Appendix A
Historical Notes

We provide here a number of historical and other notes on the material of this work.

Section 1.3: A comprehensive treatment of stable processes and their integral representations can be found in Samorodnitsky and Taqqu [56]. Univariate stable distributions is the focus of a fascinating monograph by Uchaikin and Zolotarev [63], as well as of the classic monograph by Zolotarev [69]. For a more recent treatment of stable distributions and processes, see Rachev and Mittnik [43] for applications in finance, and Nolan [32].

We assumed in Section 1.3 and throughout the work that stable processes are $S\alpha S$. In the study of stationary stable processes and their connections to flows, *skewness* was included with "minor" modifications in Rosiński [45] and Kolodyński and Rosiński [24]. Extensions to stationary stable *fields*, that is, stable processes $X_\alpha(t)$ indexed by $t \in \mathbb{R}^d$ or $t \in \mathbb{Z}^d$, are not immediate and were considered in Rosiński [47] and Roy and Samorodnitsky [49]. Similar developments concerning skewness and random fields are expected but not available yet in the context of self-similar mixed moving averages.

Section 2.1: The definition (2.3) of minimal integral representations was given by Hardin [19, 20]. Rosiński [48] reexamined minimal integral representations in greater depth and provided alternative formulations, including those in (2.4)–(2.5) and Remark 2.1. Pipiras [34] showed that a minimal integral representation can be achieved naturally from a nonminimal one by removing a so-called nonminimal set from the space underlying the nonminimal integral representation.

Despite significant progress in the theory, determining whether a given integral representation is minimal, may not be immediate. See, for example, Examples 2.2 and 3.3 concerning stationary and stationary increments moving averages.

Section 2.2: Theorem 2.1, characterizing linear isometries of spaces L^α, appears in Banach [4] and Lamperti [29]. It is a well-known result in real analysis, for example, part of the classic by Royden [50], Chapter 15. For a more advanced and

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comprehensive treatment, including Rudin's theorem (see (2.36)–(2.37)), see Fleming and Jamison [14], Section 3. Section 3.5, in particular, has interesting notes and remarks.

The statement and proof of Proposition 2.2, relating minimal integral representations and isometries, are taken from Rosiński [48].

Section 2.3: As indicated in the introduction of Section 1.1, the connection between stationary stable processes and nonsingular flows outlined in Section 2.3.1 is due to Rosiński [46]. Nonsingular flows, cocycles, and related notions (Hopf decomposition, special flows) are part of ergodic theory (Cornfeld et al. [8], Krengel [26], Zimmer [68]), and, especially, infinite[1] ergodic theory (Aaronson [1], Glasner [15]).

1- and 2-semi-additive functionals arise specifically when relating self-similar mixed moving averages and flows. The terms are coined by analogy to additive functionals $f_h(s)$ (for a flow $\phi_h(s)$) satisfying

$$f_{h_1+h_2}(s) = f_{h_1}(s) + f_{h_2}(\phi_{h_1}(s)), \quad s \in S,\ h_1, h_2 \in \mathbb{R}$$

(Kubo [27, 28]). See Pipiras and Taqqu [41].

Having established a connection between stable processes and flows, it is natural to ask how ergodic or other properties of flows affect those of the corresponding stable processes. For stationary stable processes, this is studied in Samorodnitsky [52, 53].

Section 3.1: The name mixed moving averages is adopted from the stationary case, where mixed moving averages are represented as

$$\int_X \int_{\mathbb{R}} G(x, t+u) M(dx, du).$$

These processes were studied in Surgailis et al. [60], and are stationary stable processes generated by dissipative flows in the decomposition established by Rosiński [46].

Using a suitable transformation, Surgailis et al. [61] associated stable processes with stationary increments with stable stationary processes, and then decomposed them based on the decomposition of stationary processes of Rosiński [46]. In this approach, mixed moving averages with stationary increments are associated with stationary mixed moving averages and can be represented by (3.1). From the perspective of these structural results, it should be noted that mixed moving averages make just a single, even if large, class of stable processes with stationary increments (namely, those generated by dissipative flows).

