

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_θ is constructed for absolutely continuous, strictly increasing time reparametrizations θ , acting on functions that are square-integrable over σ -compact sets. Applying U_θ 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 $L^2_{\sigma\text{-comp}}(\mathbb{R})$, making the operator applicable to typical realizations. A zero-localization measure $\mu(dt) = \delta(Z(t)) |Z'(t)| dt$ 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 pure point, simple spectrum equal to the zero 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 σ -compact sets and local L^2

Definition 1

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

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

with each K_n compact.

Definition 2

[Square-integrability on σ -compact sets] Define

$$L^2_{\sigma\text{-comp}}(\mathbb{R}) := \left\{ f: \mathbb{R} \rightarrow \mathbb{C}: \int_U |f(t)|^2 dt < \infty \text{ for every } \sigma\text{-compact } U \subseteq \mathbb{R} \right\} \quad (2)$$

Remark 3. Every bounded measurable set in \mathbb{R} is σ -compact; hence $L^2_{\sigma\text{-comp}}(\mathbb{R})$ 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 $\theta: \mathbb{R} \rightarrow \mathbb{R}$ 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 θ maps σ -compact sets to σ -compact sets. Define, for f measurable,

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

Proposition 5

[Inverse map] The inverse map is given by

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

which is well-defined almost everywhere on every σ -compact set.

Proof. Since $\dot{\theta}(t) = 0$ only on sets of measure zero, and θ^{-1} maps sets of measure zero to sets of measure zero (as 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 σ -compact set, which suffices for defining an element of $L^2_{\sigma\text{-comp}}(\mathbb{R})$. \square

Theorem 6

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

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

Moreover, U_θ^{-1} is the inverse of U_θ on $L^2_{\sigma\text{-comp}}(\mathbb{R})$.

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

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

Since θ 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 θ maps σ -compact sets to σ -compact sets, as t ranges over U , $s = \theta(t)$ ranges over $\theta(U)$, which is σ -compact. Therefore:

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

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

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

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

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

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

$$U_\theta U_\theta^{-1} = U_\theta^{-1} U_\theta = I \tag{11}$$

on $L^2_{\sigma\text{-comp}}(\mathbb{R})$. □

Theorem 7

[Unitarity on $L^2(\mathbb{R})$] $U_\theta: L^2(\mathbb{R}) \rightarrow L^2(\mathbb{R})$ is unitary:

$$\int_{\mathbb{R}} |(U_\theta f)(t)|^2 dt = \int_{\mathbb{R}} |f(s)|^2 ds \tag{12}$$

and U_θ^{-1} is its inverse.

Proof. For $f \in L^2(\mathbb{R})$, we have:

$$\int_{\mathbb{R}} |(U_\theta f)(t)|^2 dt = \int_{\mathbb{R}} \dot{\theta}(t) |f(\theta(t))|^2 dt \tag{13}$$

By the change of variables

$$s = \theta(t) \tag{14}$$

with

$$ds = \dot{\theta}(t) dt \tag{15}$$

, and since $\theta: \mathbb{R} \rightarrow \mathbb{R}$ is bijective:

$$\int_{\mathbb{R}} \dot{\theta}(t) |f(\theta(t))|^2 dt = \int_{\mathbb{R}} |f(s)|^2 ds \tag{16}$$

The inverse relationship follows from the same computation as in Theorem 6, applied globally. \square

2 Oscillatory Processes (Priestley)

Definition 8

[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

$$\varphi_t(\lambda) := A_t(\lambda) e^{i\lambda t} \quad (17)$$

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

$$\begin{aligned} Z(t) &= \int_{\mathbb{R}} \varphi_t(\lambda) d\Phi(\lambda) \\ &= \int_{\mathbb{R}} A_t(\lambda) e^{i\lambda t} d\Phi(\lambda) \end{aligned} \quad (18)$$

where Φ is a complex orthogonal random measure with spectral measure F , that is,

$$\mathbb{E}[\Phi(d\lambda) \overline{\Phi(d\mu)}] = \delta(\lambda - \mu) dF(\lambda) \quad (19)$$

and corresponding covariance kernel

$$\begin{aligned} R_Z(t, s) &= \mathbb{E}[Z(t) \overline{Z(s)}] \\ &= \int_{\mathbb{R}} A_t(\lambda) \overline{A_s(\lambda)} e^{i\lambda(t-s)} dF(\lambda) \\ &= \int_{\mathbb{R}} \phi_t(\lambda) \overline{\phi_s(\lambda)} dF(\lambda) \end{aligned} \quad (20)$$

