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# One-parameter Semigroups of Positive Operators

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*This Latex version of the book  
“One-Parameter Semigroups of  
Positive Operators” is dedicated to the  
memory of our co-authors, Heinrich P.  
Lotz, Ulrich Moustakas, 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	G. 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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**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 (1980), Goldstein (1985a), Pazy (1983) or Hille-Phillips (1957)) 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 (Section 2) and to discuss standard constructions of new semigroups from a given one (Section 3). 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  $L(E)$ , usually written as  $(T(t))_{t \geq 0}$ , such that

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

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  $(L(E), \cdot)$ . Similarly, a one-parameter group  $(T(t))_{t \in \mathbb{R}}$  will be a homomorphic image of the group  $(\mathbb{R}, +)$  in  $(L(E), \cdot)$ .

### 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  $L(E)$  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  $L(E)$ . We single out the strong operator topology on  $L(E)$  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  $L(E)$ , i.e.,  $\lim_{t \rightarrow t_0} \|T(t)f - T(t_0)f\| = 0$  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: From now on ‘semigroup’ always means 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.

- Remark 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  $T(t)f \rightarrow f$  as  $t \rightarrow 0$ .
- (ii) For every strongly continuous semigroup  $(T(t))_{t \geq 0}$  there exist constants  $M \geq 1$ ,  $\omega \in \mathbb{R}$  such that  $\|T(t)\| \leq M \cdot e^{\omega t}$  for every  $t \geq 0$ .
- (iii) If  $(T(t))_{t \geq 0}$  is a one-parameter semigroup such that  $\|T(t)\|$  is bounded for  $0 \leq t \leq \delta$  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  $E$ .

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

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

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 3.1 that  $\omega_0$  may be any number  $-\infty \leq \omega_0 < +\infty$ . Moreover the reader should observe that the infimum in  $(*)$  need not be attained and that  $M$  may be larger than 1 even for bounded semigroups.

- Example A-I.1** (i) Take  $E = \mathbb{C}^2$ ,  $A = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$  and  $T(t) = e^{tA} = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix}$ . Then for the 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  $f \in E$  and  $t \geq 0$  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  $f := 1_{[0,t]}$ . Therefore  $(T(t))_{t \geq 0}$  is a strongly continuous semigroup which is bounded, hence has  $\omega_0 = 0$ , but the constant  $M$  in  $(*)$  cannot be chosen to be 1.

**Definition 1.4** To every semigroup  $(T(t))_{t \geq 0}$  there belongs an operator  $(A, D(A))$ , called the generator and defined on the domain

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

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

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(i)). In general the precise extent of the domain  $D(A)$  is essential for the characterisation 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  $(A, D(A))$ .

**Proposition 1.5** *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*

$$\frac{d}{dt} T(t)f = AT(t)f = T(t)Af. \quad (\text{A-I.1})$$

- (iii) *Every  $f \in E$  one has  $\int_0^t T(s)f ds \in D(A)$  and*

$$A \int_0^t T(s)f ds = T(t)f - f. \quad (\text{A-I.2})$$

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

$$T(t)f = f + \int_0^t AT(s)f ds = f + \int_0^t T(s)Af ds.$$

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

**Theorem 1.6** *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’ (ACP)*

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

*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 the important 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 2.1 below), it always enjoys a weaker but useful property.

**Definition 1.7** 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.

$$f_n \in D(B), f_n \rightarrow f \text{ and } Bf_n \rightarrow g \text{ implies } f \in D(B) \text{ and } Bf = g. \quad (\text{A-I.3})$$

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.,  $D(B) \subset D(C)$  and  $Bf = Cf$  for every  $f \in D(B)$ . In that case,  $B$  is called closable, a property which is equivalent to the following:

$$f_n \in D(B), f_n \rightarrow 0 \text{ and } Bf_n \rightarrow g \text{ implies } g = 0. \quad (\text{A-I.4})$$

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.

**Proposition 1.8** *For the generator  $A$  of a strongly continuous semigroup  $(T(t))_{t \geq 0}$  the following holds:*

- (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 A-I.2* 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 1.9** *For the generator  $A$  of a strongly continuous semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$  the following holds. 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,*

$$R(\lambda, A)^{n+1} f = \frac{(-1)^n}{n!} \left( \frac{d}{d\lambda} \right)^n R(\lambda, A) f = \int_0^\infty e^{-\lambda t} \frac{t^n}{n!} T(t) f dt \quad (\text{A-I.5})$$

for  $n \in \mathbb{N}$ ,  $f \in E$  and all  $\lambda$  with  $\operatorname{Re} \lambda > \omega$ .

**Remark 1.10** (i) For continuous Banach space valued functions such as  $t \mapsto T(t)f$  we consider the Riemann integral and define  $\int_0^\infty T(t) f dt$  as  $\lim_{t \rightarrow \infty} \int_0^t T(s) f ds$ . Sometimes such integrals for strongly continuous semigroups  $(T(t))_{t \geq 0}$  are written as  $\int_a^b T(t) dt$  and understood in the strong sense.



- (ii) Since the generator  $(A, D(A))$  determines the semigroup  $(T(t))_{t \geq 0}$  uniquely, we will speak occasionally of the growth bound of the generator instead of the semigroup, i.e., we write  $\omega = \omega(A) = \omega((T(t))_{t \geq 0})$ .
- (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 (1980), 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.

### 2.1 Uniformly Continuous Semigroups

It follows from elementary operator theory that for every bounded operator  $A \in L(E)$  the sum exists and determines a unique uniformly continuous (semi)group  $(e^{tA})_{t \in \mathbb{R}}$  having  $A$  as its generator.

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

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  $T(0) = Id$  as  $t \rightarrow 0$ . Therefore for some  $t' \neq 0$  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  $s := \text{trace } A$ ,  $d := \det A$  and  $D := (s^2 - 4d)^{1/2}$ . Then

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

if  $D \neq 0$  and

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

if  $D = 0$  resp.

## 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 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 space  $L^p(X, \Sigma, \mu)$ ,  $1 \leq p \leq \infty$ , 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

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

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

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 ( $p$ -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

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

one obtains the following characterizations.

**Proposition 2.11** *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 follows:

$$\omega = \sup\{\operatorname{Re} q(x) : x \in X\} \text{ in the case } E = C_0(X),$$

$$\omega = \operatorname{ess-sup}\{\operatorname{Re} q(x) : x \in X\} \text{ in the case } E = L^p(\mu).$$

It is a nice exercise to characterize those multiplication operators which generate strongly continuous groups.

