Evidence Holonomy and Entropy Production: From Universal Coding to Irreversibility

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Abstract

We define an "evidence holonomy" functional on loops of representation transforms applied to sample paths. Using pointwise universality of code lengths for stationary ergodic processes, we prove two reductions: (i) **representation-space holonomy** converges (up to $o(n)$) to the entropy-rate difference $h(Q) - h(P)$; (ii) **KL-holonomy**—implemented by transporting a universal code trained under P to one trained under Q—converges to the relative-entropy rate $\mathsf{d}(P\|Q)$. For finite-state Markov processes, KL-holonomy along the time-reversal loop equals the entropy-production rate σ (bits/step). We show asymptotic code-invariance of KL-holonomy and validate the framework on synthetic Markov processes with extensions to Arrow-of-Time classification tasks.

1 Setup and Definitions

Alphabet and path space. Fix a finite alphabet $\mathcal{X}$. Let $\mathcal{X}^n$ denote length-n strings and $\mathcal{X}^{\mathbb{N}}$ the one-sided sequence space with its product σ-algebra. Let P be a stationary ergodic probability measure on $(\mathcal{X}^{\mathbb{N}}, \mathcal{F})$. Write $X_{0:n-1}$ for the length-n prefix of a sample from P and P_n for its law on $\mathcal{X}^n$.

Universal codes. A *universal code* on alphabet $\mathcal{A}$ is a map $\mathcal{E}_{\mathcal{A}} : \bigcup_{n\geq 1} \mathcal{A}^n \to \mathbb{R}_+$ assigning a code length in bits to any finite string, such that for every stationary ergodic law Q on $\mathcal{A}^{\mathbb{N}}$,

$$\frac{1}{n}\Big(\mathcal{E}_{\mathcal{A}}(Y_{0:n-1}) + \log_2 Q_n(Y_{0:n-1})\Big) \xrightarrow[n\to\infty]{Q\text{-a.s.}} 0, \tag{1}$$

with convergence also in $L^1(Q)$. Classical examples include LZ78, Krichevsky–Trofimov mixtures for finite-order Markov models, and CTW [1, 2, 3, 6, 7].

Standing assumptions. Unless stated otherwise, alphabets are finite; processes are stationary and ergodic; and when KL rates are finite we assume absolute continuity $P \ll Q$. All identities are per-symbol, up to $O(1)$ boundary terms (negligible when divided by n). All logs are base 2.

Representation transforms and loops. For each n, let $F_{i,n}$ be a measurable map $F_{i,n}$: $\mathcal{X}_{i-1}^{n_{i-1}(n)} \to \mathcal{X}_i^{n_i(n)}$, where the alphabets $\mathcal{X}_i$ may differ by step, and $n_0(n) = n$. Define successive images $x^{(0)} = x \in \mathcal{X}^n$ and $x^{(i)} = F_{i,n} \circ \cdots \circ F_{1,n}(x^{(0)}) \in \mathcal{X}_i^{n_i(n)}$. A finite list $\gamma = (F_{1,n}, \ldots, F_{m,n})$ is a *loop at scale n* if $\mathcal{X}_m = \mathcal{X}_0 = \mathcal{X}$ and $n_m(n) = n + O(1)$. We write $L_n = F_{m,n} \circ \cdots \circ F_{1,n}$. When $n_m(n) \neq n$, evaluations are aligned by truncating/offsetting one argument (e.g., "tail alignment" $X_{1:n-1}$ versus a length $n-1$ loop output); this contributes only $O(1)$ boundary terms, negligible after dividing by n.

Why 'holonomy'? In differential geometry, holonomy measures the failure of a vector to return unchanged after parallel transport around a closed loop; the effect depends on the connection and reflects curvature. Here, the 'vector' is a description length (or log-likelihood) assigned by an observer (a code), the 'connection' is the rule transporting this observer along a loop of representation transforms, and the holonomy is the net change after completing the loop. Zero holonomy corresponds to flatness (e.g., bijective relabelings), whereas coarse-grainings or time-reversal in nonequilibrium systems induce positive 'curvature' detected by nonzero holonomy. This analogy motivates the terminology and clarifies why observer choice acts like a gauge: our KL-holonomy rate is asymptotically gauge-invariant across universal codes.