Remark 9. [Real-valuedness] Z is real-valued if and only if

$$A_t(-\lambda) = \overline{A_t(\lambda)} \quad (21)$$

for F -a.e. λ , equivalently

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

for F -a.e. λ . TODO: this needs to be recast as a theorem

Theorem 10

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

$$\int_{\mathbb{R}} |A_t(\lambda)|^2 dF(\lambda) < \infty \forall t \in \mathbb{R} \quad (23)$$

then there exists a complex orthogonal random measure Φ with spectral measure F such that

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

is well-defined in $L^2(\Omega)$ and has covariance R_Z as in (20) above.

Proof. We construct the stochastic integral using the standard extension procedure. First, define the integral for simple functions of the form

$$g(\lambda) = \sum_{j=1}^n c_j 1_{E_j}(\lambda) \quad (25)$$

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

$$\int_{\mathbb{R}} g(\lambda) \Phi(d\lambda) := \sum_{j=1}^n c_j \Phi(E_j) \quad (26)$$

For such simple functions, the isometry property holds:

$$\begin{aligned} \mathbb{E} \left[\left| \int_{\mathbb{R}} g(\lambda) \Phi(d\lambda) \right|^2 \right] &= \mathbb{E} \left[\left| \sum_{j=1}^n c_j \Phi(E_j) \right|^2 \right] \\ &= \sum_{j=1}^n \sum_{k=1}^n c_j \bar{c}_k \mathbb{E}[\Phi(E_j) \overline{\Phi(E_k)}] \\ &= \sum_{j=1}^n |c_j|^2 F(E_j) \\ &= \int_{\mathbb{R}} |g(\lambda)|^2 dF(\lambda) \end{aligned} \quad (27)$$

Since simple functions are dense in $L^2(F)$, we extend by continuity to all $g \in L^2(F)$. For each t , since

$$\varphi_t(\lambda) = A_t(\lambda) e^{i\lambda t} \quad (28)$$

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

$$Z(t) = \int_{\mathbb{R}} \varphi_t(\lambda) \Phi(d\lambda) \quad (29)$$

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

$$\begin{aligned} R_Z(t, s) &= \mathbb{E}[Z(t) \overline{Z(s)}] \\ &= \mathbb{E}\left[\int_{\mathbb{R}} \varphi_t(\lambda) \Phi(d\lambda) \int_{\mathbb{R}} \overline{\varphi_s(\mu)} \overline{\Phi(d\mu)}\right] \\ &= \int_{\mathbb{R}} \int_{\mathbb{R}} \varphi_t(\lambda) \overline{\varphi_s(\mu)} \mathbb{E}[\Phi(d\lambda) \overline{\Phi(d\mu)}] \\ &= \int_{\mathbb{R}} \varphi_t(\lambda) \overline{\varphi_s(\lambda)} dF(\lambda) \\ &= \int_{\mathbb{R}} A_t(\lambda) \overline{A_s(\lambda)} e^{i\lambda(t-s)} dF(\lambda) \end{aligned} \quad (30) \quad \square$$

3 Stationary Processes and Time Change

3.1 Stationary processes

Definition 11

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

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

which has covariance

$$R_X(t-s) = \int_{\mathbb{R}} e^{i\lambda(t-s)} dF(\lambda) \quad (32)$$

3.2 Stationary \rightarrow oscillatory via U_θ

Theorem 12

[Time change yields oscillatory process] Let X be zero-mean stationary as in Definition 11. For θ as in Definition 4, define

$$\begin{aligned} Z(t) &= (U_\theta X)(t) \\ &= \sqrt{\dot{\theta}(t)} X(\theta(t)) \end{aligned} \quad (33)$$

