps (resp. weak\*-semigroup of Schwarz maps). Then for all  $\lambda \in \mathbb{C}$  with  $\operatorname{Re}(\lambda) > 0$  we have*

$$(R(\lambda, A)x)(R(\lambda, A)x)^* \leq \operatorname{Re}(\lambda)^{-1} R(\operatorname{Re}(\lambda), A)xx^*, \quad x \in M.$$

In particular for all  $(\mu, \alpha) \in \mathbb{R}_+ \times \mathbb{R}$  and  $x \in M$

$$(\mu R(\mu + i\alpha, A)x)(\mu R(\mu + i\alpha, A)x)^* \leq \mu R(\mu, A)(xx^*).$$

**Proof** Let  $\lambda \in \mathbb{C}$  with  $\operatorname{Re}(\lambda) > 0$ . Then the semigroup

$$S := \left( e^{-i(\lambda)t} T(t) \right)_{t \geq 0}$$

fulfills the assumption of Theorem 2.1 and  $B := A - i\lambda$  is the generator of  $S$ . Consequently  $R(\lambda, A) = R(\operatorname{Re} \lambda, B)$  and the corollary follows from Theorem 2.1.  $\square$

**Remark 2.3** (Bratteli and Robinson [2, Theorem 5]) Since

$$T(t)x = \lim_n \left( \frac{n}{t} R\left(\frac{n}{t}, A\right) \right)^n x, \quad x \in M,$$

it follows from above, that  $\mathcal{T}$  is a semigroup of Schwarz-type, if and only if  $\mu R(\mu, A)$  is a Schwarz-operator for every  $\mu \in \mathbb{R}_+$ .

As in Section C-III the following notion will be an important tool for the spectral theory of semigroups on  $C^*$ - and  $W^*$ -algebras.

**Definition 2.4** Let  $E$  be a Banach space and let  $D$  be a non-empty open subset of  $\mathbb{C}$ . A family  $\mathcal{R}: D \mapsto L(E)$  is called a *pseudo-resolvent* on  $D$  with values in  $E$  if

$$R(\lambda) - R(\mu) = -(\lambda - \mu)R(\lambda)R(\mu) \quad (\text{Resolvent Equation})$$

for all  $\lambda, \mu$  in  $D$  and  $R \in \mathcal{R}$ .

If  $\mathcal{R}$  is a pseudo-resolvent on  $D = \{\lambda \in \mathbb{C}: \operatorname{Re}(\lambda) > 0\}$  with values in a  $C^*$ - or  $W^*$ -algebra, then  $\mathcal{R}$  is called of Schwarz type if

$$(R(\lambda)x)(R(\lambda)x)^* \leq (\operatorname{Re} \lambda)^{-1} R(\operatorname{Re} \lambda)xx^*$$

and *identity preserving* if  $\lambda R(\lambda)\mathbb{1} = \mathbb{1}$  for all  $\lambda \in D$  and  $R \in \mathcal{R}$ . For examples and properties of a pseudo-resolvent, see C-III, 2.5.

We state what will be used without further reference.

- (i) If  $\alpha \in \mathbb{C}$  and  $x \in E$  such that  $(\alpha - \lambda)R(\lambda)x = x$  for some  $\lambda \in D$ , then  $(\alpha - \mu)R(\mu)x = x$  for all  $\mu \in D$  (use the *resolvent equation*).
- (ii) If  $F$  is a closed subspace of  $E$  such that  $R(\lambda)F \subseteq F$  for some  $\lambda \in D$ , then  $R(\mu)F \subseteq F$  for all  $\mu$  in a neighborhood of  $\lambda$ . This follows from the fact that for all  $\mu \in D$  near  $\lambda$  the pseudo-resolvent in  $\mu$  is given by

$$R(\mu) = \sum_n (\lambda - \mu)^n R(\lambda)^{n+1}.$$

**Definition 2.5** We call a semigroup  $\mathcal{T}$  on the *predual*  $M_*$  of a  $W^*$ -algebra  $M$  *identity preserving and of Schwarz type* if its adjoint weak\*-semigroup has these properties. Similarly, a pseudo-resolvent  $\mathcal{R}$  on  $D = \{\lambda \in \mathbb{C}: \operatorname{Re}(\lambda) > 0\}$  with values in  $M_*$  is said to be identity preserving and of Schwarz type if  $\mathcal{R}'$  has these properties.

For a semigroup of contractions on a Banach space we have

$$\begin{aligned} \operatorname{Fix}(T) &= \bigcap_{t \geq 0} \ker(\operatorname{Id} - T(t)) \\ &= \ker(\operatorname{Id} - \lambda R(\lambda, A)) = \operatorname{Fix}((\lambda R(\lambda, A))) \end{aligned}$$

for all  $\lambda \in \mathbb{C}$  with  $\operatorname{Re}(\lambda) > 0$ . Therefore a semigroup of contractions on  $M$  is identity preserving, if and only if the pseudo-resolvent on  $D = \{\lambda \in \mathbb{C}: \operatorname{Re}(\lambda) > 0\}$  given by

$$R(\lambda) := R(\lambda, A)|_D$$

is identity preserving. By Corollary 2.2 an analogous statement holds for *Schwarz type*.

### 3 Induction and Reduction

1. If  $E$  is a Banach space and  $\mathcal{S} \subseteq \mathcal{L}(E)$  is a semigroup of bounded operators, then a closed subspace  $F$  is called  $\mathcal{S}$ -invariant, if  $SF \subseteq F$  for all  $S \in \mathcal{S}$ . We call the semigroup  $\mathcal{S}|_F := \{S|_F : S \in \mathcal{S}\}$  the reduced semigroup. Note that for a one-parameter semigroup  $\mathcal{T}$  (resp., pseudo-resolvent  $\mathcal{R}$ ) the reduced semigroup is again strongly continuous (resp.  $\mathcal{R}|_F$  is again a pseudo-resolvent). (Compare A-I, 3.2).
2. Let  $M$  be a  $W^*$ -algebra,  $p \in M$  a projection and  $S \in LM$  such that

$$S(p^\perp M) \subseteq p^\perp M \quad \text{and} \quad S(Mp^\perp) \subseteq Mp^\perp,$$

where  $p^\perp := \mathbb{1} - p$ . Since for all  $x \in M$

$$p[S(x) - S(pxp)] = p[S(p^\perp xp) + S(xp^\perp)]p = 0,$$

we obtain  $p(Sx)p = p(S(pxp))p$ . Therefore, the map

$$S_p := (x \mapsto p(Sx)p) : pMp \rightarrow pMp$$

is well defined and we call  $S_p$  the *induced map*. If  $S$  is an identity preserving Schwarz map, then it is easy to see that  $S_p$  is again a Schwarz map such that  $S_p(p) = p$ .

3. If  $\mathcal{T} = (T(t))_{t \geq 0}$  is a weak\*-semigroup on  $M$  which is of Schwarz type and if  $T(t)(p^\perp) \leq p^\perp$  for all  $t \in \mathbb{R}_+$ , then  $T$  leaves  $p^\perp M$  and  $Mp^\perp$  invariant. One can verify that the induced semigroup  $T_p = (T(t)p)_{t \geq 0}$  is again a weak\*-semigroup. If  $\mathcal{R}$  is an identity preserving pseudo-resolvent of Schwarz type on  $D = \{\lambda \in \mathbb{C} : \operatorname{Re}(\lambda) > 0\}$  with values in  $M$  such that  $R(\mu)p^\perp \leq p^\perp$  for some  $\mu \in \mathbb{R}_+$ , then  $p^\perp M$  and  $Mp^\perp$  are  $\mathcal{R}$ -invariant. It follows directly that the induced pseudo-resolvent  $\mathcal{R}_p$  has both the Schwarz type property and is identity preservation.
4. Let  $\varphi$  be a positive normal linear functional on a  $W^*$ -algebra  $M$  such that  $T_*\varphi = \varphi$  for some identity preserving Schwarz map  $T$  on  $M$  with preadjoint  $T_* \in L(M_*)$ . Then  $T(s(\varphi)^\perp) \leq s(\varphi)^\perp$  where  $s(\varphi)$  is the support projection of  $\varphi$ .  
Let

$$L_\varphi := \{x \in M : \varphi(xx^*) = 0\} \quad \text{and} \quad M_\varphi := L_\varphi \cap L_\varphi^*.$$

Since  $\varphi$  is  $T_*$ -invariant and  $T$  is a Schwarz map, the subspaces  $L_\varphi$  and  $M_\varphi$  are  $T$ -invariant. From  $M_\varphi = s(\varphi)^\perp M s(\varphi)^\perp$  and  $T(s(\varphi)^\perp) \leq 1$  it follows that  $T(s(\varphi)^\perp) \leq s(\varphi)^\perp$ .

Let  $T_{s(\varphi)}$  be the induced map on  $M_{s(\varphi)}$  and define

$$s(\varphi)M_*s(\varphi) := \{\psi \in M_* : \psi = s(\varphi)\psi s(\varphi)\}$$

where  $\langle s(\varphi)\psi s(\varphi), x \rangle := \langle \psi, s(\varphi)x s(\varphi) \rangle$  ( $x \in M$ ). For any  $\psi \in s(\varphi)M_s(\varphi)$  and all  $x \in M$ , the following equalities holds

$$\begin{aligned}
(T_*\psi)(x) &= \psi(Tx) = \langle \psi, s(\varphi)(Tx)s(\varphi) \rangle \\
&= \langle \psi, s(\varphi)(T(s(\varphi)xs(\varphi)))s(\varphi) \rangle = \langle T_*\psi, s(\varphi)xs(\varphi) \rangle,
\end{aligned}$$

hence  $T_*\psi \in s(\varphi)M_*s(\varphi)$ . Since the dual of  $s(\varphi)M_*s(\varphi)$  is  $M_{s(\varphi)}$ , it follows that the adjoint of the reduced map  $T_{*|}$  is identity preserving and of Schwarz type. For example, if  $\mathcal{T}$  is an identity preserving semigroup of Schwarz type on  $M_*$  such that  $\varphi \in \text{Fix}(T)$ , then the semigroup  $T_{|(s(\varphi)M_*s(\varphi))}$  is again identity preserving and of Schwarz type. Furthermore, if  $\mathcal{R}$  is a pseudo-resolvent on

$$D = \{\lambda \in \mathbb{C}: \text{Re}(\lambda) > 0\}$$

with values in  $M_*$  which is identity preserving and of Schwarz type such that  $R(\mu)\varphi = \varphi$  for some  $\mu \in \mathbb{R}_+$ , then  $\mathcal{R}_{|s(\varphi)M_*s(\varphi)}$  has the same properties.

## Notes

We refer to Bratteli and Robinson [2], Davies [3] and the survey article of Osledeets [4].

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## Chapter D-II

# Characterization of Positive Semigroups on $W^*$ -Algebras

Since the positive cone of a  $C^*$ -algebra has non-empty interior, many results of Chapter B-II can be applied verbatim to the characterization of the generator of positive semigroups on  $C^*$ -algebras. On the other hand, a concrete and detailed representation of such generators has been found only in the uniformly continuous case (see Lindblad [4]). A third area of active research has been the following: Which maps on  $C^*$ -algebras (in particular, which derivations) commuting with certain automorphism groups are automatically generators of strongly continuous positive semigroups. For more information we refer to the survey article of Evans [3].

### 1 Semigroups on Properly Infinite $W^*$ -Algebras

The aim of this section is to show that strongly continuous semigroups of Schwarz maps on properly infinite  $W^*$ -algebras are already uniformly continuous. In particular, our theorem is applicable to such semigroups on  $B(H)$ .

It is worthwhile to remark that the result of Lotz [5] on the uniform continuity of every strongly continuous semigroup on  $L^\infty$  (see A-II, Sec.3) does not extend to arbitrary  $W^*$ -algebras.

*Example 1.1* Take  $M = \mathcal{B}(H)$ ,  $H$  infinite dimensional, and choose a projection  $p \in M$  such that  $Mp$  is topologically isomorphic to  $H$ . Therefore  $M = H \oplus M_0$ , where  $M_0 = \text{Ker}(x \mapsto xp)$ . Next, take a strongly, but not uniformly continuous semigroup  $\mathcal{T}$  on  $H$  and consider the strongly continuous semigroup  $\mathcal{T} \oplus \text{Id}$  on  $M$ .

For results on the classification theory of  $W^*$ -algebras needed in our approach we refer to Sakai [7, 2.2] and Takesaki [10, V.1].

**Theorem 1.2** *Every strongly continuous one-parameter semigroup of Schwarz type on a properly infinite  $W^*$ -algebra  $M$  is uniformly continuous.*

**Proof** Let  $\mathcal{T} = (T(t)_{t \geq 0})$  be strongly continuous on  $M$  and suppose  $\mathcal{T}$  not to be uniformly continuous. Then there exists a sequence  $(T_n)$  in  $\mathcal{T}$  and  $\varepsilon > 0$  such that  $\|T_n - \text{Id}\| \geq \varepsilon$ , but  $T_n \rightarrow \text{Id}$  in the strong operator topology. We claim that for every sequence  $(p_k)$  of mutually orthogonal projections and all bounded sequences  $(x_k)$  in  $M$

$$\lim_n \|(T_n - \text{Id})(p_k x_k p_k)\| = 0$$

uniformly in  $k \in \mathbb{N}$ . This follows from the *Lemma of Phillips* (Schaefer [9]) and the fact that the sequence  $(p_k x_k p_k)$  is summable in the  $s^*(M, M_*)$ -topology (compare Elliot [2], Lemma 2.).

Let  $(p_k)$  be a sequence of mutually orthogonal projections in  $M$  such that every  $p_k$  is equivalent to  $\mathbb{1}$  via some  $u_k \in M$  [7, 2.2]. Without loss of generality we may assume  $\|(T_n - \text{Id})(u_n)\| \leq n^{-1}$  since the semigroup  $T$  is strongly continuous. Thus we obtained the following.

- (i)  $\lim_n \|(T_n - \text{Id})(p_k x_k p_k)\| = 0$  uniformly in  $k \in \mathbb{N}$  for every bounded sequence  $(x_k)$  in  $M$ .
- (ii) Every projection  $p_k$  is equivalent to 1 via some  $u_k \in M$ .
- (iii)  $\|(T_n - \text{Id})u_n\| \leq n^{-1}$  for all  $n \in \mathbb{N}$ .

For the following construction see A-I,3.6 and D-II,Sec.2. Take

- (i)  $\widehat{M}$  be an ultrapower of  $M$ ,
- (ii) let  $p := \widehat{(p_k)} \in \widehat{M}$ ,
- (iii) let  $T := \widehat{(T_n)} \in L(\widehat{M})$
- (iv) and let  $u := \widehat{(u_k)} \in \widehat{M}$ .

Then  $T$  is identity preserving and of Schwarz type on  $\widehat{M}$ .

Since  $u^*u = p$  and  $uu^* = \mathbb{1}$ , it follows  $pu^* = u^*$  and  $(uu^*)x(uu^*) = x$  for all  $x \in \widehat{M}$ . Finally,  $T(pxp) = pxp$  for all  $x \in \widehat{M}$  which follows from (i), and  $T(u^*) = T(pu^*) = pu^* = u^*$  and  $T(u) = u$ , which follows from (iii). Using the Schwarz, inequality we obtain

$$T(uu^*) = T(\mathbb{1}) \leq \mathbb{1} = uu^* = T(u)T(u)^*.$$

From D-III, Lemma 1.1., we conclude  $T(ux) = uT(x)$  and  $T(xu^*) = T(x)u^*$  for all  $x \in \widehat{M}$ . Hence

$$\begin{aligned} T(x) &= T(uu^*xuu^*) = uT(u^*xu)u^* = uT(pu^*xup)u^* \\ &= upu^*xupu^* = uu^*xuu^* = x \end{aligned}$$

for all  $x \in \widehat{M}$ . From this we obtain that for every bounded sequence  $(x_k)$  in  $M$

$$\lim_k \|T_k x_k - x_k\| = 0$$

for some subsequence of the  $T_k$ 's and of the  $x_k$ 's. This conflicts with our assumption at the beginning, hence the theorem is proved.  $\square$

## Notes

Let  $M$  be a  $W^*$ -algebra and  $H$  be an infinite-dimensional Hilbert-space. Then the  $W^*$ -tensor product  $N := \overline{M \otimes \mathcal{B}(H)}$  is a properly infinite  $W^*$ -algebra (Sakai [7, Thm. 2.6.6]). Let  $\mathcal{S}$  be the semigroup

$$S(t) = T(t) \otimes \text{Id}_H \quad (t \geq 0).$$

Then  $S(t)$  is a Schwarz-map on  $N$  and contractive (Takesaki [10, Prop. IV.5.13.]), hence the smigroup  $\mathcal{S}$  is equicontinuous in  $LN$ .

Let  $x \in M$  and  $\xi \in H$ . Since the norm on  $N$  is a cross-norm, we obtain

$$\lim_{t \rightarrow 0} \|(S(t) - \text{Id})x \otimes \xi\| = \lim_{t \rightarrow 0} \|(S(t) - \text{Id})x\| \|\xi\| = 0.$$

From Schaefer [8, III.4.5] it follows that  $\mathcal{S}$  is strongly-continuous, hence norm-continuous on  $N$  from which we conclude, that  $\mathcal{T}$  is norm-continuous on  $M$ .

*Remark 1.3* If  $M$  is a finite  $W^*$ -algebra of Type I, then  $M$  is a Grothendieck space and has the Dunford-Pettis property. Hence we can apply the results of Lotz [5]. However, has  $W^*$ -algebra have the Dunford-Pettis property iff it is finite and of Type I (Chu and Iochum [1]). But is known that every  $W^*$ -algebra is a Grothendieck space (Pfitzner [6]).



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## Chapter D-III

# Spectral Theory of Positive Semigroups on $W^*$ -Algebras and their Preduals

Motivated by the classical results of Perron and Frobenius one expects the following spectral properties for the generator  $A$  of a positive semigroup on a  $C^*$ -algebra.

The spectral bound  $s(A) := \sup\{\operatorname{Re} \lambda : \lambda \in \sigma(A)\}$  belongs to the spectrum  $\sigma(A)$  and the boundary spectrum  $\sigma_b(A) := \sigma(A) \cap \{s(A) + i\mathbb{R}\}$  possesses a certain symmetric structure, called cyclicity.

