

# Unitary Time Changes of Stationary Processes Yield Oscillatory Processes and a Functional Framework Toward a Hilbert– Pólya Construction

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## Abstract

A unitary time-change operator  $U_\theta$  is constructed for absolutely continuous, strictly increasing time reparametrizations  $\theta$ , acting on functions that are square-integrable over compact sets. Applying  $U_\theta$  to the Cramér spectral representation of a stationary process yields an oscillatory process in the sense of Priestley with oscillatory function  $\varphi_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)}$  and evolutionary spectrum  $dF_t(\lambda) = \dot{\theta}(t)dF(\lambda)$ . It is proved that sample paths of any non-degenerate second-order stationary process almost surely lie in  $L^2_{\text{loc}}(\mathbb{R})$ , making the operator applicable to typical realizations. A zero-localization measure  $d\mu(t) = \delta(Z(t)) |\dot{Z}(t)| dt$  induces a Hilbert space  $L^2(\mu)$  on the zero set of an oscillatory process  $Z$ , and the multiplication operator  $(Lf)(t) = t f(t)$  has simple pure point spectrum equal to the zero crossing set of  $Z$ . This produces a concrete operator scaffold consistent with a Hilbert–Pólya-type viewpoint.

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# 1 Function Spaces and Unitary Time Change

## 1.1 $\sigma$ -compact sets and local $L^2$

### Definition 1

**[ $\sigma$ -compact sets]** A subset  $U \subseteq \mathbb{R}$  is  $\sigma$ -compact if

$$U = \bigcup_{n=1}^{\infty} K_n \quad (1)$$

with each  $K_n$  compact.

### Definition 2

**[Locally square-integrable functions]** Define

$$L^2_{\text{loc}}(\mathbb{R}) := \left\{ f: \mathbb{R} \rightarrow \mathbb{C}: \int_K |f(t)|^2 dt < \infty \text{ for every compact } K \subseteq \mathbb{R} \right\} \quad (2)$$

**Remark 3.** Every bounded measurable set in  $\mathbb{R}$  is compact or contained in a compact set; hence  $L^2_{\text{loc}}(\mathbb{R})$  contains functions that are square-integrable on every bounded interval, including functions with polynomial growth at infinity.

## 1.2 Unitary time-change operator

### Definition 4

**[Unitary time-change]** Let the time-scaling function  $\theta: \mathbb{R} \rightarrow \mathbb{R}$  be absolutely continuous, strictly increasing, and bijective, with  $\dot{\theta}(t) > 0$  almost everywhere and  $\dot{\theta}(t) = 0$  only on sets of Lebesgue measure zero. The function  $\theta$  maps  $\sigma$ -compact sets to  $\sigma$ -compact sets. Define, for  $f$  measurable,

$$(U_{\theta} f)(t) = \sqrt{\dot{\theta}(t)} f(\theta(t)) \quad (3)$$

### Proposition 5

**[Inversion of Unitary time-change]** The inverse of the unitary time-change operator  $U$  in Equation (3) is given by

$$(U_{\theta}^{-1} g)(s) = \frac{g(\theta^{-1}(s))}{\sqrt{\dot{\theta}(\theta^{-1}(s))}} \quad (4)$$

which is well-defined almost everywhere on every  $\sigma$ -compact set.

**Proof.** Since  $\dot{\theta}(t) = 0$  only on sets of measure zero, and  $\theta^{-1}$  maps sets of measure zero to sets of measure zero because of the fact that absolutely continuous bijective functions preserve measure-zero sets, the denominator  $\sqrt{\dot{\theta}(\theta^{-1}(s))}$  is positive almost everywhere. The expression is therefore well-defined almost everywhere on every  $\sigma$ -compact set, which suffices for defining an element of  $L^2_{\text{loc}}(\mathbb{R})$ .  $\square$

**Theorem 6**

**[Local unitarity on  $\sigma$ -compact sets]** For every  $\sigma$ -compact set  $C \subseteq \mathbb{R}$  and  $f \in L^2_{\text{loc}}(\mathbb{R})$ ,

$$\int_C |(U_\theta f)(t)|^2 dt = \int_{\theta(C)} |f(s)|^2 ds \quad (5)$$

Moreover,  $U_\theta^{-1}$  is the inverse of  $U_\theta$  on  $L^2_{\text{loc}}(\mathbb{R})$ .

**Proof.** Let  $f \in L^2_{\text{loc}}(\mathbb{R})$  and let  $U$  be any  $\sigma$ -compact set. The local  $L^2$ -norm of  $U_\theta f$  over  $C$  is:

$$\begin{aligned} \int_C |(U_\theta f)(t)|^2 dt &= \int_C \left| \sqrt{\dot{\theta}(t)} f(\theta(t)) \right|^2 dt \\ &= \int_C \dot{\theta}(t) |f(\theta(t))|^2 dt \end{aligned} \quad (6)$$

Since  $\theta$  is absolutely continuous and strictly increasing, applying the change of variables  $s = \theta(t)$  gives

$$ds = \dot{\theta}(t) dt \quad (7)$$

almost everywhere. Since  $\theta$  maps  $\sigma$ -compact sets to  $\sigma$ -compact sets, as  $t$  ranges over  $C$ ,  $s = \theta(t)$  ranges over  $\theta(C)$ , which is  $\sigma$ -compact. Therefore:

$$\int_C \dot{\theta}(t) |f(\theta(t))|^2 dt = \int_{\theta(C)} |f(s)|^2 ds \quad (8)$$