## 2.4 Translation (Semi)Groups

Let  $E$  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  $E = L^p$ :

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

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

with domain

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

**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  $f' = Af$ .  $\square$

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

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

with domain

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

## 2.5 Rotation Groups

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

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

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

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

$$Af(z) = (2\pi i/\tau) \cdot z \cdot f'(z).$$

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'

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

with generator

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

$$Af := f'.$$

## 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 its domain is

$$D(A) = \{f \in L^p([0, \tau]) : f \text{ absolutely continuous, } f' \in L^p([0, \tau]), f(\tau) = 0\}.$$

In fact, if  $f \in D(A)$  then  $f$  is absolutely continuous with  $f' \in E$ . By Prop.1.6.i 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 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

$$e_n \otimes e_n : f \rightarrow \left( \int_0^1 f(x) e_n(x) dx \right) e_n = \langle f, e_n \rangle e_n$$

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

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

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

Die Jacobi-Identität

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

und trigonometrische Beziehungen zeigen, dass

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

welches eine positive Funktion auf  $[0, 1]^2$  ist. Daher ist  $T(t)$  ein beschränkter Operator auf  $C[0, 1]$  mit

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

## 2.8 n-dimensional Diffusion Semigroup

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

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

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

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

Moreover,

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

by Young's inequality [Reed-Simon (1975), p.28], hence  $\|T(t)\| \leq 1$  for every  $t > 0$ .

Next we observe that  $\mathcal{S}(\mathbb{R}^n)$  is dense in  $E$  and invariant under each  $T(t)$ . Therefore we can apply the Fourier transformation  $\mathcal{F}$  which leaves  $\mathcal{S}(\mathbb{R}^n)$  invariant and yields

$$\mathcal{F}(\psi_t * f) = (2\pi)^{n/2} \mathcal{F}(\psi_t) \cdot \mathcal{F}(f) = (2\pi)^{n/2} \hat{\psi}_t \cdot \hat{f}$$

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

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

$$B\hat{f}(x) := -|x|^2 \hat{f}(x)$$

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

Applying the inverse Fourier transformation and observing that the topology of  $\mathcal{S}(\mathbb{R}^n)$  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 Remark 1.2, (3)) and 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  $f \in \mathcal{S}(\mathbb{R}^n)$ .

Since  $\mathcal{S}(\mathbb{R}^n)$  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-Simon (1975).

### 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: Take any isomorphism  $S \in L(E, F)$  between two Banach spaces  $E$  and  $F$ . Then

$$U(t) := ST(t)S^{-1}, \quad t \geq 0,$$

defines a semigroup on  $F$  which is strongly continuous if and only if  $(T(t))_{t \geq 0}$  has this property. In this case the generator  $B$  of  $(U(t))_{t \geq 0}$  is given by

$$B = SAS^{-1} \text{ with } D(B) = SD(A).$$



## Chapter A-II

# Characterization of Semigroups on Banach Spaces

In this chapter two different problems are treated:

- (i) to characterize generators of strongly continuous semigroups;
- (ii) to characterize various properties of strongly continuous semigroups in terms of their generators.

In Section 1 the first problem is solved by finding conditions on the Cauchy problem associated with  $A$  and also by finding conditions on the resolvent of  $A$ . The second problem is treated for a hierarchy of smoothness properties of the semigroup.

Contraction semigroups are considered in Section 2. Here, the first problem has a simple and extremely useful solution: A densely defined operator  $A$  is generator of a contraction semigroup if and only if  $A$  is dissipative and satisfies a range condition.

Our approach is quite general. We do not only consider contractions with respect to the norm but also with respect to “half-norms”. This will allow us to obtain results on positive contraction semigroups simultaneously by choosing a suitable half-norm (cf. C-II, Sec.1).

The last section contains a surprising result: on certain Banach spaces (e.g.,  $L^\infty$ ) only bounded operators are generators of strongly continuous semigroups.

### 1 The Abstract Cauchy Problem, Special Semigroups and Perturbation

Linear differential equations in Banach spaces are intimately connected with the theory of one-parameter semigroups. In fact, given a closed linear operator  $A$  with dense domain  $D(A)$  the following statement is true (with some reservation regarding a technical detail): The abstract Cauchy problem

$$\begin{aligned} \dot{u}(t) &= Au(t) \quad (t \geq 0) \\ u(0) &= f \end{aligned}$$

has a unique solution for every  $f \in D(A)$  if and only if  $A$  is the generator of a strongly continuous semigroup.

This is one characterization of generators which illustrates their important role for applications. The fundamental Hille-Yosida theorem gives a different characterization in terms of the resolvent and yields a powerful tool for actually proving that a given operator is the generator of a semigroup.

Another problem we will treat here is how diverse properties of a semigroup can be described in terms of its generator. This is a reasonable question from the theoretical point of view (since the generator uniquely determines the semigroup). It is of interest from the practical point of view as well: the generator is the given object, defined by the differential equation. It is useful to dispose of conditions of the generator itself giving information on the solutions (which might not be known explicitly). We discuss smoothness properties such as analyticity, differentiability, norm continuity and compactness of the semigroup.

A frequent method to obtain new generators out of a given one is by perturbation. We will have a brief look at this circle of problems at the end of this section.

The results are explained and illustrated by examples. Proofs are only given when new aspects are presented which are not yet contained in the literature, otherwise we refer to the recent monographs Davies (1980), Goldstein (1985a), Pazy (1983).

## 1.1 The Abstract Cauchy Problem

Let  $A$  be a closed operator on a Banach space  $E$  and consider the abstract Cauchy problem

$$(ACP) \quad \begin{cases} \dot{u}(t) &= Au(t) \quad (t \geq 0) \\ u(0) &= f. \end{cases}$$

By a solution of (ACP) for the initial value  $f \in D(A)$  we understand a continuously differentiable function  $u : [0, \infty) \rightarrow E$  satisfying  $u(0) = f$  and  $u(t) \in D(A)$  for all  $t \geq 0$  such that  $\dot{u}(t) = Au(t)$  for  $t \geq 0$ .

By A-I, Thm. 1.7 there exists a unique solution of (ACP) for all initial values in the domain  $D(A)$  whenever  $A$  is the generator of a strongly continuous semigroup. The converse does not hold (see Example 1.4. below). However, for the operator  $A_1$  on the Banach space  $E_1 = D(A)$  (see A-I, 3.5) with domain  $D(A_1) = D(A^2)$  given by  $A_1 f = Af$  ( $f \in D(A_1)$ ) the following holds.