Results of this type have been proved in Chapter B-III for positive semigroups on commutative  $C^*$ -algebras, however in the non-commutative case the situation is more complicated. While “ $s(A) \in \sigma(A)$ ” still holds (see Greiner et al. [6] or the notes of this chapter), the cyclicity of the boundary spectrum  $\sigma_b(A)$  is true only under additional assumptions on the semigroup (e.g., irreducibility, see Section 1 below).

For technical reasons we consider mostly strongly continuous semigroups on the predual of a  $W^*$ -algebra  $M$  or its adjoint semigroup which is a weak\*-continuous semigroup on  $M$ .

## 1 Spectral Theory for Positive Semigroups on Preduals

The aim of this section is to develop a Perron-Frobenius theory for identity preserving semigroups of Schwarz type on  $W^*$ -algebras. However we will show in the example preceding Theorem 1.11 on page 202 below that the boundary spectrum is no longer cyclic. The appropriate hypothesis on the semigroup implying the desired results seems to be the concept of *irreducibility*.

Let us first recall some facts on normal linear functionals. If  $\varphi$  is a normal linear functional on a  $W^*$ -algebra  $M$ , then there exists a partial isometry  $u \in M$  and a positive linear functional  $|\varphi| \in M_*$  such that

$$\begin{aligned}\varphi(x) &= |\varphi|(xu) =: (u|\varphi|)(x) \quad (x \in M), \\ u^*u &= s(|\varphi|),\end{aligned}$$

where  $s(|\varphi|)$  denotes the support projection of  $|\varphi|$  in  $M$ . We refer to this as the *polar decomposition* of  $\varphi$ . In addition,  $|\varphi|$  is *uniquely determined* by the following two conditions.

$$\left. \begin{aligned} \|\varphi\| &= \| |\varphi| \| \\ |\varphi(x)|^2 &\leq |\varphi|(xx^*) \quad (x \in M) \end{aligned} \right\} (*)$$

For the polar decomposition of the adjoint  $\varphi^*$ , where  $\varphi^*(x) = \overline{\varphi(x^*)}$ , we obtain

$$\varphi^* = u^* |\varphi^*|, \quad |\varphi^*| = u |\varphi| u^* \quad \text{and} \quad uu^* = s(|\varphi^*|).$$

It is easy to see that  $u^* \in s(|\varphi|)M$  (Takesaki [15, Theorem III.4.2 & Proposition III.4.6]).

If  $\Psi$  is a subset of the state space of a  $C^*$ -algebra  $M$ , then  $\Psi$  is called *faithful* if  $0 \leq x \in M$  and  $\psi(x) = 0$  for all  $\psi \in \Psi$  implies  $x = 0$ . Moreover  $\Psi$  is called *subinvariant* for a positive map  $T \in LM$  (resp., positive semigroup  $\mathcal{T}$ ) if  $T'\psi \leq \psi$  for all  $\psi \in \Psi$  (resp.  $T(t)'\psi \leq \psi$  for all  $T(t) \in \mathcal{T}$  and  $\psi \in \Psi$ ). Recall that for every positive map  $T \in LM$  there exists a state  $\varphi$  on  $M$  such that  $T'\varphi = r(T)\varphi$ , where  $r(T)$  denotes the spectral radius of  $T$  (Groh [7, Theorem 2.1]).

Let us start our investigation with two lemmata where  $\text{Fix}(T)$  is the fixed space of  $T$ , i.e., the set  $\{x \in M : Tx = x\}$ .

**Lemma 1.1** *Suppose  $M$  to be a  $C^*$ -algebra and  $T \in LM$  an identity preserving Schwarz map.*

- (i) *Let  $b : M \times M \rightarrow M$  be a sesquilinear map such that  $b(z, z) \geq 0$  for all  $z \in M$ . Then  $b(x, x) = 0$  for some  $x \in M$  if and only if  $b(x, y) = 0$  and  $b(y, x) = 0$  for all  $y \in M$ .*
- (ii) *If there exists a faithful family  $\Psi$  of subinvariant states for  $T$  on  $M$ , then  $\text{Fix}(T)$  is a  $C^*$ -subalgebra of  $M$  and  $T(xy) = xT(y)$  for all  $x \in \text{Fix}(T)$  and  $y \in M$ .*

**Proof** (i) Take  $0 \leq \psi \in M^*$  and consider  $f := \psi \circ b$ . Then  $f$  is a positive semidefinite sesquilinear form on  $M$  with values in  $\mathbb{C}$ . From the Cauchy-Schwarz inequality it follows that  $f(x, x) = 0$  for some  $x \in M$  if and only if  $f(x, y) = 0$  and  $f(y, x) = 0$  for all  $y \in M$ . Since the positive cone  $M_+^*$  is generating, assertion (i) is proved.

(ii) Since  $T$  is positive, it follows that  $T(x)^* = T(x^*)$  for all  $x \in M$ . Hence  $\text{Fix}(T)$  is a self adjoint subspace of  $M$ , i.e., invariant under the involution on  $M$ . For every  $x, y \in M$  define

$$b(x, y) := T(xy^*) - T(x)T(y)^*.$$

Then  $b$  satisfies the assumptions of (i).

If  $x \in \text{Fix}(T)$ , then

$$0 \leq xx^* = (Tx)(Tx)^* \leq T(xx^*),$$

hence

$$0 \leq \psi(T(xx^*) - xx^*) = 0 \quad \text{for all } \psi \in \Psi.$$



But this implies  $T(xx^*) = T(x)T(x)^* = xx^*$  and consequently,  $b(x, x) = 0$ . Hence  $T(xy^*) = xT(y)^*$  for all  $y \in M$  and (ii) is proved.  $\square$

**Lemma 1.2** *Let  $M$  be a  $W^*$ -algebra,  $T$  an identity preserving Schwarz map on  $M$  and  $S \in LM$  such that  $S(x)(Sx)^* \leq T(xx^*)$  for every  $x \in M$ .*

- (i) *If  $v \in M$  such that  $S(v^*) = v^*$  and  $T(v^*v) = v^*v$ , then  $T(xv) = S(x)v$  for all  $x \in M$ .*
- (ii) *Suppose there exists  $\varphi \in M_*$  with polar decomposition  $\varphi = u|\varphi|$  such that  $S_*\varphi = \varphi$  and  $T_*|\varphi| = |\varphi|$ . If the closed subspace  $s(|\varphi|)M$  is  $T$ -invariant, then  $Su^* = u^*$  and  $T(u^*u) = u^*u$ .*

**Proof** (i) Define a positive semidefinite sesquilinear map  $b : M \times M \mapsto M$  by

$$b(x, y) := T(xy^*) - S(x)S(y)^* \quad (x, y \in M).$$

Since  $b(v^*, v^*) = 0$  we obtain  $b(x, v^*) = 0$  for all  $x \in M$ , hence  $T(xv) = S(x)v$ . (Lemma 1.1 (i))

(ii) Since  $s(|\varphi|)M$  is a closed right ideal, the closed face  $F := s(|\varphi|)(M_+)s(|\varphi|)$  determines  $s(|\varphi|)M$  uniquely, i.e.,

$$s(|\varphi|)M = \{x \in M : xx^* \in F\}$$

(Pedersen [13, Theorem 1.5.2]). Since  $T$  is a Schwarz map and  $s(|\varphi|)M$  is  $T$ -invariant, it follows  $TF \subseteq F$ . On the other hand, if  $x \in s(|\varphi|)M$ , then  $xx^* \in F$ . Consequently,

$$0 \leq S(x)S(x)^* \leq T(xx^*) \in F,$$

whence  $S(x) \in s(|\varphi|)M$ .

Next we show  $T(u^*u) = u^*u$  and  $Su^* = u^* \in s(|\varphi|)M$ . First of all

$$\begin{aligned} 0 &\leq (Su^* - u^*)(Su^* - u^*)^* \\ &\leq T(u^*u) - u^*S(u^*)^* - (Su^*)u + u^*u. \end{aligned}$$

Since  $S_*\varphi = \varphi$ ,  $T_*|\varphi| = |\varphi|$  and  $\varphi = u|\varphi|$  it follows

$$\begin{aligned} 0 &\leq |\varphi|((Su^* - u^*)(Su^* - u^*)^*) \\ &\leq 2|\varphi|(u^*u) - |\varphi|(S(u^*)u)^* - |\varphi|(S(u^*)u) \\ &= 2|\varphi|(uu^*) - \varphi(u^*)^* - \varphi(u^*) \\ &= 2(|\varphi|(u^*u) - |\varphi|(u^*u)) = 0. \end{aligned}$$

But  $(Su^* - u^*)(Su^* - u^*) \in F$  and  $|\varphi|$  is faithful on  $F$ . Hence we obtain  $Su^* = u^*$ . Consequently,

$$0 \leq u^*u = (Su^*)(Su^*)^* \leq T(u^*u)$$

and  $T(u^*u) = u^*u$  by the faithfulness and  $T$ -invariance of  $|\varphi|$ .  $\square$

**Remark 1.3** Take  $S$  and  $T$  as in Lemma 1.2 (ii). If  $V_{u^*}$  (resp.  $V_u$ ) is the map  $(x \mapsto xu^*)$  (resp.  $(x \mapsto xu)$ ) on  $M$ , then  $V_{u^*}$  is a continuous bijection from  $Ms(|\varphi|)$  onto  $Ms(|\varphi^*|)$  with inverse  $V_u$  (because  $V_u \circ V_{u^*} = \text{Id}_{Ms(|\varphi|)}$  and  $V_{u^*} \circ V_u = \text{Id}_{Ms(|\varphi^*|)}$ ). Let  $x \in M$ . From  $T(xu) = S(x)u$  we obtain  $T(xu)u^* = S(x)uu^*$ . In particular, if  $Ms(|\varphi^*|)$  is  $S$ -invariant, then

$$(V_{u^*} \circ T \circ V_u)(x) = T(xu)u^* = S(x)$$

for every  $x \in Ms(|\varphi^*|)$ . Let  $T|$  (resp.  $S|$ ) be the restriction of  $T$  to  $Ms(|\varphi|)$  (resp. of  $S$  to  $Ms(|\varphi^*|)$ ). Then the following diagram is commutative:

$$\begin{array}{ccc} Ms(|\varphi|) & \xrightarrow{T|} & Ms(|\varphi|) \\ \downarrow V_u & & \downarrow V_{u^*} \\ Ms(|\varphi^*|) & \xrightarrow{S|} & Ms(|\varphi^*|) \end{array}$$

In particular,  $\sigma(S|) = \sigma(T|)$ . Therefore we may deduce spectral properties of  $S|$  from  $T|$  and vice versa. More concrete applications of Lemma 1.2 will follow.

We now investigate the fixed space  $\text{Fix}(\mathcal{R}) := \text{Fix}(\lambda R(\lambda))$ ,  $\lambda \in D$ , of a pseudo-resolvent  $\mathcal{R}$  with values in the predual of a  $W^*$ -algebra  $M$ .

**Proposition 1.4** *Let  $\mathcal{R}$  be a pseudo-resolvent on  $D = \{\lambda \in \mathbb{C} : \text{Re } \lambda > 0\}$  with values in the predual  $M_*$  of a  $W^*$ -algebra  $M$  and suppose  $\mathcal{R}$  to be identity preserving and of Schwarz type.*

- (i) *If  $\alpha \in \mathbb{R}$  and  $\psi \in M_*$  such that  $(\gamma - i\alpha)R(\gamma)\psi = \psi$  for some  $\gamma \in D$ , then  $\lambda R(\lambda)|\psi| = |\psi|$  and  $\lambda R(\lambda)|\psi^*| = |\psi^*|$  for all  $\lambda \in D$ .*
- (ii)  *$\text{Fix}(\mathcal{R})$  is invariant under the involution in  $M_*$ . If  $\psi \in \text{Fix}(\mathcal{R})$  is self-adjoint, then the positive part  $\psi^+$  and the negative part  $\psi^-$  of  $\psi$  are elements of  $\text{Fix}(\mathcal{R})$ .*

**Proof** If  $(\gamma - i\alpha)R(\gamma)\psi = \psi$  then  $(\lambda - i\alpha)R(\lambda)\psi = \psi$  for all  $\lambda \in D$ . In particular,  $\mu R(\mu + i\alpha)\psi = \psi$  ( $\mu \in \mathbb{R}_+$ ). For all  $x \in M$  we obtain

$$\begin{aligned} |\psi(x)|^2 &= |\langle \mu R(\mu + i\alpha)'x, \psi \rangle|^2 \leq \\ &\leq \|\psi\| \langle (\mu R(\mu + i\alpha)'x)(\mu R(\mu + i\alpha)'x)^*, \psi \rangle \leq \\ &\leq \|\psi\| \langle \mu R(\mu)'(xx^*), |\psi| \rangle \end{aligned}$$

(D-I, Corollary 2.2). Since

$$\begin{aligned} \|\psi\| &= \|\|\psi\|\| = |\psi|(1) = \\ &= \langle \mu R(\mu)'1, |\psi| \rangle = \|\mu R(\mu)|\psi\|, \end{aligned}$$

we obtain  $\mu R(\mu)|\psi| = |\psi|$  by the uniqueness theorem (\*) above for the absolute value—therefore  $|\psi| \in \text{Fix}(\mathcal{R})$ . Since

$$0 \leq (\mu R(\mu)'x)(\mu R(\mu)'x)^* \leq \mu R(\mu)'xx^*,$$

the map  $R(\mu)$  is positive. Consequently  $(\mu + i\alpha)R(\mu)\psi^* = \psi^*$  from which  $|\psi^*| \in \text{Fix}(\mathcal{R})$  follows. If  $\varphi \in \text{Fix}(\mathcal{R})$  is selfadjoint with Jordan decomposition  $\varphi = \varphi^+ - \varphi^-$ , then  $|\varphi| = \varphi^+ + \varphi^-$  (Takesaki [15, Theorem III.4.2.]). From this we obtain that  $\varphi^+$  and  $\varphi^-$  are in  $\text{Fix}(\mathcal{R})$ .  $\square$

**Corollary 1.5** *Let  $\mathcal{T}$  be an identity preserving semigroup of Schwarz type on  $M_*$  with generator  $A$  and suppose  $P\sigma(A) \cap i\mathbb{R} \neq \emptyset$ .*

- (i) *If  $\alpha \in \mathbb{R}$  and  $\psi \in \ker(i\alpha - A)$ , then  $|\psi|$  and  $|\psi^*|$  are elements of  $\text{Fix}(\mathcal{T}) = \text{Ker}(A)$ .*
- (ii)  *$\text{Fix}(\mathcal{T})$  is invariant under the involution of  $M_*$ . If  $\psi \in \text{Fix}(\mathcal{T})$  is selfadjoint, then the positive part  $\psi^+$  and the negative part  $\psi^-$  of  $\psi$  are elements of  $\text{Fix}(\mathcal{T})$ .*

The proof follows immediately from Proposition 1.4 and the fact that  $\text{Ker}(A) = \text{Fix}(\lambda R(\lambda, A))$  for all  $\lambda \in \mathbb{C}$  with  $\text{Re } \lambda > 0$ .

If  $\mathcal{T}$  is the semigroup of translations on  $L^1(\mathbb{R})$  and  $A'$  the generator of the adjoint weak\*-semigroup, then  $P\sigma(A) \cap i\mathbb{R} = \emptyset$ , while  $P\sigma(A') \cap i\mathbb{R} = i\mathbb{R}$ . For that reason we cannot expect a simple connection between these two sets. But as we shall see below, if a semigroup on the predual of a  $W^*$ -algebra has sufficiently many invariant states, then the point spectra contained in  $i\mathbb{R}$  of  $A$  and  $A'$  are identical. Helpful for these investigations will be the next lemma.

**Lemma 1.6** *Let  $\mathcal{R}$  be a pseudo-resolvent on  $D = \{\lambda \in \mathbb{C} : \text{Re } \lambda > 0\}$  with values in a Banach space  $E$  such that  $\|R(\mu + i\alpha)\| \leq 1$  for all  $(\mu, \alpha) \in \mathbb{R}_+ \times \mathbb{R}$ . Then*

$$\dim \text{Fix}(\lambda R(\lambda + i\alpha)) \leq \dim \text{Fix}(\lambda R(\lambda + i\alpha)')$$

for all  $\lambda \in D$ .

**Proof** Let  $(\mu, \alpha) \in \mathbb{R}_+ \times \mathbb{R}$  and  $S := \mu R(\mu + i\alpha)$ . Since  $S$  is a contraction, its adjoint  $S'$  maps the dual unit ball  $E'_1$  into itself.

Let  $\mathcal{U}$  be a free ultrafilter on  $[1, \infty[$  which converges to 1. Since  $E'_1$  is  $\sigma(E', E)$ -compact,

$$\psi_0 := \lim_{\mathcal{U}} (\lambda - 1)R(\lambda, S)'\psi$$

exists for each  $\psi \in E'_1$ . Since  $S'$  is  $\sigma(E', E)$ -continuous and since  $S'R(\lambda, S)' = \lambda R(\lambda, S') - \text{Id}$  we conclude  $\psi_0 \in \text{Fix}(S')$ .

Take now  $0 \neq x_0 \in \text{Fix}(S)$  and choose  $\psi \in E'_1$  such that  $\psi(x_0)$  is different from zero. From the considerations above it follows

$$\psi_0(x_0) = \lim_{\mathcal{U}} (\lambda - 1)\psi(R(\lambda, S)x_0) = \psi(x_0) \neq 0$$

hence  $0 \neq \psi_0 \in \text{Fix}(S)$ . Therefore  $\text{Fix}(S')$  separates the points of  $\text{Fix}(S)$ . From this it follows that

$$\dim \operatorname{Fix}(S) \leq \dim \operatorname{Fix}(S').$$

Since  $\mathcal{R}$  and  $\mathcal{R}'$  are pseudo-resolvents, the assertion is proved.  $\square$

**Corollary 1.7** *Let  $\mathcal{T}$  be a semigroup of contractions on a Banach space  $E$  with generator  $A$ . Then*

$$\dim \operatorname{Ker}(i\alpha - A) \leq \dim \operatorname{Ker}(i\alpha - A')$$

for all  $\alpha \in \mathbb{R}$ .

This follows from Lemma 1.6 on page 199 because  $\operatorname{Fix}(\lambda R(\lambda + i\alpha)) = \operatorname{Ker}(i\alpha - A)$ .