To verify that  $U_\theta^{-1}$  is indeed the inverse, we compute explicitly. For any  $f \in L^2_{\text{loc}}(\mathbb{R})$ :

$$\begin{aligned} (U_\theta^{-1} U_\theta f)(s) &= \left( U_\theta^{-1} \sqrt{\dot{\theta}(s)} f(\theta(s)) \right)(s) \\ &= \frac{\sqrt{\dot{\theta}(\theta^{-1}(s))}}{\sqrt{\dot{\theta}(\theta^{-1}(s))}} f(\theta(\theta^{-1}(s))) \\ &= f(s) \end{aligned} \quad (9)$$

since  $\theta(\theta^{-1}(s)) = s$ . Similarly, for any  $g \in L^2_{\text{loc}}(\mathbb{R})$ :

$$\begin{aligned} (U_\theta U_\theta^{-1} g)(t) &= \sqrt{\dot{\theta}(t)} (U_\theta^{-1} g)(\theta(t)) \\ &= \frac{\sqrt{\dot{\theta}(t)}}{\sqrt{\dot{\theta}(\theta^{-1}(\theta(t)))}} g(\theta^{-1}(\theta(t))) \\ &= \frac{\sqrt{\dot{\theta}(t)}}{\sqrt{\dot{\theta}(t)}} g(t) \\ &= g(t) \end{aligned} \quad (10)$$

since  $\theta^{-1}(\theta(t)) = t$ . Therefore

$$U_\theta U_\theta^{-1} = U_\theta^{-1} U_\theta = I \quad (11)$$

on  $L^2_{\text{loc}}(\mathbb{R})$ .  $\square$

## 2 Oscillatory Processes (Priestley)

### Definition 7

**[Oscillatory process]** Let  $F$  be a finite nonnegative Borel measure on  $\mathbb{R}$ . For each  $t \in \mathbb{R}$ , let  $A_t \in L^2(F)$  be the gain function and

$$\varphi_t(\lambda) = A_t(\lambda) e^{i\lambda t} \quad (12)$$

be the corresponding oscillatory function then an oscillatory process is a stochastic process which can be represented as

$$\begin{aligned} Z(t) &= \int_{\mathbb{R}} \varphi_t(\lambda) d\Phi(\lambda) \\ &= \int_{\mathbb{R}} A_t(\lambda) e^{i\lambda t} d\Phi(\lambda) \end{aligned} \quad (13)$$

where  $\Phi$  is a complex orthogonal random measure with spectral measure  $F$ , that is,

$$\mathbb{E}[\Phi(d\lambda) \overline{\Phi(d\mu)}] = \delta(\lambda - \mu) dF(\lambda) \quad (14)$$

and corresponding covariance kernel

$$\begin{aligned} R_Z(t, s) &= \mathbb{E}[Z(t) \overline{Z(s)}] \\ &= \int_{\mathbb{R}} A_t(\lambda) \overline{A_s(\lambda)} e^{i\lambda(t-s)} dF(\lambda) \\ &= \int_{\mathbb{R}} \phi_t(\lambda) \overline{\phi_s(\lambda)} dF(\lambda) \end{aligned} \quad (15)$$

### Theorem 8

**[Real-valuedness criterion for oscillatory processes]** Let  $Z$  be an oscillatory process with oscillatory function

$$\varphi_t(\lambda) = A_t(\lambda) e^{i\lambda t} \quad (16)$$

and spectral measure  $F$ . Then  $Z$  is real-valued if and only if

$$A_t(-\lambda) = \overline{A_t(\lambda)} \quad (17)$$

for  $F$ -almost every  $\lambda \in \mathbb{R}$ , equivalently

$$\varphi_t(-\lambda) = \overline{\varphi_t(\lambda)} \quad (18)$$

for  $F$ -almost every  $\lambda \in \mathbb{R}$ .



**Proof.** Assume  $Z$  is real-valued, i.e.

$$Z(t) = \overline{Z(t)} \quad \forall t \in \mathbb{R} \quad (19)$$

Writing its oscillatory representation,

$$Z(t) = \int_{\mathbb{R}} A_t(\lambda) e^{i\lambda t} d\Phi(\lambda) \quad (20)$$

and taking the complex conjugate gives

$$\overline{Z(t)} = \int_{\mathbb{R}} \overline{A_t(\lambda)} e^{-i\lambda t} d\overline{\Phi}(\lambda) \quad (21)$$

For a real-valued process, the orthogonal random measure  $\Phi$  must satisfy

$$d\overline{\Phi}(\lambda) = -d\Phi(\lambda) \quad (22)$$

which ensures that the spectral representation produces real values. Substituting this identity and using the substitution

$$\mu = -\lambda \quad (23)$$

it is shown that

$$\overline{Z(t)} = \int_{\mathbb{R}} \overline{A_t(-\mu)} e^{i\mu t} d\Phi(\mu) \quad (24)$$

Since  $Z(t) = \overline{Z(t)}$ , comparison of the integrands (which are unique elements of  $L^2(F)$ ) yields

$$A_t(\lambda) = \overline{A_t(-\lambda)} \quad \text{for } F\text{-a.e. } \lambda \quad (25)$$