Section 3.2: Sections 3.2.1 and 3.2.2 are based on Pipiras and Taqqu [35], Section 3.2.3 on Pipiras and Taqqu [36, 37], Section 3.2.5 on Pipiras and Taqqu [36, 40], and Section 3.2.6 on Pipiras and Taqqu [39].

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[1] "Infinite" refers here to the fact that the measure on the space underlying a flow is not finite. Another term used is "nonsingular ergodic theory."

Several notable differences between Section 3.2 and these references are the following. Definition 3.2 found in [35, 36] does not stipulate for $j_c(x)$ to be a 2-semi-additive functional. By making this assumption, the current definition thus provides a description of the structure of $j_c(x)$ as a function in (c,x). This is useful, for example, in establishing canonical representations of self-similar mixed moving averages (see the proof of Theorem 3.11). To account for the change in the definition, we had to modify the proofs of the fundamental Theorem 3.1 and several other results.

Proposition 3.2 on the existence of minimal mixed moving average representations was proved in [35] under the assumption $\alpha \in (1,2)$. This assumption was then made throughout [35, 36]. The proposition was extended to the entire range $\alpha \in (0,2)$ in Pipiras [34], making it possible to assume this range throughout Section 3.2. Finally, we also note that fixed fractional stable motions (FFSMs) were called mixed linear fractional stable motions (mixed LFSMs) in [36, 39, 40]. While the latter term was motivated by the canonical representation in Theorem 3.11, the term FFSM used in Section 3.2 is in line with the nature of the underlying (that is, fixed) flow, and the analogous terms cLFSM for cyclic fractional stable motion and PFSM for periodic fractional stable motion.

Other notes: Natural connections to nonsingular flows are available not only for stable processes but also for the so-called max-stable processes. If stable distributions arise as limits of normalized partial sums, max-stable distributions arise as limits of normalized partial maxima. Max-stable processes thus play an important role in extreme value theory (Coles [7], de Haan and Ferreira [9]).

Minimal representations, max-linear isometries, and glimpses of flows in the context of max-stable processes date back at least to de Haan and Pickands [10]. A flow-based decomposition of stationary max-stable processes, parallel to that of Rosiński [46] for stationary stable processes, was established by Wang and Stoev [67]. Parallels between max-stable and stable frameworks are studied in Kabluchko [21] and Wang and Stoev [66].

Appendix B
Standard Lebesgue Spaces and Projections

A measure space $(S,\mathscr{S},\nu)$ is called a *standard Lebesgue space* when $(S,\mathscr{S})$ is a *standard Borel space*, equipped with a σ-finite measure μ. In a standard Borel space, S can be thought as a Borel subset of a Polish space, and the σ-field $\mathscr{S}$ is the σ-field of Borel sets $\mathscr{B}(S)$ defined as $\mathscr{B}(S)=\sigma\{A : A\subset S \text{ is open}\}$. An example of a standard Lebesgue space is the Euclidean space $\mathbb{R}^n$, with a measure consisting of Lebesgue measure and discrete point masses.

Standard Lebesgue spaces (or standard Borel spaces) are convenient to work with, have nice properties and are widely used in ergodic theory (Walters [65], Petersen [33]) and in other areas of mathematics (Mackey [31], Arveson [3], Zimmer [68]).

In this book, we used a number of times the notion of projection. If S_1 and S_2 are two spaces, the projection of a set $E\in S_1\times S_2$ onto S_1 is defined as

$$\mathrm{proj}_{S_1}E=\{s_1\in S_1 : \exists s_2\in S_2 : (s_1,s_2)\in E\}.$$

The projection $\mathrm{proj}_{S_2}E$ is defined in a similar way. When $S_1=S_2=S$, proj_S is understood as the projection onto the first variable.