**Proposition 1.8** *Let  $\mathcal{T}$  be an identity preserving semigroup of Schwarz type with generator  $A$  on the predual of a  $W^*$ -algebra and suppose that there exists a faithful family  $\Psi$  of  $\mathcal{T}$ -invariant states. Then for all  $\alpha \in \mathbb{R}$  we have*

$$\dim \operatorname{Ker}(i\alpha - A) = \dim \operatorname{Ker}(i\alpha - A')$$

and

$$P\sigma(A) \cap i\mathbb{R} = P\sigma(A') \cap i\mathbb{R}.$$

**Proof** The inequality  $\dim \operatorname{Ker}(i\alpha - A) \leq \dim \operatorname{Ker}(i\alpha - A')$  follows from Corollary 1.7.

Let  $D = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda > 0\}$  and  $\mathcal{R}$  the pseudo-resolvent induced by  $R(\lambda, A)$  on  $D$ . Then  $\mathcal{R}$  is identity preserving and of Schwarz type. Take  $i\alpha \in P\sigma(A)$  ( $\alpha \in \mathbb{R}$ ) and choose  $0 < \mu \in \mathbb{R}$ .

If  $\psi_\alpha \in M_*$  is of norm one with polar decomposition  $\psi_\alpha = u_\alpha |\psi_\alpha|$  such that  $\psi_\alpha = (\mu - i\alpha)R(\mu)\psi_\alpha$  then  $\mu R(\mu)|\psi_\alpha| = |\psi_\alpha|$  (Proposition 1.4 (i) on page 198). Since

$$\mu R(\mu)'(1 - s(|\psi_\alpha|)) \leq 1 - s(|\psi_\alpha|),$$

we obtain  $\mu R(\mu)'s(|\psi_\alpha|) = s(|\psi_\alpha|)$  by the faithfulness of  $\Psi$ . Hence the maps  $S := (\mu - i\alpha)R(\mu)'$  and  $T := \mu R(\mu)'$  fulfill the assumptions of Lemma 1.2 (ii) on page 197. Therefore  $Su_\alpha^* = u_\alpha^*$  or  $(\mu - i\alpha)R(\mu)'u_\alpha^* = u_\alpha^*$  which implies  $u_\alpha^* \in D(A')$  and  $A'u_\alpha^* = i\alpha u_\alpha^*$ .

If  $i\alpha \in P\sigma(A')$ ,  $\alpha \in \mathbb{R}$ , choose  $0 \neq v_\alpha$  such that

$$v_\alpha = (\mu - i\alpha)R(\mu)'v_\alpha \quad (\mu \in \mathbb{R}_+)$$

and  $\psi \in \Psi$  such that  $\psi(v_\alpha v_\alpha^*) \neq 0$ .

Since

$$0 \leq v_\alpha v_\alpha^* = ((\mu - i\alpha)R(\mu)'v_\alpha)((\mu - i\alpha)R(\mu)'v_\alpha)^* \leq \mu R(\mu)'(v_\alpha v_\alpha^*),$$

we obtain  $\mu R(\mu)'(v_\alpha v_\alpha^*) = v_\alpha v_\alpha^*$  because  $\Psi$  is faithful.

Hence from Lemma 1.2 (i) on page 197 it follows that

$$\mu R(\mu)'(xv_\alpha^*) = ((\mu - i\alpha)R(\mu)'x)v_\alpha^*$$

for all  $x \in M$ .

Let  $\psi_\alpha$  be the normal linear functional ( $x \mapsto \psi(xv_\alpha^*)$ ) on  $M$  and note that  $\psi_\alpha(v_\alpha) \neq 0$ . Then

$$\begin{aligned} \langle x, (\mu - i\alpha)R(\mu)\psi_\alpha \rangle &= \langle ((\mu - i\alpha)R(\mu)'x)v_\alpha^*, \psi \rangle \\ &= \langle \mu R(\mu)'(xv_\alpha^*), \psi \rangle = \psi(xv_\alpha^*) = \psi_\alpha(x) \end{aligned}$$

for all  $x \in M$ . Consequently  $i\alpha \in P\sigma(A)$  and

$$\dim \text{Ker}((i\alpha - A')) \leq \dim \text{Ker}((i\alpha - A))$$

which proves the assertion.  $\square$

*Remark 1.9* From the above proof we obtain the following: If  $0 \neq \psi_\alpha \in \text{Ker}(i\alpha - A)$  for  $\alpha \in \mathbb{R}$  with polar decomposition  $\psi_\alpha = u_\alpha |\psi_\alpha|$  ( $\alpha \in \mathbb{R}$ ), then  $A'u_\alpha = i\alpha u_\alpha$ . Conversely, if  $0 \neq v_\alpha \in \text{Ker}(i\alpha - A')$ , then there exists  $\psi \in \Psi$  such that  $\psi(v_\alpha v_\alpha^*) \neq 0$  and the normal linear form

$$\psi_\alpha := (x \mapsto \psi(xv_\alpha^*))$$

is an eigenvector of  $A$  pertaining to the eigenvalue  $i\alpha$ .

If  $\mathcal{T}$  is a  $C_0$ -semigroup of Markov operators on a commutative  $\mathbb{C}^*$ -algebra with generator  $A$ , it has been shown in B-III, that the boundary spectrum  $\sigma(A) \cap i\mathbb{R}$  of its generator is additively cyclic. This is no longer true in the non commutative case.

*Example 1.10* For  $0 \neq \lambda \in i\mathbb{R}$  and  $t \in \mathbb{R}$  let

$$u_t := \begin{pmatrix} 1 & 0 \\ 0 & e^{\lambda t} \end{pmatrix} \in M_2(\mathbb{C}).$$

The semigroup of  $*$ -automorphisms ( $x \mapsto u_t x u_t^*$ ) on  $M_2(\mathbb{C})$  is identity preserving and of Schwarz type, but the spectrum of its generator is  $\{0, \lambda, \lambda^*\}$  hence is not additively cyclic.

It turns out that, in order to obtain a non commutative analogue of the Perron-Frobenius theorems, one has to consider semigroups which are irreducible. Recall that a semigroup  $\mathcal{S}$  of positive operators on an ordered Banach space  $(E, E_+)$  is called *irreducible* if no closed face of  $E_+$ , different from  $\{0\}$  and  $E_+$ , is invariant under  $\mathcal{S}$ . In the context of  $W^*$ -algebras  $M$  we call a semigroup  $\mathcal{S}$  of positive maps on  $M$  *weak\*-irreducible* if no  $\sigma(M, M_*)$ -closed face of  $M_+$  is  $\mathcal{S}$ -invariant.

Since the norm closed faces of  $M_*$  and the  $\sigma(M, M_*)$ -closed faces of  $M$  are related by formation of polars with respect to the dual system  $\langle M, M_* \rangle$  (see Pedersen [13, Theorem 3.6.11 and Theorem 3.10.7.]) a semigroup  $\mathcal{S}$  is (norm) irreducible on  $M_*$  if and only if its adjoint semigroup is weak\*-irreducible.

**Theorem 1.11** *Let  $\mathcal{T}$  be an irreducible, identity preserving semigroup of Schwarz type with generator  $A$  on the predual of a  $W^*$ -algebra and suppose  $P\sigma(A) \cap i\mathbb{R} \neq \emptyset$ .*

- (i) *The fixed space of  $\mathcal{T}$  is one dimensional and spanned by a faithful normal state.*
- (ii)  *$P\sigma(A) \cap i\mathbb{R}$  is an additive subgroup of  $i\mathbb{R}$ ,*

$$\sigma(A) = \sigma(A) + (P\sigma(A) \cap i\mathbb{R})$$

*and every eigenvalue in  $i\mathbb{R}$  is simple.*

- (iii) *The fixed space of the adjoint weak\*-semigroup  $\mathcal{T}'$  is one-dimensional.*
- (iv)  *$P\sigma(A') \cap i\mathbb{R} = P\sigma(A) \cap i\mathbb{R}$  for the generator  $A'$  of the adjoint semigroup, and every  $\gamma \in P\sigma(A') \cap i\mathbb{R}$  is simple.*

**Proof** Since  $P\sigma(A) \cap i\mathbb{R} \neq \emptyset$ , there exists  $\psi \in \text{Fix}(\mathcal{T})_+$  of norm one (Corollary 1.5). If  $F := \{x \in M_+ : \psi(x) = 0\}$ , then  $F$  is a  $\sigma(M, M_*)$ -closed,  $\mathcal{T}'$ -invariant face in  $M$ , hence  $F = \{0\}$ . Therefore every  $0 \neq \psi \in \text{Fix}(\mathcal{T})_+$  is faithful.

Let  $\psi_1, \psi_2 \in \text{Fix}(\mathcal{T})_+$  be states such that  $f := \psi_1 - \psi_2$  is different from zero. If  $f = f^+ - f^-$  is the Jordan decomposition of  $f$ , then  $f^+$  and  $f^-$  are elements of  $\text{Fix}(\mathcal{T})$ , whence faithful. Since the support projections of these two normal linear functionals are orthogonal, we obtain  $f^+ = 0$  or  $f^- = 0$  which implies  $\psi_1 \leq \psi_2$  or  $\psi_2 \leq \psi_1$ . Consequently  $\psi_2 = \psi_1$ .

Since  $\text{Fix}(\mathcal{T})$  is positively generated (Corollary 1.5 on page 199),  $\text{Fix}(\mathcal{T}) = \{\lambda\varphi : \lambda \in \mathbb{C}\} =: \mathbb{C}\cdot\varphi$  for some faithful normal state  $\varphi$ .

Let  $\mu \in \mathbb{R}_+$  and  $\alpha \in \mathbb{R}$  such that  $i\alpha \in P\sigma(A)$ . If  $\psi_\alpha = u_\alpha|\psi_\alpha|$  is a normalized eigenvector of  $A$  pertaining to  $i\alpha$ , then  $\varphi = |\psi_\alpha| = |\psi_\alpha^*|$  (Corollary 1.5 and the above considerations). Hence  $u_\alpha u_\alpha^* = u_\alpha^* u_\alpha = s(\varphi) = 1$ .

Since

$$(\mu - i\alpha)R(\mu, A)\psi_\alpha = \psi_\alpha$$

and

$$\mu R(\mu, A)|\psi_\alpha| = |\psi_\alpha|,$$

we obtain by Lemma 1.2 (ii) on page 197 that

$$\mu R(\mu, A) = V_\alpha \circ \mu R(\mu + i\alpha, A) \circ V_\alpha^{-1} \quad (1)$$

where  $V_\alpha$  is the map  $(x \mapsto xu_\alpha)$  on  $M$ .

Similarly, for  $i\beta \in P\sigma(A)$  we find  $V_\beta$  such that  $1 = u_\beta u_\beta^* = u_\beta u_\beta^*$  and

$$\mu R(\mu, A) = V_\beta \circ \mu R(\mu + i\beta, A) \circ V_\beta^{-1}. \quad (2)$$

Hence

$$\mu R(\mu, A) = V_{\alpha\beta} \circ \mu R(\mu + i(\alpha + \beta), A) \circ V_{\alpha\beta}^{-1} \quad (3)$$

where  $V_{\alpha\beta} := V_\alpha \circ V_\beta$ .

Since  $u_\alpha$  is unitary in  $M$ , it follows from (1) that  $i\alpha$  is an eigenvalue which is simple because  $\text{Fix}(T) = \text{Fix}(\mu R(\mu, A))$  is one dimensional.

From (3) it follows that  $i(\alpha + \beta) \in P\sigma(A)$  since  $0 \in P\sigma(A)$  and  $V_{\alpha\beta}$  is bijective. From the identity (1) we conclude that  $\sigma(R(\mu, A)) = \sigma(R(\mu + i\alpha))$ , which proves

$$\sigma(A) + (P\sigma(A) \cap i\mathbb{R}) \subseteq \sigma(A).$$

The other inclusion is trivial since  $0 \in P\sigma(A)$ .  $\square$

**Remarks 1.12** (i) Let  $\varphi$  be the normal state on  $M$  such that  $\text{Fix}(T) = \mathbb{C}\varphi$  and let  $H := P\sigma(A) \cap i\mathbb{R}$ . From the proof of Theorem 1.10 it follows that there exists a family  $\{u_\eta : \eta \in H\}$  of unitaries in  $M$  such that  $A'u_\eta = -\eta u_\eta$  and  $A(u_\eta\varphi) = \eta(u_\eta\varphi)$  for all  $\eta \in H$ .

(ii) If the group  $H$  is generated by a single element, i.e.,  $H = i\gamma\mathbb{Z}$  for some  $\gamma \in \mathbb{R}$ , then  $\{u_\gamma^k : k \in \mathbb{Z}\}$  is a complete family of eigenvectors pertaining to the eigenvalues in  $H$ , where  $u_\gamma \in M$  is unitary such that  $A'u_\gamma = i\gamma u_\gamma$ .

**Proposition 1.13** Suppose that  $\mathcal{T}$  and  $M$  satisfy the assumptions of Theorem 1.10, and let  $N_*$  be the closed linear subspace of  $M_*$  generated by the eigenvectors of  $A$  pertaining to the eigenvalues in  $i\mathbb{R}$ . Denote by  $T_0$  the restriction of  $\mathcal{T}$  to  $N_*$ . Then

- (i)  $G := (T_0)^- \subseteq L_s(N_*)$  is a compact, Abelian group in the strong operator topology.
- (ii)  $\text{Id}_{|N_*} \in \overline{\{T_0(t) : t > s\}} \subseteq L_s(N_*)$  for all  $0 < s \in \mathbb{R}$ .

**Proof** For  $\eta \in H := P\sigma(A) \cap i\mathbb{R}$  let

$$U(\eta) := \{\psi \in D(A) : A\psi = \eta\psi\}$$

and  $U = \{U(\eta) : \eta \in H\}$ . Then  $(U)^- = N_*$ .

For each  $\psi \in U$  there exists  $\eta \in H$  such that

$$\{T_0(t)\psi : t \in \mathbb{R}_+\} = \{e^{-\eta t}\psi : t \in \mathbb{R}_+\}.$$

Consequently this set is relatively compact in  $L_s(N_*)$ . From [Schaefer (1966), III.4.5] we obtain that  $G$  is compact in the strong operator topology.

Next choose  $\psi_1, \dots, \psi_n \in U$ ,  $0 < s \in \mathbb{R}$  and  $\delta > 0$ . Since  $T_0(t)\psi_i = e^{\eta_i t}\psi_i$  ( $1 \leq i \leq n$ ) for some  $\eta_i \in H$ , it follows from a theorem of Kronecker (see, Jacobs [11, Satz 6.1., p.77]) that there exists  $s < t$  such that

$$|(1, 1, \dots, 1) - (e^{\eta_1 t}, e^{\eta_2 t}, \dots, e^{\eta_n t})| < \delta,$$

hence

$$\sup\{\|\psi_i - T_0(t)\psi_i\| : 1 \leq i \leq n\} < \delta$$

or  $\text{Id}_{|N_*} \in \overline{\{T_0(t) : t > s\}} \subseteq L_s(N_*)$ .

Finally we prove the group property of  $G$ . Let  $\mathfrak{U}$  be an ultrafilter on  $\mathbb{R}$  such that  $\lim_{\mathfrak{U}} T_0(t) = \text{Id}$  in the strong operator topology. For positive  $s \in \mathbb{R}$  let  $S := \lim_{\mathfrak{U}} T(t - s)$ . Then  $ST_0(s) = T_0(s)S = \text{Id}$ , hence  $T_0(s)^{-1}$  exists in  $G$  for all  $s \in \mathbb{R}_+$ . From this it follows that  $G$  is a group.  $\square$

*Remark 1.14* (i) Let  $\kappa : \mathbb{R} \rightarrow G$  be given by

$$\kappa(t) = \begin{cases} T_0(t) & \text{if } 0 \leq t, \\ T_0(t)^{-1} & \text{if } t \leq 0. \end{cases}$$

Then  $\kappa$  is a continuous homomorphism with dense range, i.e.,  $(G, \kappa)$  is solenoidal (see Hewitt and Ross [10]).

(ii) The compact group  $G$  and the discrete group  $P\sigma(A) \cap i\mathbb{R}$  are dual as locally compact Abelian groups.

(iii) Let  $(G, \kappa)$  be a solenoidal compact group and let  $N_* = L^1(G)$ . Then the induced lattice semigroup  $T = (\kappa(t))_{t \geq 0}$  fulfils the assertions of Theorem 1.10. For example, if  $G$  is the dual of  $\mathbb{R}_d$ , then  $P\sigma(A) \cap i\mathbb{R} = i\mathbb{R}$ . Since the fixed space of  $\kappa(t)$  is given by

$$\text{Fix}(\kappa(t)) = \overline{\left( \bigcup_{k \in \mathbb{Z}} \text{Ker}\left(\frac{2\pi i k}{t} - A\right) \right)},$$

however no  $T(t) \in \mathcal{T}$  is irreducible.

(iv) If  $\mathcal{T}$  is the irreducible semigroup of Schwarz type on the predual of  $B(H)$  given in Evans [3], then  $P\sigma(A) \cap i\mathbb{R} = \emptyset$ .

## 2 Spectral Properties of Uniformly Ergodic Semigroups

The aim of this section is the study of spectral properties of semigroups which are uniformly ergodic, identity preserving and of Schwarz type. For the basic theory of uniformly ergodic semigroups on Banach spaces we refer to Dunford and Schwartz [2].

Our first result yields an estimate for the dimension of the eigenspaces pertaining to eigenvalues of a pseudo-resolvent.

**Proposition 2.1** *Let  $\mathcal{R}$  be an identity preserving pseudo-resolvent of Schwarz type on  $D = \{\lambda \in \mathbb{C} : \text{Re } \lambda > 0\}$  with values in the predual of a  $W^*$ -algebra  $M$ . If  $\text{Fix } \lambda \mathcal{R}(\lambda)$  is finite dimensional for some  $\lambda \in D$ , then*

$$\dim \text{Fix}((\gamma - i\alpha) \mathcal{R}(\gamma)) \leq \dim \text{Fix}(\lambda \mathcal{R}(\lambda))$$

for all  $\gamma \in D$  and  $\alpha \in \mathbb{R}$ .