**Theorem 1.1** *The following assertions are equivalent.*

- (a) *For every  $f \in D(A)$  there exists a unique solution of (ACP).*
- (b)  *$A_1$  is the generator of a strongly continuous semigroup.*

**Proof** (i) implies (ii). Assume that (i) holds; i.e., for every  $f \in D(A)$  there exists a unique solution  $u(\cdot, f) \in C^1([0, \infty), E)$  of (ACP). For  $f \in E_1$  define  $T_1(t)f := u(t, f)$  ( $t \geq 0$ ). By the uniqueness of the solutions it follows that  $T_1(t)$  is a linear

operator on  $E_1$  and  $T_1(s+t) = T_1(s)T_1(t)$ . Moreover, since  $u(\cdot, f) \in C^1$ , it follows that  $t \mapsto T_1(t)f$  is continuous from  $[0, \infty)$  into  $E_1$ . We show that  $T_1(t)$  is a continuous operator for all  $t > 0$ .

Let  $t > 0$ . Consider the mapping  $\eta : E_1 \rightarrow C([0, t], E_1)$  given by  $\eta(f) = T_1(\cdot)f = u(\cdot, f)$ . We show that  $\eta$  has a closed graph. In fact, let  $f_n \rightarrow f$  in  $E_1$  and  $\eta(f_n) = u(\cdot, f_n) \rightarrow v$  in  $C([0, t], E_1)$ . Then  $u(s, f_n) = f_n + \int_0^s Au(r, f_n)dr$ . Letting  $n \rightarrow \infty$  we obtain  $v(s) = f + \int_0^s Av(r)dr$  for  $0 \leq s \leq t$ . Let  $\tilde{v}(s) = T_1(s-t)v(t)$  for  $s > t$ , and  $\tilde{v}(s) = v(s)$  for  $0 \leq s \leq t$ .

Then  $\tilde{v}$  is a solution of (ACP). It follows that  $\tilde{v}(s) = T_1(s)f$  for all  $s \geq 0$ . Hence  $v = \eta(f)$ . We have shown that  $\eta$  has a closed graph and so  $\eta$  is continuous. This implies the continuity of  $T_1(t)$ . It remains to show that  $A_1$  is the generator of  $(T_1(t))_{t \geq 0}$ .

We first show that for  $f \in D(A^2)$  one has

$$AT_1(t)f = T_1(t)Af. \quad (1.1)$$

In fact, let  $v(t) = f + \int_0^t u(s, Af)ds$ . Then  $\dot{v}(t) = u(t, Af) = Af + \int_0^t Au(s, Af)ds = A(f + \int_0^t u(s, Af)ds) = Av(t)$ . Since  $v(0) = f$ , it follows that  $v(t) = u(t, f)$ . Hence  $Au(t, f) = Av(t) = \dot{v}(t) = u(t, Af)$ . This is (1.1).

Now denote by  $B$  the generator of  $(T_1(t))_{t \geq 0}$ . For  $f \in D(A^2)$  we have

$$\lim_{t \rightarrow 0} \frac{T_1(t)f - f}{t} = Af$$

and by (1.1),

$$\lim_{t \rightarrow 0} A \frac{T_1(t)f - f}{t} = \lim_{t \rightarrow 0} \frac{T_1(t)Af - Af}{t} = A^2f \text{ in the norm of } E.$$

Hence  $\lim_{t \rightarrow 0} \frac{T_1(t)f - f}{t} = Af$  in the norm of  $E_1$ .

This shows that  $A_1 \subset B$ . In order to show the converse, let  $f \in D(B)$ . Then  $\lim_{t \rightarrow 0} A \frac{T_1(t)f - f}{t}$  exists in the norm of  $E$ . Since  $\lim_{t \rightarrow 0} \frac{T_1(t)f - f}{t} = Af$  in the norm of  $E$ , it follows that  $Af \in D(A)$ , since  $A$  is closed. Thus  $f \in D(A^2) = D(A_1)$ . We have shown that  $B = A_1$ .

(ii) implies (i). Assume that  $A_1$  is the generator of a strongly continuous semigroup  $(T_1(t))_{t \geq 0}$  on  $E_1$ . Let  $f \in D(A)$  and set  $u(t) = T_1(t)f$ . Then  $u \in C([0, \infty), E)$  and  $Au(\cdot) \in C([0, \infty), E)$ . Moreover,  $\int_0^t u(s)ds = \int_0^t T_1(s)fds \in D(A_1) = D(A^2)$  and  $A \int_0^t u(s)ds = u(t) - u(0) = u(t) - f$  (by A-I, (1.3)). Consequently,  $u(t) = f + A \int_0^t u(s)ds = f + \int_0^t Au(s)ds$ . Hence  $u \in C^1([0, \infty), E)$  and  $\dot{u}(t) = Au(t)$ . Thus  $u$  is a solution of (ACP).

In order to show uniqueness, assume that  $u$  is a solution of (ACP) with initial value 0. We have to show that  $u \equiv 0$ . Let  $v(t) = \int_0^t u(s)ds$ . Then  $v(t) \in D(A)$  and  $Av(t) = \int_0^t Au(s)ds = \int_0^t \dot{u}(s)ds = u(t) \in D(A)$ . Consequently,  $v(t) \in D(A^2)$  for all  $t \geq 0$ . Moreover,  $\dot{v}(t) = u(t) = Av(t)$  and  $\frac{d}{dt}Av(t) = Au(t) = A\dot{v}(t) = A^2v(t)$ .

Thus  $v \in C^1([0, \infty), E_1)$  and  $\dot{v}(t) = A_1 v(t)$ . Since  $v(0) = 0$ , it follows that  $v \equiv 0$ . Thus  $u \equiv v \equiv 0$ .  $\square$

If (ACP) has a unique solution for every initial value in  $D(A)$ , then  $A$  is the generator of a strongly continuous semigroup only if some additional assumptions on the solutions (continuous dependence from the initial value) or on  $A$  ( $\varrho(A) \neq \emptyset$ ) are made.