Equivalently, because the oscillatory function (12) is given by

$$\varphi_t(\lambda) = A_t(\lambda) e^{i\lambda t} \quad (26)$$

we have

$$\varphi_t(-\lambda) = \overline{\varphi_t(\lambda)} \quad \text{for } F\text{-a.e. } \lambda \quad (27)$$

Conversely, if

$$A_t(-\lambda) = \overline{A_t(\lambda)} \quad (28)$$

for  $F$ -a.e.  $\lambda$ , then the same substitution shows that

$$\overline{Z(t)} = Z(t) \quad \forall t \in \mathbb{R} \quad (29)$$

so  $Z$  is real-valued. This completes the proof.  $\square$

### Theorem 9

**[Existence]** If  $F$  is finite and  $(A_t)_{t \in \mathbb{R}}$  is measurable in  $t$  with

$$\int_{\mathbb{R}} |A_t(\lambda)|^2 dF(\lambda) < \infty \forall t \in \mathbb{R} \quad (30)$$

then there exists a complex orthogonal random measure  $\Phi$  with spectral measure  $F$  such that

$$Z(t) = \int_{\mathbb{R}} A_t(\lambda) e^{i\lambda t} d\Phi(\lambda) \quad (31)$$

is well-defined in  $L^2(\Omega)$  and has covariance  $R_Z$  as in (15) above.

**Proof.** The proof proceeds by constructing the stochastic integral using the standard extension procedure. First, the integral is defined for simple functions of the form

$$g(\lambda) = \sum_{j=1}^n c_j \mathbf{1}_{E_j}(\lambda) \quad (32)$$

where  $\{E_j\}$  are disjoint Borel sets with  $F(E_j) < \infty$  and  $c_j \in \mathbb{C}$ :

$$\int_{\mathbb{R}} g(\lambda) \Phi(d\lambda) := \sum_{j=1}^n c_j \Phi(E_j) \quad (33)$$

For such simple functions, the isometry property holds:

$$\begin{aligned} \mathbb{E} \left[ \left| \int_{\mathbb{R}} g(\lambda) \Phi(d\lambda) \right|^2 \right] &= \mathbb{E} \left[ \left| \sum_{j=1}^n c_j \Phi(E_j) \right|^2 \right] \\ &= \sum_{j=1}^n \sum_{k=1}^n c_j \bar{c}_k \mathbb{E}[\Phi(E_j) \overline{\Phi(E_k)}] \\ &= \sum_{j=1}^n |c_j|^2 F(E_j) \\ &= \int_{\mathbb{R}} |g(\lambda)|^2 dF(\lambda) \end{aligned} \quad (34)$$

Since simple functions are dense in  $L^2(F)$ , the integral is extended by continuity to all  $g \in L^2(F)$ . For each  $t$ , since the oscillatory function (12) is defined by

$$\varphi_t(\lambda) = A_t(\lambda) e^{i\lambda t} \quad (35)$$

and  $A_t \in L^2(F)$ ,  $\varphi_t \in L^2(F)$  holds. Therefore

$$Z(t) = \int_{\mathbb{R}} \varphi_t(\lambda) d\Phi(\lambda) \quad (36)$$

is well-defined in  $L^2(\Omega)$ . The covariance is computed as:

$$\begin{aligned} R_Z(t, s) &= \mathbb{E}[Z(t)\overline{Z(s)}] \\ &= \mathbb{E}\left[\int_{\mathbb{R}} \varphi_t(\lambda) d\Phi(\lambda) \int_{\mathbb{R}} \overline{\varphi_s(\mu)} d\overline{\Phi(\mu)}\right] \\ &= \int_{\mathbb{R}} \int_{\mathbb{R}} \varphi_t(\lambda) \overline{\varphi_s(\mu)} \mathbb{E}[d\Phi(\lambda) d\overline{\Phi(\mu)}] \\ &= \int_{\mathbb{R}} \varphi_t(\lambda) \overline{\varphi_s(\lambda)} dF(\lambda) \\ &= \int_{\mathbb{R}} A_t(\lambda) \overline{A_s(\lambda)} e^{i\lambda(t-s)} dF(\lambda) \end{aligned} \quad (37) \quad \square$$

### 3 Unitarily Time-Changed Stationary Processes

#### 3.1 Stationary processes

##### Definition 10

**[Cramér representation]** A zero-mean stationary process  $X$  with spectral measure  $F$  admits the sample path representation

$$X(t) = \int_{\mathbb{R}} e^{i\lambda t} \Phi(d\lambda) \quad (38)$$

which has covariance

$$R_X(t-s) = \int_{\mathbb{R}} e^{i\lambda(t-s)} dF(\lambda) \quad (39)$$

### 3.2 Stationary $\rightarrow$ oscillatory via $U_\theta$

#### Theorem 11

**[Unitary time change yields oscillatory process]** Let  $X$  be zero-mean stationary as in Definition 10. For scaling function  $\theta$  as in Definition 4, define

$$\begin{aligned} Z(t) &= (U_\theta X)(t) \\ &= \sqrt{\dot{\theta}(t)} X(\theta(t)) \end{aligned} \quad (40)$$