1.1 Two holonomy functionals

Definition 1.1 (Representation-space holonomy)**.** Given universal codes $\mathcal{E}_{\mathcal{X}_i}$ for intermediate alphabets, define

$$\begin{aligned}\mathrm{Hol}_n^{\mathrm{out},\gamma}(x) &= \sum_{i=1}^{m} \Big(\mathcal{E}_{\mathcal{X}_i}\big(x^{(i)}\big) - \mathcal{E}_{\mathcal{X}_{i-1}}\big(x^{(i-1)}\big) \Big) \\ &= \mathcal{E}_{\mathcal{X}}\big(L_n(x)\big) - \mathcal{E}_{\mathcal{X}}(x).\end{aligned}$$

Definition 1.2 (KL (observer-transported) holonomy)**.** Let P_n be the law of $X_{0:n-1}$ and $Q_n = (L_n)\#P_n$. Define the ideal codelengths $\mathcal{L}_n^{(P)}(x) = -\log_2 P_n(x)$ and $\mathcal{L}_n^{(Q)}(x) = -\log_2 Q_n(x)$. The (ideal) KL holonomy is

$$\mathrm{Hol}_n^{\mathrm{KL},\gamma}(x) \;=\; \mathcal{L}_n^{(Q)}(x) - \mathcal{L}_n^{(P)}(x) \;=\; \log_2 \frac{P_n(x)}{Q_n(x)}.$$

Hence $\frac{1}{n}\mathbb{E}_P[\mathrm{Hol}_n^{\mathrm{KL},\gamma}] = \frac{1}{n}\mathrm{D}(P_n\|Q_n) \to \mathsf{d}(P\|Q)$. *Implementation note.* In experiments we approximate $\mathcal{L}_n^{(P)}$ and $\mathcal{L}_n^{(Q)}$ with universal coders; under standard log-loss consistency for the model class used, the empirical rates converge in L^1 to the ideal ones.

2 Reductions via Universality

Convention. All statements below are per symbol, with $O(1)$ boundary discrepancies (e.g., from alignment) absorbed into the $o(1)$ terms.

Lemma 2.1 (Pointwise reductions)**.** *Assume* (1) *for the relevant laws.*

1. *For* $\mathrm{Hol}^{\mathrm{out}}$*: with* $\mathcal{E}_{\mathcal{X}}$ *universal for both* P *and the pushforward process,*

$$\frac{1}{n}\Big(\mathrm{Hol}_n^{\mathrm{out},\gamma}(X_{0:n-1}) - \log_2 \frac{P_n(X_{0:n-1})}{Q_n(L_n(X_{0:n-1}))} \Big) \xrightarrow[n\to\infty]{P\text{-a.s.}} 0. \tag{2}$$

2. *For* $\mathrm{Hol}^{\mathrm{KL},\gamma}$*:*

$$\frac{1}{n}\Big(\mathrm{Hol}_n^{\mathrm{KL},\gamma}(X_{0:n-1}) - \log_2 \frac{P_n(X_{0:n-1})}{Q_n(X_{0:n-1})} \Big) \xrightarrow[n\to\infty]{P\text{-a.s.}} 0. \tag{3}$$

Both convergences also hold in $L^1(P)$.

Proof. Apply (1) (Barron's strong pointwise coding theorem) to each code/law pair and subtract the limits; see [5, 7, 6]. $\square$

Averaging yields the two central identities.

Theorem 2.2 (Expectation-level reductions)**.** *Under L^1 universality,*

$$\frac{1}{n}\,\mathbb{E}_P\big[\mathrm{Hol}_n^{\mathrm{out},\gamma}\big] = h(Q) - h(P) + o(1), \tag{4}$$

$$\frac{1}{n}\,\mathbb{E}_P\big[\mathrm{Hol}_n^{\mathrm{KL},\gamma}\big] = \frac{1}{n}\,\mathrm{D}(P_n\|Q_n) \xrightarrow[n\to\infty]{} \mathsf{d}(P\|Q) \;\geq 0. \tag{5}$$

Proof. Take expectations in (2)–(3) and note $\mathbb{E}_P[-\log_2 P_n(X_{0:n-1})] = H(P_n)$, $\mathbb{E}_P[-\log_2 Q_n(L_n(X_{0:n-1}))] = H(Q_n)$, and $\mathbb{E}_P\big[\log_2 \frac{P_n(X)}{Q_n(X)}\big] = \mathrm{D}(P_n\|Q_n)$. $\square$

Remark 2.3 (Scope)*.* Equation (4) is gauge-invariant and measures net compression or expansion under the loop. Equation (5) is the *irreversibility* functional implemented in our code (KL-rate holonomy): it is observer-transported and non-negative.