**Proof** By D-IV, Remark 3.2.c, we may assume without loss of generality that there exists a faithful family of  $\mathcal{R}$ -invariant normal states on  $M$ . In particular the fixed space  $N$  of the adjoint pseudo-resolvent  $\mathbb{R}\mathcal{R}'$  is a  $W^*$ -subalgebra of  $M$  with  $\mathbb{1} \in N$  (by Lemma 1.1 (ii)). Since  $N$  is finite dimensional, there exist a natural number  $n$  and a set  $P := \{p_1, \dots, p_n\}$  of minimal, mutually orthogonal projections in  $N$  such that  $\sum_{k=1}^n p_k = \mathbb{1}$ . These projections are also mutually orthogonal in  $M$  with sum  $\mathbb{1}$ .



Let  $R_j$  be the  $\sigma(M, M_*)$ -closed right ideal  $p_j M$  and  $L_j$  the closed left invariant subspace  $M_* p_j$  for  $(1 \leq j \leq n)$ . Since the map  $\mu R(\mu)'$ ,  $\mu \in \mathbb{R}_+$  is an identity preserving Schwarz map, we obtain from Lemma 1.1.b that for all  $x \in N$  and  $y \in M$ ,

$$\mu R(\mu)'(xy) = x(\mu \mathcal{R}'(\mu)y).$$

In particular,  $R_j$ , resp.  $L_j$  are invariant under  $\mathcal{R}'$ , respectively,  $\mathcal{R}$ . Furthermore, if  $\psi \in L_j$  with polar decomposition  $\psi = u|\psi|$ , then  $u^*u \leq s(|\psi|) \leq p_j$ . Consequently,  $|\psi| \in L_j$ .

Let now  $\alpha \in \mathbb{R}$  and suppose that there exists  $\psi_\alpha \in L_j$  of norm 1,  $\psi_\alpha = u_\alpha |\psi_\alpha|$ , such that

$$\psi_\alpha \in \text{Fix}((\lambda - i\alpha)R(\lambda)), \lambda \in D.$$

Since  $\lambda R(\lambda)|\psi_\alpha| = |\psi_\alpha|$  (Proposition 1.4 on page 198), we obtain

$$\mu R(\mu)'(1 - s(|\psi_\alpha|)) \leq (1 - s(|\psi_\alpha|)), \mu \in \mathbb{R}_+.$$

From the existence of a faithful family of  $\mathcal{R}$ -invariant normal states and since  $\mathcal{R}'$  is identity preserving, it follows that

$$\mu R(\mu)'s(|\psi_\alpha|) = s(|\psi_\alpha|).$$

Thus  $s(|\psi_\alpha|) \leq p_j$  and even  $s(|\psi_\alpha|) = p_j$  by the minimality property of  $p_j$ .

On the other hand,  $\psi_\alpha^* \in \text{Fix}((\lambda + i\alpha)R(\lambda))$ . As above we obtain

$$\mu R(\mu)'s(|\psi_\alpha^*|) = s(|\psi_\alpha^*|).$$

Consequently, the closed left ideals  $Ms(|\psi_\alpha^*|)$  and  $Ms(|\psi_\alpha|)$  are  $\mathcal{R}'$ -invariant.

Next fix  $\mu \in \mathbb{R}_+$ , let  $S := (\mu - i\alpha)R(\mu)'$  and  $T = \mu R(\mu)'$ . Then

$$(Sx)(Sx)^* \leq T(xx^*), S_*(\psi_\alpha^*) = \psi_\alpha^*, T_*(|\psi_\alpha^*|) = |\psi_\alpha^*|,$$

and  $T$  is an identity preserving Schwarz map. Since  $s(|\psi_\alpha^*|)M$  is  $T$ -invariant, the assumptions of Lemma 1.2 on page 197 are fulfilled and we obtain for every  $x \in M$

$$S(x)u_\alpha^* = T(xu_\alpha^*).$$

The closed left ideal  $Mp_j$  is  $S$ -invariant, therefore it follows

$$S(x) = T(xu_\alpha^*)u_\alpha, x \in Mp_j$$

(see Remark 1.3 on page 197). Since  $u_\alpha$  does not depend on  $\mu \in \mathbb{R}_+$ , we obtain for all  $\mu \in \mathbb{R}_+$

$$\mu R(\mu + i\alpha)'x = \mu R(\mu)'(xu_\alpha^*)u_\alpha.$$

Consequently, the holomorphic functions

$$(\mu \mapsto \mu R(\mu)'(xu_\alpha^*)u_\alpha) \quad \text{and} \quad (\mu \mapsto \mu R(\mu + i\alpha)'x)$$

coincide on  $\mathbb{R}_+$  from which we conclude

$$\lambda R(\lambda + i\alpha)'x = \lambda R(\lambda)'(xu_\alpha^*)u_\alpha$$

for every  $\lambda \in D$  and all  $x \in Mp_j$ .

Since the map  $(y \mapsto yu_\alpha)$  is a continuous bijection from  $M(u_\alpha u_\alpha^*)$  onto  $Mp_j$  with inverse  $(y \mapsto yu_\alpha^*)$ , we can deduce that

$$\begin{aligned} \dim \operatorname{Fix}((\lambda - i\alpha)R(\lambda)'|Mp_j) &= \dim \operatorname{Fix}(\lambda R(\lambda)'|M(u_\alpha u_\alpha^*)) \\ &\leq \dim \operatorname{Fix}(\mathcal{R}'). \end{aligned}$$

Since  $\bigoplus_{j=1}^n Mp_j = M$  and  $\bigoplus_{j=1}^n L_j = M_*$ , we obtain

$$\begin{aligned} \dim \operatorname{Fix}((\lambda - i\alpha)R(\lambda)') &= \dim \operatorname{Fix}(\lambda R(\lambda)'), \\ &= \dim \operatorname{Fix}(\lambda R(\lambda)), \end{aligned}$$

and the assertion follows from Lemma 1.6 on page 199.  $\square$

Before going on let us recall the basic facts of the *ultrapower*  $\hat{E}$  of a Banach space  $E$  with respect to some free ultrafilter  $\mathfrak{U}$  on  $\mathbb{N}$  (compare A-I,3.6). If  $\ell^\infty(E)$  is the Banach space of all bounded functions on  $\mathbb{N}$  with values in  $E$ , then

$$c_{\mathfrak{U}}(E) := \{(x_n) \in \ell^\infty(E) : \lim_{\mathfrak{U}} \|x_n\| = 0\}$$

is a closed subspace of  $\ell^\infty(E)$  and equal to the kernel of the seminorm

$$\|(x_n)\| := \lim_{\mathfrak{U}} \|x_n\|, (x_n) \in \ell^\infty(E).$$

By the *ultrapower*  $\hat{E}$  we understand the quotient space  $\ell^\infty(E)/c_{\mathfrak{U}}(E)$  with norm

$$\|\hat{x}\| = \lim_{\mathfrak{U}} \|x_n\|, (x_n) \in \hat{x} \in \hat{E}.$$

Moreover, for a bounded linear operator  $T \in L(E)$ , we denote by  $\hat{T}$  the well defined operator  $\hat{T}\hat{x} := (Tx_n) + c_{\mathfrak{U}}(E)$ ,  $(x_n) \in \hat{x}$ .

It is clear by virtue of  $(x \mapsto (x, x, \dots) + c_{\mathfrak{U}}(E))$  that each  $x \in E$  defines an element  $\hat{x} \in \hat{E}$ . This isometric embedding as well as the operator map  $(T \mapsto \hat{T})$  are called canonical. In particular, if  $\mathcal{R}: (D \rightarrow L(E))$  is a pseudo-resolvent, then

$$\hat{\mathcal{R}} := (\lambda \mapsto R(\lambda)^\wedge) : D \rightarrow L(\hat{E})$$

is a pseudo-resolvent, too. Recall that the approximative point spectrum  $A\sigma(T)$  is equal to the point spectrum  $P\sigma(\hat{T})$  (see, e.g., Schaefer [14, Chapter V, §1]).

This construction gives us the possibility to characterize uniformly ergodic semi-groups with finite dimensional fixed space.

**Lemma 2.2** *Let  $\mathcal{R}$  be a pseudo-resolvent on  $D = \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda > 0\}$  such that  $\|R(\mu + i\alpha)\| \leq 1$  for all  $(\mu, \alpha) \in \mathbb{R}_+ \times \mathbb{R}$  and suppose*

$$0 < \dim \operatorname{Fix}((\lambda - i\alpha)\hat{R}(\lambda)) < \infty \quad \text{for some } \lambda \in D, \alpha \in \mathbb{R}.$$

For the canonical extension  $\hat{R}$  on some ultrapower  $\hat{E}$ , the following assertions hold.

- (i)  $(\lambda - i\alpha)^{-1}$  is a pole of the resolvent  $R(., R(\lambda))$  for all  $\lambda \in D$ .
- (ii)  $\dim \operatorname{Fix}((\lambda - i\alpha)R(\lambda)) = \dim \operatorname{Fix}((\lambda - i\alpha)\hat{R}(\lambda))$  for all  $\lambda \in D$ .
- (iii)  $i\alpha$  is a pole of the pseudo-resolvent  $\mathcal{R}$  and the residue of  $\mathcal{R}$  and  $R(., R(\lambda))$  in  $i\alpha$  respectively  $(\lambda - i\alpha)^{-1}$  are identical.

**Proof** Take a normalized sequence  $(x_n)$  in  $E$  with

$$\lim_n \|(\lambda - i\alpha)R(\lambda)x_n - x_n\| = 0.$$

The existence of such a sequence follows from the fact that the fixed space of  $(\lambda - i\alpha)\hat{R}(\lambda)$  is non trivial. Suppose  $(x_n)$  is not relatively compact. Then we may assume that there exists  $\delta > 0$  such that

$$\|x_n - x_m\| > \delta \quad \text{for } n \neq m.$$

Take  $k \in \mathbb{N}$  and let  $\hat{x}_k$  be the image of  $(x_{n+k})$  in  $\hat{E}$ . Since

$$\lim_n \|(\lambda - i\alpha)R(\lambda)x_{n+k} - x_{n+k}\| = 0,$$

the so defined  $\hat{x}_k$ 's belong to  $\operatorname{Fix}((\lambda - i\alpha)\hat{R}(\lambda))$ . Since this space is finite dimensional there exist  $j < \ell$ , such that

$$\|\hat{x}_j - \hat{x}_\ell\| \leq \frac{\delta}{2}.$$

From the definition of the norm in  $\hat{E}$  it follows that there are natural numbers  $n < m$  such that

$$\|x_n - x_m\| \leq \frac{\delta}{2},$$

leading to a contradiction.

Therefore every approximate eigenvector of  $(\lambda - i\alpha)R(\lambda)$  pertaining to  $\alpha$  is relatively compact. In particular, it has a convergent subsequence from which it follows that the fixed space of  $(\lambda - i\alpha)R(\lambda)$  is non trivial.

Obviously

$$\dim \operatorname{Fix}((\lambda - i\alpha)R(\lambda)) \leq \dim \operatorname{Fix}((\lambda - i\alpha)\hat{R}(\lambda)).$$

If the last inequality is strict, then there exists  $\gamma > 0$  and a normalized  $\hat{x} \in \operatorname{Fix}((\lambda - i\alpha)\hat{R}(\lambda))$  such that

$$\gamma \leq \|\hat{y} - \hat{x}\|$$

for all  $y \in \operatorname{Fix}((\lambda - i\alpha)R(\lambda))$ .

Take a normalized sequence  $(x_n) \in \hat{x}$ . Then  $(x_n)$  has a convergent subsequence, whence we may assume that  $\lim_n x_n = z$  exists in  $E$ . Thus  $0 \neq z \in \operatorname{Fix}((\lambda - i\alpha)R(\lambda))$ . From this we obtain the contradiction

$$0 \leq \gamma \leq \|\hat{z} - \hat{x}\| = \lim \|z - x_n\| = 0$$

Consequently,

$$\dim \operatorname{Fix}((\lambda - i\alpha)R(\lambda)) = \dim \operatorname{Fix}(\lambda - i\alpha)\hat{R}(\lambda).$$

Let  $\{x_1, \dots, x_n\}$  be a base of  $\operatorname{Fix}((\lambda - i\alpha)R(\lambda))$  and choose  $\{\varphi_1, \dots, \varphi_n\}$  in  $\operatorname{Fix}((\lambda - i\alpha)R(\lambda)')$  such that  $\varphi_k(x_j) = \delta_{k,j}$  (Lemma 1.6). Then

$$E = \operatorname{Fix}((\lambda - i\alpha)R(\lambda)) \oplus \bigcap_{j=1}^n \operatorname{Ker}(\varphi_j),$$

where both subspaces on the right are  $(\lambda - i\alpha)R(\lambda)$ -invariant and 1 is a pole of  $(\lambda - i\alpha)R(\lambda)|_{\operatorname{Fix}((\lambda - i\alpha)R(\lambda))}$  by the finite dimensionality of  $\operatorname{Fix}((\lambda - i\alpha)R(\lambda))$ . Suppose 1 belongs to the spectrum of  $S$  where  $S$  is the restriction of  $(\lambda - i\alpha)R(\lambda)$  to  $\bigcap_{j=1}^n \operatorname{Ker} \varphi_j$ . Then there exists a normalized sequence  $(y_n)$  in  $\bigcap_{j=1}^n \operatorname{Ker}(\varphi_j)$  such that

$$\lim_n \|(\lambda - i\alpha)R(\lambda)y_n - y_n\| = 0.$$

Therefore  $(y_n)$  has an accumulation point different from zero contained in

$$\operatorname{Fix}((\lambda - i\alpha)R(\lambda)) \cap \left(\bigcap_{j=1}^n \operatorname{Ker} \varphi_j\right).$$

This contradiction implies that 1 does not belong to the spectrum of  $S$ . Since  $\operatorname{Fix}((\lambda - i\alpha)R(\lambda))$  is finite dimensional, it follows from general spectral theory that  $(\lambda - i\alpha)^{-1}$  is a pole of  $R(\cdot, R(\lambda))$  for every  $\lambda$ . Thus (i) and (ii) are proved and assertion (iii) follows from the resolvent equality as in the proof of Greiner [4, Proposition 1.2].  $\square$

**Proposition 2.3** *Let  $\mathcal{T}$  be a semigroup of contractions on a Banach space  $E$  with generator  $A$ . Then the following assertions are equivalent.*

- (a) *Each  $i\alpha$ ,  $\alpha \in \mathbb{R}$ , is a pole of the resolvent  $R(\cdot, A)$  such that the corresponding residue has finite rank.*
- (b)  *$\dim \operatorname{Fix}((\lambda - i\alpha)\hat{R}(\lambda, A)) < \infty$  for some (hence all)  $\lambda \in \mathbb{C}$ ,  $\operatorname{Re} \lambda > 0$  and the canonical extensions  $\hat{R}(\lambda, A)$  of  $R(\lambda, A)$  to some ultrapower.*

**Proof** Let  $P_\alpha$  be the residue of the resolvent  $R(\cdot, A)$  in  $i\alpha$ . Then  $P_\alpha = \lim_{\lambda \rightarrow i\alpha} (\lambda - i\alpha)R(\lambda, A)$  in the operator norm of  $L(E)$ . Since the canonical map  $(T \mapsto \hat{T})$  is isometric and since  $\hat{E}$  is an ultrapower, we obtain

$$\hat{P}_\alpha = \lim_{\lambda \rightarrow i\alpha} (\lambda - i\alpha)\hat{R}(\lambda, A)$$

in  $L(\hat{E})$  and  $\operatorname{rank}(P_\alpha) = \operatorname{rank}(\hat{P}_\alpha)$ . Because of

$$\hat{P}_\alpha(\hat{E}) = \operatorname{Fix}((\lambda - i\alpha)\hat{R}(\lambda))$$

one part of the corollary is proved. The other follows from Lemma 2.2 on page 206.  $\square$

**Remarks 2.4** (i) By the results in Lin [12] a semigroup of contractions on a Banach space is uniformly ergodic if and only if 0 is a pole of the generator with order  $\leq 1$ . The residue of the resolvent in 0 and the associated ergodic projection are identical.

(ii) Let  $M$  be a  $W^*$ -algebra with predual  $M_*$ ,  $\mathcal{U}$  a free ultrafilter on  $\mathbb{N}$  and  $\widehat{M}$  (resp.  $(M_*)^\wedge$ ) the ultrapower of  $M$  (resp.  $M_*$ ) with respect to  $\mathcal{U}$ . Then it is easy to see that  $c_{\mathcal{U}}(M)$  is a two sided ideal in  $\ell^\infty(M)$  hence  $\widehat{M}$  is a  $C^*$ -algebra, but in general not a  $W^*$ -algebra. Note that the unit of  $\widehat{M}$  is the canonical image of 1. For  $\hat{x} \in \widehat{M}$  and  $\hat{\varphi} \in (M_*)^\wedge$  let  $J : (M_*)^\wedge \rightarrow \widehat{M}'$  be defined by

$$\langle x, J(\hat{\varphi}) \rangle := \lim_{\mathcal{U}} \varphi_n(x_n), \quad (x_n) \in \hat{x}, \quad (\varphi_n) \in \hat{\varphi}.$$

Then  $J$  is well defined and an isometric embedding. It turns out that  $J((M_*)^\wedge)$  is a translation invariant subspace of  $\widehat{M}'$ . Hence there exists a central projection  $z \in \widehat{M}''$  such that  $J((M_*)^\wedge) = \widehat{M}''z$  (Groh [9, Proposition 2.2]).

Below we identify  $(M_*)^\wedge$  via  $J$  with this translation invariant subspace. From the construction the following is obvious: If  $T$  is an identity preserving Schwarz map with preadjoint  $T_* \in L(M_*)$ , then  $\widehat{T}$  is an identity preserving Schwarz map on  $\widehat{M}$  such that  $(T_*)^\wedge = \widehat{T}'|_{(M_*)^\wedge}$ .

