

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

BY STEPHEN CROWLEY

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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 $\varphi_t(\lambda) = \sqrt{\theta'(t)} e^{i\lambda\theta(t)}$ and evolutionary spectrum $dF_t(\lambda) = \theta'(t) dF(\lambda)$. 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 $U = \bigcup_{n=1}^{\infty} K_n$ with each K_n compact.

Definition 2. [Square-integrability on σ -compact sets] Define

$$L_{\sigma\text{-comp}}^2(\mathbb{R}) := \left\{ f: \mathbb{R} \rightarrow \mathbb{C}: \int_U |f(t)|^2 dt < \infty \text{ for every } \sigma\text{-compact } U \subseteq \mathbb{R} \right\} \quad (1)$$

Remark 3. Every bounded measurable set in \mathbb{R} is σ -compact; hence $L_{\sigma\text{-comp}}^2(\mathbb{R})$ 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 $\theta'(t) > 0$ almost everywhere and $\theta'(t) = 0$ only on sets of Lebesgue measure zero. The function θ maps σ -compact sets to σ -compact sets. Define, for f measurable,

$$(U_{\theta} f)(t) := \sqrt{\theta'(t)} f(\theta(t)) \quad (2)$$

Proposition 5. [Inverse map] The inverse map is given by

$$(U_{\theta}^{-1} g)(s) = \frac{g(\theta^{-1}(s))}{\sqrt{\theta'(\theta^{-1}(s))}} \quad (3)$$

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

Proof. Since $\theta'(t) = 0$ 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 $\sqrt{\theta'(\theta^{-1}(s))}$ is positive almost everywhere. The expression is therefore well-defined almost everywhere on every σ -compact set, which suffices for defining an element of $L_{\sigma\text{-comp}}^2(\mathbb{R})$. \square

Theorem 6. [Local unitarity on σ -compact sets] For every σ -compact set $U \subseteq \mathbb{R}$ and $f \in L_{\sigma\text{-comp}}^2(\mathbb{R})$,

$$\int_U |(U_{\theta} f)(t)|^2 dt = \int_{\theta(U)} |f(s)|^2 ds \quad (4)$$

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

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

$$\int_U |(U_\theta f)(t)|^2 dt = \int_U |\sqrt{\theta'(t)} f(\theta(t))|^2 dt \quad (5)$$

$$= \int_U \theta'(t) |f(\theta(t))|^2 dt \quad (6)$$

Since θ is absolutely continuous and strictly increasing, applying the change of variables $s = \theta(t)$ gives $ds = \theta'(t) dt$ 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:

$$\int_U \theta'(t) |f(\theta(t))|^2 dt = \int_{\theta(U)} |f(s)|^2 ds \quad (7)$$

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

$$(U_\theta^{-1} U_\theta f)(s) = (U_\theta^{-1}) [\sqrt{\theta'(\cdot)} f(\theta(\cdot))](s) \quad (8)$$

$$= \frac{[\sqrt{\theta'(\theta^{-1}(s))} f(\theta(\theta^{-1}(s)))]}{\sqrt{\theta'(\theta^{-1}(s))}} \quad (9)$$

$$= \frac{\sqrt{\theta'(\theta^{-1}(s))} f(s)}{\sqrt{\theta'(\theta^{-1}(s))}} \quad (10)$$

$$= f(s) \quad (11)$$

where we used $\theta(\theta^{-1}(s)) = s$.

Similarly, for any $g \in L_{\sigma\text{-comp}}^2(\mathbb{R})$:

$$(U_\theta U_\theta^{-1} g)(t) = \sqrt{\theta'(t)} (U_\theta^{-1} g)(\theta(t)) \quad (12)$$

$$= \sqrt{\theta'(t)} \frac{g(\theta^{-1}(\theta(t)))}{\sqrt{\theta'(\theta^{-1}(\theta(t)))}} \quad (13)$$

$$= \sqrt{\theta'(t)} \frac{g(t)}{\sqrt{\theta'(t)}} \quad (14)$$

$$= g(t) \quad (15)$$

where we used

$$\theta^{-1}(\theta(t)) = t \quad (16)$$

Therefore $U_\theta U_\theta^{-1} = U_\theta^{-1} U_\theta = I$ on $L^2_{\sigma\text{-comp}}(\mathbb{R})$. \square

Theorem 7. *[Unitarity on $L^2(\mathbb{R})$] $U_\theta: L^2(\mathbb{R}) \rightarrow L^2(\mathbb{R})$ is unitary:*

$$\int_{\mathbb{R}} |(U_\theta f)(t)|^2 dt = \int_{\mathbb{R}} |f(s)|^2 ds \quad (17)$$

and U_θ^{-1} is its inverse.