Then Z is oscillatory with oscillatory function

$$\varphi_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)} \quad (34)$$

, gain function

$$A_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} \quad (35)$$

, and covariance

$$R_Z(t, s) = \int_{\mathbb{R}} \sqrt{\dot{\theta}(t) \dot{\theta}(s)} e^{i\lambda(\theta(t)-\theta(s))} dF(\lambda) \quad (36)$$

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

$$\begin{aligned} Z(t) &= (U_\theta X)(t) \\ &= \sqrt{\dot{\theta}(t)} X(\theta(t)) \\ &= \sqrt{\dot{\theta}(t)} \int_{\mathbb{R}} e^{i\lambda\theta(t)} d\Phi(\lambda) \\ &= \int_{\mathbb{R}} \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)} d\Phi(\lambda) \\ &= \int_{\mathbb{R}} \varphi_t(\lambda) d\Phi(\lambda) \end{aligned} \quad (37)$$

where

$$\varphi_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)} \quad (38)$$

To verify this constitutes an oscillatory representation according to Definition 8, we must write $\varphi_t(\lambda)$ in the form $A_t(\lambda) e^{i\lambda t}$:

$$\begin{aligned} \varphi_t(\lambda) &= \sqrt{\dot{\theta}(t)} e^{i\lambda\theta(t)} \\ &= \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} e^{i\lambda t} \\ &= A_t(\lambda) e^{i\lambda t} \end{aligned} \quad (39)$$

where

$$A_t(\lambda) = \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} \quad (40)$$

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:

$$\begin{aligned} \int_{\mathbb{R}} |A_t(\lambda)|^2 dF(\lambda) &= \int_{\mathbb{R}} \left| \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} \right|^2 dF(\lambda) \\ &= \int_{\mathbb{R}} \dot{\theta}(t) |e^{i\lambda(\theta(t)-t)}|^2 dF(\lambda) \\ &= \dot{\theta}(t) \int_{\mathbb{R}} dF(\lambda) \\ &= \dot{\theta}(t) F(\mathbb{R}) < \infty \end{aligned} \quad (41)$$

where we used $|e^{i\alpha}| = 1$ for all real α . The covariance is computed as:

$$\begin{aligned} R_Z(t, s) &= \mathbb{E}[Z(t)\overline{Z(s)}] \\ &= \mathbb{E}\left[\sqrt{\dot{\theta}(t)} X(\theta(t)) \sqrt{\dot{\theta}(s)} \overline{X(\theta(s))}\right] \\ &= \sqrt{\dot{\theta}(t)\dot{\theta}(s)} \mathbb{E}[X(\theta(t))\overline{X(\theta(s))}] \\ &= \sqrt{\dot{\theta}(t)\dot{\theta}(s)} R_X(\theta(t) - \theta(s)) \\ &= \sqrt{\dot{\theta}(t)\dot{\theta}(s)} \int_{\mathbb{R}} e^{i\lambda(\theta(t)-\theta(s))} dF(\lambda) \end{aligned} \quad (42)$$

□

Corollary 13

[Evolutionary spectrum] The evolutionary spectrum is

$$\begin{aligned} dF_t(\lambda) &= |A_t(\lambda)|^2 dF(\lambda) \\ &= \dot{\theta}(t) dF(\lambda) \end{aligned} \quad (43)$$

Proof. By definition of the evolutionary spectrum and using the gain function from Theorem 12:

$$\begin{aligned} dF_t(\lambda) &= |A_t(\lambda)|^2 dF(\lambda) \\ &= \left| \sqrt{\dot{\theta}(t)} e^{i\lambda(\theta(t)-t)} \right|^2 dF(\lambda) \\ &= \dot{\theta}(t) |e^{i\lambda(\theta(t)-t)}|^2 dF(\lambda) \\ &= \dot{\theta}(t) dF(\lambda) \end{aligned} \quad (44)$$

since

$$|e^{i\alpha}| = 1 \forall \alpha \in \mathbb{R} \quad (45) \quad \square$$

3.3 Covariance operator conjugation

Proposition 14

[Operator conjugation] Let

$$(T_K f)(t) := \int_{\mathbb{R}} K(|t-s|) f(s) \, ds \quad (46)$$

with stationary kernel

$$K(h) = \int_{\mathbb{R}} e^{i\lambda h} \, dF(\lambda) \quad (47)$$

Define the transformed kernel

$$K_{\theta}(s, t) := \sqrt{\dot{\theta}(t) \dot{\theta}(s)} K(|\theta(t) - \theta(s)|) \quad (48)$$

and corresponding integral covariance operator

$$(T_{K_{\theta}} f)(t) := \int_{\mathbb{R}} K_{\theta}(s, t) f(s) \, ds \quad (49)$$