3 Canonical Loops and Corollaries

3.1 Gauge invariance for bijective loops

Corollary 3.1 (Gauge invariance)**.** *If each $F_{i,n}$ is a bijection and the loop is the identity on $\mathcal{X}^n$, then*

$$\frac{1}{n}\,\mathrm{Hol}_n^{\mathrm{out},\gamma}(X_{0:n-1}) \to 0 \quad \textit{and} \quad \frac{1}{n}\,\mathrm{Hol}_n^{\mathrm{KL},\gamma}(X_{0:n-1}) \to 0$$

in P-probability and in $L^1(P)$.

Proof. Then $Q_n = P_n$ for all n, so both (4) and (5) vanish. $\square$

3.2 Coarse-graining loops via channels

Let K_n be a (possibly many-to-one) Markov kernel on $\mathcal{X}^n$ and R_n any measurable right-inverse (a "lift") so that $L_n := R_n \circ K_n : \mathcal{X}^n \to \mathcal{X}^n$ is a loop. If $Q_n := L_n\#P_n$ arises from a stationary Q, then (5) gives

$$\frac{1}{n}\,\mathbb{E}_P\big[\mathrm{Hol}_n^{\mathrm{KL},\gamma}\big] \to \mathsf{d}(P\|Q) \geq 0,$$

i.e. KL holonomy is non-negative by construction (by non-negativity of KL). Moreover, if both P_n and Q_n are mapped through the same observation channel, data processing yields a lower bound on the holonomy of the observed records.

When is the pushforward stationary? For a general sequence of maps L_n, the marginals $Q_n = (L_n)\#P_n$ need not be the n-marginals of any stationary process. A sufficient condition is that the loop arises from a shift-commuting, finite-memory map on the two-sided shift (a sliding-block code): i.e., there exist F and memory m such that $(L_n(x))_t = F(x_{t-m:t+m})$ for all t, and F commutes with the left-shift. Then, if P is stationary, so is the pushforward process Q. The canonical time-reversal loop and coarse-graining channels satisfy this property. In our theorems that invoke entropy-rate limits for Q, we implicitly assume such a stationary extension exists (or restrict to cases where it is direct, e.g. time reversal).

3.3 Time reversal and entropy production for Markov chains

Let P be a stationary Markov chain on $\mathcal{X} = \{1, \ldots, k\}$ with transition T and stationary π. Its time-reversal P^{rev} has transitions $T^*_{ji} = \frac{\pi_i T_{ij}}{\pi_j}$.

Canonical time-reversal loop. Let $x_{0:n-1}$ be a path from a stationary finite-state Markov chain P with transition matrix T. Define three maps on paths of length n: (i) the transition encoder E mapping $(x_{t-1}, x_t)_{t=1}^{n-1}$ to the edge sequence; (ii) reversal R mapping an edge sequence $(e_1, \ldots, e_{n-1})$ to $(e_{n-1}, \ldots, e_1)$; (iii) a state decoder D that reconstructs a path from the reversed edge sequence given the terminal state x_{n-1} as anchor. The loop is $L_n := D \circ R \circ E$. One checks that $(L_n)\#P_n = P_n^{\text{rev}}$, the n-path law of the time-reversed chain.

> **Algorithm:** Time-reversal loop L_n
> **Input:** $x_{0:n-1}$
> 1. $E \leftarrow ((x_{t-1}, x_t))_{t=1}^{n-1}$
> 2. $E' \leftarrow \text{reverse}(E)$
> 3. $\hat{x}_{n-1} \leftarrow x_{n-1}$ (anchor)
> 4. For $t = n-1$ down to 1:
> Set $\hat{x}_{t-1}$ as the unique predecessor such that $(\hat{x}_{t-1}, \hat{x}_t) = E'_{n-t}$
> **Output:** $L_n(x) = \hat{x}_{0:n-1}$

Remark 3.2 (Practical variant). Our implementation uses a length-n–1 variant: encode transitions, reverse, and *decode the second state* of each reversed edge. We then evaluate on $X_{1:n-1}$ to match lengths. This avoids explicit anchoring by x_{n-1} and differs only by $O(1)$ boundary terms, hence the per-symbol limits are unchanged.