When $(S_1,\mathscr{B}(S_1))$ and $(S_2,\mathscr{B}(S_2))$ are two standard Borel spaces, and $E\in\mathscr{B}(S_1)\times\mathscr{B}(S_2)$, it is well known that $\mathrm{proj}_{S_1}E$ is not necessarily in $\mathscr{B}(S_1)$. This important fact has essentially given rise to the field of the so-called (classical) descriptive set theory. See, for example, the monographs of Kechris [23] and Srivastava [59].

One of the key notions in descriptive set theory is that of *projective classes* $\Sigma_n^1(S),\Pi_n^1(S),\Delta_n^1(S)$, $n\in\mathbb{N}$, on a Polish space S. They can be defined recursively in n as follows. For $n=1$,

$$\Sigma_1^1(S)=\{B : B=\mathrm{proj}_S A \text{ for } A\in\mathscr{B}(S^2)\}, \tag{B.1}$$

$$\Pi_1^1(S)=\{B^c : B\in\Sigma_1^1(S)\},\quad \Delta_1^1(S)=\Sigma_1^1(S)\cap\Pi_1^1(S).$$

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The elements of $\Sigma_1^1(S)$ and $\Pi_1^1(S)$ are called *analytic* and *coanalytic* sets, respectively, and $\Delta_1^1(S) = \mathscr{B}(S)$. Then, recursively in n,

$$\Sigma_{n+1}^1(S) = \{B : B = \mathrm{proj}_S A \text{ for } A \in \Pi_n^1(S^2)\},$$

$$\Pi_{n+1}^1(S) = \{B^c : B \in \Sigma_{n+1}^1(S)\}, \quad \Delta_{n+1}^1(S) = \Sigma_{n+1}^1(S) \cap \Pi_{n+1}^1(S).$$

Another, more general way is to define the class Σ_{n+1}^1 as images of sets from the projective class Π_n^1 under Borel maps (projection, as in (B.1), is one such map).

Much is known about the above projective classes. For example, in the following diagram, any class is a subset of every class to the right of it:

$$\begin{array}{cccccc} & \Sigma_1^1(S) & & \Sigma_2^1(S)\ \ldots & & \\ \mathscr{B}(S) = \Delta_1^1(S) & & \Delta_2^1(S) & \ldots & \overline{\mathscr{B}}(S) \\ & \Pi_1^1(S) & & \Pi_2^1(S)\ \ldots & & \end{array} \tag{B.2}$$

where

$$\overline{\mathscr{B}}(S) := \overline{\mathscr{B}}_\mu(S)$$

is the completion σ-field of $\mathscr{B}(S)$ under μ. The classes $\Sigma_n^1(S)$ and $\Pi_n^1(S)$ are closed under countable unions and intersections, and $\Delta_n^1(S)$ are σ-fields, and so on. Except the proof of Lemma B.1 below, the various intermediate classes in (B.2) are not used directly in the book. But they are naturally related to projections, and as discussed here, are behind a useful theory of classes in between the commonly used spaces $\mathscr{B}(S)$ and $\overline{\mathscr{B}}(S)$.

Another important idea is that of *uniformization* and *uniformizing functions* defined in Kechris [23], or measurable sections defined in Srivastava [59], or measurable selections defined in Wagner [64]. We are not going to describe the many related results here. We shall only state next an auxiliary result which was used above (e.g., Lemma 2.3). The function h appearing below is called a measurable selection.

Lemma B.1. *Let $(S_1, \mathscr{S}_1, \nu_1)$ and $(S_2, \mathscr{S}_2, \nu_2)$ be two standard Lebesgue spaces and $(S_1 \times S_2, \mathscr{S}_1 \times \mathscr{S}_2, \nu_1 \times \nu_2)$ be their Cartesian product. Let also $A \in \mathscr{S}_1 \times \mathscr{S}_2$ be a Borel set of $S_1 \times S_2$. Then, the set*

$$\mathrm{proj}_{S_1} A := \{s_1 \in S_1 : \exists s_2 \in S_2 : (s_1, s_2) \in A\}$$

is ν_1-measurable, that is, belongs to $\overline{\mathscr{B}}_{\mu_1}(S_1)$, and there is a ν_1-measurable function $h : \mathrm{proj}_{S_1} A \mapsto A$ such that $(s_1, h(s_1)) \in A$ for all $s_1 \in \mathrm{proj}_{S_1} A$.