Then

$$T_{K_{\theta}} = U_{\theta} T_K U_{\theta}^{-1} \quad (50)$$

on $L^2_{\sigma\text{-comp}}(\mathbb{R})$.

Proof. For any $g \in L^2_{\sigma\text{-comp}}(\mathbb{R})$, we transform the integral operator from coordinates (r, w) to coordinates (t, s) by applying both coordinate transformations

$$r = \theta(t) \quad (51)$$

and

$$w = \theta(s) \quad (52)$$

by simultaneously substitution with Jacobians

$$dr = \dot{\theta}(t) \, dt \quad (53)$$

and

$$dw = \dot{\theta}(s) \, ds \quad (54)$$

The operator T_K in (r, w) coordinates is:

$$(T_K f)(r) = \int_{\mathbb{R}} K(|r - w|) f(w) dw \quad (55)$$

Under the simultaneous transformation $r = \theta(t)$ and $w = \theta(s)$:

$$\begin{aligned} ((U_\theta T_K U_\theta^{-1}) g)(t) &= \sqrt{\dot{\theta}(t) \dot{\theta}(s)} \int_{\mathbb{R}} K(|\theta(t) - \theta(s)|) (U_\theta^{-1} g)(\theta(s)) \frac{\dot{\theta}(s)}{\sqrt{\dot{\theta}(s)}} ds \\ &= \sqrt{\dot{\theta}(t) \dot{\theta}(s)} \int_{\mathbb{R}} K(|\theta(t) - \theta(s)|) \frac{g(s)}{\sqrt{\dot{\theta}(s)}} \sqrt{\dot{\theta}(s)} ds \\ &= \sqrt{\dot{\theta}(t) \dot{\theta}(s)} \int_{\mathbb{R}} K(|\theta(t) - \theta(s)|) g(s) ds \\ &= \int_{\mathbb{R}} \sqrt{\dot{\theta}(t) \dot{\theta}(s)} K(|\theta(t) - \theta(s)|) g(s) ds \\ &= \int_{\mathbb{R}} K_\theta(t, s) g(s) ds \\ &= (T_{K_\theta} g)(t) \end{aligned} \quad (56)$$

where

$$K_\theta(t, s) = \sqrt{\dot{\theta}(t) \dot{\theta}(s)} K(|\theta(t) - \theta(s)|) \quad (57)$$

Therefore

$$T_{K_\theta} = U_\theta T_K U_\theta^{-1} \quad (58) \quad \square$$

4 Sample Paths Live in $L^2_{\sigma\text{-comp}}$

Theorem 15

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

$$\sigma^2 := \mathbb{E}[X(t)^2] < \infty \quad (59)$$

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

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

$$Y_{[a, b]} := \int_a^b X(t)^2 dt \quad (60)$$

By stationarity and Fubini's theorem:

$$\begin{aligned}\mathbb{E}[Y_{[a,b]}] &= \mathbb{E}\left[\int_a^b X(t)^2 dt\right] = \int_a^b \mathbb{E}[X(t)^2] dt \\ &= \int_a^b \sigma^2 dt \\ &= \sigma^2(b-a) < \infty\end{aligned}\tag{61}$$

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

$$P(Y_{[a,b]} > M) \leq \frac{\mathbb{E}[Y_{[a,b]}]}{M} = \frac{\sigma^2(b-a)}{M}\tag{62}$$

Taking $M \rightarrow \infty$, we conclude

$$P(Y_{[a,b]} < \infty) = 1\tag{63}$$

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

$$\mathbb{R} = \bigcup_{n=1}^{\infty} [-n, n]\tag{64}$$

by countable subadditivity of probability:

$$P\left(\bigcap_{n=1}^{\infty} \left\{\int_{-n}^n X(t)^2 dt < \infty\right\}\right) = 1\tag{65}$$