**Corollary 1.2** *Let  $A$  be a closed operator. Consider the following existence and uniqueness condition.*

(EU) *For every  $f \in D(A)$  there exists a unique solution  $u(\cdot, f) \in C^1([0, \infty), E)$  of the Cauchy problem associated with  $A$  having the initial value  $u(0, f) = f$ .*

*The following assertions are equivalent.*

- (a)  *$A$  is the generator of a strongly continuous semigroup.*
- (b)  *$A$  satisfies (EU) and  $\varrho(A) \neq \emptyset$ .*
- (c)  *$A$  satisfies (EU) and for every  $\mu \in \mathbb{R}$  there exists  $\lambda > \mu$  such that  $(\lambda - A)D(A) = E$ .*
- (d)  *$A$  satisfies (EU), has dense domain and for every sequence  $(f_n)$  in  $D(A)$  satisfying  $\lim_{n \rightarrow \infty} f_n = 0$  one has  $\lim_{n \rightarrow \infty} u(t, f_n) = 0$  uniformly in  $t \in [0, 1]$ .*

**Proof** It is clear that (i) implies the remaining assertions. So assume that  $A$  satisfy (EU). Then by Theorem 1.1.,  $A_1$  is a generator. If there exists  $\lambda \in \varrho(A)$ , then  $(\lambda - A)$  is an isomorphism from  $E_1$  onto  $E$  and  $A$  is similar to  $A_1$  via this isomorphism [since  $D(A_1) = \{(\lambda - A)^{-1}f : f \in D(A)\}$  and  $Af = (\lambda - A)A_1(\lambda - A)^{-1}f$  for all  $f \in D(A)$ , see A-I,3.0]. Thus  $A$  is a generator on  $E$  and we have shown that (ii) implies (i).

If (iii) holds, then there exists  $\lambda > s(A_1)$  such that  $(\lambda - A)D(A) = E$ . We show that  $(\lambda - A)$  is injective. Then  $\lambda \in \varrho(A)$  since  $A$  is closed. Assume that  $Af = \lambda f$  for some  $f \in D(A)$ . Then  $f \in D(A^2) = D(A_1)$ , and so  $f = 0$  since  $\lambda \in \varrho(A_1)$ . This proves that (iii) implies (ii). We have shown existence.

It remains to show that (iv) implies (i).

Assertion (iv) implies that for all  $t \geq 0$  there exist bounded operators  $T(t) \in \mathcal{L}(E)$  such that  $u(t, f) = T(t)f$  if  $f \in D(A)$ . Moreover,  $\sup_{0 \leq t \leq 1} \|T(t)\| < \infty$ . It follows that  $T(\cdot)f$  is strongly continuous for all  $f \in E$  (since it is so for  $f \in D(A)$  and  $D(A)$  is dense). Let  $t > 1$ . There exist unique  $n \in \mathbb{N}$  and  $s \in [0, 1)$  such that  $t = n + s$ . Let  $T(t) := T(1)^n T(s)$ . From the uniqueness of the solutions it follows that  $T(t)f = u(t, f)$  for all  $t \geq 0$  as well as  $T(t+s)f = T(s)T(t)f$  for all  $f \in D(A)$  and  $s, t \geq 0$ . Thus  $(T(t))_{t \geq 0}$  is a semigroup. Denote by  $B$  its generator. It follows from the definition that  $A \subset B$ . Moreover,  $D(A)$  is invariant under the semigroup. So by A-I, Prop. 1.9.(ii)  $D(A)$  is a core of  $B$ . Since  $A$  is closed this implies that  $A = B$ .  $\square$

**Remark 1.3** It is surprising that from condition (ii) and (iii) in the corollary it follows automatically that  $D(A)$  is dense. On the other hand this condition cannot be omitted in (iv). In fact, consider any generator  $\tilde{A}$  and its restriction  $A$  with domain  $D(A) = \{0\}$ . Then  $A$  satisfies the remaining conditions in (iv) but is not a generator (if  $\dim E > 0$ ).

*Example A-II.1* We give a densely defined closed operator  $A$ , such that there exists a unique solution of (ACP) for all initial values in  $D(A)$ , but  $A$  is not a generator. Let  $B$  be a densely defined unbounded closed operator on a Banach space  $F$ . Consider  $E = F \oplus F$  and  $A$  on  $E$  given by

$$A = \begin{pmatrix} 0 & B \\ 0 & 0 \end{pmatrix}$$

with domain  $F \times D(B)$ .

Then  $D(A^2) = \{(f, g) \in F \times D(B) : Bg \in F\} = D(A)$  and so  $A_1 \in \mathcal{L}(E_1)$ . In particular,  $A_1$  is a generator. But  $A$  is not. For instance condition (ii) in Corollary 1.2. does not hold, since for each  $\lambda \in \mathbb{C}$ ,

$$(\lambda - A)D(A) = \{(\lambda f - Bg, \lambda g) : f \in F, g \in D(B)\} \subset F \times D(B) \neq F \times F = E.$$

So  $\varrho(A) = \emptyset$ .

As a further illustration, we note that the solution of the corresponding abstract Cauchy problem for the initial value  $(f, g) \in F \times D(B)$  is given by  $u(t) = (f + tBg, g)$ . Since  $B$  is unbounded, condition (iv) of Corollary 1.2. is clearly violated.



# Chapter A-III

## Spectral Theory

### 1 Introduction

In this chapter we start a systematic analysis of the spectrum of a strongly continuous semigroup  $T = (T(t))_{t \geq 0}$  on a complex Banach space  $E$ . By the spectrum of the semigroup we understand the spectrum  $\sigma(A)$  of the generator  $A$  of  $T$ . 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  $T$  by the spectrum of the generator.

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

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

and show how it is related to the spectral bound

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

of the generator  $A$  and to the growth bound

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

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

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

$$r(T(t)) = e^{\omega t}$$

*for every  $t \geq 0$ .*



## Chapter A-IV

# Asymptotics of Semigroups on Banach Spaces

In this chapter we study the asymptotic behavior of the solutions of the initial value problem

$$\dot{u}(t) = Au(t) + F(t), \quad u(0) = f$$

with respect to time  $t \geq 0$ . Here  $A$  will be a generator of a strongly continuous semigroup  $(T(t))_{t \geq 0}$  on a Banach space  $E$  and  $F(\cdot)$  is a function from  $\mathbb{R}_+$  with values in  $E$ .

In Section 1 we investigate whether and how fast a solution  $T(\cdot)f$  of the homogeneous problem tends to the zero solution as  $t \rightarrow \infty$ . In Section 2 we consider the long term behavior of the solutions of (\*) for different classes of forcing terms  $F$ .