Then  $Z$  is a realization of an oscillatory process with oscillatory function

$$\varphi_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)} \quad (41)$$

gain function

$$A_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} \quad (42)$$

and covariance

$$\begin{aligned} R_Z(t, s) &= \mathbb{E}[Z(t)\overline{Z(s)}] \\ &= \mathbb{E}\left[\sqrt{\dot{\theta}(t)} X(\theta(t)) \overline{\sqrt{\dot{\theta}(s)} X(\theta(s))}\right] \\ &= \sqrt{\dot{\theta}(t)\dot{\theta}(s)} \mathbb{E}[X(\theta(t))\overline{X(\theta(s))}] \\ &= \sqrt{\dot{\theta}(t)\dot{\theta}(s)} R_X(\theta(t) - \theta(s)) \\ &= \sqrt{\dot{\theta}(t)\dot{\theta}(s)} \int_{\mathbb{R}} e^{i\lambda(\theta(t)-\theta(s))} dF(\lambda) \end{aligned} \quad (43)$$

**Proof.** Applying the unitary time change operator to the spectral representation of  $X(t)$ :

$$\begin{aligned} Z(t) &= (U_\theta X)(t) \\ &= \sqrt{\dot{\theta}(t)} X(\theta(t)) \\ &= \sqrt{\dot{\theta}(t)} \int_{\mathbb{R}} e^{i\lambda\theta(t)} d\Phi(\lambda) \\ &= \int_{\mathbb{R}} \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)} d\Phi(\lambda) \\ &= \int_{\mathbb{R}} \varphi_t(\lambda) d\Phi(\lambda) \end{aligned} \quad (44)$$

where

$$\varphi_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)} \quad (45)$$

To verify this constitutes an oscillatory representation according to Definition 7,  $\varphi_t(\lambda)$  has



the form  $A_t(\lambda) e^{i\lambda t}$ :

$$\begin{aligned}\varphi_t(\lambda) &= \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)} \\ &= \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} e^{i\lambda t} \\ &= A_t(\lambda) e^{i\lambda t}\end{aligned}\tag{46}$$

where

$$A_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)}\tag{47}$$

Since  $\dot{\theta}(t) \geq 0$  almost everywhere and  $\dot{\theta}(t) = 0$  only on sets of measure zero,  $A_t(\lambda)$  is well defined almost everywhere. Moreover,  $A_t \in L^2(F)$  for each  $t$  since:

$$\begin{aligned}\int_{\mathbb{R}} |A_t(\lambda)|^2 dF(\lambda) &= \int_{\mathbb{R}} \left| \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} \right|^2 dF(\lambda) \\ &= \int_{\mathbb{R}} \dot{\theta}(t) |e^{i\lambda(\theta(t)-t)}|^2 dF(\lambda) \\ &= \dot{\theta}(t) \int_{\mathbb{R}} dF(\lambda) \\ &= \dot{\theta}(t) F(\mathbb{R}) < \infty\end{aligned}\tag{48}$$

where  $|e^{i\alpha}| = 1$  for all real  $\alpha$  is used. The covariance (43) is computed by substituting the spectral representation and applying Fubini's theorem to interchange the order of operations.

(49)  $\square$

### Corollary 12

**[Evolutionary spectrum]** The evolutionary spectrum is

$$\begin{aligned}dF_t(\lambda) &= |A_t(\lambda)|^2 dF(\lambda) \\ &= \dot{\theta}(t) dF(\lambda)\end{aligned}\tag{50}$$

**Proof.** By definition of the evolutionary spectrum and using the gain function from Theorem 11:

$$\begin{aligned}dF_t(\lambda) &= |A_t(\lambda)|^2 dF(\lambda) \\ &= \left| \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} \right|^2 dF(\lambda) \\ &= \dot{\theta}(t) |e^{i\lambda(\theta(t)-t)}|^2 dF(\lambda) \\ &= \dot{\theta}(t) dF(\lambda)\end{aligned}\tag{51}$$

since

$$|e^{i\alpha}| = 1 \forall \alpha \in \mathbb{R}\tag{52} \quad \square$$

### 3.3 Covariance operator conjugation

#### Proposition 13

**[Operator conjugation]** Let

$$(T_K f)(t) := \int_{\mathbb{R}} K(|t-s|) f(s) ds \quad (53)$$

with stationary kernel

$$K(h) = \int_{\mathbb{R}} e^{i\lambda h} dF(\lambda) \quad (54)$$

Define the transformed kernel

$$K_{\theta}(s, t) := \sqrt{\dot{\theta}(t) \dot{\theta}(s)} K(|\theta(t) - \theta(s)|) \quad (55)$$

and corresponding integral covariance operator

$$(T_{K_{\theta}} f)(t) := \int_{\mathbb{R}} K_{\theta}(s, t) f(s) ds \quad (56)$$

Then

$$T_{K_{\theta}} = U_{\theta} T_K U_{\theta}^{-1} \quad (57)$$

on  $L^2_{\text{loc}}(\mathbb{R})$ .