Now let U be any σ -compact set. Then

$$U = \bigcup_{m=1}^{\infty} K_m\tag{66}$$

where each K_m is compact. Each compact set K_m is bounded, so

$$K_m \subseteq [-N_m, N_m]\tag{67}$$

for some N_m . Therefore:

$$\begin{aligned}\int_U X(t)^2 dt &= \int_{\bigcup_{m=1}^{\infty} K_m} X(t)^2 dt \\ &\leq \sum_{m=1}^{\infty} \int_{K_m} X(t)^2 dt \\ &\leq \sum_{m=1}^{\infty} \int_{-N_m}^{N_m} X(t)^2 dt\end{aligned}\tag{68}$$

Since each integral

$$\int_{-N_m}^{N_m} X(t)^2 dt < \infty \quad (69)$$

almost surely, and the sum of countably many finite terms is finite, we have

$$\int_U X(t)^2 dt < \infty \quad (70)$$

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

5 Zero Localization and Hilbert–Pólya Scaffold

5.1 Zero localization measure

Definition 16

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

$$Z(t_0) = 0 \Rightarrow Z'(t_0) \neq 0 \quad (71)$$

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

$$\mu(B) := \int_{\mathbb{R}} 1_B(t) \delta(Z(t)) |Z'(t)| dt \quad (72)$$

Theorem 17

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

$$\int_{\mathbb{R}} \phi(t) \delta(Z(t)) |Z'(t)| dt = \sum_{t_0: Z(t_0)=0} \phi(t_0) \quad (73)$$

hence

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

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 we can apply the one-dimensional change of variables formula for the Dirac delta.

Specifically, near t_0 where $Z(t_0) = 0$ and $Z'(t_0) \neq 0$, we have locally

$$Z(t) = (t - t_0) Z'(t_0) + O((t - t_0)^2) \quad (75)$$

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

$$\delta(Z(t)) = \sum_{t_0: Z(t_0)=0} \frac{\delta(t-t_0)}{|Z'(t_0)|} \quad (76)$$

Therefore:

$$\begin{aligned} \int_{\mathbb{R}} \phi(t) \delta(Z(t)) |Z'(t)| dt &= \int_{\mathbb{R}} \phi(t) |Z'(t)| \sum_{t_0: Z(t_0)=0} \frac{\delta(t-t_0)}{|Z'(t_0)|} dt \\ &= \sum_{t_0: Z(t_0)=0} \int_{\mathbb{R}} \phi(t) \frac{|Z'(t)| \delta(t-t_0)}{|Z'(t_0)|} dt \\ &= \sum_{t_0: Z(t_0)=0} \frac{|Z'(t_0)| \phi(t_0)}{|Z'(t_0)|} \\ &= \sum_{t_0: Z(t_0)=0} \phi(t_0) \end{aligned} \quad (77)$$

This shows that μ is the discrete measure

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

assigning unit mass to each zero. □

5.2 Hilbert space on zeros and multiplication operator

Definition 18

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

$$\langle f, g \rangle = \int f(t) \overline{g(t)} \mu(dt) \quad (79)$$

Proposition 19

[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 μ , for any $f \in L^2(\mu)$:

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

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

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

This shows the isomorphism with ℓ^2 . The functions e_{t_0} defined by

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

satisfy:

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

so they form an orthonormal set. Any $f \in \mathcal{H}$ can be written as

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

proving they form a basis. □

Definition 20

[Multiplication operator] Define $L: \mathcal{D}(L) \subset \mathcal{H} \rightarrow \mathcal{H}$ by

$$(L f)(t) = t f(t) \quad (89)$$

on $\text{supp}(\mu)$ with domain

$$\mathcal{D}(L) := \left\{ f \in \mathcal{H}: \int |t f(t)|^2 \mu(dt) < \infty \right\} \quad (90)$$

Theorem 21

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

$$\sigma(L) = \{t \in \mathbb{R}: Z(t) = 0\} \quad (91)$$

with eigenvalues $\lambda = t_0$ and eigenvectors e_{t_0} .

