# Cyclic Time - What does it actually mean?

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## Abstract

This paper addresses the longstanding tension between cyclic conceptions of time and the thermodynamic arrow imposed by the Second Law of Thermodynamics. Classical cyclic models, whether cosmological or philosophical, require the universe to return to prior states, yet quantitative analysis of entropy production in radiative, gravitational, chemical, and quantum processes demonstrates that such exact recurrence is overwhelmingly improbable. Using explicit estimates of entropy growth across astrophysical and terrestrial systems, we show that cumulative irreversibility renders traditional cyclic evolution physically untenable.

To resolve this conflict, we propose a reformulation in which cyclicity is not attributed to the dynamical evolution of the universe but to the structure of observer-dependent experience within a fixed spacetime manifold. Adopting an eternalist or block-universe ontology consistent with relativity, we model observers as worldlines and introduce a formal reassignment operator acting on sequences of conscious states. This operator permits cyclic experiential ordering without requiring any violation of thermodynamic laws or reversal of entropy gradients.

We develop the framework using tools from statistical mechanics, general relativity, and quantum theory, including entropy functionals, density matrix evolution, and spacetime geometry. We further analyze continuity and identity under discontinuous experiential mappings, drawing analogies with wormhole geometries and decoherence-induced effective discontinuities. The resulting model preserves causal structure and physical continuity while allowing a form of recurrence grounded in experiential reassignment rather than physical repetition.

This approach reframes the problem of cyclic time as one of ontology and observer structure rather than cosmological dynamics. While it avoids the thermodynamic inconsistencies of classical cyclic models, it raises new questions concerning the nature of consciousness, identity, and temporal ordering within the block universe. These issues are discussed along with implications for the philosophy of time and the foundations of physics.

# 1 Introduction

The nature of time remains one of the most profound and unresolved questions in both physics and philosophy. While everyday experience presents time as a linear progression from past to future, numerous philosophical and religious traditions have proposed that time may instead be cyclic, with history repeating itself in an eternal recurrence.

However, the notion of cyclic time faces a fundamental challenge when confronted with modern physics. In particular, the Second Law of Thermodynamics establishes that entropy in a closed system tends to increase over time, thereby defining a preferred temporal direction commonly referred to as the "arrow of time" [7, 12]. This irreversible behavior appears to rule out the possibility of exact recurrence of past states, as each cycle would accumulate entropy and deviate from previous ones.

This tension between cyclic conceptions of time and thermodynamic irreversibility has led to widespread skepticism regarding the physical plausibility of cyclic models of the universe [**?**]. In standard cosmological and physical frameworks, any model that requires the universe to return to an identical prior state appears to violate well-established laws.

In this paper, we revisit the problem of cyclic time and propose a reformulation that seeks to avoid these contradictions. Rather than interpreting cyclic time as a physical repetition of cosmic evolution, we explore the possibility that recurrence may instead be understood as a form of *cyclic experience*. In this framework, the structure of spacetime is treated as fixed and complete, consistent with the block universe interpretation suggested by relativity theory, while the apparent recurrence arises from a discontinuous traversal of this structure.

This shift in perspective allows us to retain the phenomenological appeal of cyclic time while remaining consistent with the Second Law of Thermodynamics. However, it introduces new conceptual challenges, particularly concerning continuity, causality, and the ontology of time beyond the observed segment of history.

The aim of this paper is therefore twofold: first, to critically analyze the incompatibility between traditional cyclic time models and thermodynamics; and second, to develop and evaluate an alternative framework based on discontinuous recurrence within a static spacetime structure.

The paper is organized as follows. In Section 2, we examine the thermodynamic arrow of time and its implications. Section 3 reviews classical cyclic models and their limitations. Sections 4 and 5 introduce the philosophical frameworks of presentism and eternalism. In Sections 6 and 7, we develop the concept of cyclic experience and discontinuous temporal transitions. Sections 8 through 10 address entropy, continuity paradoxes, and broader ontological questions. Finally, we conclude with a discussion of the implications and open problems of the proposed model.

The nature of time remains one of the most profound and unresolved questions in both physics and philosophy. While ordinary experience suggests that time unfolds as a linear progression from past to future, numerous philosophical, religious, and cosmological traditions have proposed that time may instead be cyclic, with events recurring in an eternal sequence. Despite its intuitive and historical appeal, the hypothesis of cyclic time encounters a fundamental obstacle when confronted with modern physical theory.