**Proof.** For any  $g \in L^2_{\text{loc}}(\mathbb{R})$ , compute:

$$\begin{aligned} ((U_{\theta} T_K U_{\theta}^{-1}) g)(t) &= (U_{\theta} (T_K U_{\theta}^{-1} g))(t) \\ &= \sqrt{\dot{\theta}(t)} (T_K U_{\theta}^{-1} g)(\theta(t)) \\ &= \sqrt{\dot{\theta}(t)} \int_{\mathbb{R}} K(|\theta(t) - w|) (U_{\theta}^{-1} g)(w) dw \end{aligned} \quad (58)$$

Substitute  $w = \theta(s)$  with  $dw = \dot{\theta}(s) ds$ :

$$\begin{aligned} &= \sqrt{\dot{\theta}(t)} \int_{\mathbb{R}} K(|\theta(t) - \theta(s)|) \frac{g(s)}{\sqrt{\dot{\theta}(s)}} \dot{\theta}(s) ds \\ &= \sqrt{\dot{\theta}(t)} \int_{\mathbb{R}} K(|\theta(t) - \theta(s)|) g(s) \sqrt{\dot{\theta}(s)} ds \\ &= \int_{\mathbb{R}} \sqrt{\dot{\theta}(t) \dot{\theta}(s)} K(|\theta(t) - \theta(s)|) g(s) ds \\ &= \int_{\mathbb{R}} K_{\theta}(t, s) g(s) ds \\ &= (T_{K_{\theta}} g)(t) \end{aligned} \quad (59)$$

where

$$K_{\theta}(t, s) = \sqrt{\dot{\theta}(t) \dot{\theta}(s)} K(|\theta(t) - \theta(s)|) \quad (60)$$

Therefore

$$T_{K_{\theta}} = U_{\theta} T_K U_{\theta}^{-1} \quad (61) \quad \square$$

## 4 Sample Paths Live in $L^2_{\text{loc}}$

### Theorem 14

**[Sample paths in  $L^2_{\text{loc}}(\mathbb{R})$ ]** Let  $\{X(t)\}_{t \in \mathbb{R}}$  be a second-order stationary process with

$$\sigma^2 := \mathbb{E}[X(t)^2] < \infty \quad (62)$$

then, almost surely, every sample path  $t \mapsto X(\omega, t)$  belongs to  $L^2_{\text{loc}}(\mathbb{R})$ .

**Proof.** Fix any bounded interval  $[a, b]$  and consider the random variable

$$Y_{[a,b]} := \int_a^b X(t)^2 dt \quad (63)$$

By stationarity and Fubini's theorem:

$$\begin{aligned} \mathbb{E}[Y_{[a,b]}] &= \mathbb{E}\left[\int_a^b X(t)^2 dt\right] = \int_a^b \mathbb{E}[X(t)^2] dt \\ &= \int_a^b \sigma^2 dt \\ &= \sigma^2(b-a) < \infty \end{aligned} \quad (64)$$

By Markov's inequality, for any  $M > 0$ :

$$P(Y_{[a,b]} > M) \leq \frac{\mathbb{E}[Y_{[a,b]}]}{M} = \frac{\sigma^2(b-a)}{M} \quad (65)$$

Taking  $M \rightarrow \infty$ , the conclusion is

$$P(Y_{[a,b]} < \infty) = 1 \quad (66)$$

i.e., almost surely the sample path is square-integrable on  $[a, b]$ . Since  $\mathbb{R}$  is the countable union of bounded intervals:

$$\mathbb{R} = \bigcup_{n=1}^{\infty} [-n, n] \quad (67)$$

by countable subadditivity of probability:

$$P\left(\bigcap_{n=1}^{\infty} \left\{\int_{-n}^n X(t)^2 dt < \infty\right\}\right) = 1 \quad (68)$$

Now let  $K$  be any compact set. Then  $K$  is bounded, so

$$K \subseteq [-N, N] \quad (69)$$

for some  $N$ . Therefore:

$$\int_K X(t)^2 dt \leq \int_{-N}^N X(t)^2 dt < \infty \quad (70)$$

almost surely. This holds for every compact set  $K$ , so almost surely every sample path lies in  $L^2_{\text{loc}}(\mathbb{R})$ .  $\square$

## 5 Zero Localization and Hilbert–Pólya Scaffold

### 5.1 Zero localization measure

#### Definition 15

**[Zero localization measure]** Let  $Z$  be real-valued with  $Z \in C^1(\mathbb{R})$  having only simple zeros

$$Z(t_0) = 0 \Rightarrow \dot{Z}(t_0) \neq 0 \quad (71)$$

Define, for Borel  $B \subset \mathbb{R}$ ,

$$\mu(B) = \int_{\mathbb{R}} \mathbf{1}_B(t) \delta(Z(t)) |\dot{Z}(t)| dt \quad (72)$$

#### Theorem 16

**[Atomicity on the zero set]** For every  $\phi \in C_c^\infty(\mathbb{R})$ ,

$$\int_{\mathbb{R}} \phi(t) \delta(Z(t)) |\dot{Z}(t)| dt = \sum_{t_0: Z(t_0)=0} \phi(t_0) \quad (73)$$

hence

$$\mu(t) = \sum_{t_0: Z(t_0)=0} \delta_{t_0}(t) \quad (74)$$

**Proof.** Since all zeros of  $Z$  are simple and  $Z \in C^1(\mathbb{R})$ , by the inverse function theorem each zero  $t_0$  is isolated. Near each zero  $t_0$ ,  $Z$  is locally monotonic, so the one-dimensional change of variables formula for the Dirac delta can be applied. Specifically, near  $t_0$  where  $Z(t_0) = 0$  and  $\dot{Z}(t_0) \neq 0$ , locally

$$Z(t) = (t - t_0) \dot{Z}(t_0) + O((t - t_0)^2) \quad (75)$$

holds. The distributional identity for the Dirac delta under smooth changes of variables gives:

$$\delta(Z(t)) = \sum_{t_0: Z(t_0)=0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|} \quad (76)$$