Theorem 3.3 (KL holonomy rate equals entropy production)**.** *For the Markov setting above,*

$$\mathsf{d}(P \| P^{\text{rev}}) \;=\; \sum_{i,j} \pi_i T_{ij} \, \log_2 \frac{\pi_i T_{ij}}{\pi_j T_{ji}} \;=\; \sigma \quad (\textit{bits/step}), \tag{6}$$

and the KL-holonomy satisfies

$$\frac{1}{n} \, \mathbb{E}_P \left[\text{Hol}_n^{\text{KL,time-rev}} \right] \;\to\; \sigma. \tag{7}$$

Proof. The path log-likelihood ratio between P and the reversed path law under P^{rev} is

$$\log \frac{P_n(X_{0:n-1})}{P_n^{\text{rev}}(R_n(X_{0:n-1}))} = \sum_{t=1}^{n-1} \log \frac{\pi_{X_t}}{\pi_{X_{t-1}}} + \sum_{t=1}^{n-1} \log \frac{T_{X_{t-1}X_t}}{T_{X_t X_{t-1}}}.$$

The stationary term telescopes to $O(1)$; divide by n and take expectations. Identity (6) is standard in stochastic thermodynamics [9, 10]. Equation (7) is (5) with $Q = P^{\text{rev}}$. □

Remark 3.4 (Absolute continuity). The rate in (6) is finite iff $T_{ij} > 0 \Rightarrow T_{ji} > 0$ for all i, j; otherwise $\mathsf{d}(P \| P^{\text{rev}}) = +\infty$.

Remark 3.5 (Why not merely $h(Q) - h(P)$?). For stationary Markov chains, $h(P) = h(P^{\text{rev}})$, so representation-space holonomy would vanish. The KL version (observer-transported) returns the irreversible production σ.

3.4 General ergodic reversal

Let P^* be any stationary time-reversed process absolutely continuous w.r.t. P on cylinders, with finite $\mathsf{d}(P\|P^*)$. Then, by the same argument,

$$\frac{1}{n}\,\mathbb{E}_P\big[\mathrm{Hol}_n^{\mathrm{KL,time\text{-}rev}}\big] \;\to\; \mathsf{d}(P\|P^*). \tag{8}$$

4 Observer Independence

Theorem 4.1 (Code-robustness of KL holonomy)**.** *Let $\mathcal{E}^{(1)}$ and $\mathcal{E}^{(2)}$ be universal on $\mathcal{X}$ for the laws appearing in Lemma 2.1. Then, for any fixed loop γ,*

$$\frac{1}{n}\Big|\mathrm{Hol}^{\mathrm{KL},\gamma}_{n,\mathcal{E}^{(1)}}(X_{0:n-1}) - \mathrm{Hol}^{\mathrm{KL},\gamma}_{n,\mathcal{E}^{(2)}}(X_{0:n-1})\Big| \xrightarrow[n\to\infty]{P\text{-}a.s.} 0,$$

and likewise in $L^1(P)$.

Proof. Apply Lemma 2.1 to both codes and subtract. □

5 Code & Data

All code and data are available at: https://github.com/jbwinters/Evidence-Holonomy

6 Numerical validation (UEC battery)

We validate the theoretical predictions across window sizes $n \in \{2^9, 2^{11}, 2^{13}, 2^{15}\}$ and multiple random seeds. For synthetic Markov chains, we compare ground-truth entropy production σ with KL-holonomy rate estimates (Table 1, Figure 1). The median relative error converges to under 10% for $n \geq 2^{11}$ across different chain types.

Observer independence was tested by comparing KL-holonomy estimates from different universal coders: KT with varying Markov orders ($R \in \{1, 3\}$) and prior decay parameters. These yield nearly identical rates across windows (Figure 2: $r > 0.99$, mean $|\Delta| < 10^{-6}$ bits/step). We also include an LZ78 *representation-space* baseline that computes $h(Q) - h(P)$ via separate compression rather than cross-entropy. While LZ78 captures similar irreversibility trends, it measures a different functional than KL-holonomy $\mathsf{d}(P\|Q)$.

AoT demos (audio / sensors / finance). For window-level arrow-of-time classification, two choices align AUC with holonomy and our theory: *loop-negatives* (Encode→Reverse→DecodeSecond) instead of literal reversal, and domain preprocessing (`--aot_diff` for audio/sensors, `--aot_logreturn` for finance). These match the time-reversal loop used by the holonomy and avoid negative-KL pathologies. The script logs per-file AUC and bits/step(/s) and writes a scoreboard CSV.