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

$$\int_{\mathbb{R}} |(U_\theta f)(t)|^2 dt = \int_{\mathbb{R}} \theta'(t) |f(\theta(t))|^2 dt \quad (18)$$

By the change of variables $s = \theta(t)$ with $ds = \theta'(t) dt$, and since $\theta: \mathbb{R} \rightarrow \mathbb{R}$ is bijective:

$$\int_{\mathbb{R}} \theta'(t) |f(\theta(t))|^2 dt = \int_{\mathbb{R}} |f(s)|^2 ds \quad (19)$$

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 $A_t \in L^2(F)$ and set $\varphi_t(\lambda) := A_t(\lambda) e^{i\lambda t}$. An oscillatory process is a stochastic process*

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

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

$$\mathbb{E}[\Phi(d\lambda) \overline{\Phi(d\mu)}] = \delta(\lambda - \mu) dF(\lambda) \quad (21)$$

Its covariance kernel is

$$R_Z(t, s) = \mathbb{E}[Z(t) \overline{Z(s)}] = \int_{\mathbb{R}} A_t(\lambda) \overline{A_s(\lambda)} e^{i\lambda(t-s)} dF(\lambda) \quad (22)$$

Remark 9. [Real-valuedness] Z is real-valued if and only if $A_t(-\lambda) = \overline{A_t(\lambda)}$ for F -a.e. λ , equivalently $\varphi_t(-\lambda) = \overline{\varphi_t(\lambda)}$ for F -a.e. λ .

Theorem 10. *[Existence] If F is finite and $(A_t)_{t \in \mathbb{R}}$ is measurable in t with $\int_{\mathbb{R}} |A_t(\lambda)|^2 dF(\lambda) < \infty$ for each t , then there exists a complex orthogonal random measure Φ with spectral measure F such that*

$$Z(t) = \int_{\mathbb{R}} A_t(\lambda) e^{i\lambda t} \Phi(d\lambda) \quad (23)$$

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

Proof. We construct the stochastic integral using the standard extension procedure. First, define the integral for simple functions of the form $g(\lambda) = \sum_{j=1}^n c_j 1_{E_j}(\lambda)$ where $\{E_j\}$ are disjoint Borel sets with $F(E_j) < \infty$ and $c_j \in \mathbb{C}$:

$$\int_{\mathbb{R}} g(\lambda) \Phi(d\lambda) := \sum_{j=1}^n c_j \Phi(E_j) \quad (24)$$

For such simple functions, the isometry property holds:

$$\mathbb{E} \left[\left| \int_{\mathbb{R}} g(\lambda) \Phi(d\lambda) \right|^2 \right] = \mathbb{E} \left[\left| \sum_{j=1}^n c_j \Phi(E_j) \right|^2 \right] \quad (25)$$

$$= \sum_{j=1}^n \sum_{k=1}^n c_j \bar{c}_k \mathbb{E}[\Phi(E_j) \overline{\Phi(E_k)}] \quad (26)$$

$$= \sum_{j=1}^n |c_j|^2 F(E_j) \quad (27)$$

$$= \int_{\mathbb{R}} |g(\lambda)|^2 dF(\lambda) \quad (28)$$

Since simple functions are dense in $L^2(F)$, we extend by continuity to all $g \in L^2(F)$. For each t , since $\varphi_t(\lambda) = A_t(\lambda) e^{i\lambda t}$ and $A_t \in L^2(F)$, we have $\varphi_t \in L^2(F)$. Therefore $Z(t) = \int_{\mathbb{R}} \varphi_t(\lambda) \Phi(d\lambda)$ is well-defined in $L^2(\Omega)$.