The central difficulty arises from the Second Law of Thermodynamics, which introduces a preferred temporal direction through the monotonic increase of entropy. For an isolated system, the entropy $S$ satisfies

$$\frac{dS}{dt} \geq 0, \tag{1}$$

thereby defining the thermodynamic arrow of time. This asymmetry is not merely phenomenological but follows from the statistical structure of phase space, as expressed in Boltzmann's relation

$$S = k_{\mathrm{B}} \ln W, \tag{2}$$

where $W$ denotes the number of microstates compatible with a given macrostate.

The implications of equation (2) are severe for any doctrine of exact recurrence. If two macrostates differ in entropy by $\Delta S$, then the ratio of their multiplicities is

$$\frac{W_2}{W_1} = \exp\left(\frac{\Delta S}{k_{\mathrm{B}}}\right), \tag{3}$$

which becomes astronomically large even for modest entropy differences. Consequently, the exact restoration of a prior low-entropy macrostate is overwhelmingly improbable. When extended to cosmological and terrestrial processes, including radiative transfer, gravitational collapse, chemical irreversibility, and biological evolution, this argument implies that any literal cyclic reproduction of history is physically untenable.

Classical cyclic cosmologies attempt to evade this conclusion by proposing periodic dynamics of the universe, often described through oscillatory solutions of the Friedmann equations. However, as first emphasized by Tolman and subsequently reinforced by modern cosmology, entropy production accumulates across cycles. If $S_n$ denotes the entropy of the $n$-th cycle, then

$$S_{n+1} > S_n, \tag{4}$$

implying that successive cycles cannot be identical. Instead of exact periodicity, such models yield an evolving sequence of increasingly entropic states, thereby undermining the very notion of cyclic recurrence.

In parallel with these physical considerations, the metaphysical interpretation of time plays a decisive role. Presentism, which asserts that only the present exists, aligns naturally with the thermodynamic arrow but encounters significant difficulties in relativistic contexts due to the relativity of simultaneity. Eternalism, by contrast, treats spacetime as a four-dimensional block in which past, present, and future events coexist. This framework is strongly supported by the structure of special and general relativity, where temporal ordering is observer-dependent and no unique global present can be defined.

The central thesis of this paper is that the failure of classical cyclic models arises from an implicit assumption that cyclicity must be realized through physical evolution of the universe. Once this assumption is relaxed, it becomes possible to formulate an alternative conception of cyclic time that remains consistent with thermodynamics and relativity. In particular, we propose that cyclicity should be understood not as a property of global cosmological dynamics, but as a feature of observer-dependent experiential ordering within a fixed spacetime manifold.

Within this framework, spacetime is treated as a complete four-dimensional structure, and observers are represented by timelike worldlines. Let an observer trajectory be given by

$$\gamma : \tau \mapsto x^{\mu}(\tau), \tag{5}$$

with proper time $\tau$. The sequence of experienced states along this trajectory can be modeled as a functional of the physical configuration. We introduce the possibility that the ordering of these experiential states need not coincide globally with the monotonic increase of proper time. Instead, a mapping between distinct segments of the worldline may generate a cyclic ordering of experience without requiring any reversal of physical processes or decrease of entropy.

This shift from cyclic evolution to cyclic experience preserves the validity of the Second Law while retaining a meaningful notion of recurrence. However, it introduces new conceptual challenges, particularly concerning continuity, causality, and the nature of identity across discontinuous transitions. These issues require careful analysis within both relativistic and quantum frameworks.

The structure of the paper is as follows. Section 2 develops the thermodynamic arrow of time using quantitative estimates from statistical mechanics and astrophysics. Section 3 examines classical cyclic cosmological models and demonstrates their incompatibility with entropy growth. Sections 4 and 5 analyze presentism and eternalism, respectively, as competing ontological frameworks. Section 6 introduces the formal concept of cyclic experience through a reassignment operator acting on observer trajectories. Section 7 addresses continuity paradoxes, causal structure, and the role of wormhole-like geometries as conceptual analogues. The concluding sections discuss broader implications, limitations, and open questions.