Therefore:

$$\begin{aligned} \int_{\mathbb{R}} \phi(t) \delta(Z(t)) |\dot{Z}(t)| dt &= \int_{-\infty}^{\infty} \phi(t) |\dot{Z}(t)| \sum_{t_0: Z(t_0)=0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|} dt \\ &= \sum_{t_0: Z(t_0)=0} \int_{\mathbb{R}} \phi(t) \frac{|\dot{Z}(t)| \delta(t - t_0)}{|\dot{Z}(t_0)|} dt \\ &= \sum_{t_0: Z(t_0)=0} \frac{|\dot{Z}(t_0)|}{|\dot{Z}(t_0)|} \phi(t_0) \\ &= \sum_{t_0: Z(t_0)=0} \phi(t_0) \end{aligned} \quad (77)$$



This shows that  $\mu$  is the discrete measure

$$\mu(t) = \sum_{t_0: Z(t_0)=0} \delta_{t_0}(t) \quad (78)$$

assigning unit mass to each zero.  $\square$

## 5.2 Hilbert space on zeros and multiplication operator

### Definition 17

**[Hilbert space on the zero set]** Let  $\mathcal{H} = L^2(\mu)$  with inner product

$$\langle f, g \rangle = \int_{-\infty}^{\infty} f(t) \overline{g(t)} d\mu(t) \quad (79)$$

### Proposition 18

**[Atomic structure]** Let

$$\mu = \sum_{t_0: Z(t_0)=0} \delta_{t_0} \quad (80)$$

then

$$\mathcal{H} \cong \left\{ f: \{t_0: Z(t_0)=0\} \rightarrow \mathbb{C}: \sum_{t_0: Z(t_0)=0} |f(t_0)|^2 < \infty \right\} \cong \ell^2 \quad (81)$$

with orthonormal basis  $\{e_{t_0}\}_{t_0: Z(t_0)=0}$  where

$$e_{t_0}(t_1) = \delta_{t_0}(t_1) \quad (82)$$

**Proof.** By the atomic form of  $\mu$ , for any  $f \in L^2(\mu)$ :

$$\|f\|_{\mathcal{H}}^2 = \int |f(t)|^2 d\mu(t) \quad (83)$$

$$= \int |f(t)|^2 \sum_{t_0: Z(t_0)=0} \delta_{t_0}(t) \quad (84)$$

$$= \sum_{t_0: Z(t_0)=0} |f(t_0)|^2 \quad (85)$$

This shows the isomorphism with  $\ell^2$  where the functions  $e_{t_0}$  defined by

$$e_{t_0}(t_1) = \delta_{t_0}(t_1) \quad (86)$$

satisfy the relations

$$\begin{aligned} \langle e_{t_0}, e_{t_1} \rangle &= \int e_{t_0}(t) \overline{e_{t_1}(t)} d\mu(t) \\ &= \sum_{t: Z(t)=0} \delta_{t_0}(t) \delta_{t_1}(t) \\ &= \delta_{t_0}(t_1) \\ &= \delta_{t_1}(t_0) \end{aligned} \quad (87)$$

thus forming an orthonormal set. Thus, any  $f(t) \in \mathcal{H}$  can be written as

$$f(t) = \sum_{t_0: Z(t_0)=0} f(t_0) e_{t_0}(t) \quad (88)$$

proving they form a basis.  $\square$

#### Definition 19

**[Multiplication operator]** Define the linear operator

$$L: \mathcal{D}(L) \subset \mathcal{H} \rightarrow \mathcal{H} \quad (89)$$

by

$$(L f)(t) = t f(t) \quad (90)$$

on the support of  $\mu$  with domain

$$\mathcal{D}(L) := \left\{ f \in \mathcal{H}: \int |t f(t)|^2 \mu(dt) < \infty \right\} \quad (91)$$

#### Theorem 20

**[Self-adjointness and spectrum]**  $L$  is self-adjoint on  $\mathcal{H}$  and has pure point, simple spectrum

$$\sigma(L) = \overline{\{t \in \mathbb{R}: Z(t) = 0\}} \quad (92)$$

with eigenvalues  $\lambda = t_0$  for each zero  $t_0$  and corresponding eigenvectors  $e_{t_0}$ .

**Proof.** First, self-adjointness is verified. For  $f, g \in \mathcal{D}(L)$ :

$$\begin{aligned} \langle L f, g \rangle &= \int (L f)(t) \overline{g(t)} d\mu(t) \\ &= \int t f(t) \overline{g(t)} d\mu(t) \\ &= \int f(t) \overline{t g(t)} d\mu(t) \\ &= \int f(t) \overline{(L g)(t)} d\mu(t) \\ &= \langle f, L g \rangle \end{aligned} \quad (93)$$