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

$$\begin{aligned}
\langle Lf, g \rangle &= \int (Lf)(t) \overline{g(t)} \mu(dt) \\
&= \int t f(t) \overline{g(t)} \mu(dt) \\
&= \int f(t) \overline{t g(t)} \mu(dt) \\
&= \int f(t) \overline{(Lg)(t)} \mu(dt) \\
&= \langle f, Lg \rangle
\end{aligned} \tag{92}$$

Thus L is symmetric and acts as

$$(Lf)(t_0) = t_0 f(t_0) \tag{93}$$

for each t_0 in the atomic representation where $Z(t_0) = 0$. This is unitarily equivalent to the diagonal operator on ℓ^2 with diagonal entries $\{t_0: Z(t_0) = 0\}$. Such diagonal operators are self-adjoint. For the spectrum calculation: We have

$$L e_{t_0} = t_0 e_{t_0} \tag{94}$$

so each t_0 where $Z(t_0) = 0$ is an eigenvalue of L with eigenvector e_{t_0} . Since $\{e_{t_0}\}$ forms an orthonormal basis, L has pure point spectrum. To show there are no other spectral points, suppose $\lambda \notin \{t_0: Z(t_0) = 0\}$. Then for any $f \in \mathcal{D}(L)$, $(L - \lambda I)f$ has components

$$((L - \lambda I)f)(t_0) = (t_0 - \lambda) f(t_0) \tag{95}$$

Since $t_0 - \lambda \neq 0$ for all zeros t_0 , we can solve

$$(L - \lambda I)f = g \tag{96}$$

uniquely for any $g \in \mathcal{H}$ by setting

$$f(t_0) = \frac{g(t_0)}{t_0 - \lambda} \tag{97}$$

This shows $L - \lambda I$ is invertible, so $\lambda \notin \sigma(L)$. Therefore

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

and the eigenvalues are simple. □

Remark 22. [Operator scaffold] The construction

$$\text{stationary } X \xrightarrow{U_\theta} \text{oscillatory } Z \xrightarrow{\mu=\delta(Z)|Z'|dt} L^2(\mu) \xrightarrow{L:t\cdot} (L, \sigma(L)) \quad (99)$$

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

6 Appendix: Regularity and Simple Zeros

Definition 23

[Regularity and simplicity] Assume $Z \in C^1(\mathbb{R})$ and every zero is simple: $Z(t_0) = 0 \Rightarrow Z'(t_0) \neq 0$.

Lemma 24

[Local finiteness and delta decomposition] Under Definition 23, zeros are locally finite and

$$\delta(Z(t)) = \sum_{t_0: Z(t_0)=0} \frac{\delta(t-t_0)}{|Z'(t_0)|} \quad (100)$$

whence

$$\mu = \sum_{t_0: Z(t_0)=0} \delta_{t_0} \quad (101)$$

Proof. Since $Z \in C^1(\mathbb{R})$ and $Z'(t_0) \neq 0$ 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 $Z'(t_0) \neq 0$, 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, consider the one-dimensional change of variables formula for the Dirac delta. If $g: I \rightarrow \mathbb{R}$ is C^1 on interval I with $g'(x) \neq 0$ for all $x \in I$, then

$$\delta(g(x)) = \sum_{x_0: g(x_0)=0} \frac{\delta(x-x_0)}{|g'(x_0)|} \quad (102)$$

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

$$\delta(Z(t)) = \sum_{t_0: Z(t_0)=0} \frac{\delta(t-t_0)}{|Z'(t_0)|} \quad (103)$$

Consequently:

$$\begin{aligned} \mu(dt) &= \delta(Z(t)) |Z'(t)| dt \\ &= \sum_{t_0: Z(t_0)=0} \frac{|Z'(t)|}{|Z'(t_0)|} \delta(t-t_0) dt \\ &= \sum_{t_0: Z(t_0)=0} \delta_{t_0}(dt) \end{aligned} \quad (104)$$

where the last equality uses the fact that

$$\frac{|Z'(t)|}{|Z'(t_0)|} = 1 \quad (105)$$

when evaluating at $t = t_0$. □