PROOF: The set $\mathrm{proj}_{S_1} A$ is ν_1-measurable because the map $\mathrm{proj}_{S_1}(s_1, s_2) = s_1$ is continuous and the set A can be approximated $(\nu_1 \times \nu_2)$-a.e. by rectangles whose projections are measurable. (In the case $S_1 = S_2 = S$, this also follows from the inclusions in (B.2) where all the classes, including $\Sigma_1^1(S)$, are subsets of $\overline{\mathscr{B}}(S)$.)

We will show next that there is a ν_1-measurable map $h : \mathrm{proj}_{S_1} A \mapsto A$ such that $(s_1, h(s_1)) \in A$ for $s_1 \in \mathrm{proj}_{S_1} A$. To do so, we will use Theorem 3.4.3 in Arveson [3],

p. 77, which concerns the so-called cross sections of Borel maps. Consider the map $f = \mathrm{proj}_{S_1} : A \mapsto f(A) = \mathrm{proj}_{S_1} A$. The image set $f(A)$, together with the induced Borel structure

$$\mathscr{F}(A) = \{f(A) \cap B : B \in \mathscr{S}_1\},$$

is a Borel space. Moreover, this Borel space is countably separated (as defined in Arveson [3], p. 69) since the underlying standard Lebesgue space $(S_1, \mathscr{S}_1, \nu_1)$ is countably separated. The Borel set A, equipped with the Borel structure

$$\mathscr{A} = \{A \cap B : B \in \mathscr{S}_1 \times \mathscr{S}_2\},$$

is also a Borel space. It is an analytic Borel space (as defined in Arveson [3], p. 71) by using Corollary in Arveson [3], p. 65, and the fact that A is a Borel set. Since $f^{-1}(f(A) \cap B) = A \cap (B \times \mathbb{R}) \in \mathscr{A}$ for all $B \in \mathscr{S}_1$, the map

$$f : (A, \mathscr{A}) \mapsto (f(A), \mathscr{F}(A))$$

is Borel. It follows from Theorem 3.4.3 in Arveson [3] that there is a ν_1-measurable map $g : f(A) \mapsto A$ such that $f(g(s_1)) = s_1$. Since f is a projection, we have that $g(s_1) = (s_1, h(s_1))$ for some ν-measurable map $h(s_1)$ and hence that there is a ν-measurable map $h(s_1)$ such that $(s_1, h(s_1)) \in A$. $\square$

Appendix C
Notation Summary

We denote by

$$X_\alpha^D,\ X_\alpha^C,\ X_\alpha^P,\ X_\alpha^F,\ X_\alpha^L,\ X_\alpha^{C\setminus P}$$

the processes generated respectively by dissipative (D), conservative (C), periodic (P), fixed (F), cyclic (L), and conservative but not periodic ($C \setminus P$) flows. These processes are abbreviated respectively

$$\text{DFSM, CFSM, PFSM, FFSM, cLFSM, (C}\backslash\text{P)FSM.}$$

They are characterized in terms of minimal representations. The dissipative (D) and conservative (C) sets associated with a flow can also be characterized through the structure of the kernel function G in (3.1). The processes

$$X_\alpha^P,\ X_\alpha^F,\ X_\alpha^L,\ X_\alpha^{C\setminus P}$$

can also be characterized through the structure of the kernel function G in (3.1), namely through respectively, the following subsets of C,

$$C_P,\ C_F,\ C_L,\ C \setminus C_P.$$

Note that the linear fractional stable motion (LFSM) defined in Example 2.5 is also a FFSM as indicated in Example 3.14.

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