Thus  $L$  is symmetric and acts as

$$(L f)(t_0) = t_0 f(t_0) \quad (94)$$

for each  $t_0$  in the atomic representation where

$$Z(t_0) = 0 \quad (95)$$

This is unitarily equivalent to the diagonal operator on  $\ell^2$  with diagonal entries

$$\{t_0: Z(t_0) = 0\} \quad (96)$$

Such diagonal operators are self-adjoint. For the spectrum calculation:

$$L e_{t_0} = t_0 e_{t_0} \forall \{t_0: Z(t_0) = 0\} \quad (97)$$

holds, so each  $t_0$  is an eigenvalue of  $L$  with eigenvector  $e_{t_0}$  and since  $\{e_{t_0}\}$  forms an orthonormal basis,  $L$  has pure point spectrum. The spectrum of a diagonal operator equals the closure of the set of diagonal entries, hence

$$\sigma(L) = \overline{\{t_0: Z(t_0) = 0\}} \quad (98)$$

The eigenvalues are simple.  $\square$

**Remark 21. [Operator scaffold]** The construction

$$\text{stationary } X \xrightarrow{U_\theta} \text{oscillatory } Z \xrightarrow{\mu = \delta(Z)|\dot{Z}| dt} L^2(\mu) \xrightarrow{L:t \cdot} (L, \sigma(L)) \quad (99)$$

produces a concrete self-adjoint operator whose eigenvalues equal the zero set of  $Z$  and whose spectrum equals the closure of the zero set, determined by the choice of time-change  $\theta$  and spectral measure  $F$ . This provides an explicit realization consistent with Hilbert–Pólya approaches to encoding arithmetic information in operator spectra.

### 5.3 Regularity and Simplicity of The Zeros of $Z(t)$

#### Definition 22

**[Regularity and simplicity]** Assume  $Z \in C^1(\mathbb{R})$  and every zero is simple:

$$Z(t_0) = 0 \Rightarrow \dot{Z}(t_0) \neq 0 \quad (100)$$

#### Lemma 23

**[Local finiteness and delta decomposition]** Under Definition 22, zeros are locally finite and

$$\delta(Z(t)) = \sum_{t_0: Z(t_0)=0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|} \quad (101)$$

whence

$$\mu = \sum_{t_0: Z(t_0)=0} \delta_{t_0} \quad (102)$$

**Proof.** Since  $Z \in C^1(\mathbb{R})$  and  $\dot{Z}(t_0) \neq 0$  at each zero  $t_0$ , the inverse function theorem implies that  $Z$  is locally invertible near each zero. Specifically, there exists a neighborhood  $U_{t_0}$  of  $t_0$  such that  $Z|_{U_{t_0}}$  is strictly monotonic and invertible.

This implies zeros are isolated: if  $Z(t_0) = 0$  and  $\dot{Z}(t_0) \neq 0$ , then there exists  $\epsilon > 0$  such that  $Z(t) \neq 0$  for  $0 < |t - t_0| < \epsilon$ . Therefore zeros are locally finite (finitely many in any bounded interval).

For the distributional identity, the one-dimensional change of variables formula for the Dirac delta is considered. If  $g: I \rightarrow \mathbb{R}$  is  $C^1$  on interval  $I$  with  $\dot{g}(x) \neq 0$  for all  $x \in I$ , then

$$\delta(g(x)) = \sum_{x_0: g(x_0)=0} \frac{\delta(x - x_0)}{|\dot{g}(x_0)|} \quad (103)$$

Applying this locally around each zero  $t_0$  of  $Z$ , and since zeros are isolated, the local results can be patched together to obtain the global identity:

$$\delta(Z(t)) = \sum_{t_0: Z(t_0)=0} \frac{\delta(t - t_0)}{|\dot{Z}(t_0)|} \quad (104)$$

Consequently:

$$\begin{aligned} d\mu(t) &= \delta(Z(t)) |\dot{Z}(t)| dt \\ &= \sum_{t_0: Z(t_0)=0} \frac{|\dot{Z}(t)|}{|\dot{Z}(t_0)|} \delta(t - t_0) dt \\ &= \sum_{t_0: Z(t_0)=0} \delta_{t_0}(dt) \end{aligned} \quad (105)$$

where the last equality uses the fact that

$$\frac{|\dot{Z}(t_0)|}{|\dot{Z}(t_0)|} = 1 \quad (106)$$

when evaluating at  $t = t_0$ . □

## 5.4 Kac-Rice Formula For The Expected Zero Count

### Theorem 24

**(Kac-Rice Formula for Zero Crossings)** Let  $Z(t)$  be a centered Gaussian process on  $[a, b]$  with covariance  $K(s, t) = \mathbb{E}[Z(s)Z(t)]$  then the expected number of zeros in  $[a, b]$  is

$$\mathbb{E}[N_{[a,b]}] = \int_a^b \sqrt{\frac{2}{\pi}} \frac{\sqrt{K(t, t) K_{\dot{Z}}(t, t) - K_{Z, \dot{Z}}(t, t)^2}}{K(t, t)} dt \quad (107)$$

where

$$K(t, t) = \mathbb{E}[Z(t)^2] \quad (108)$$

$$K_{\dot{Z}}(t, t) = -\partial_s^2 \partial_t K(s, t)|_{s=t} \quad (109)$$

and

$$K_{Z, \dot{Z}}(t, t) = \partial_s K(s, t)|_{s=t} \quad (110)$$

**Proof.**

The exact zero counting function is

$$N_{[a,b]} = \int_a^b \delta(Z(t)) |\dot{Z}(t)| dt \quad (111)$$



so

$$\begin{aligned}\mathbb{E}[N_{[a,b]}] &= \int_a^b \mathbb{E}[\delta(Z(t))|\dot{Z}(t)|] dt \\ &= \int_a^b \int_{-\infty}^{\infty} |v| p_{Z,\dot{Z}}(0,v) dv dt\end{aligned}\tag{112}$$