**Theorem 2.5** *Let  $\mathcal{T}$  be an identity preserving semigroup of Schwarz type with generator  $A$  on the predual of a  $W^*$ -algebra  $M$ . If  $\mathcal{T}$  is uniformly ergodic with finite dimensional fixed space, then every  $\gamma \in \sigma(A) \cap i\mathbb{R}$  is a pole of the resolvent  $R(\cdot, A)$  and  $\dim \text{Ker}(\gamma - A) \leq \dim \text{Fix}(T)$ .*

**Proof** Let  $D = \{\lambda \in \mathbb{C} : \text{Re } \lambda > 0\}$  and  $\mathcal{R}$  the  $M_*$ -valued pseudo-resolvent of Schwarz type induced by  $R(\cdot, A)$  on  $D$ . Then

$$P = \lim_{\mu \downarrow 0} \mu R(\mu)$$

exists in the uniform operator topology. Since  $P(E) = \text{Fix}(T)$ , we obtain  $\hat{P}(\hat{E}) = \text{Fix}(\hat{T})$  and  $\dim \text{Fix}(T) = \dim \text{Fix}(\hat{T}) < \infty$ , where  $\hat{P}$  is the canonical extension of  $P$  onto  $(M_*)^\wedge$ . Since  $\hat{P} = \lim_{\mu \downarrow 0} \mu R(\mu)^\wedge$  it follows that

$$\dim \text{Fix}((\lambda - i\alpha)\hat{R}(\lambda)) \leq \dim \text{Fix}(\hat{T}) < \infty$$

for all  $\alpha \in \mathbb{R}$  (Proposition 2.1 on page 204). Therefore the assertion follows from Lemma 2.2 on page 206.  $\square$

The consequences of this result for the asymptotic behavior of one-parameter semigroups will be discussed in D-IV, Section 4.

## Notes

*Section 1:* The Perron-Frobenius theory for a single positive operator on a non-commutative operator algebra is worked out in Alberverio and Hoegh-Krohn [1] and Groh [7]. The limitations of the theory (in the continuous as in the discrete case) are explained by the example following Remark 1.9 on page 201 (see also Groh [8]). Therefore we concentrate on irreducible semigroups. Our main result Theorem 1.11 on page 202 extends B-III, Thm.3.6 to the non-commutative setting.

*Section 2:* Theorem 2.5 on page 209 has its roots in the Niiri-Sawashima Theorem for a single irreducible positive operator on a Banach lattice (see Schaefer [14, V.5.4]). The analogous semigroup result on Banach lattices is due to Greiner [5]. The ultrapower technique in our proof is developed in Groh [9].

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## Chapter D-IV

# Asymptotics of Positive Semigroups on $C^*$ - and $W^*$ -Algebras

### 1 Stability of Positive Semigroups

As explained in A-III, Section 1, it is possible to deduce uniform exponential stability of strongly continuous semigroups from the location of the spectrum of its generator if the spectral bound  $s(A)$  and the growth bound  $\omega_0$  coincide. In this section we prove  $s(A) = \omega_0$  for positive semigroups on  $C^*$ -algebras and preduals of  $W^*$ -algebras. A more general discussion of the “ $s(A) = \omega_0$ ” problem can be found in Greiner et al. [8]. For the results of this section the existence of a unit is essential.

**Theorem 1.1** *Let  $M$  be a  $C^*$ -algebra with unit and  $\mathcal{T} = (T(t))_{t \geq 0}$  a positive semigroup on  $M$ . Then*

$$-\infty < s(A) = \omega_0 \in \sigma(A).$$

**Proof** For every  $t \geq 0$  there exists  $\varphi_t$  in the state space  $S(M)$  of  $M$  such that

$$T(t)' \varphi_t = r(T(t)) \varphi_t = \exp(\omega_0 t) \varphi_t$$

(see, e.g., Groh [9, 2.1]).

Let  $n \in \mathbb{N}$  and

$$E_n := \{\varphi \in S(M) : T(2^{-n})\varphi = \exp(\omega_0 2^{-n})\varphi\}.$$

Then  $\emptyset \neq E_{n+1} \subseteq E_n$ , ( $n \in \mathbb{N}$ ). Since  $S(M)$  is  $\sigma(M, M')$ -compact, there exists  $\varphi \in \bigcap_{n \in \mathbb{N}} E_n$ . Then  $T(t)' \varphi = \exp(\omega_0 t) \varphi$  follows for all  $0 \leq t$  because the adjoint semigroup  $(T(t)')_{t \geq 0}$  is a weak\*-semigroup on  $M'$ .

Suppose  $-\infty = \omega_0$ . Then for  $t > 0$  either  $r(T(t)) = 0$  (A-III, Prop. 1.1) or  $T(t)' \varphi = 0$ , in particular  $\varphi(T(t) \mathbb{1}) = 0$ . From this we obtain the contradiction  $\varphi(\mathbb{1}) = 0$ .

Hence  $-\infty < \omega_0$  and  $\exp(\omega_0 t) \in \varrho(T(t)')$  for every  $t \in \mathbb{R}_+$ . Thus  $\omega_0 \in \sigma(A)$  or  $\omega_0 = s(A)$ .  $\square$

**Remark 1.2** (i) If we consider the nilpotent translation semigroup on the  $C^*$ -algebra  $C_0([0, 1])$ , then  $\sigma(A) = \emptyset$  and  $\omega_0 = -\infty$ . This shows that the existence of a unit is essential.

(ii) The equality  $s(A) = \omega_0$  still holds for positive semigroups on commutative  $C^*$ -algebras without unit (see B-IV, Rem.1.2.b).

**Theorem 1.3** *Let  $M$  be a  $W^*$ -algebra with predual  $M_*$  and let  $(T(t))_{t \geq 0}$  be a positive semigroup on  $M_*$ . Then  $s(A) = \omega_0$ .*

**Proof** For all  $\lambda > s(A)$  and  $\varphi \in M_*$

$$R(\lambda, A)\varphi = \int_0^\infty e^{-\lambda t} T(s)\varphi ds$$

which follows as in C-III, Section 1 or Greiner et al. [8, Theorem 3]. Since  $\|\varphi\| = \varphi(\mathbb{1})$  for every  $\varphi \in M_*^+$  and since the norm is additive on the positive cone of  $M_*$ , the integral

$$\int_0^\infty e^{\lambda t} \|T(s)\varphi\| ds$$

exists for all  $\varphi \in M_*$  and all  $\lambda > s(A)$ . From this the assumption follows by A-IV, Thm.1.11.  $\square$

**Corollary 1.4** *Let  $M$  be a  $C^*$ -algebra and  $(T(t))_{t \geq 0}$  a positive semigroup on  $M'$ . Then  $s(A) = \omega_0$  holds.*

This follows from the fact that the bidual of a  $C^*$ -algebra is a  $W^*$ -algebra (see Takesaki [24, Theorem III.2.4.]).

**Remark 1.5** A simple modification of A-III, Example 1.4 (take  $c_0$  instead of  $\ell^2$ ) shows that Theorem 1.3 is no longer true for non-positive semigroups (for details see Groh and Neubrandner [13, Beispiel 2.5]).

While the growth bound  $\omega_0$  characterizes uniform exponential stability of the semigroup there are other (and weaker) stability concepts (cf. A-IV, Section 1).

**Definition 1.6** Let  $E$  be a Banach space and  $(T(t))_{t \geq 0}$  a semigroup on  $E$ . We call the semigroup

- (i) *uniformly exponentially stable* if  $\|T(t)\| \leq M e^{-\omega t}$  for some  $\omega, M > 0$  and all  $t \geq 0$ .
- (ii) *uniformly stable* if  $\lim_{t \rightarrow \infty} T(t) = 0$  in the strong operator topology.
- (iii) *weakly stable* if  $\lim_{t \rightarrow \infty} T(t) = 0$  in the weak operator topology.

Surprisingly all these properties coincide for positive semigroups on  $C^*$ -algebras with unit.

**Theorem 1.7** *Let  $M$  be a  $C^*$ -algebra with unit and  $(T(t))_{t \geq 0}$  a positive semigroup on  $M$ . Then the following assertions are equivalent.*

- (a)  $s(A) < 0$ .

- (b) The semigroup  $(T(t))_{t \geq 0}$  is uniformly exponentially stable.
- (c) The semigroup  $(T(t))_{t \geq 0}$  is uniformly stable.
- (d) The semigroup  $(T(t))_{t \geq 0}$  is weakly stable.

**Proof** Since  $s(A) = \omega_0$  by Theorem 1.3, it suffices to show that (d) implies (a). For  $t > 0$  there exists  $\varphi \in S(M)$  such that

$$T(t)' \varphi = r(T(t)) \varphi.$$

Then for  $x \in M$

$$\varphi(T(t)^n x) = (r(T(t)))^n \varphi(x) \rightarrow 0$$

as  $n \rightarrow \infty$ . Therefore  $r(T(t)) < 1$  or  $\omega_0 < 0$ . Since  $s(A) \leq \omega_0$  the assertion follows.  $\square$

*Remark 1.8* Consider the translation semigroup  $(T(t))_{t \geq 0}$  on  $C_0(\mathbb{R}_+)$ . Then  $\|T(t)\| = 1$ , hence  $s(A) = 1$ , but  $(T(t))_{t \geq 0}$  is strongly stable. The same holds for the translation semigroup on  $L^1(\mathbb{R}_+)$ . Thus Theorem 1.7 is not true for semigroups on  $C^*$ -algebras without unit or on preduals of  $W^*$ -algebras. For the discussion of the commutative situation we refer to B-IV, Section 1.

## 2 Stability of Implemented Semigroups

Let  $H$  be a Hilbert space,  $\mathcal{U} = (U(t))_{t \geq 0}$  a strongly continuous semigroup on  $H$  with generator  $B$  and  $M \subseteq \mathcal{B}(H)$  a  $W^*$ -algebra, where  $\mathcal{B}(H)$  is the  $W^*$ -algebra of all bounded linear operators on  $H$ . Suppose  $\mathcal{U}(t)^* M U(t) \subseteq M$ . Then one can define a weak\*-continuous semigroup  $\mathcal{T}$  on  $M$  by

$$T(t)x := U(t)^* x U(t) \quad (t \in \mathbb{R}_+, x \in M).$$

We call  $\mathcal{T}$  an *implemented semigroup*. Every map  $T(t) \in \mathcal{T}$  of an implemented semigroup is weak\*-continuous and  $n$ -positive for every  $n \in \mathbb{N}$ .

**Remarks 2.1** (i) Because of

$$\|T(t)\| = \|T(t)\mathbb{1}\| = \|U(t)^* U(t)\| = \|U(t)\|^2$$

it follows that  $\omega_0(\mathcal{T}) = 2\omega_0(\mathcal{U})$ .

(ii) If  $\mathcal{T}$  is an implemented semigroup, then the preadjoint semigroup is strongly continuous on  $M_*$ . Therefore  $s(A) = \omega_0$  for  $\mathcal{T}$  by Theorem 1.3.

(iii) Since  $\mathcal{U}$  is a strongly continuous semigroup on  $H$ , the same is true for the adjoint semigroup  $\mathcal{U}^* = \{U(t)^*: U(t) \in \mathcal{U}\}$  and its generator is given by  $B^*$ . In analogy to Bratteli and Robinson [3, 3.2.55] the following assertions for  $x \in M$  are equivalent.

- (a)  $x \in D(A)$ ,  $A$  the generator of  $\mathcal{T}$ .

(b) For  $\xi \in D(B)$  it follows  $x\xi \in D(B^*)$  and the linear mapping

$$(\xi \mapsto x(B\xi) + B^*(x\xi)) : D(B) \rightarrow H \quad (*)$$

has a continuous extension to  $H$ .

Then for  $A$  is given as the continuous extension of  $(*)$ , i.e.,  $Ax = xB + B^*x$  for  $x \in D(A)$

In the next theorem we give some equivalent conditions for the uniform exponential stability of an implemented semigroup. As we shall see, the operator equality

$$yB + B^*y = -x \quad (x, y \in M_+)$$

is necessary and sufficient, which is in complete analogy to the classical Liapunov stability result.

**Theorem 2.2** *Let  $M$  be a  $W^*$ -algebra on a Hilbert space  $H$  and let  $\mathcal{T} = (T(t))_{t \geq 0}$  be a weak\*-semigroup on  $M$  with generator  $A$  implemented by the semigroup  $\mathcal{U}$  on  $H$  with generator  $B$ . Then the following assertions are equivalent.*

- (a)  $\omega_0(\mathcal{T}) = s(A) < 0$ .
- (b) The semigroup  $(U(t))_{t \geq 0}$  is uniformly exponentially stable.
- (c) There exists  $0 \leq x \in D(A)$  such that  $Ax = -\mathbb{1}$ .
- (d) There exists  $0 \leq x \in D(A)$  such that  $x(D(B)) \subseteq D(B^*)$  and  $xB + B^*x = -\mathbb{1}$ .
- (e) For every  $0 \leq x \in D(A)$  there exists  $0 \leq y \in D(A)$  such that  $Ay = -x$ .
- (f) For every  $0 \leq x \in D(A)$  there exists  $0 \leq y \in D(A)$  such that  $y(D(B)) \subseteq D(B^*)$  and  $yB + B^*y = -x$ .
- (g)  $\int_0^\infty \|U(s)\xi\|^2 ds$  exists for all  $\xi \in H$ .
- (h)  $\int_0^\infty |(T(s)x)\xi| \zeta ds$  exists for all  $\xi, \zeta \in H$  and all  $x \in M$ .

**Proof** The equivalence of (a) and (b) follows from Remark 2.1 (i), whereas (c) and (d), resp. (e) and (f) are equivalent by the Remark 2.1 (iii)

(a)  $\implies$  (c): Since  $s(A) < 0$  the resolvent  $R(0, A)$  exists and is a positive map on  $M$ . Therefore  $R(0, A)\mathbb{1} \in D(A)_+$  or  $Ax = -\mathbb{1}$  for some  $x \in D(A)_+$ .

(c)  $\implies$  (e): Let  $x \in D(A)_+$  such that  $Ax = -\mathbb{1}$ . Then

$$T(t)x - x = \int_0^t T(s)Ax ds = - \int_0^t T(s)\mathbb{1} ds \quad (t \geq 0),$$

hence

$$0 \leq \int_0^t T(s)\mathbb{1} ds \leq x \quad (t \in \mathbb{R}_+).$$

Since the family  $(\int_0^t T(s)\mathbb{1} ds)_{t \geq 0}$  is increasing and bounded,

$$\lim_{t \rightarrow \infty} \int_0^t T(s)\mathbb{1} ds$$

exists in the weak operator topology on  $\mathcal{B}(H)$ .

Since on bounded sets of  $M$ , the weak operator topology is equivalent to the  $\sigma(M, M_*)$ -topology, for every  $\varphi \in M_*$  the integral  $\int_0^\infty \varphi(T(s)\mathbb{1}) ds$  exists (Sakai [20, 1.15.2.]). Take  $x \in M_+$  and  $\varphi \in M_*^+$ . Then  $x \leq \|x\|\mathbb{1}$  and therefore

$$\varphi(T(s)x) \leq \|x\|\varphi(T(s)\mathbb{1}) \quad (s \in \mathbb{R}_+).$$

Hence  $\int_0^\infty \varphi(T(s)x)ds$  exists. Since the positive cones of  $M$  and  $M_*$  are generating,  $\int_0^\infty \varphi(T(s)x)ds$  exists for every  $x \in M$  and  $\varphi \in M_*$ . Therefore  $R(0, A)$  exists and is positive which proves (e).

(c)  $\implies$  (g): From the last paragraph we obtain that for all  $\xi \in H$

$$\int_0^\infty \|U(s)\|^2 ds = \int_0^\infty (T(s)\mathbb{1}\xi|\xi)ds$$

exists.

(g)  $\implies$  (h): It follows from the polarization identity that the integral

$$\int_0^\infty (U(s)\xi|U(s)\zeta)ds$$

exists for all  $\xi, \zeta \in H$ . Using Takesaki [24, Theorem III.4.2 and Theorem II.2.6], we conclude as in the implication from (c) to (e) that for all  $\xi, \zeta \in H$  the integral

$$\int_0^\infty ((T(s)x)\xi|\zeta)ds \quad (x \in M)$$

is finite.

(g)  $\implies$  (a): Since the vector states are dense in the predual of  $M$  and since the preadjoint semigroup of  $\mathcal{T}$  is strongly continuous, it is easy to see that the integral

$$\int_0^\infty \varphi(T(s)x)ds$$

exists for all  $x \in M$  and  $\varphi \in M_*$  (Takesaki [24, Theorem II.2.6]). Therefore, the resolvent  $R(0, A)$  exists and is positive, hence  $s(A) < 0$ .  $\square$

### 3 Convergence of Positive Semigroups

In this section the asymptotic behavior of positive semigroups  $(T(t))_{t \geq 0}$  on  $W^*$ -algebras will be described in more detail. Essentially we distinguish three cases.

- (i) The Cesàro means  $\frac{1}{s} \int_0^s T(t)dt$  converge strongly to a projection  $P$  onto the fixed space of  $(T(t))_{t \geq 0}$  (see Proposition 3.3 & 3.4).
- (ii) The maps  $T(t)$  converge strongly to  $P$  (see Proposition 3.7, ?? & ??).
- (iii) The maps  $T(t)$  behave asymptotically as a periodic group (Theorem 3.11).

Much of the following is based on the theory of weakly compact operator semigroups. Therefore the following compactness criterium is quite useful.

**Proposition 3.1** *Let  $M$  be a  $W^*$ -algebra,  $\mathcal{T}$  a bounded semigroup of positive maps on  $M_*$  and suppose that there exists a faithful family  $\Phi$  of  $\mathcal{T}$ -subinvariant states in  $M_*$ . Then  $\mathcal{T}$  is relatively compact in the weak operator topology of  $LM_*$ . In particular,  $\mathcal{T}$  is strongly ergodic, i.e.,*

$$\lim_{s \rightarrow \infty} \frac{1}{s} \int_0^s T(t)x \, dt$$

*exists for every  $x$  in  $M$  and yields a projection onto  $\text{Fix}(\mathcal{T})$ .*

**Proof** Since the positive cone of  $M_*$  is generating, it is enough to show that for every  $0 \leq \varphi \in M_*$  the orbit  $\{T(t)\varphi : t \in \mathbb{R}_+\}$  is relatively weak compact. For this we use Takesaki [24, Theorem III.5.4.(iii)].