The proposal advanced here does not claim to resolve all aspects of the problem of time. Rather, it seeks to reformulate the notion of cyclicity in a manner that is consistent with established physical principles while opening new directions for theoretical and philosophical investigation.

## 2 The Arrow of Time and Entropy

The central obstacle to any doctrine of exact cyclic recurrence is the thermodynamic asymmetry codified in the Second Law. The problem is not merely that ordinary processes in nature look irreversible; rather, the quantitative machinery of statistical mechanics gives precise reasons why the overwhelming majority of physically accessible macrostates evolve from lower entropy to higher entropy, and why the exact reconstitution of a previous low-entropy world-state is fantastically improbable. This point has been stressed in both the physics and philosophy literatures, including the classic discussions of thermodynamic asymmetry by Reichenbach, Grünbaum, Penrose, Callender, Price, Wallace, and Gołosz If time were literally periodic in the sense that the entire universe returned to exactly the same microphysical condition after a finite interval, then the cumulative irreversibility encoded in stellar burning, diffusion, gravitation, radiation, chemistry, biological evolution, and geological history would have to be undone with perfect precision. The present section formulates that problem in explicit thermodynamic and statistical terms.

At the phenomenological level the Second Law is frequently introduced through the Clausius inequality. For a cyclic process, the heat increments $\delta Q$ exchanged reversibly with a bath at temperature $T$ satisfy

$$\oint \frac{\delta Q}{T} \leq 0, \tag{6}$$

with equality only for a reversible cycle [13,14]. From this one defines a state function $S$

such that for a reversible path

$$dS = \frac{\delta Q_{\mathrm{rev}}}{T}, \tag{7}$$

while for an arbitrary process between neighboring equilibrium states,

$$dS \geq \frac{\delta Q}{T}. \tag{8}$$

Equations (6)–(8) already imply that in an isolated system, for which $\delta Q = 0$, entropy cannot decrease:

$$dS \geq 0. \tag{9}$$

If one imagines a universe that is closed in the thermodynamic sense, then (9) does not merely describe a tendency; it is the macroscopic summary of an enormous statistical bias toward higher-entropy macrostates [8, 15, 16].

For an infinitesimal reversible transformation in a simple compressible system,

$$dU = T\,dS - p\,dV + \mu\,dN, \tag{10}$$

where $U$ is internal energy, $V$ volume, $N$ particle number, and $\mu$ the chemical potential [13]. Equation (10) permits a useful estimate of entropy changes associated with finite energy degradation. Suppose a quantity of energy $\Delta E$ is irreversibly thermalized in a reservoir near temperature $T$. To first approximation,

$$\Delta S \approx \frac{\Delta E}{T}. \tag{11}$$

This apparently modest relation becomes decisive on cosmic scales. The solar luminosity is approximately

$$L_\odot \approx 3.83 \times 10^{26}\ \mathrm{W}, \tag{12}$$

so over a period of 5000 years, or

$$\Delta t_{5000} \approx 5000 \times 365.25 \times 24 \times 3600 \approx 1.58 \times 10^{11}\ \mathrm{s}, \tag{13}$$

the total emitted radiant energy is

$$E_{\odot,5000} = L_\odot \Delta t_{5000} \approx 6.05 \times 10^{37}\ \mathrm{J}. \tag{14}$$

Even if only a tiny fraction of this energy participates in terrestrial irreversible processes, the associated entropy production is vast. For a characteristic terrestrial sink temperature near

$$T_\oplus \approx 255\ \mathrm{K}, \tag{15}$$

one obtains the order-of-magnitude entropy generation

$$\Delta S_{\mathrm{terr}} \sim \frac{E_{\odot,5000}}{T_\oplus} \approx 2.37 \times 10^{35}\ \mathrm{J\,K^{-1}}. \tag{16}$$

This crude estimate ignores the fact that entropy flow from the Sun to the Earth is better calculated from the temperature difference between source and sink, but it already shows why any exact restoration of a past terrestrial state would require an entropy bookkeeping miracle.