Artifacts and reproducibility. The script writes

- `results/aot_wav.json`, `results/aot_csv.json` (single-file AoT).
- `results/scoreboard.csv`, `results/scoreboard.json` (folder runs).
- `results/summary.json` (aggregated suite summary for the run).

Representative commands and flags for the AoT demos are documented inline in the repository (e.g., `--aot_bins`, `--aot_win`, `--aot_stride`, `--aot_rate`).

Table 1: Entropy production rate σ (bits/step): ground truth vs. estimate.

Chain (states)	n	σ_{true}	σ_{hat}	Rel. error
3-state	2^9	0.175	0.200	15.0%
4-state	2^9	0.673	0.713	3.8%
5-state	2^9	0.944	0.929	3.6%
3-state	2^{11}	0.175	0.203	48.3%
4-state	2^{11}	0.673	0.644	8.8%
5-state	2^{11}	0.944	0.925	5.5%
3-state	2^{13}	0.175	0.174	9.9%
4-state	2^{13}	0.673	0.658	4.8%
5-state	2^{13}	0.944	0.950	4.3%
4-state	2^{14}	0.868	0.859	1.8%
3-state	2^{15}	0.175	0.179	12.6%
4-state	2^{15}	0.673	0.668	0.4%
5-state	2^{15}	0.944	0.947	0.5%

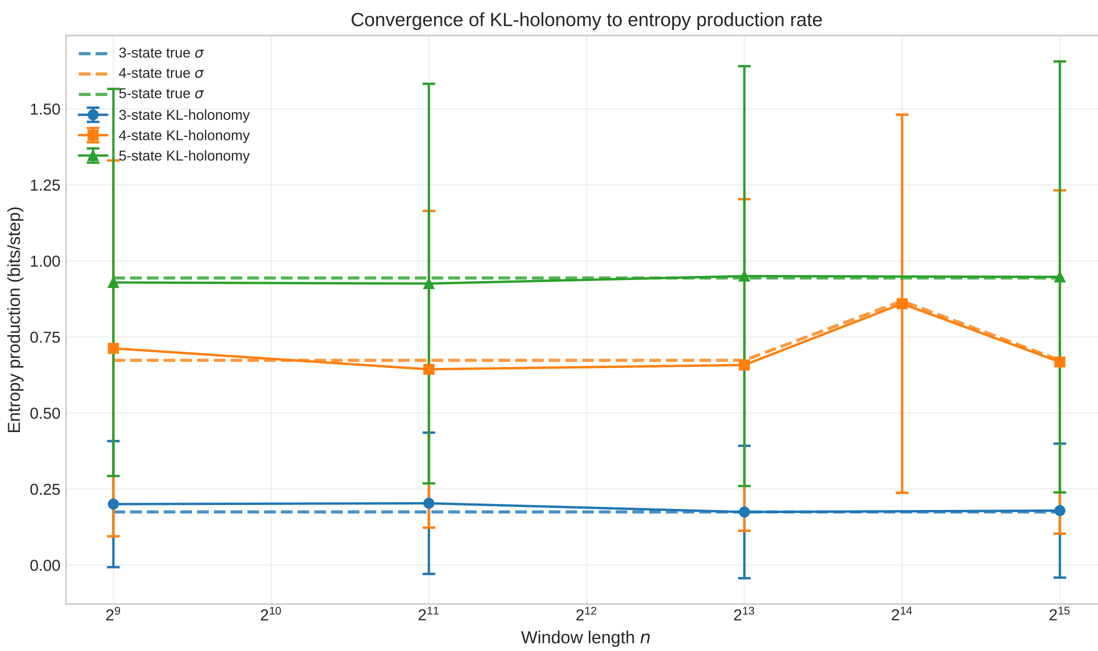

Figure 1: Estimated KL-holonomy rate vs. window length n; horizontal line is σ_{true}.

Discussion

We distinguished two operational regimes. If one evaluates evidence *in the representation reached by the loop*, holonomy reduces to the *entropy-rate difference* $h(Q) - h(P)$ (Theorem 2.2); this yields gauge invariance and detects net compression/expansion by the loop. If instead one *transports the observer* and evaluates evidence against the loop's pushforward law on the *original coordinates*, holonomy equals the *relative entropy rate* $\mathsf{d}(P\|Q)$, recovering irreversibility and, for Markov time reversal, the entropy production rate.