### 1 Stability: Homogeneous Case

Let  $(T(t))_{t \geq 0}$  be a semigroup on  $E$  with generator  $A$ . An initial value  $f \in D(A)$  is called *stable* if the solution  $t \mapsto T(t)f$  of

$$\dot{u}(t) = Au(t), \quad u(0) = f$$

converges to zero as  $t$  tends to infinity. The semigroup is called *stable* if every solution converges to zero; i.e., if every initial value  $f \in D(A)$  is stable.

If the space  $E$  is finite dimensional, then the stability of the semigroup implies that the decay is exponential. More precisely, the statements

- (a)  $\|T(t)f\| \rightarrow 0$  for every  $f \in \mathbb{C}^n$ ,
- (b)  $\|T(t)\| \leq Me^{-\omega t}$  for some  $\omega > 0$



**Part B**  
**Positive Semigroups on Spaces  $C_0(X)$**



**Chapter B-I**  
**Basic Results on  $C_0(X)$**



**Chapter B-II**  
**Characterization of Positive Semigroups on**  
 **$C_0(X)$**





**Chapter B-III**  
**Spectral Theory of Positive Semigroups on**  
 **$C_0(X)$**



## **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**





**Chapter C-II**  
**Characterization of Positive Semigroups on**  
**Banach Lattices and Positive Operators**



**Chapter C-III**  
**Spectral Theory of Positive Semigroups on**  
**Banach Lattices**



**Chapter C-IV**  
**Asymptotics of Positive Semigroups on Banach**  
**Lattices**



**Part D**  
**Positive Semigroups on**  
 **$C^\star$ - and  $W^\star$ -Algebras**





## Chapter D-I

# Basic Results on Semigroups and Operator Algebras

This is not a systematic introduction into the theory of strongly continuous semigroups on  $C^*$ - and  $W^*$ -algebras. For that we refer to [2], [3] and the survey article of [7]. We only prepare for the subsequent chapters on spectral theory and asymptotics by fixing the notations and introducing some standard constructions.

### 1 Notations

1. By  $M$  we shall denote a  $C^*$ -algebra with unit 1.  $M^{sa} := \{x \in M : x^* = x\}$  is the self-adjoint part of  $M$  and  $M_+ := \{x^*x : x \in M\}$  the positive cone in  $M$ . If  $M'$  is the dual of  $M$ , then  $M'_+ := \{\psi \in M' : \psi(x) \geq 0, x \in M_+\}$  is a weak\*-closed generating cone in  $M'$ .  $S(M) := \{\psi \in M'_+ : \psi(1) = 1\}$  is called the state space of  $M$ . For the theory of  $C^*$ -algebras and related notions we refer to [8].

$M$  is called 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  $\psi \in M_*$  a normal linear functional. It is known that  $M_*$  is unique [9, 1.13.3]. For further properties of  $M_*$  we refer to [10, Chapter III].

2. A map  $T \in L(M)$  is called positive (in symbols  $T \geq 0$ ) if  $T(M_+) \subseteq M_+$ .  $T \in L(M)$  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  $T \in L(M)$  a Schwarz map if  $T$  satisfies the inequality

$$T(x)T(x)^* \leq T(xx^*), x \in M.$$

Note that such  $T$  is necessarily a contraction. It is well known that every  $n$ -positive contraction,  $n \geq 2$  and that every positive contraction on a commutative  $C^*$ -algebra is a Schwarz map [10, Corollary IV. 3.8.]. As we shall see, the Schwarz inequality is crucial for our investigations.

3. If  $M$  is a  $C^*$ -algebra we assume  $T = (T(t))_{t \geq 0}$  to be a strongly continuous semigroup (abbreviated semigroup) while on  $W^*$ -algebras we consider weak\*-semigroups, i.e. the mapping  $(t \mapsto T(t)x)$  is continuous from  $\mathbb{R}_+$  into  $(M, \sigma(M, M_*))$ ,  $M_*$  the predual of  $M$ , and every  $T(t) \in T$  is  $\sigma(M, M_*)$ -continuous. Note that the preadjoint semigroup

$$T_* = \{T(t)_* : T(t) \in T\}$$

is weakly, hence strongly continuous on  $M_*$  (see e.g., Davies (1980), Prop.1.23). We call  $T$  identity preserving if  $T(t)1 = 1$  and of Schwarz type if every  $T(t) \in T$  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 of the book with the corresponding results for commutative  $C^*$ -algebras, i.e. for  $C_0(X)$ ,  $C(K)$  and  $L^\infty(\mu)$  (see Part B).

## 2 A Fundamental Inequality for the Resolvent

If  $T = (T(t))_{t \geq 0}$  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  $s(A) \leq 0$ . Then for  $\lambda \in \mathbb{C}$ ,  $\operatorname{Re}(\lambda) > 0$ , 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 [2] it is shown that  $T$  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 operator. This inequality will be needed later.

**Theorem 2.1** *Let  $T = (T(t))_{t \geq 0}$  be a semigroup of Schwarz type and  $S = (S(t))_{t \geq 0}$  a semigroup on a  $C^*$ -algebra  $M$  with generators  $A$  and  $B$ , respectively. If*

$$(*) \quad (S(t)x)(S(t)x)^* \leq T(t)xx^*$$

*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  $T$  is a weak\*-semigroup of Schwarz type and  $S$  is a weak\*-semigroup on a  $W^*$ -algebra  $M$  such that  $(*)$  is fulfilled.*

**Proof** From the assumption (\*) it follows that

$$\begin{aligned} 0 &\leq (S(r)x - S(t)x)(S(r)x - S(t)x)^* = \\ &= (S(r)x)(S(r)x)^* - (S(r)x)(S(t)x)^* - (S(t)x)(S(r)x)^* + (S(t)x)(S(t)x)^* \\ &\leq T(r)xx^* + T(t)xx^* - (S(r)x)(S(t)x)^* - (S(t)x)(S(r)x)^* \end{aligned}$$

for every  $r, t \in \mathbb{R}_+$ . Hence

$$(S(r)x)(S(t)x)^* + (S(t)x)(S(r)x)^* \leq T(r)xx^* + T(t)xx^*.$$

Obviously,  $\|S(t)\| \leq 1$  for all  $t \in \mathbb{R}_+$ . Then for all  $\mu \in \mathbb{R}_+$  and  $x \in M$ :

$$\begin{aligned} (R(\mu, B)x)(R(\mu, B)x)^* &= \left( \int_0^\infty e^{-\mu r} S(r)x \, dr \right) \left( \int_0^\infty e^{-\mu t} S(t)x \, dt \right)^* \\ &= \left( \int_0^\infty \int_0^\infty e^{-\mu(r+t)} (S(r)x)(S(t)x)^* \, dr \, dt \right) \\ &\leq \int_0^\infty \int_0^\infty e^{-\mu(r+t)} (T(r)xx^* + T(t)xx^*)/2 \, dr \, dt \\ &= \int_0^\infty e^{-\mu r} T(r)xx^* \, dr \int_0^\infty e^{-\mu t} \, dt \\ &= \mu^{-1} \int_0^\infty e^{-\mu r} T(r)xx^* \, dr = R(\mu, A)xx^*. \end{aligned}$$