A more refined estimate compares incoming and outgoing entropy fluxes. If radiant energy $\Delta E$ leaves the solar photosphere at an effective temperature

$$T_\odot \approx 5772 \text{ K}, \tag{17}$$

the entropy carried by that radiation at emission is of order

$$\Delta S_{\text{in}} \approx \frac{\Delta E}{T_\odot}. \tag{18}$$

When the same energy is reradiated by the Earth at $T_\oplus$, the outgoing entropy is approximately

$$\Delta S_{\text{out}} \approx \frac{\Delta E}{T_\oplus}. \tag{19}$$

The net entropy exported to the environment by degrading high-temperature solar photons into low-temperature infrared photons is therefore

$$\Delta S_{\text{prod}} \approx \Delta E \left( \frac{1}{T_\oplus} - \frac{1}{T_\odot} \right). \tag{20}$$

Using (14), (15), and (17), one finds

$$\Delta S_{\text{prod}} \approx 6.05 \times 10^{37} \left( \frac{1}{255} - \frac{1}{5772} \right) \approx 2.26 \times 10^{35} \text{ J K}^{-1}, \tag{21}$$

consistent with the estimate in (16). Consequently, over a putative 5000-year historical cycle the radiative economy of the Earth-Sun system alone accumulates an entropy increase large enough to make the exact restoration of all earlier material states physically implausible.

The phenomenological law is sharpened by Boltzmann's relation between entropy and multiplicity,

$$S = k_{\text{B}} \ln W, \tag{22}$$

where $W$ is the number of microstates compatible with a macrostate and

$$k_{\text{B}} = 1.380649 \times 10^{-23} \text{ J K}^{-1}. \tag{23}$$

Suppose two macrostates differ in entropy by $\Delta S$. The ratio of multiplicities is

$$\frac{W_2}{W_1} = \exp\left( \frac{\Delta S}{k_{\text{B}}} \right). \tag{24}$$

If $\Delta S$ is merely $1 \text{ J K}^{-1}$, then

$$\frac{\Delta S}{k_{\text{B}}} \approx 7.24 \times 10^{22}, \tag{25}$$

and therefore

$$\frac{W_2}{W_1} \approx e^{7.24 \times 10^{22}}, \tag{26}$$

an astronomically enormous factor. Since realistic cosmic or geological entropy differences are not of order unity but of order $10^{20}$, $10^{30}$, or much larger in SI units, exact return to a lower-entropy macrostate is not prohibited by logical contradiction, but it is overwhelmingly disfavored statistically [15, 16, 19]. This is precisely why the appeal to a genuine physical cycle is so problematic.

For a classical distribution function $\rho(\Gamma)$ on phase space $\Gamma$, the Gibbs entropy is

$$S_{\mathrm{G}} = -k_{\mathrm{B}} \int \rho(\Gamma) \ln \rho(\Gamma)\, d\Gamma. \tag{27}$$

Under exact Liouville evolution one has

$$\frac{d\rho}{dt} = \{\rho, H\} = 0 \tag{28}$$

along trajectories, and therefore the fine-grained Gibbs entropy remains constant:

$$\frac{dS_{\mathrm{G}}}{dt} = 0. \tag{29}$$

This fact is the origin of the standard paradox: how can irreversible thermodynamics arise from reversible microscopic laws [20, 60, 61]? The answer, following Boltzmann, lies in the distinction between fine-grained constancy and coarse-grained growth. One partitions phase space into cells of finite observational resolution and defines a coarse-grained density $\bar{\rho}$, giving

$$\bar{S}_{\mathrm{G}} = -k_{\mathrm{B}} \int \bar{\rho}(\Gamma) \ln \bar{\rho}(\Gamma)\, d\Gamma, \tag{30}$$

which typically increases because initially localized distributions filament through phase space and occupy more coarse cells. In this way the Second Law reflects not a fundamental asymmetry in Hamiltonian mechanics but the combination of low-entropy initial conditions, coarse graining, and the overwhelming predominance of equilibrium macrostates [8, 16, 21].

A standard kinetic realization appears in Boltzmann's $H$-theorem. For a dilute gas with one-particle distribution function $f(\mathbf{r}, \mathbf{v}, t)$, define

$$H(t) = \int f \ln f\, d^3r\, d^3v. \tag{31}$$

Under the Stosszahlansatz and the Boltzmann equation, one obtains

$$\frac{dH}{dt} \leq 0, \tag{32}$$

so that the corresponding kinetic entropy

$$S_{\mathrm{B}}(t) = -k_{\mathrm{B}} H(t) \tag{33}$$

satisfies

$$\frac{dS_{\mathrm{B}}}{dt} \geq 0. \tag{34}$$

Although the theorem depends on statistical assumptions and does not evade Loschmidt's reversibility objection in a strictly mechanical sense, it explains why entropy increase is robust in practice and why exact time-reversed histories require exquisitely special correlations that ordinary states do not possess [19, 22, 60].