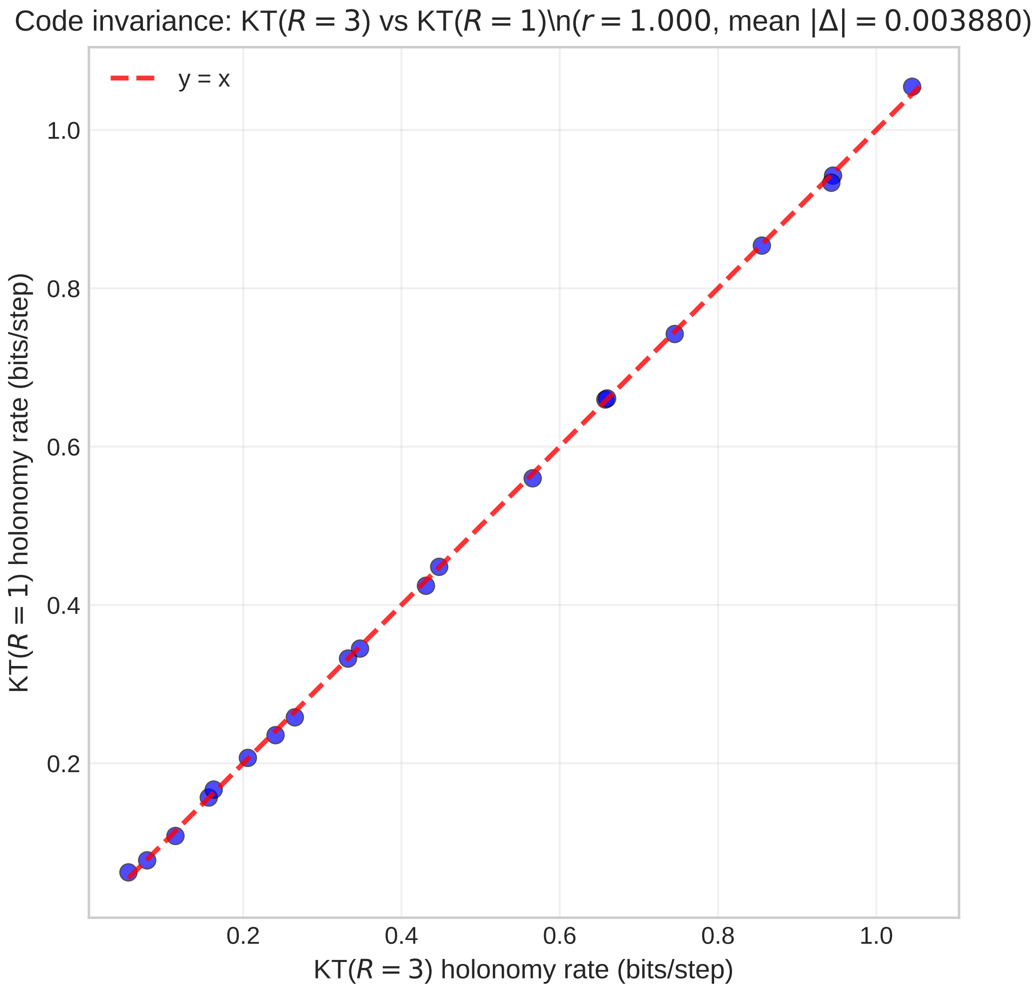

Figure 2: Code invariance: KL-holonomy rate from $\mathrm{KT}(R = 3)$ vs. $\mathrm{KT}(R = 1)$ across windows. Points lie tightly along the diagonal ($r > 0.99$, mean $|\Delta| < 10^{-6}$ bits/step), demonstrating that the KL-holonomy functional is robust to coder hyperparameters.

Technical extensions. The finite-alphabet assumption can be relaxed via quantization and standard approximation. The Markov time-reversal equality extends to hidden Markov models at the level of path measures; holonomy on observed records gives a certified lower bound by data processing (and in the quantum setting by Lindblad/Uhlmann monotonicity [15, 16]). Absolute continuity requirements ensure finite rates (e.g., $\sigma < \infty$ requires $T_{ij} > 0 \Rightarrow T_{ji} > 0$).

Limitations & scope. Our framework requires finite alphabets and stationarity for entropy-rate convergence arguments. Universal code approximations introduce finite-sample error that decreases as $O(\log n/n)$ under standard conditions. The pushforward stationarity condition (sliding-block property) restricts the class of admissible loops but covers the main examples of interest.

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