The covariance is computed as:

$$R_Z(t, s) = \mathbb{E}[Z(t) \overline{Z(s)}] \quad (29)$$

$$= \mathbb{E} \left[\int_{\mathbb{R}} \varphi_t(\lambda) \Phi(d\lambda) \int_{\mathbb{R}} \overline{\varphi_s(\mu)} \overline{\Phi(d\mu)} \right] \quad (30)$$

$$= \int_{\mathbb{R}} \int_{\mathbb{R}} \varphi_t(\lambda) \overline{\varphi_s(\mu)} \mathbb{E}[\Phi(d\lambda) \overline{\Phi(d\mu)}] \quad (31)$$

$$= \int_{\mathbb{R}} \varphi_t(\lambda) \overline{\varphi_s(\lambda)} dF(\lambda) \quad (32)$$

$$= \int_{\mathbb{R}} A_t(\lambda) \overline{A_s(\lambda)} e^{i\lambda(t-s)} dF(\lambda) \quad (33)$$

□

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*

$$X(t) = \int_{\mathbb{R}} e^{i\lambda t} \Phi(d\lambda), \quad R_X(t-s) = \int_{\mathbb{R}} e^{i\lambda(t-s)} dF(\lambda).$$

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*

$$Z(t) := (U_\theta X)(t) = \sqrt{\theta'(t)} X(\theta(t)) \quad (34)$$

Then Z is oscillatory with oscillatory function

$$\varphi_t(\lambda) = \sqrt{\theta'(t)} e^{i\lambda\theta(t)} \quad (35)$$

, gain function

$$A_t(\lambda) = \sqrt{\theta'(t)} e^{i\lambda(\theta(t)-t)} \quad (36)$$

, and covariance

$$R_Z(t, s) = \int_{\mathbb{R}} \sqrt{\theta'(t)\theta'(s)} e^{i\lambda(\theta(t)-\theta(s))} dF(\lambda).$$

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

$$Z(t) = (U_\theta X)(t) \quad (37)$$

$$= \sqrt{\theta'(t)} X(\theta(t)) \quad (38)$$

$$= \sqrt{\theta'(t)} \int_{\mathbb{R}} e^{i\lambda\theta(t)} \Phi(d\lambda) \quad (39)$$

$$= \int_{\mathbb{R}} \sqrt{\theta'(t)} e^{i\lambda\theta(t)} \Phi(d\lambda) \quad (40)$$

$$= \int_{\mathbb{R}} \varphi_t(\lambda) \Phi(d\lambda) \quad (41)$$

where $\varphi_t(\lambda) = \sqrt{\theta'(t)} e^{i\lambda\theta(t)}$.

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

$$\varphi_t(\lambda) = \sqrt{\theta'(t)} e^{i\lambda\theta(t)} \quad (42)$$

$$= \sqrt{\theta'(t)} e^{i\lambda(\theta(t)-t)} e^{i\lambda t} \quad (43)$$

$$= A_t(\lambda) e^{i\lambda t} \quad (44)$$

where

$$A_t(\lambda) = \sqrt{\theta'(t)} e^{i\lambda(\theta(t)-t)} \quad (45)$$

Since $\theta'(t) \geq 0$ almost everywhere and $\theta'(t) = 0$ 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:

$$\int_{\mathbb{R}} |A_t(\lambda)|^2 dF(\lambda) = \int_{\mathbb{R}} |\sqrt{\theta'(t)} e^{i\lambda(\theta(t)-t)}|^2 dF(\lambda) \quad (46)$$

$$= \int_{\mathbb{R}} \theta'(t) |e^{i\lambda(\theta(t)-t)}|^2 dF(\lambda) \quad (47)$$

$$= \theta'(t) \int_{\mathbb{R}} dF(\lambda) \quad (48)$$

$$= \theta'(t) F(\mathbb{R}) < \infty \quad (49)$$

where we used $|e^{i\alpha}| = 1$ for all real α .