Let  $(p_n)_{n \in \mathbb{N}}$  be a decreasing sequence of projections in  $M$  such that  $\inf_n p_n = 0$ . Then  $\lim_n \varphi(p_n) = 0$  for every  $\varphi \in \Phi$ . Since

$$(T(t)p_n)^2 \leq T(t)p_n, \quad t \in \mathbb{R}_+,$$

we obtain by a classical *inequality of Kadison* that

$$0 \leq \varphi((T(t)p_n)^2) \leq \varphi(T(t)p_n) \leq \varphi(p_n),$$

hence  $\lim_n \varphi(T(t)p_n) = 0$  uniformly in  $t \in \mathbb{R}_+$ . Since the family  $\Phi$  is faithful on  $M$ , it follows from Takesaki [24, Proposition III.5.3] that  $(T(t)p_n)$  converges to zero in the  $s(M, M_*)$ -topology uniformly in  $t \in \mathbb{R}_+$ . Since this topology is finer than the weak\*-topology on  $M$ , we obtain the relative compactness of  $\mathcal{T}$  which implies the strong ergodicity.  $\square$

Let  $\mathcal{T}$  be an identity preserving semigroup of Schwarz type on the predual of a  $W^*$ -algebra  $M$ . We call

$$p_r := \sup\{s(|\varphi|) : \varphi \in \text{Fix}(\mathcal{T})\}$$

the recurrent projection associated with  $\mathcal{T}$ . For a motivation of this definition compare, e.g., Davies [4, Section 6.3].

Since  $T(t)|\varphi| = |\varphi|$  for all  $\varphi \in \text{Fix}(\mathcal{T})$  (D-III, Cor. 1.5), we obtain  $T(t)'p_r \geq p_r$  (see D-I, Sec. 3.(c)). Let  $\mathcal{T}^{(r)}$  be the reduced semigroup on  $p_r M_* p_r$  with generator  $A^{(r)}$ . Then  $\mathcal{T}^{(r)}$  is identity preserving and of Schwarz type. Similarly, if  $\mathcal{R}$  is a pseudo-resolvent on  $D = \{\lambda \in \mathbb{C} : \text{Re}(\lambda) > 0\}$  with values in  $M_*$  such that  $\mathcal{R}$  is identity preserving and of Schwarz type, then the recurrent projection associated with  $\mathcal{R}$  is defined using  $\text{Fix}(\mathcal{R})$ .

**Remark 3.2** (i) Let  $\varphi \in M_*$  and  $\alpha \in \mathbb{R}$  such that  $(\mu - i\alpha)R(\mu)\varphi = \varphi$  for some  $\mu \in \mathbb{R}_+$ . Since  $s(|\varphi|)$  and  $s(|\varphi^*|)$  are majorized by  $p_r$  (D-III, Prop. 1.4), it follows that  $\varphi$  and  $\varphi^*$  are in  $p_r M_* p_r$ .

(ii) From (i) and the observation that the family  $\{|\varphi| : \varphi \in \text{Fix}(\mathcal{T})\}$  is faithful on  $p_r M p_r$  and consists of  $\mathcal{T}^{(r)}$ -invariant elements, it follows that

- $P\sigma(A) \cap i\mathbb{R} = P_\sigma(A^{(r)}) \cap i\mathbb{R}$ .
- $\text{Ker}((i\alpha - A)) \subset p_r M_* p_r$  for all  $\alpha \in \mathbb{R}$ .
- The semigroup  $\mathcal{T}^{(r)}$  is relatively compact in the weak operator topology and therefore strongly ergodic.

(iii) Similarly, let  $\mathcal{R}$  be an identity preserving pseudo-resolvent with values in  $M_*$  on  $D = \{\lambda \in \mathbb{C} : \text{Re}(\lambda) > 0\}$  which is of Schwarz type. It follows as in (b) that  $\text{Fix}((\lambda - i\alpha)R(\lambda))$  is contained in  $p_r M_* p_r$  for all  $\lambda \in D$  and  $\alpha \in \mathbb{R}$ , where  $p_r$  is the associated recurrent projection.

We now give a characterization of strong ergodicity of semigroups which are identity preserving and of Schwarz type. For this we need that the Cesàro means

$$C(s)x = \frac{1}{s} \int_0^s T(t)x dt \quad (x \in M, 0 \leq s \in \mathbb{R})$$

are Schwarz maps. We omit the simple calculation (compare D-I, Thm.2.1).

**Proposition 3.3** *Let  $\mathcal{T}$  be an identity preserving semigroup of Schwarz type on the predual of a  $W^*$ -algebra  $M$ . Then the following assertions are equivalent.*

- (a)  $\mathcal{T}$  is strongly ergodic on  $M_*$ .
- (b)  $\sigma(M, M_*)$ - $\lim_{s \rightarrow \infty} C(s)' p_r = 1$ .
- (c)  $s^*(M, M_*)$ - $\lim_{s \rightarrow \infty} C(s)' p_r = 1$ .

**Proof** Suppose that (a) holds. Since  $\text{Fix}(T)$  separates  $\text{Fix}(T')$  (see Krengel [15, Chap.2, Thm.1.4]), the fixed space of  $\mathcal{T}'$  is non trivial, hence  $p_r \neq 0$ . Let  $0 \leq \psi \in M_*$ , then  $\psi_0 := \lim_{s \rightarrow \infty} C(s)\psi \in \text{Fix}(T)$  and  $s(\psi_0) \leq p_r$ . Therefore

$$\begin{aligned} \lim_{s \rightarrow \infty} \psi(C(s)' p_r) &= \lim_{s \rightarrow \infty} (C(s)\psi)(p_r) = \psi_0(p_r) \\ &= \psi_0(1) = \lim_{s \rightarrow \infty} (C(s)\psi)(1) = \psi(1) \end{aligned}$$

which proves (b).

Suppose that (b) is satisfied. Since  $C(s)' p_r \leq 1$  for all  $s \in \mathbb{R}_+$ , we obtain (c). (Use that for  $(x_\alpha) \in M_+$  we have  $\lim_\alpha x_\alpha = 0$  in the weak\*-topology if and only if  $\lim_\alpha x_\alpha = 0$  in the  $s^*(M, M_*)$ -topology.)

Suppose that (c) holds. Since each  $C(s)'$  is an identity preserving Schwarz map, we obtain for all  $x \in M$

$$\begin{aligned} (C(s)'((1 - p_r)x))(C(s)'((1 - p_r)x)^*) &\leq C(s)'((1 - p_r)xx^*(1 - p_r)) \\ &\leq \|x\|^2 C(s)'(1 - p_r), \end{aligned}$$

hence

$$s^*(M, M_*)\text{-}\lim_{s \rightarrow \infty} C(s)'((1 - p_r)x) = 0.$$

In particular, we obtain for all  $x \in \text{Fix}(\mathcal{T}')$  that  $x = \sigma(M, M_*)\text{-}\lim_{s \rightarrow \infty} C(s)'x = \sigma(M, M_*)\text{-}\lim_{s \rightarrow \infty} C(s)'(p_r x)$ .

Especially for  $0 \neq x \in \text{Fix}(\mathcal{T})$  we obtain  $p_r x p_r \neq 0$ . Since the  $W^*$ -algebra  $p_r M p_r$  is the dual of  $p_r M_* p_r$  and since  $\mathcal{T}^{(r)}$  is strongly ergodic, it follows that the fixed space of  $\mathcal{T}$  separates the points of  $\text{Fix}(\mathcal{T}')$ . Thus  $\mathcal{T}$  is strongly ergodic (Krengel [15, Chap. 2, Thm. 1.4]).  $\square$

It follows from the result above that the semigroup in Evans [6] cannot be strongly ergodic on  $\mathcal{B}(H)_*$  since the associated recurrent projection is zero. But for irreducible semigroups we have the following result.

**Proposition 3.4** *Let  $\mathcal{T}$  be an identity preserving semigroup of Schwarz type on the predual of a  $W^*$ -algebra  $M$ . Then the following assertions are equivalent.*

- (a)  $\mathcal{T}$  is irreducible and  $P\sigma(A) \cap i\mathbb{R} \neq \emptyset$ .
- (b)  $\mathcal{T}$  is relatively compact in the weak operator topology and the fixed space of  $\mathcal{T}$  is generated by a faithful state.
- (c)  $\mathcal{T}$  is strongly ergodic and the fixed space of  $\mathcal{T}$  is generated by a faithful state.
- (d) The fixed space of  $\mathcal{T}$  is generated by a faithful state.

**Proof** Suppose (a) is satisfied. Since  $\text{Fix}(\mathcal{T}) \neq \{0\}$ , there exists a faithful normal state  $\varphi$  on  $M$  such that  $\text{Fix}(\mathcal{T}) = \mathbb{C}\varphi$  (D-III, Thm.1.10.). Therefore  $\mathcal{T}$  is relatively compact in the weak operator topology by Proposition 3.1., whence (b) holds and the implications from (b) to (c) and (c) to (d) are obvious.

Suppose that (d) holds. Let  $\varphi$  be a faithful normal state on  $M$  such that  $\text{Fix}(\mathcal{T}) = \mathbb{C}\varphi$ . By Proposition 3.1 the semigroup  $\mathcal{T}$  is strongly ergodic. Therefore the fixed space of  $\mathcal{T}$  separates the points of  $\text{Fix}(\mathcal{T}')$ . Consequently  $\text{Fix}(\mathcal{T}') = \mathbb{C}1$ . Thus the ergodic projection associated with  $\mathcal{T}$  is given by  $P = 1 \otimes \varphi$ , i.e.,  $P\psi = \psi(1)\varphi$  for all  $\psi \in M_*$ . Let  $F$  be a closed  $\mathcal{T}$ -invariant face of  $M_*^+$ . If  $0 \neq \psi \in F$  then

$$\lim_{s \rightarrow \infty} C(s)\psi = \psi(1)\varphi \in F.$$

Hence  $\varphi \in F$  and therefore  $F = M_*^+$  by the faithfulness of  $\varphi$  which proves (a).  $\square$

The next theorem is an extension of D-III, Thm.1.10 and shows the usefulness of the theory of semitopological semigroups. Assume  $\mathcal{T} \subseteq LM_*$  to be relatively compact in the weak operator topology. Since  $\mathcal{T}$  is commutative its closure  $\mathcal{S} = (\mathcal{T})^- \subseteq L_w(M_*)$  contains a unique minimal ideal  $\mathcal{K}$ , called the kernel of  $\mathcal{S}$ , which is a compact Abelian group (DeLeeuw and Glicksberg [5], Junghenn [14] & Krengel [15, § 2.4]). The identity  $Q$  of  $\mathcal{K}$  is a projection onto the closed linear span of all eigenvectors of  $A$  pertaining to the eigenvalues in  $i\mathbb{R}$ .

Moreover, the dual group of  $\mathcal{K}$  can be identified with the subgroup of  $i\mathbb{R}$  generated by  $P\sigma(A) \cap i\mathbb{R}$ . We call  $Q$  the semigroup projection associated with  $\mathcal{T}$ . On the other hand,  $\mathcal{T}$  is always strongly ergodic with projection  $P$  onto  $\text{Fix}(\mathcal{T})$ . Obviously, the relation

$$0 \leq P \leq Q \leq \text{Id}$$

holds, where the order relation is defined by the inclusion of the range spaces.



There are two extreme cases. First,  $Q = \text{Id}$  and  $\text{rank}(P)$ . This corresponds to the Halmos-von Neumann Theorem in commutative ergodic theory and is discussed, at least for irreducible semigroups, in Olesen et al. [19].

Second,  $\text{Id} > Q = P$ , in particular  $\text{rank}(P) = 1$ . This latter case will be investigated in detail for  $M = \mathcal{B}(H)$ , the  $W^*$ -algebra of all bounded linear operators on a Hilbert space  $H$ . But we first need some preparations.

**Theorem 3.5** *Let  $\mathcal{T}$  be an identity preserving semigroup of Schwarz type on the predual of a  $W^*$ -algebra  $M$  and suppose there exists a faithful family of  $\mathcal{T}$ -invariant states on  $M$ . Let  $N$  be the  $\sigma(M, M_*)$ -closed linear span of all eigenvectors of  $A'$  pertaining to the eigenvalues in  $i\mathbb{R}$ . If  $Q$  is the semigroup projection associated with  $\mathcal{T}$ , then the following holds.*

- (i) *The adjoint of  $Q$  is a faithful normal conditional expectation from  $M$  onto the  $W^*$ -subalgebra  $N$ .*
- (ii) *The restriction of  $T'$  to  $N$  can be embedded into a  $\sigma(M, M_*)$ -continuous, one-parameter group of  $*$ -automorphisms.*
- (iii) *If, in addition,  $\mathcal{T}$  is irreducible and if  $\varphi$  is the normal state generating the fixed space of  $\mathcal{T}$ , then  $\varphi|_N$  is a faithful normal trace.*

**Proof** Consider  $H := P\sigma(A) \cap i\mathbb{R}$  which is not empty by assumptions. From Proposition 3.1 it follows that  $\mathcal{T}$  is relatively compact in the weak operator topology. Let  $K$  be the semigroup kernel of  $\overline{\mathcal{T}w} \subset L(M_*)$  and  $Q$  the unit of  $K$ . Recall that  $Q\psi_n = \psi_n$  for all  $\psi_n \in M_*$  such that  $A\psi_n = n\psi_n$  ( $n \in H$ ). Let  $\mathcal{E}$  be the family of all eigenvectors of  $A'$  pertaining to the eigenvalues in  $H$ .

Then  $\mathcal{E}$  is closed with respect to the multiplication in  $M$  and the formation of adjoints. Thus  $N$  is a  $W^*$ -subalgebra of  $M$ , Sakai [20, Corollary 1.7.9.], and  $\mathcal{T}_0(t)' := T(t)'|_N$  is multiplicative (for this see D-III, Lemma 1.1).

Since  $Q \in \overline{\mathcal{T}w} \subseteq L_w(M_*)$ , there exists an ultrafilter  $\mathfrak{U}$  on  $\mathbb{R}_+$  such that

$$\lim_{\mathfrak{U}} \langle T(t)\psi, x \rangle = \langle Q\psi, x \rangle$$

for all  $x \in M$  and  $\psi \in M_*$ . If  $n \in H$  and  $\psi_n \in M_*$  such that  $A\psi_n = n\psi_n$ , then for all  $x \in M$  we obtain

$$\langle \psi_n, x \rangle = \langle Q\psi_n, x \rangle = \lim_{\mathfrak{U}} \langle T(t)\psi_n, x \rangle = (\lim_{\mathfrak{U}} e^{nt}) \langle \psi_n, x \rangle,$$

hence  $\lim_{\mathfrak{U}} e^{nt} = 1$ . From this it follows that for all  $\psi \in M_*$  we have

$$\langle \psi, Q'(u_n) \rangle = \lim_{\mathfrak{U}} \langle \psi, T(t)'u_n \rangle = (\lim_{\mathfrak{U}} e^{nt}) \langle \psi, u_n \rangle = \langle \psi, u_n \rangle.$$

Hence  $N \subseteq Q'(M)$ .

For  $\gamma$  in the dual group of  $K$  and  $x \in M$  we define  $x_\gamma$  by

$$\psi(x_\gamma) := \int_K \langle S\psi, x \rangle \langle S, \gamma \rangle^* dm(S) \quad (\psi \in M_*^+).$$

Then  $x_\gamma \in M$  and  $T(t)'x_\gamma = \langle QT(t), \gamma \rangle x_\gamma$ . Therefore  $x_\gamma \in N$ . Thus the inclusion  $Q'M \subseteq N$  is proved if we can show that  $Q'M$  belongs to the  $\sigma(M, M_*)$ -closed linear span of  $\{x_\gamma : \gamma \in K, x \in M\}$ . For this it is enough to show that every linear form  $\psi \in M_*$  such that  $\psi(x_\gamma) = 0$  for all  $\gamma \in K$  satisfies  $\psi(Qx) = 0$  for all  $x \in M$ . But if  $\psi(x_\gamma) = 0$ , then

$$\int_K \langle S\psi, x \rangle \langle S, \gamma \rangle^* dm(S) = 0, \gamma \in K.$$

Since the map  $(S \mapsto \psi(Sx))$  is continuous on  $K$  and since the elements of  $K$  form a complete orthonormal basis in  $L^2(K, dm)$ , we obtain  $\psi(Sx) = 0$  for all  $S \in K$ , in particular  $\psi(Qx) = 0$  as desired.

Since the range of  $Q'$  is a  $W^*$ -subalgebra of  $M$  it follows from Takesaki [24, Theorem III.3.4] that  $Q'$  is a completely positive, normal conditional expectation. This  $Q'$  is faithful, i.e.,  $\text{Ker}(Q') \cap M_+ = \{0\}$  since  $Q\varphi = \varphi$  for the faithful linear form  $\varphi$ .

Let  $\varphi$  be the faithful normal state generating  $\text{Fix}(T)$  and let  $\mathcal{U}$  be a family of unitary eigenvectors of  $A'$  pertaining to the eigenvalues in  $H$  (see D-III, Remark 1.11). If  $u_1, u_2 \in U$ , then

$$\varphi(u_1 u_2^*) = \varphi(T_0(t)'(u_1 u_2^*)) = e^{(n_1 - n_2)t} \varphi(u_1 u_2^*).$$

Therefore

$$\varphi(u_1 u_2^*) = \begin{cases} 0 & \text{if } n_1 \neq n_2, \\ 1 & \text{if } n_1 = n_2. \end{cases}$$

Hence  $\varphi(u_1 u_2^*) = \varphi(u_2^* u_1)$  from which it follows that  $\tau := \varphi|_N$  is a faithful normal trace.  $\square$

**Remarks 3.6** (i) Since  $QM_* = N_*$  and  $Q'M = N$ , where  $N_*$  is as in D-III, Proposition 1.12, it follows from general duality theory that  $(N_*)' = N$ .

(ii) If  $\psi \in N_*$ , then  $|\psi| \in N_*$ . To see this, note that  $Q\psi = \psi$  and  $Q$  is an identity preserving Schwarz map. Then the assertion follows from D-III, Proposition 1.4.

(iii) If  $\psi \in N_*$ , then  $|T_0(t)\psi| = T_0(t)|\psi|$  for all  $t \in \mathbb{R}$ . This follows immediately from the fact that  $\mathcal{T}_0(t)'$  is a  $*$ -automorphism on  $N$ .

(iv) Let us add a few words concerning the structure of  $N$ : If  $\mathcal{T}$  is irreducible and  $K$  is the semigroup kernel of  $\mathcal{T}^- \subseteq L_w(M_*)$ , then  $(S \mapsto S') : K \rightarrow L((N, \sigma(N, N_*)))$  is a representation of the compact, Abelian group  $K$  as group of  $*$ -automorphism such that the fixed space is one dimensional. Therefore we are able to apply the results of Olesen et al. [19]. There are three possibilities for  $N$ .