Here we used the inequality derived above in the first step. The second step follows from  $S(t)$  being a contraction semigroup and the third step is achieved by integration.  $\square$

**Remark 2.2** The assumption that  $T$  is a semigroup of Schwarz type cannot be weakened in general to  $T$  being a positive contraction semigroup. This is shown by examples in [4] where  $S(t)x$  is given by  $e^{tB}x$  for a skew-adjoint generator  $B$  and  $T(t)x \equiv x$ .

**Corollary 2.3** Let  $T = (T(t))_{t \geq 0}$  be a semigroup of Schwarz type on a  $C^*$ -algebra  $M$  with generator  $A$ . Then for all  $\mu \in \mathbb{R}_+$  and  $x \in M$ :

$$(\mu R(\mu, A)x)(\mu R(\mu, A)x)^* \leq \mu R(\mu, A)(xx^*).$$

**Proof** Just set  $S = T$  in Theorem 2.1.

$$\begin{aligned}
&= \frac{1}{2} \left( \int_0^\infty \int_0^\infty e^{-\mu(r+t)} ((S(r)x)(S(t)x)^* \right. \\
&\quad \left. + (S(t)x)(S(r)x)^*) dr dt \right) \\
&\leq \frac{1}{2} \left( \int_0^\infty \int_0^\infty e^{-\mu(r+t)} (T(r)xx^* + T(t)xx^*) dr dt \right) \\
&= \left( \int_0^\infty e^{-\mu s} ds \right) \left( \int_0^\infty e^{-\mu t} T(t)xx^* dt \right) = \mu^{-1} R(\mu, A)xx^*
\end{aligned}$$

where the handling of the integral is justified by [1, §8, n° 4, Proposition 9].  $\square$

**Corollary 2.4** *Let  $T$  be a semigroup of Schwarz maps (resp., weak\*-semigroup of Schwarz maps). Then for all  $\lambda \in \mathbb{C}$  with  $\operatorname{Re}(\lambda) > 0$ :*

$$(R(\lambda, A)x)(R(\lambda, A)x)^* \leq (\operatorname{Re} \lambda)^{-1} R(\operatorname{Re} \lambda, A)xx^*, \quad x \in M.$$

*In particular for all  $(\mu, \alpha) \in \mathbb{R}_+ \times \mathbb{R}$ ,  $x \in M$ :*

$$(\mu R(\mu + i\alpha, A)x)(\mu R(\mu + i\alpha, A)x)^* \leq \mu R(\mu, A)(xx^*).$$

**Proof** Let  $\lambda \in \mathbb{C}$  with  $\operatorname{Re}(\lambda) > 0$ . Then the semigroup

$$S := (e^{-i\operatorname{Im}(\lambda)t} T(t))_{t \geq 0}$$

fulfils the assumption of Thm 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.

As in Section C-III the following notion will be an important tool for the spectral theory of semigroups.

**Definition 2.5** Let  $E$  be a Banach space and  $\emptyset \neq D$  an open subset of  $\mathbb{C}$ . A family  $R : D \rightarrow L(E)$  is called a pseudo-resolvent on  $D$  with values in  $E$  if

$$R(\lambda) - R(\mu) = -(\lambda - \mu)R(\lambda)R(\mu)$$

for all  $\lambda$  and  $\mu$  in  $D$ .

If  $R$  is a pseudo-resolvent on  $D = \{\lambda \in \mathbb{C} : \operatorname{Re}(\lambda) > 0\}$  with values in a  $C^*$ - or  $W^*$ -algebra, then  $R$  is called of Schwarz type if

$$(R(\lambda)x)(R(\lambda)x)^* \leq (\operatorname{Re} \lambda)^{-1} R(\operatorname{Re} \lambda)xx^*$$

for all  $\lambda \in D$  and  $x \in M$ .  $R$  is called identity preserving if  $\lambda R(\lambda)1 = 1$  for all  $\lambda \in D$ .

For examples and properties of a pseudo-resolvent see C-III, 2.5. We state what will be used without further reference.

- (a) 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”).

- (b) 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 neighbourhood 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 2.6** We call a semigroup  $T$  on the predual  $M_*$  of a  $W^*$ -algebra  $M$  identity preserving and of Schwarz type, if its adjoint weak\*-semigroup has these properties. Likewise, a pseudo-resolvent  $R$  on  $D = \{\lambda \in \mathbb{C} : \operatorname{Re}(\lambda) > 0\}$  with values in  $M_*$  is called identity preserving and of Schwarz type, if  $R'$  has these properties.

Since for a semigroup of contractions on a Banach space

$$\begin{aligned} \operatorname{Fix}(T) &= \bigcap_{t \geq 0} \ker(\operatorname{Id} - T(t)) = \\ &= \ker(\operatorname{Id} - \lambda R(\lambda, A)) = \operatorname{Fix}(\lambda R(\lambda, A)) \end{aligned}$$

for all  $\lambda \in \mathbb{C}$  with  $\operatorname{Re}(\lambda) > 0$ , it follows that 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 2.3 an analogous statement holds for “Schwarz type”.

### 3 Induction and Reduction

1. If  $E$  is a Banach space and  $S \subseteq L(E)$  a semigroup of bounded operators, then a closed subspace  $F$  is called  $S$ -invariant, if  $SF \subseteq F$  for all  $S \in S$ . We call the semigroup  $S|_F := \{S|_F : S \in S\}$  the reduced semigroup. Note that for a one-parameter semigroup  $T$  (resp., pseudo-resolvent  $R$ ) the reduced semigroup is again strongly continuous (resp.  $R|_F$  is again a pseudo-resolvent) (compare the construction in A-I,3.2).