The covariance is computed as:

$$R_Z(t, s) = \mathbb{E}[Z(t)\overline{Z(s)}] \quad (50)$$

$$= \mathbb{E}[\sqrt{\theta'(t)} X(\theta(t)) \sqrt{\theta'(s)} \overline{X(\theta(s))}] \quad (51)$$

$$= \sqrt{\theta'(t)\theta'(s)} \mathbb{E}[X(\theta(t)) \overline{X(\theta(s))}] \quad (52)$$

$$= \sqrt{\theta'(t)\theta'(s)} R_X(\theta(t) - \theta(s)) \quad (53)$$

$$= \sqrt{\theta'(t)\theta'(s)} \int_{\mathbb{R}} e^{i\lambda(\theta(t)-\theta(s))} dF(\lambda) \quad (54)$$

□

Corollary 13. *[Evolutionary spectrum] The evolutionary spectrum is*

$$dF_t(\lambda) = |A_t(\lambda)|^2 dF(\lambda) = \theta'(t) dF(\lambda) \quad (55)$$

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

$$dF_t(\lambda) = |A_t(\lambda)|^2 dF(\lambda) \quad (56)$$

$$= |\sqrt{\theta'(t)} e^{i\lambda(\theta(t)-t)}|^2 dF(\lambda) \quad (57)$$

$$= \theta'(t) |e^{i\lambda(\theta(t)-t)}|^2 dF(\lambda) \quad (58)$$

$$= \theta'(t) dF(\lambda) \quad (59)$$

since $|e^{i\alpha}| = 1$ for all real α . □

3.3 Covariance operator conjugation

Proposition 14. *[Operator conjugation] Let $(T_K f)(t) := \int_{\mathbb{R}} K(|t-s|) f(s) ds$ with stationary kernel $K(h) = \int_{\mathbb{R}} e^{i\lambda h} dF(\lambda)$. Define the transformed kernel*

$$K_{\theta}(s, t) := \sqrt{\theta'(t)\theta'(s)} K(|\theta(t) - \theta(s)|) \quad (60)$$

and operator

$$(T_{K_{\theta}} f)(t) := \int_{\mathbb{R}} K_{\theta}(s, t) f(s) ds \quad (61)$$

Then

$$T_{K_{\theta}} = U_{\theta} T_K U_{\theta}^{-1} \quad (62)$$

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

Proof. For any $g \in L_{\sigma\text{-comp}}^2(\mathbb{R})$, compute $(U_{\theta} T_K U_{\theta}^{-1} g)(t)$ step by step.

First,

$$(U_{\theta}^{-1} g)(s) = \frac{g(\theta^{-1}(s))}{\sqrt{\theta'(\theta^{-1}(s))}} \quad (63)$$

Second,

$$(T_K U_{\theta}^{-1} g)(t) = \int_{\mathbb{R}} K(|t-s|) \frac{g(\theta^{-1}(s))}{\sqrt{\theta'(\theta^{-1}(s))}} ds \quad (64)$$

Apply change of variables $u = \theta^{-1}(s)$, so $s = \theta(u)$ and $ds = \theta'(u) du$:

$$(T_K U_{\theta}^{-1} g)(t) = \int_{\mathbb{R}} K(|t - \theta(u)|) \frac{g(u)}{\sqrt{\theta'(u)}} \theta'(u) du \quad (65)$$

$$= \int_{\mathbb{R}} K(|t - \theta(u)|) g(u) \sqrt{\theta'(u)} du \quad (66)$$

Third, $(U_{\theta} T_K U_{\theta}^{-1} g)(t) = \sqrt{\theta'(t)} (T_K U_{\theta}^{-1} g)(\theta(t))$:

$$= \sqrt{\theta'(t)} \int_{\mathbb{R}} K(|\theta(t) - \theta(u)|) g(u) \sqrt{\theta'(u)} du \quad (67)$$

$$= \int_{\mathbb{R}} \sqrt{\theta'(t)\theta'(u)} K(|\theta(t) - \theta(u)|) g(u) du \quad (68)$$