1.  $N = L^\infty(K, dm)$  and  $\mathcal{T}|_N$  is the translation group on  $N$ .
2.  $N \cong \mathcal{R}$  where  $\mathcal{R}$  is the (unique) hyperfinite factor of type  $\text{II}_1$ . In that case (the image of)  $K$  is approximately inner on  $\mathcal{R}$  [i.e., Theorem 5.8].
3. There exists a closed subgroup  $G$  of  $K$  such that

$$N = L^\infty(K/G, dm) \otimes \mathcal{R}$$

where  $R$  is as in (ii) and  $dm$  the normalized Haar measure on  $K/G$  [l.c., Theorem 5.15].

So far we have studied weak\*-semigroups on general  $W^*$ -algebras. We apply now these results to weak\*-semigroup on  $\mathcal{B}(H)$ . To do this we call a triple  $(M, \varphi, \mathcal{T})$  a  $W^*$ -dynamical system if  $M$  is a  $W^*$ -algebra,  $\mathcal{T}$  a weak\*-semigroup of identity preserving Schwarz maps on  $M$  and  $\varphi$  a faithful family of  $\mathcal{T}$ -invariant normal states. We call  $(M, \varphi, \mathcal{T})$  irreducible, if the preadjoint semigroup is irreducible (alternatively, if the fixed space of  $\mathcal{T}$  is one dimensional).

**Proposition 3.7** *Let  $(\mathcal{B}(H), \varphi, \mathcal{T})$  be a  $W^*$ -dynamical system on the  $W^*$ -algebra  $\mathcal{B}(H)$  of all bounded linear operators on a Hilbert space  $H$ . Then the following assertions are equivalent:*

- (a)  $P\sigma(A) \cap i\mathbb{R} = \{0\}$ ,
- (b)  $\lim_{s \rightarrow \infty} T(s)_* = P_*$  in the strong operator topology on  $L\mathcal{B}(H)_*$ .

**Proof** Obviously (b) implies (a). Suppose that (a) is fulfilled. Then the ergodic projection  $P_*$  of the preadjoint semigroup is equal to the associated semigroup projection. Consequently there exists an ultrafilter  $\mathfrak{U}$  on  $\mathbb{R}_+$  such that  $\lim_{\mathfrak{U}} T(t) = P$  in the weak operator topology. We claim that the convergence holds even in the strong operator topology. Taking this for granted it follows, since for every  $t \in \mathbb{R}_+$   $T(t)$  is a contraction, that

$$\lim_{t \rightarrow \infty} \|T(t)_* \varphi\| = 0$$

for all  $\varphi \in \text{Ker}((\cdot)P_*)$ . Since  $T(t)_* \psi = \psi$  for every  $\psi \in \text{im}(P_*)$  and

$$\mathcal{B}(H)_* = \text{im}(P_*) \oplus \text{Ker}((\cdot)P_*)$$

the assertion is proved.

It remains to show that  $\lim_{\mathfrak{U}} T(t)_* = P_*$  in the strong operator topology. Choose  $0 \leq \varphi \in \mathcal{B}(H)_*$ ,  $\|\varphi\| \leq 1$  and let  $\varphi_t := T(t)_* \varphi$  ( $t > 0$ ).  $\varphi_0 := P_* \varphi$  and let  $\{p_i : i \in A\}$  be an increasing net of projections of finite rank in  $\mathcal{B}(H)$  with strong limit 1. Since the set  $K := \{\varphi_t : t \geq 0\}$  is relatively compact in the  $\sigma(\mathcal{B}(H)_*, \mathcal{B}(H))$ -topology, there exists for every  $\delta > 0$  an index  $i_0 \in A$  such that

$$\|(1 - p_i)\psi(1 - p_i)\| \leq \delta$$

for every  $\psi \in K$  and  $i \geq i_0$  (Takesaki [24, Theorem III.5.4.(vi)]). In particular

$$|\psi(1 - p_i)| \leq \delta, \quad \psi \in K, i(0) \leq i.$$

Let  $p := p_{i(0)}$ . Then for all  $x$  in the unit ball of  $M$  it follows that

$$\begin{aligned} |(\varphi_t - \varphi_0)(x)| &\leq \\ |(\varphi_t - \varphi_0)(p x p)| &+ |(\varphi_t - \varphi_0)((1 - p)x p)| \\ + |(\varphi_t - \varphi_0)(x(1 - p))| &\leq |(\varphi_t - \varphi_0)(p x p)| + 4\sqrt{\delta}. \end{aligned}$$

Since the  $W^*$ -algebra  $p\mathcal{B}(H)p$  is finite dimensional, there exists  $U \in \mathfrak{U}$  such that

$$\|(\varphi_t - \varphi_0)|_{p\mathcal{B}(H)p}\| \leq \delta.$$

for all  $t \in U$ . Consequently

$$\|(\varphi_t - \varphi_0)\| \leq (\delta + 4\sqrt{\delta})$$

for all  $t \in U$ . Therefore  $\lim_{\mathfrak{U}} T(t)_*\varphi = P_*\varphi$  in the strong operator topology. Since the positive cone of  $\mathcal{B}(H)_*$  is generating, the assertion is proved.  $\square$

We show next, that for irreducible  $W^*$ -dynamical systems on  $\mathcal{B}(H)$  the above properties always hold.

**Theorem 3.8** *Let  $(\mathcal{B}(H), \varphi, \mathcal{T})$  be an irreducible  $W^*$ -dynamical system. Then*

$$P\sigma(A) \cap i\mathbb{R} = \{0\}.$$

**Proof** Let  $N$  be the  $W^*$ -subalgebra of  $M = \mathcal{B}(H)$  generated by the eigenvectors of  $A$  pertaining to the eigenvalues on  $i\mathbb{R}$  and let  $Q$  be the faithful normal conditional expectation from  $M$  onto  $N$  (Proposition 3.7). Since  $M$  is atomic,  $N$  is atomic (Størmer [23]).  $N$  is finite since there exists a finite, faithful normal trace on  $N$ . In particular the center of  $N$  is isomorphic to  $\ell^\infty$ .

Let  $\mathcal{S}$  be the restriction of  $\mathcal{T}$  to the center. Then  $\mathcal{S}$  is a weak\*-semigroup such that every  $S(t) \in \mathcal{S}$  is  $\sigma(\ell^\infty, \ell^1)$ -continuous and a \*-automorphism. From this it follows that  $S(t)$  is induced by some continuous flow  $\kappa_t : \mathbb{N} \rightarrow \mathbb{N}$ . Indeed, if  $\delta_n((\xi_m)) = \xi_n$  ( $n \in \mathbb{N}, (\xi_m) \in \ell^\infty$ ), then  $\delta_n \circ S(t)$  is a normal scalar valued \*-homomorphism hence of the form  $\delta_m$  for some  $m = \kappa_t(n)$ . But the function  $t \mapsto \kappa_t$  is continuous from  $\mathbb{R}$  into  $\mathbb{N}$ , whence constant. Hence  $S(t) = \text{Id}$ . But the semigroup  $\mathcal{S}$  is weak\*-irreducible on the center. Consequently, the center is one dimensional. Using [Takesaki, Theorem V.1.27] we obtain  $N = B(H_n)$  where  $H_n$  is a finite dimensional Hilbert space. But if  $0 \neq i\alpha \in P\sigma(A) \cap i\mathbb{R}$  then  $i\alpha\mathbb{Z} \subset P\sigma(A)$  by D-III, Thm.1.10, whence  $N$  must be infinite dimensional. Therefore  $P\sigma(A) \cap i\mathbb{R} = \{0\}$  as desired.  $\square$

**Corollary 3.9** *If  $(\mathcal{B}(H), \varphi, T)$  is an irreducible  $W^*$ -dynamical system, then*

$$\lim_{s \rightarrow \infty} T(s) = 1 \otimes \varphi$$

*in the strong operator topology on  $L(\mathcal{B}(H)_*)$ , where  $\varphi$  is the unique normal state generating the fixed space of  $T_*$ .*

We are now going to discuss the asymptotic behavior of positive semigroups whose generator has boundary point spectrum different from 0. The standard example is the following. If  $\Gamma$  is the unit circle,  $dm$  the normalized Haar measure on  $\Gamma$  and  $0 < \tau \in \mathbb{R}$ , then we define the maps  $T_\tau(t)$ ,  $t \in \mathbb{R}_+$ , on  $L^1(\Gamma, m)$  by

$$(T_\tau(t)f)(\xi) = f(\xi \exp(\frac{2\pi i}{\tau}t)) \quad (f \in L^1(\Gamma, dm), \xi \in \Gamma).$$

Then  $\mathcal{T} := (T_\tau(t))_{t \geq 0}$  forms a strongly continuous one parameter semigroup which is identity preserving and of Schwarz type. Since  $\mathcal{T}$  is periodic of period  $\tau$ , it follows that 0 is a pole of the resolvent of its generator  $B$  with residuum  $P = 1 \otimes 1$  and  $\{\frac{2\pi i}{\tau} \cdot k : k \in \mathbb{Z}\} = \sigma(B)$ . Thus  $\mathcal{T}$  is irreducible and uniformly ergodic on  $L^1(\Gamma, dm)$  (see A-II, Section 5).

Now let  $\mathcal{T}$  be a semigroup on a predual  $M_*$  of a von Neumann-algebra  $M$ . It is called *partially periodic*, if there exists a projection  $Q \in L(M_*)$  reducing  $T$  such that  $Q(M_*) \cong L^1(\Gamma, dm)$  and  $T|_{\text{im}(Q)}$  is conjugate to a periodic semigroup on  $L^1(\Gamma, dm)$ .

In the main result we present a non commutative version of Nagel [18] showing that certain dynamical systems are partially periodic semigroups.

**Proposition 3.10** *Let  $\mathcal{T}$  be an irreducible, identity preserving semigroup of Schwarz type with generator  $A$  on the predual of a  $W^*$ -algebra  $M$ .*

*If  $\mathcal{T}$  is uniformly ergodic, then  $\sigma(A) \cap i\mathbb{R} = P\sigma(A) \cap i\mathbb{R} = i\alpha\mathbb{Z}$ , for some  $\alpha \in \mathbb{R}$ . If additionally  $\sigma(A) \cap i\mathbb{R} \neq \{0\}$ , there exists a strictly positive projection  $Q$  on  $M_*$  which is identity preserving and completely positive such that*

- (i)  $Q$  reduces  $\mathcal{T}$  and  $Q(M_*) \cong L^1(\Gamma)$ ,  $\Gamma$  being the one dimensional torus.
- (ii) The restriction  $T_0$  of  $\mathcal{T}$  to  $\text{im}(Q)$  is irreducible and conjugate to a rotation semigroup of period  $\tau = \frac{2\pi}{\alpha}$  on  $\Gamma$ .
- (iii) The spectral bound  $s(A|_{\text{Ker}(\cdot)Q})$  is strictly smaller than 0.

**Proof** By D-III, Thm.1.11 and D-III, Thm.2.5 it follows that

$$\sigma(A) \cap i\mathbb{R} = P\sigma(A) \cap i\mathbb{R} = i\alpha\mathbb{Z}$$

for some  $\alpha \in \mathbb{R}$ . Suppose  $\alpha \neq 0$ . Since  $\sigma(A) + i\alpha\mathbb{Z} = \sigma(A)$  and since every  $n \in i\alpha\mathbb{Z}$  is isolated, it follows that there exists  $\delta > 0$  such that

$$\sigma(A) \setminus i\alpha\mathbb{Z} \subseteq \{\lambda \in \mathbb{C} : \text{Re}(\lambda) \leq \delta\}.$$

Let  $\{u_\alpha^k : k \in \mathbb{Z}\}$  be a family of unitary eigenvectors of  $A'$  pertaining to the eigenvalues in  $i\mathbb{R}$ . Then  $Q'(M)$  is a commutative  $W^*$ -algebra. For  $\tau := \frac{2\pi}{\alpha}$ , we obtain  $T(\tau)u_\alpha^k = u_\alpha^k$ , hence  $T|_{\text{im}(Q)}$  is periodic. From the Halmos-von Neumann theorem (see Schaefer [22, Thm. III.7.11]) it follows that  $T|_{\text{im}(Q)}$  is conjugate to the rotation semigroup of period  $\tau$  on  $L^1(\Gamma, m)$ .  $\square$

Using this proposition we obtain the following theorem.

**Theorem 3.11** *Let  $T = (T(t))_{t \geq 0}$  be a uniformly ergodic, identity preserving semigroup of Schwarz type on the predual of a  $W^*$ -algebra  $M$  and suppose*

$$\sigma(A) \cap i\mathbb{R} \neq \{0\}.$$

*Then there exists a partially periodic, identity preserving semigroup  $S = (S(t))_{t \geq 0}$  of Schwarz type on  $M_*$  such that*

$$\lim_{t \rightarrow \infty} (T(t) - S(t)) = 0$$

in the strong operator topology.

**Proof** Let  $\varphi$  be the normal state on  $M$  generating the fixed space of  $\mathcal{T}$ . Let  $S = (S(t))_{t \geq 0}$  where  $S(t) := T(t) \circ Q$  and  $Q$  is as in 2.6. Obviously,  $S$  is partially periodic and  $\varphi \in \text{Fix}(S)$ . Let  $H_\varphi$  be the GNS-Hilbert space pertaining to  $\varphi$ . Since  $\varphi$  is fixed under  $\mathcal{T}$ ,  $S$  and  $Q$ , these objects have a canonical extension to  $H_\varphi$  (in the following denoted by the same symbols). If  $H_0 := \text{Ker}(\cdot)Q \subseteq H_\varphi$ , then it is easy to see that  $H_0$  is invariant under the extension to  $H_\varphi$  and for the multiplication maps we defined in D-III, Remark 1.3.

Consequently, using the results in Groh and Kümmerer [12], it follows that there exists  $c \in \mathbb{R}$  such that for all  $\gamma$  near 0 and all  $\beta \in \mathbb{R}$ :

$$\|R(\gamma + i\beta A_0)\| \leq c, \quad (*)$$

where  $A_0 := A|_{\text{Ker}(\cdot)Q}$  (the norm taken in  $L(H_\varphi)$ ). Using the result in A-III, Cor. 7.11 it follows that

$$\lim_{t \rightarrow \infty} \|T(t)|_{H_0}\| = 0.$$

Since the  $s(M, M_*)$ -topology on the unit ball of  $M$  is nothing else than the restriction of the norm topology on  $H_\varphi$ , we obtain

$$s(M, M_*)\text{-}\lim_{t \rightarrow \infty} (T(t)' - S(t)')(x) = 0$$

uniformly on  $M_1$ . From this the assertion follows.  $\square$

## 4 Uniform Ergodic Theorems

As we have seen, uniformly ergodic semigroups have strong spectral properties. In this section we study sufficient conditions which imply uniform ergodicity thereby generalizing results of Groh [10]. We first need some preparations.

**Lemma 4.1** *Let  $\mathcal{R}$  be an identity preserving pseudo-resolvent of Schwarz type on  $D = \{\lambda \in \mathbb{C} : \text{Re}(\lambda) > 0\}$  with values in the predual of a  $W^*$ -algebra  $M$ . If the fixed space of  $\mathcal{R}$  is infinite dimensional, then there exists a sequence of states in  $\text{Fix}(\mathcal{R})$  such that the corresponding support projections are mutually orthogonal in  $M$ .*

**Proof** Let  $\Phi = \{\varphi \in \text{Fix}(\mathcal{R}) : \varphi \text{ state on } M\}$  and let  $p = \sup\{s(\varphi) : \varphi \in \Phi\}$ . Since  $\lambda R(\lambda)\varphi = \varphi$  for all  $\varphi \in \Phi$  and  $\lambda \in D$ , it follows  $\mu R(\mu)(\mathbb{1} - s(\varphi)) = (\mathbb{1} - s(\varphi))$ . Hence  $\mu R(\mu)(\mathbb{1} - p) = (\mathbb{1} - p)$  for all  $\mu \in \mathbb{R}_+$ . Let  $\mathcal{R}_1$  be the induced pseudo-resolvent on  $pM_*p$  (D-I, Section 3.(c)). Then the family  $\Phi$  is faithful on  $M_p$  and contained in the fixed space of  $\mathcal{R}_1$ . The adjoint  $\mu R_1(\mu)'$  is an identity preserving Schwarz map. Consequently it follows from D-III, Lemma 1.1.(b) and, the  $\sigma(M_p, (M_p)_*)$ -continuity of  $\mu R_1(\mu)'$  that  $\text{Fix}(\mathcal{R}_1')$  is a  $W^*$ -subalgebra of  $M_p$  and by D-III, Lemma 1.5,  $\dim \text{Fix}(\mathcal{R}) \leq \dim \text{Fix}(\mathcal{R}_1')$ .

If  $\text{Fix}(\mathcal{R})$  is infinite dimensional, let  $(p_n)$  be a sequence of mutually orthogonal projections in  $\text{Fix}(\mathcal{R}) \subseteq M_p$  and choose a sequence  $(\varphi_n)$  in  $\Phi$  such that  $\varphi_n(p_n) \neq 0$ . For  $n \in \mathbb{N}$  let  $\psi_n$  be the normal state

$$\psi_n(x) = \varphi_n(p_n)^{-1} \varphi_n(p_n x p_n)$$

on  $M$ . Because of  $s(\psi_n) \leq p_n \leq p$ , the support projections of the  $\psi_n$ 's are mutually orthogonal in  $M$ . For  $\mu \in \mathbb{R}_+$  and  $x \in M$  we obtain

$$\begin{aligned} \langle x, \mu R(\mu) \psi_n \rangle &= \varphi_n(p_n)^{-1} \langle \mu p_n (R(\mu)' x) p_n, \varphi_n \rangle = \\ &= \varphi_n(p_n)^{-1} \langle \mu p_n p (R(\mu) p' x) p_n, \varphi_n \rangle = \\ &= \varphi_n(p_n)^{-1} \langle \mu p_n (p R_1(\mu)' x p) p_n, \varphi_n \rangle = \\ &= \varphi_n(p_n)^{-1} \langle \mu (p_n R_1(\mu)' x p_n), \varphi_n \rangle = \\ &= \varphi_n(p_n)^{-1} \varphi_n(x) = \psi_n(x). \end{aligned}$$

Therefore  $\psi_n \in \text{Fix}(\mathcal{R})$  for all  $n \in \mathbb{N}$ . □

**Remark 4.2** (i) If  $\dim \text{Fix}(\mathcal{R}) \geq 2$  then the Jordan decomposition of self adjoint linear functionals implies that at least two states in  $\text{Fix}(\mathcal{R})$  have orthogonal support (compare D-III, Theorem 1.10.(a)).