2. Let  $M$  be a  $W^*$ -algebra,  $p \in M$  a projection and  $S \in L(M)$  such that  $S(p^\perp M) \subseteq p^\perp M$  and  $S(Mp^\perp) \subseteq Mp^\perp$ , where  $p^\perp := 1 - p$ . 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. 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  $S_p(p) = p$ .

If  $T = (T(t))_{t \geq 0}$  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  $M p^\perp$  invariant. It is easy to see that the induced semigroup  $T_p = (T(t)_p)_{t \geq 0}$  is again a weak\*-semigroup.

If  $R$  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  $M p^\perp$  are  $R$ -invariant. Again, the induced pseudo-resolvent  $R_p$  is of Schwarz type and identity preserving.

3. 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  $\varphi$ .

To see this let  $L_\varphi := \{x \in M : \varphi(xx^*) = 0\}$  and  $M_\varphi := L_\varphi \cap L_\varphi^*$ . 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  $M_{s(\varphi)}$ . If

$$s(\varphi)M_*s(\varphi) := \{\psi \in M_* : \psi = s(\varphi)\psi s(\varphi)\}$$

where  $\langle s(\varphi)\psi s(\varphi), x \rangle := \langle \psi, s(\varphi)xs(\varphi) \rangle$  ( $x \in M$ ), and if  $\psi \in s(\varphi)M_*s(\varphi)$ , then for all  $x \in M$ :

$$\begin{aligned} (T_*\psi)(x) &= \psi(Tx) = \langle \psi, s(\varphi)(Tx)s(\varphi) \rangle = \\ &= \langle \psi, s(\varphi)(T(s(\varphi)xs(\varphi)))s(\varphi) \rangle = \langle T_*\psi, s(\varphi)xs(\varphi) \rangle, \end{aligned}$$

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  $T_*|_{s(\varphi)M_*s(\varphi)}$  is identity preserving and of Schwarz type.

For example, if  $T$  is an identity preserving semigroup of Schwarz type on  $M_*$  such that  $\varphi \in \operatorname{Fix}(T)$ , then the semigroup  $T|(s(\varphi)M_*s(\varphi))$  is again identity preserving and of Schwarz type. Furthermore, if  $R$  is a pseudo-resolvent on  $D = \{\lambda \in \mathbb{C} : \operatorname{Re}(\lambda) > 0\}$  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  $R|s(\varphi)M_*s(\varphi)$  has the same properties.

## 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 (1976)). 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 [5].

### 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 [6] 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 D-II.1* Take  $M = B(H)$ ,  $H$  infinite dimensional, and choose a projection  $p \in M$  such that  $Mp$  is topologically isomorphic to  $H$ . Therefore  $M = H \oplus M_0$ , where  $M_0 = \ker(x \mapsto xp)$ . Next take a strongly, but not uniformly continuous, semigroup  $S$  on  $H$  and consider the strongly continuous semigroup  $S \oplus \text{Id}$  on  $M$ .

For results from the classification theory of  $W^*$ -algebras needed in our approach we refer to [9, 2.2] and [10, V.1].

**Theorem 1.1** *Every strongly continuous one-parameter semigroup of Schwarz type on a properly infinite  $W^*$ -algebra  $M$  is uniformly continuous.*

**Proof** Let  $T = (T(t))_{t \geq 0}$  be strongly continuous on  $M$  and suppose  $T$  not to be uniformly continuous. Then there exists a sequence  $(T_n) \subset T$  and  $\epsilon > 0$  such that

$\|T_n - \text{Id}\| \geq \epsilon$  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 an application of the *Lemma of Phillips* and the fact that the sequence  $(P_k x_k P_k)$  is summable in the  $s^*(M, M_*)$ -topology (compare Elliot (1972)).

Let  $(P_k)$  be a sequence of mutually orthogonal projections in  $M$  such that every  $P_k$  is equivalent to 1 via some  $u_k \in M$  [9, 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. Let

- (i)  $\widehat{M}$  be an ultrapower of  $M$ ,
- (ii) let  $p := \widehat{(P_k)} \in \widehat{M}$ ,
- (iii)  $T := \widehat{(T_n)} \in L(\widehat{M})$
- (iv) and  $u := \widehat{(u_k)} \in \widehat{M}$ .

Then  $T$  is identity preserving and of Schwarz type on  $\widehat{M}$ . Since  $u^*u = p$  and  $uu^* = 1$  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

$$T(uu^*) = T(1) \leq 1 = uu^* = T(u)T(u)^*.$$

Using D-III, Lemma 1.1. we conclude  $T(ux) = uT(x)$  and  $T(xu^*) = T(x)u^*$  for all  $x \in \widehat{M}$ . Hence

$$\begin{aligned} T(x) &= T(uu^*xu^*) = uT(u^*xu)u^* = uT(pu^*xup)u^* \\ &= upu^*xupu^* = uu^*xu^* = x \end{aligned}$$

for all  $x \in \widehat{M}$ . From this we obtain that for every bounded sequence  $(x_k)$  in  $M$

$$\lim_m \|T_m x_m - x_m\| = 0$$

for some subsequence of the  $T_n$ 's and of the  $x_k$ 's. This conflicts with our assumption at the beginning, hence the theorem is proved.  $\square$



## 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: The spectral bound  $s(A) := \sup\{\Re(\lambda) : \lambda \in \sigma(A)\}$  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, but in the non-commutative case the situation is more complicated. While “ $s(A) \in \sigma(A)$ ” still holds (see Greiner-Voigt-Wolff (1980)) 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. But as we will show in the example preceding Theorem 1.1 below 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

$$\varphi(x) = |\varphi|(xu) =: (u|\varphi|)(x), x \in M$$

$$u^*u = s(|\varphi|),$$

where  $s(|\varphi|)$  denotes the support projection of  $|\varphi|$  in  $M$ . We refer to this as the *polar decomposition* of  $\varphi$  [Takesaki (1979), Theorem III.4.2]. In addition,  $|\varphi|$  is uniquely determined by the following two conditions [Takesaki (1979), Proposition III.4.6]:

$$\|\varphi\| = \| |\varphi| \|,$$

(\*)

$$|\varphi(x)|^2 \leq |\varphi|(xx^*) \quad (x \in M).$$

For the polar decomposition of  $\varphi^*$ , where  $\varphi^*(x) = \varphi(x^*)^*$ , we obtain

$$\varphi^* = u^* |\varphi^*|, \quad |\varphi^*| = u |\varphi| u^* \quad \text{and} \quad uu^* = s(|\varphi^*|).$$

It is easy to see that  $u^* \in s(|\varphi|)M$ .