Finally, changing variables back with $s = \theta(u)$:

$$= \int_{\mathbb{R}} \sqrt{\theta'(t)\theta'(s)} K(|\theta(t) - \theta(s)|) g(s) ds \quad (69)$$

$$= \int_{\mathbb{R}} K_{\theta}(s, t) g(s) ds \quad (70)$$

$$= (T_{K_{\theta}} g)(t) \quad (71)$$

This establishes the conjugation relation $T_{K_\theta} = U_\theta T_K U_\theta^{-1}$. \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 $\sigma^2 := \mathbb{E}[X(t)^2] < \infty$. 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

$$Y_{[a,b]} := \int_a^b X(t)^2 dt \quad (72)$$

By stationarity and Fubini's theorem:

$$\mathbb{E}[Y_{[a,b]}] = \mathbb{E}\left[\int_a^b X(t)^2 dt\right] = \int_a^b \mathbb{E}[X(t)^2] dt = \int_a^b \sigma^2 dt = \sigma^2(b-a) < \infty \quad (73)$$

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

$$P(Y_{[a,b]} > M) \leq \frac{\mathbb{E}[Y_{[a,b]}]}{M} = \frac{\sigma^2(b-a)}{M} \quad (74)$$

Taking $M \rightarrow \infty$, we conclude $P(Y_{[a,b]} < \infty) = 1$, i.e., almost surely the sample path is square-integrable on $[a, b]$.

Since \mathbb{R} is the countable union of bounded intervals:

$$\mathbb{R} = \bigcup_{n=1}^{\infty} [-n, n] \quad (75)$$

by countable subadditivity of probability:

$$P\left(\bigcap_{n=1}^{\infty} \left\{\int_{-n}^n X(t)^2 dt < \infty\right\}\right) = 1 \quad (76)$$

Now let U be any σ -compact set. Then $U = \bigcup_{m=1}^{\infty} K_m$ where each K_m is compact. Each compact set K_m is bounded, so $K_m \subseteq [-N_m, N_m]$ for some N_m . Therefore:

$$\int_U X(t)^2 dt = \int_{\bigcup_{m=1}^{\infty} K_m} X(t)^2 dt \leq \sum_{m=1}^{\infty} \int_{K_m} X(t)^2 dt \leq \sum_{m=1}^{\infty} \int_{-N_m}^{N_m} X(t)^2 dt \quad (77)$$

Since each integral $\int_{-N_m}^{N_m} X(t)^2 dt < \infty$ almost surely, and the sum of countably many finite terms is finite, we have $\int_U X(t)^2 dt < \infty$ 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 $Z \in C^1(\mathbb{R})$ and only simple zeros $Z(t_0) = 0 \Rightarrow Z'(t_0) \neq 0$. Define, for Borel $B \subset \mathbb{R}$,*

$$\mu(B) := \int_{\mathbb{R}} 1_B(t) \delta(Z(t)) |Z'(t)| dt \quad (78)$$

Theorem 17. *[Atomicity on the zero set] For every $\phi \in C_c^\infty(\mathbb{R})$,*

$$\int_{\mathbb{R}} \phi(t) \delta(Z(t)) |Z'(t)| dt = \sum_{t_0: Z(t_0)=0} \phi(t_0) \quad (79)$$

hence

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

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 $Z(t) = (t - t_0) Z'(t_0) + O((t - t_0)^2)$. The distributional identity for the Dirac delta under smooth changes of variables gives:

$$\delta(Z(t)) = \sum_{t_0: Z(t_0)=0} \frac{\delta(t - t_0)}{|Z'(t_0)|} \quad (81)$$

Therefore:

$$\int_{\mathbb{R}} \phi(t) \delta(Z(t)) |Z'(t)| dt = \int_{\mathbb{R}} \phi(t) |Z'(t)| \sum_{t_0: Z(t_0)=0} \frac{\delta(t - t_0)}{|Z'(t_0)|} dt \quad (82)$$

$$= \sum_{t_0: Z(t_0)=0} \int_{\mathbb{R}} \phi(t) \frac{|Z'(t)| \delta(t - t_0)}{|Z'(t_0)|} dt \quad (83)$$

$$= \sum_{t_0: Z(t_0)=0} \frac{|Z'(t_0)| \phi(t_0)}{|Z'(t_0)|} \quad (84)$$

$$= \sum_{t_0: Z(t_0)=0} \phi(t_0) \quad (85)$$

This shows that μ is the discrete measure $\mu = \sum_{t_0: Z(t_0)=0} \delta_{t_0}$ assigning unit mass to each zero. \square