(ii) If  $\mathcal{R}$  is a pseudo-resolvent with values in a  $W^*$ -algebra such that  $\text{Fix}(\mathcal{R}')$  is contained in  $M_*$ , then by D-III, Lemma 1.2, there exists a sequence of normal states in  $\text{Fix}(\mathcal{R}')$  with orthogonal supports in  $M$ .

**Lemma 4.3** *Let  $\mathcal{R}$  be an identity preserving pseudo-resolvent of Schwarz type on  $D = \{\lambda \in \mathbb{C} : \text{Re}(\lambda) > 0\}$  with values in the predual of a  $W^*$ -algebra  $M$ . If the fixed space of the canonical extension  $\widehat{\mathcal{R}}$  of  $\mathcal{R}$  to some ultrapower of  $M_*$  is infinite dimensional, then there exists a sequence  $(z_n)$  in  $M_1^+$  and a sequence of states  $(\varphi_n)$  in  $M_*$  such that*

- (i)  $\lim_n z_n = 0$  in the  $s^*(M, M_*)$ -topology,
- (ii)  $\lim_n \|(Id - \lambda R(\lambda)) \varphi_n\| = 0$  for all  $\lambda \in D$ ,
- (iii)  $\varphi_n(z_n) \geq \frac{1}{2}$  for all  $n \in \mathbb{N}$ .

**Proof** Let  $(M_*)^\wedge$  be the ultrapower of  $M_*$  with respect to some free ultrafilter  $\mathfrak{U}$  on  $\mathbb{N}$ . Since  $(M_*)^\wedge$  is the predual of a  $W^*$ -subalgebra of  $\widehat{M}$  (see D-III, Remark 2.4.(b)), there exists a sequence of states  $(\hat{\psi}_n)$  in  $\text{Fix}(\widehat{\mathcal{R}})$  such that the corresponding support projections are mutually orthogonal in  $\widehat{M}$  (Lemma 4.1). For every  $n \in \mathbb{N}$  let  $(\psi_{n,k})$  be a representing sequence of states,

$$\varphi := \sum_{n,k} 2^{-(n+k+1)} \psi_{n,k}$$

and

$$p := \sup\{s(\psi_{n,k}) : n, k = 1, \dots\}$$

in  $M$ . Then  $\varphi$  is a normal state on  $M$  which is faithful on the  $W^*$ -algebra  $M_p$ . Since

$$1 = \langle \psi_{n,k}, s(\psi_{n,k}) \rangle = \psi_{n,k}(p) \quad (n, k \in \mathbb{N}),$$

it follows  $\hat{\psi}_n(\hat{p}) = 1$  where  $\hat{p}$  is the canonical image of  $p$  in  $\widehat{M}$ . But this implies  $s(\hat{\psi}_n) \leq \hat{p}$  in  $\widehat{M}$ . Since  $\widehat{M}_1^+$  is  $\sigma(\widehat{M}, \widehat{M}')$ -dense in  $(\widehat{M}'')_1^+$  (Kaplansky's density theorem Sakai [20, 1.9.1] with Sakai [20, 1.8.9 and 1.8.12]), there exists for all  $n \in \mathbb{N}$  a net  $(z_{n,\gamma})$  in  $\widehat{M}_1^+$  such that

$$\sigma(\widehat{M}'', \widehat{M}')\text{-}\lim_{\gamma} \hat{z}_{n,\gamma} = s(\hat{\psi}_n).$$

From Sakai [20, 1.7.8] and the above considerations, we obtain that the net  $(p\hat{z}_{n,\gamma}\hat{p})$  converges to  $s(\hat{\psi}_n)$  in the  $\sigma(\widehat{M}'', \widehat{M}')$ -topology. Therefore we may assume  $\hat{z}_{n,\gamma} \in (\widehat{M}'_p)_1^+$ .

In the following we denote by  $\hat{\varphi}$  the canonical image of  $\varphi$  in  $(M_*)^\wedge$ .

Since the projections  $s(\hat{\psi}_n)$  are mutually orthogonal, there exists a real sequence  $(r_n)$ ,  $0 < r_n < 1$ ,  $\lim_n r_n = 0$  and  $\hat{\varphi}(s(\hat{\psi}_n)) \leq \frac{1}{2}r_n$ . For all  $n \in \mathbb{N}$  choose  $\hat{z}_n \in (\widehat{M}'_p)_1^+$  such that

$$\begin{aligned} |\langle \hat{\varphi}, s(\hat{\psi}_n) - \hat{z}_n \rangle| &\leq \frac{1}{2}r_n, \\ |\langle \hat{\psi}_n, s(\hat{\psi}_n) - \hat{z}_n \rangle| &\leq \frac{1}{2}r_n. \end{aligned}$$

Hence  $\hat{\varphi}(\hat{z}_n) \leq r_n$  and  $\hat{\psi}_n(\hat{z}_n) \geq \frac{1}{2}$  for all  $n \in \mathbb{N}$ . For every  $n \in \mathbb{N}$  let  $(z_{n,k}) \in \hat{z}_n$  be a representing sequence in  $(M_p)_1^+ = p(M_1^+)p$  (note that  $M_{\hat{p}} = \widehat{M_p}$ ) and fix  $\mu \in \mathbb{R}_+$ . Since  $\mu R(\mu)' \hat{\psi}_n = \hat{\psi}_n$ ,  $\hat{\varphi}(\hat{z}_n) \leq r_n$  and  $\hat{\psi}_n(\hat{z}_n) \geq \frac{1}{2}$ , there exists for all  $n \in \mathbb{N}$  an element  $U_n \in \mathfrak{U}$  such that for all  $k \in U_n$  and we obtain

- (i')  $\varphi(z_{n,k}) \leq r_n$ ,
- (ii')  $\|(Id - \mu R(\mu))\psi_{n,k}\| \leq r_n$ ,
- (iii')  $\psi_{n,k}(z_{n,k}) \geq \frac{1}{2}$ .

Inductively we find a sequence  $(z_n)$  in  $(M_p)_1^+$  and a sequence of states  $(\varphi_n)$  in  $M_*$  such that for all  $n \in \mathbb{N}$

- (i'')  $\lim_n \varphi_n(z_n) = 0$ ,
- (ii'')  $\lim_n \|(Id - \mu R(\mu))\varphi_n\| = 0$ ,
- (iii'')  $\varphi_n(z_n) \geq \frac{1}{2}$ .

But  $\varphi$  is faithful on  $M_p$ . Therefore condition (ii'') implies that  $\lim_n z_n = 0$  in the  $s^*(M_p, (M_p)_*)$ -topology (Takesaki [24, Proposition III.5.4]). Since

$$s^*(M_p, (M_p)_*) = s^*(M, M_*)|_{M_p},$$

(i) follows immediately from (ii''). Using the resolvent equation for  $\mathcal{R}$  it is easy to see that (ii'') implies



$$\lim_n \|(Id - \lambda R(\lambda))\varphi_n\| = 0$$

for all  $\lambda \in D$  and the proof is complete.  $\square$

Without further comments, we will use following facts in this section.

- (1) A sequence  $(\varphi_n)$  in  $M'_+$  converges in the  $\sigma(M', M)$ -topology if and only if it converges in  $\sigma(M', M'')$ -topology (Akemann et al. [1]).
- (2) We can decompose  $\varphi \in M'_+$  into its normal and singular part  $\varphi = \varphi^{(n)} + \varphi^{(s)}$ ,  $0 \leq \varphi^{(n)} \in M_*$ ,  $0 \leq \varphi^{(s)} \in M_*^\perp$  and  $\|\varphi\| = \|\varphi^{(n)}\| + \|\varphi^{(s)}\|$  (Takesaki [24, Theorem III.2.14]).
- (3) If  $(\varphi_k)$  is a sequence in  $M_*$  converging to zero in the  $\sigma(M_*, M)$ -topology and if  $(x_n)$  is a sequence in  $M$  converging to zero in the  $s^*(M, M_*)$ -topology, then  $\lim_n \varphi_k(x_n) = 0$  uniformly in  $k \in \mathbb{N}$  (Takesaki [24, Lemma III.5.5]).

**Theorem 4.4** *Let  $\mathcal{R}$  be an identity preserving pseudo-resolvent on*

$$D = \{\lambda \in \mathbb{C}: \operatorname{Re}(\lambda) > 0\}$$

*with values in a  $W^*$ -algebra  $M$  which is of Schwarz type and let  $\mathcal{R}'$  be its adjoint pseudo-resolvent. Any one of the following conditions implies  $\dim \operatorname{Fix}(\widehat{\mathcal{R}}) < \infty$  in some ultrapower of  $M$ .*

- (i) *The fixed space of  $\mathcal{R}'$  is finite dimensional.*
- (ii)  *$\lim_{\mu \rightarrow 0} \mu R(\mu) = P$  exists in the strong operator topology and  $\operatorname{rank}(P) < \infty$ .*
- (iii) *The fixed space of  $\mathcal{R}'$  is contained in  $M_*$ .*
- (iv) *Every map  $\mu R(\mu)$ ,  $\mu \in \mathbb{R}_+$  is irreducible on  $M$ .*

**Proof** Suppose that the dimension of the fixed space of  $\widehat{\mathcal{R}'}$  in some ultrapower  $(M^*)$  of  $M'$  is infinite dimensional. Since  $(M^*)$  is the predual of the  $W^*$ -algebra  $\widehat{M}$  and  $\mathcal{R}'$  is identity preserving (since  $R'1 = R1 = 1$ ) and of Schwarz type (because  $\mu R''(\mu) = (\mu R(\mu))''$  is a Schwarz map for all  $\mu \in \mathbb{R}_+$ ), we may apply Lemma 4.3. Suppose that the fixed space of the canonical extension of  $\mathcal{R}'$  to some ultrapower of  $M'$  is infinite dimensional. Thus we may choose a sequence of states  $(\varphi_k)$  in  $M'$  and a sequence  $(z_k)$  in  $(M'')_1$ ,  $0 \leq z_k$ , satisfying (i)–(ii) of Lemma 4.3. Remark (3) above implies that no subsequence of  $(\varphi_k)$  can converge in the  $\sigma(M', M'')$ -topology.

- (i) If  $\varphi$  is a  $\sigma(M', M)$ -accumulation point of  $(\varphi_k)$ , then  $\varphi \in \operatorname{Fix}(\mathcal{R}')$ . Since  $\operatorname{Fix}(\mathcal{R}')$  is finite dimensional, the set of accumulation points of the sequence  $(\varphi_k)$  is metrizable in the  $\sigma(M', M)$ -topology. Hence there exists a sequence  $(k(n))$  of natural numbers such that  $\sigma(M', M)\text{-}\lim_n \varphi_{k(n)} = \varphi$ . Consequently, by Remark (1) above,  $\varphi = \sigma(M', M'')\text{-}\lim_n \varphi_{k(n)}$ . But this leads to a contradiction proving (i).
- (ii) Since  $\dim \operatorname{Fix}(\mathcal{R}) = \dim \operatorname{Fix}(\mathcal{R}') = \operatorname{rank}(P) < \infty$ , (ii) follows from (i).
- (iii) Suppose that the fixed space of  $\mathcal{R}'$  is infinite dimensional. Since  $\operatorname{Fix}(\mathcal{R}') \subseteq M_*$ , there exists a sequence of states  $(\psi_n)$  in  $\operatorname{Fix}(\mathcal{R}')$  with mutually orthogonal support projections in  $M$  (Lemma 4.1). Since every  $\sigma(M', M)$ -accumulation point

of the  $\psi_n$ 's belongs to  $\text{Fix}(\mathcal{R}')$ , hence is normal, the sequence  $(\psi_n)$  is relatively  $\sigma(M_*, M)$ -compact.

By Eberlein's theorem, we may assume that this sequence is weakly convergent (Schaefer [21]). By the orthogonality of the  $s(\psi_n)$ 's this sequence converges to zero in the  $s^*(M, M_*)$ -topology, hence  $\lim_n \psi_k(s(\psi_n)) = 0$  uniformly in  $k \in \mathbb{N}$ , a contradiction. Consequently  $\dim \text{Fix}(\mathcal{R}) < \infty$  and (i) is proved.

(iv) We prove  $\dim \text{Fix}(\mathcal{R}') = 1$  and apply (i) once again and need the following observation: If  $\psi$  is a faithful state on  $M$ , then the normal part is faithful too. Indeed, if  $0 \neq x \in M$  such that  $\psi^{(n)}(x) = 0$ , choose a projection  $0 \neq p \in M$  such that  $\psi^{(n)}(p) = \psi^{(s)}(p) = 0$  (use Takesaki [24, Theorem III.3.8]). Hence  $\psi(p) = 0$  which conflicts with the faithfulness of  $\psi$ .

If  $2 \leq \dim \text{Fix}(\mathcal{R}')$  there are states  $\psi_1$  and  $\psi_2$  in  $\text{Fix}(\mathcal{R}')$  such that the corresponding support projections are orthogonal in  $M''$  (Remark 4.2). Since every  $\mathcal{R}'$ -invariant state  $\psi$  is faithful on  $M$ ,  $\psi_i^{(n)} \neq 0$  (otherwise the norm closed face  $\{\psi(x) = 0 : x \in M_+\}$  would be non trivial and  $\mu R(\mu)$ -invariant). The support projections of the  $\psi_i^{(n)}$ 's in  $M''$  are orthogonal (since  $\psi_1^{(n)} \leq \psi_i$ ) and different from zero. Let  $(z_\gamma)$  be a net in  $M_1^+$  such that

$$\sigma(M'', M')\text{-}\lim_\gamma z_\gamma = s(\psi_1^{(n)}).$$

Then  $\lim_\gamma \psi_1^{(n)}(z_\gamma) = 1$  but  $\lim_\gamma \psi_2^{(n)}(z_\gamma) = 0$ . Let  $z$  be a  $\sigma(M, M_*)$ -accumulation point of  $(z_\gamma)$  in  $M_+$ . Since every  $\psi_i^{(n)}$  is normal,  $\psi_1^{(n)}(z) = 1$  but  $\psi_2^{(n)}(z) = 0$ . The first condition implies  $z \neq 0$  while the second shows that  $\psi_2^{(n)}$  cannot be faithful. This is a contradiction and it implies  $\dim \text{Fix}(\mathcal{R}') = 1$ , hence (iv).  $\square$

The next corollary is an easy application of Theorem 4.4 and of D-III, Proposition 2.3.

**Corollary 4.5** *Let  $\mathcal{T}$  be an identity preserving semigroup of Schwarz type on the predual of a  $W^*$ -algebra  $M$ . Then the following assertions are equivalent.*

- (a)  $\mathcal{T}$  is uniformly ergodic with finite dimensional fixed space.
- (b) The adjoint weak\*-semigroup is strongly ergodic with finite dimensional fixed space.
- (c) Every  $\mathcal{T}''$ -invariant state is normal.

**Proof** If (a) is fulfilled, then the semigroup  $\mathcal{T}$  is strongly ergodic on  $M_*$ . Since

$$\dim \text{Fix}(\mathcal{T}) = \dim \text{Fix}(\mathcal{T}') < \infty,$$

there exist normal states  $\varphi_1, \dots, \varphi_n$  in  $\text{Fix}(\mathcal{T})$  and  $x_1, \dots, x_k$  in  $\text{Fix}(\mathcal{T}')$  such that  $\varphi_n(x_m) = \delta_{n,m}$  ( $1 \leq n, m \leq k$ ). Then

$$P = \sum_{i=1}^k \varphi_i \otimes x_i$$

is the associated ergodic projection. If  $(C(s))_{s>0}$  is the family of Cesàro means of  $\mathcal{T}$ , then

$$\lim_{s \rightarrow \infty} C(s)''(\psi) = \sum_{i=1}^k \varphi_i(\psi) x_i \in M_*$$

for every  $\psi \in M'$ . Hence  $\text{Fix}(\mathcal{T}'') \subseteq M_*$  which implies (c).

If (c) is fulfilled, then  $\text{Fix}(\mathcal{T}') = \text{Fix}(\mathcal{T}'')$ . Therefore the fixed space of  $\mathcal{T}'$  separates the points of  $\text{Fix}(\mathcal{T}'')$ , hence  $\mathcal{T}'$  is strongly ergodic on  $M$  (Krengel [15, Chap.2, Thm.1.4]).

If (b) holds, then

$$P = \lim_{\mu \rightarrow 0} \mu R(\mu, A')$$

exists in the strong operator topology with  $A'$  is the generator of  $\mathcal{T}'$ . Therefore  $\dim \text{Fix}(\overline{\mu R(\mu)}) < \infty$  in some ultrapower of  $M$  (Theorem 4.4). It follows from D-III, Proposition 2.3 that 0 is a pole of the resolvent of  $R(\cdot, A)$ . Therefore  $\mathcal{T}$  is uniformly ergodic.  $\square$

## Notes

*Section 1:* The stability concepts appearing in Theorem 1.7 coincide not only for positive semigroups on  $C^*$ -algebras but on any order unit Banach space. We refer to Batty and Robinson [2] for this more general setting and to B-IV, Section 1 for the analogous results on  $C_0(X)$ .

*Section 2:* Theorem 2.2 generalizes the Liapunov stability theorem from the matrix algebra  $B(\mathbb{C}^n)$  to arbitrary  $W^*$ -algebras. For the algebra  $\mathcal{B}(H)$  it is due to Mil'stein [17] and in the general form to Groh and Neubrandner [13].

*Section 3:* From the many papers dealing more or less explicitly with the asymptotic behavior of semigroups on operator algebras we quote Frigerio and Verri [7] and Watanabe [25]. The background for our ergodic theorems (Proposition 3.3 & 3.4) can be found best in Krengel [15]. The “automatic” convergence theorem for an irreducible  $W^*$ -dynamical system on  $\mathcal{B}(H)$  stated in Corollary 3.9 is the continuous version of a result in Groh [11]. Finally, the characterization of convergence towards a periodic semigroup through spectral properties of the generator—Theorem 3.11—is due to Nagel [18] in the commutative case, i.e., in  $L^1(\mu)$  (see also C-IV, Thm.2.14).

*Section 4:* Again we refer to Krengel [15] for the (uniform) ergodic theory for a single operator or a one-parameter semigroup on a Banach space. The characterization given in Corollary 4.5 for positive semigroups on  $W^*$ -algebras is based on a sophisticated use of ultrapower techniques and has its discrete forerunners in Lotz [16] and Groh [10].



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