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  $x = 0$ .  $\Psi$  is called *subinvariant* for a positive map  $T \in \mathcal{L}(M)$  (resp., positive semigroup  $T$ ) if  $T'\psi \leq \psi$  for all  $\psi \in \Psi$  (resp.,  $T(t)'\psi \leq \psi$  for all  $T(t) \in T$  and  $\psi \in \Psi$ ). Recall that for every positive map  $T \in \mathcal{L}(M)$  there exists a state  $\varphi$  on  $M$  such that  $T'\varphi = r(T)\varphi$  [Groh (1981), Theorem 2.1], where  $r(T)$  denotes the spectral radius of  $T$ .

Let us start our investigation with two lemmas. Recall that  $\text{Fix}((\cdot)T)$  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  $T \in \mathcal{L}(M)$  an identity preserving Schwarz map.

- (i) Let  $b : M \times M \rightarrow M$  be a sesquilinear map such that for all  $z \in M$   $b(z, z) \geq 0$ . 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  $\text{Fix}((\cdot)T)$  is a  $C^*$ -subalgebra of  $M$  and  $T(xy) = xT(y)$  for all  $x \in \text{Fix}((\cdot)T)$  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 (a) is proved.

(ii) Since  $T$  is positive it follows  $T(x)^* = T(x^*)$  for all  $x \in M$ . Hence  $\text{Fix}((\cdot)T)$  is a self adjoint subspace of  $M$ , i.e. invariant under the involution on  $M$ . For every  $x, y \in M$  let

$$b(x, y) := T(xy^*) - T(x)T(y)^*.$$

Then  $b$  satisfies the assumptions of (i).

If  $x \in \text{Fix}((\cdot)T)$  then

$$0 \leq xx^* = (Tx)(Tx)^* \leq T(xx^*),$$

hence

$$0 \leq \psi(T(xx^*) - xx^*) \leq 0 \quad \text{for all } \psi \in \Psi.$$

But this implies  $T(xx^*) = T(x)T(x)^* = xx^*$ . 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  $S \in \mathcal{L}(M)$  such that  $S(x)(Sx)^* \leq T(xx^*)$  for every  $x \in M$ .*

- (a) *If  $v \in M$  such that  $S(v^*) = v^*$  and  $T(v^*v) = v^*v$ , then  $T(xv) = S(x)v$  for all  $x \in M$ .*
- (b) *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** (a) Define a positive semidefinite sesquilinear map  $b : M \times M \rightarrow M$  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  $x \in M$  (Lemma 1.1.a), hence  $T(xv) = S(x)v$ .

- (a) 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 (1979), 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

$$\begin{aligned} 0 &\leq (Su^* - u^*)(Su^* - u^*)^* \leq \\ &\leq T(u^*u) - u^*S(u^*)^* - (Su^*)u + u^*u. \end{aligned}$$

Since  $S_*\varphi = \varphi$ ,  $T_*|\varphi| = |\varphi|$  and  $\varphi = u|\varphi|$  it follows

$$\begin{aligned} 0 &\leq |\varphi|((Su^* - u^*)(Su^* - u^*)^*) \leq \\ &\leq 2|\varphi|(u^*u) - |\varphi|(S(u^*)u)^* - |\varphi|(S(u^*)u) = \\ &= 2|\varphi|(uu^*) - \varphi(u^*)^* - \varphi(u^*) = \\ &= 2(|\varphi|(u^*u) - |\varphi|(u^*u)) = 0. \end{aligned}$$

Since  $(Su^* - u^*)(Su^* - u^*)^* \in F$  and  $|\varphi|$  is faithful on  $F$  we obtain  $Su^* = u^*$ . Consequently,

$$0 \leq u^*u = (Su^*)(Su^*)^* \leq T(u^*u).$$

Hence  $T(u^*u) = u^*u$  by the faithfulness and  $T$ -invariance of  $|\varphi|$ .

**Remark 1.1** Take  $S$  and  $T$  as in Lemma 1.2 (b). 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  $\text{Fix}(R) := \text{Fix}(\lambda R(\lambda))$ ,  $\lambda \in D$ , of a pseudo-resolvent  $R$  with values in the predual of a  $W^*$ -algebra  $M$ .

**Proposition 1.2** *Let  $R$  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  $R$  to be identity preserving and of Schwarz type.*

- (a) *If  $a \in \mathbb{R}$  and  $\psi \in M_*$  such that  $(\gamma - ia)R(\gamma)\psi = \psi$  for some  $\gamma \in D$ , then  $\lambda R(\lambda)|\psi| = |\psi|$  and  $\lambda R(\lambda)|\psi^*| = |\psi^*|$  for all  $\lambda \in D$ .*
- (b)  *$\text{Fix}(R)$  is invariant under the involution in  $M_*$ . If  $\psi \in \text{Fix}(R)$  is self adjoint, then the positive part  $\psi^+$  and the negative part  $\psi^-$  of  $\psi$  are elements of  $\text{Fix}(R)$ .*

**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 (\*) mentioned at the beginning. Therefore  $|\psi| \in \text{Fix}(R)$ . 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  $|\psi^*| \in \text{Fix}(R)$  follows. If  $\varphi \in \text{Fix}(R)$  is selfadjoint with Jordan decomposition  $\varphi = \varphi^+ - \varphi^-$ , then  $|\varphi| = \varphi^+ + \varphi^-$  [Takesaki (1979), Theorem III.4.2.]. From this we obtain that  $\varphi^+$  and  $\varphi^-$  are in  $\text{Fix}(R)$ .  $\square$

**Corollary 1.3** *Let  $T$  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  $\text{Fix}(T) = \ker(A)$ .*
- (ii)  *$\text{Fix}(T)$  is invariant under the involution of  $M_*$ . If  $\psi \in \text{Fix}(T)$  is selfadjoint, then the positive part  $\psi^+$  and the negative part  $\psi^-$  of  $\psi$  are elements of  $\text{Fix}(T)$ .*

The proof follows immediately from D-I, Corollary 2.2 and the fact that  $\ker(A) = \text{Fix}(\lambda R(\lambda, A))$  for all  $\lambda \in \mathbb{C}$  with  $\text{Re}(\lambda) > 0$ .

If  $T$  is the semigroup of translations on  $L^1(\mathbb{R})$  and  $A'$  the gene-



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