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

Proposition 19. *[Atomic structure] With $\mu = \sum_{t_0: Z(t_0)=0} \delta_{t_0}$,*

$$\mathcal{H} \cong \left\{ f: \{t_0: Z(t_0)=0\} \rightarrow \mathbb{C}: \sum_{t_0: Z(t_0)=0} |f(t_0)|^2 < \infty \right\} \cong \ell^2 \quad (86)$$

with orthonormal basis $\{e_{t_0}\}_{t_0: Z(t_0)=0}$, where $e_{t_0}(t_1) = \delta_{t_0 t_1}$.

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

$$\|f\|_{\mathcal{H}}^2 = \int |f(t)|^2 \mu(dt) \quad (87)$$

$$= \int |f(t)|^2 \sum_{t_0: Z(t_0)=0} \delta_{t_0}(dt) \quad (88)$$

$$= \sum_{t_0: Z(t_0)=0} |f(t_0)|^2 \quad (89)$$

This shows the isomorphism with ℓ^2 . The functions e_{t_0} defined by $e_{t_0}(t_1) = \delta_{t_0 t_1}$ satisfy:

$$\langle e_{t_0}, e_{t_1} \rangle = \int e_{t_0}(t) \overline{e_{t_1}(t)} \mu(dt) = \sum_{t: Z(t)=0} \delta_{t_0 t} \delta_{t_1 t} = \delta_{t_0 t_1} \quad (90)$$

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

$$f = \sum_{t_0: Z(t_0)=0} f(t_0) e_{t_0} \quad (91)$$

proving they form a basis. \square

Definition 20. *[Multiplication operator] Define $L: \mathcal{D}(L) \subset \mathcal{H} \rightarrow \mathcal{H}$ by $(L f)(t) = t f(t)$ on $\text{supp}(\mu)$ with domain*

$$\mathcal{D}(L) := \left\{ f \in \mathcal{H}: \int |t f(t)|^2 \mu(dt) < \infty \right\} \quad (92)$$

Theorem 21. *[Self-adjointness and spectrum] L is self-adjoint on \mathcal{H} and has pure point, simple spectrum*

$$\sigma(L) = \{t \in \mathbb{R} : Z(t) = 0\} \quad (93)$$

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

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

$$\langle Lf, g \rangle = \int (Lf)(t) \overline{g(t)} \mu(dt) \quad (94)$$

$$= \int t f(t) \overline{g(t)} \mu(dt) \quad (95)$$

$$= \int f(t) \overline{t g(t)} \mu(dt) \quad (96)$$

$$= \int f(t) \overline{(Lg)(t)} \mu(dt) \quad (97)$$

$$= \langle f, Lg \rangle \quad (98)$$

Thus L is symmetric.

In the atomic representation, L acts as $(Lf)(t_0) = t_0 f(t_0)$ for each t_0 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: $Le_{t_0} = t_0 e_{t_0}$, so each t_0 where $Z(t_0) = 0$ is an eigenvalue 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 $((L - \lambda I)f)(t_0) = (t_0 - \lambda)f(t_0)$. Since $t_0 - \lambda \neq 0$ for all zeros t_0 , we can solve $(L - \lambda I)f = g$ uniquely for any $g \in \mathcal{H}$ by setting $f(t_0) = \frac{g(t_0)}{t_0 - \lambda}$. This shows $L - \lambda I$ is invertible, so $\lambda \notin \sigma(L)$.

Therefore $\sigma(L) = \{t_0 : Z(t_0) = 0\}$ exactly, with simple eigenvalues. \square

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

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

$$\delta(g(x)) = \sum_{x_0: g(x_0)=0} \frac{\delta(x - x_0)}{|g'(x_0)|} \quad (101)$$

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:

$$\delta(Z(t)) = \sum_{t_0: Z(t_0)=0} \frac{\delta(t - t_0)}{|Z'(t_0)|} \quad (102)$$

Consequently:

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

where the last equality uses the fact that $|Z'(t)|/|Z'(t_0)| = 1$ when evaluating at $t = t_0$. \square