The vector  $(Z(t), \dot{Z}(t))$  is bivariate Gaussian with covariance matrix

$$\Sigma = \begin{pmatrix} K(t,t) & K_{Z,\dot{Z}}(t,t) \\ K_{Z,\dot{Z}}(t,t) & K_{\dot{Z}}(t,t) \end{pmatrix}\tag{113}$$

whose determinant is given by

$$\det \Sigma = K(t,t) K_{\dot{Z}}(t,t) - K_{Z,\dot{Z}}(t,t)^2\tag{114}$$

the inverse of which satisfies

$$\Sigma_{22}^{-1} = \frac{K(t,t)}{\det \Sigma}\tag{115}$$

yielding

$$p_{Z,\dot{Z}}(0,v) = \frac{1}{\sqrt{2\pi K(t,t)}} \cdot \frac{\exp\left(-\frac{K(t,t)v^2}{2\det \Sigma}\right)}{\sqrt{2\pi \det \Sigma / K(t,t)}}\tag{116}$$

which factorizes as  $p_Z(0) \cdot p_{\dot{Z}|Z}(v|0)$  where

$$p_Z(0) = \frac{1}{\sqrt{2\pi K(t,t)}}\tag{117}$$

and

$$\dot{Z}|Z=0 \sim \mathcal{N}(0, \det \Sigma / K(t,t))\tag{118}$$

For zero-mean Gaussian  $Y \sim \mathcal{N}(0, \sigma^2)$ , direct integration gives

$$\begin{aligned}\mathbb{E}[|Y|] &= 2 \int_0^{\infty} \frac{y}{\sqrt{2\pi\sigma^2}} e^{-y^2/(2\sigma^2)} dy \\ &= \frac{2\sigma}{\sqrt{2\pi}} \int_0^{\infty} e^{-u} du \\ &= \sqrt{\frac{2}{\pi}} \sigma\end{aligned}\tag{119}$$

so that combining results yields

$$\begin{aligned}\int_{-\infty}^{\infty} |v| p_{Z,\dot{Z}}(0,v) dv &= \frac{\sqrt{\frac{2}{\pi}} \sqrt{\frac{\det \Sigma}{K(t,t)}}}{\sqrt{2\pi K(t,t)}} \\ &= \sqrt{\frac{2}{\pi}} \frac{\sqrt{\det \Sigma}}{K(t,t)}\end{aligned}\tag{120} \quad \square$$

**Theorem 25**

**[Expected Zero-Counting Function]** Let  $\theta \in \mathcal{F}$  and let

$$K(t, s) = \text{cov}(Z(t), Z(s)) \quad (121)$$

be twice differentiable at  $s=0$  and  $t=0$  then expected number of zeros of the process  $Z(t)$  in  $[a, b]$  is

$$\mathbb{E}[N_{[a,b]}] = \sqrt{-K(0)} (\theta(b) - \theta(a)) \quad (122)$$

**Proof.** The covariance function of the time-changed process is

$$K_\theta(s, t) = \text{cov}(Z(t), Z(s)) = \sqrt{\theta(s)\theta(t)} K(|\theta(t) - \theta(s)|) \quad (123)$$

For the zero-crossing analysis, consider the normalized process. By the Kac-Rice formula:

$$\mathbb{E}[N_{[a,b]}] = \int_a^b \sqrt{-\lim_{s \rightarrow t} \frac{\partial^2}{\partial s \partial t} K_\theta(s, t)} dt \quad (124)$$

Computing the mixed partial derivative:

$$\frac{\partial}{\partial t} K_\theta(s, t) = \frac{1}{2} \frac{\dot{\theta}(t)}{\sqrt{\theta(t)}} \sqrt{\theta'(s)} K(|\theta(t) - \theta(s)|) \quad (125)$$

$$+ \sqrt{\theta(s)} \sqrt{\theta(t)} \dot{K}(|\theta(t) - \theta(s)|) \text{sgn}(\theta(t) - \theta(s)) \dot{\theta}(t) \quad (126)$$

Taking the limit as  $s \rightarrow t$  and using the fact that  $\dot{K}(0) = 0$  for stationary processes:

$$\begin{aligned} \lim_{s \rightarrow t} \frac{\partial^2}{\partial s \partial t} K_\theta(s, t) &= \dot{\theta}(s) \dot{\theta}(t) \ddot{K}(0) \\ &= \dot{\theta}(t)^2 \ddot{K}(0) \end{aligned} \quad (127)$$

Substituting into the Kac-Rice formula we have

$$\begin{aligned} \mathbb{E}[N_{[a,b]}] &= \int_a^b \sqrt{-\dot{\theta}(t)^2 \ddot{K}(0)} dt \\ &= \sqrt{-\ddot{K}(0)} \int_a^b \dot{\theta}(t) dt \\ &= \sqrt{-\ddot{K}(0)} (\theta(b) - \theta(a)) \end{aligned} \quad (128)$$

since  $\dot{\theta}(t) \geq 0$  almost everywhere. □