The recurrence theorem is often invoked by defenders of cyclicity, yet in fact it strengthens rather than weakens the practical objection. For a finite Hamiltonian system with bounded energy shell, Poincaré recurrence guarantees that trajectories eventually return arbitrarily close to their initial phase points. However, the recurrence times are typically so vast that they have no relevance for historical recurrence or exact cosmic restoration [23,24]. A crude estimate for a system with entropy $S$ is

$$\tau_{\rm rec} \sim \tau_0 \exp\left(\frac{S}{k_{\rm B}}\right), \tag{35}$$

where $\tau_0$ is a microscopic relaxation time. Even taking an extraordinarily modest entropy

$$S = 10^3 \ \mathrm{J\,K^{-1}}, \tag{36}$$

we obtain

$$\frac{S}{k_{\rm B}} \approx 7.24 \times 10^{25}, \tag{37}$$

and therefore

$$\tau_{\rm rec} \sim \tau_0 e^{7.24\times 10^{25}}, \tag{38}$$

which dwarfs all cosmological timescales. For systems with entropy remotely comparable to astrophysical systems, the recurrence time is beyond meaningful physical realization. Thus recurrence in the Poincaré sense cannot rescue a doctrine of exact periodic history over intervals of $10^3$ or $10^4$ years.

The difficulty becomes even sharper once gravitation is included. In non-gravitating systems, equilibrium corresponds to spatial homogeneity. In gravitating systems, however, clumping can increase entropy, and the entropy budget is dominated by gravitational degrees of freedom, especially black holes [8,34]. The Bekenstein–Hawking entropy of a black hole of horizon area $A$ is

$$S_{\rm BH} = \frac{k_{\rm B} c^3 A}{4G\hbar}, \tag{39}$$

and for a Schwarzschild black hole,

$$A = 4\pi r_s^2 = 4\pi \left(\frac{2GM}{c^2}\right)^2 = \frac{16\pi G^2 M^2}{c^4}. \tag{40}$$

Substituting (40) into (39) yields

$$S_{\rm BH} = \frac{4\pi k_{\rm B} G M^2}{\hbar c}. \tag{41}$$

For a solar-mass black hole,

$$M_\odot \approx 1.989 \times 10^{30} \ \mathrm{kg}, \tag{42}$$

one finds

$$\frac{S_{\rm BH}}{k_{\rm B}} \approx 1.05 \times 10^{77}, \tag{43}$$

hence

$$S_{\rm BH} \approx 1.45 \times 10^{54} \ \mathrm{J\,K^{-1}}. \tag{44}$$

Supermassive black holes increase this by many orders of magnitude. Since the observable universe contains many such objects, its entropy budget is dominated by gravitational structures, not by ordinary matter or radiation

A useful cosmological contrast is provided by the entropy of the cosmic microwave background (CMB). For blackbody radiation in volume $V$,

$$s_\gamma = \frac{4}{3} a T^3, \tag{45}$$

where $a = 4\sigma/c \approx 7.5657 \times 10^{-16}\ \mathrm{J\,m^{-3}\,K^{-4}}$ is the radiation constant. At the present CMB temperature

$$T_{\mathrm{CMB}} \approx 2.725\ \mathrm{K}, \tag{46}$$

the entropy density is

$$s_\gamma \approx \frac{4}{3}(7.5657 \times 10^{-16})(2.725)^3 \approx 2.04 \times 10^{-14}\ \mathrm{J\,m^{-3}\,K^{-1}}. \tag{47}$$

Using an observable-universe radius of roughly

$$R_{\mathrm{obs}} \approx 4.4 \times 10^{26}\ \mathrm{m}, \tag{48}$$

the observable volume is

$$V_{\mathrm{obs}} = \frac{4\pi}{3} R_{\mathrm{obs}}^3 \approx 3.57 \times 10^{80}\ \mathrm{m}^3, \tag{49}$$

yielding total CMB entropy

$$S_{\mathrm{CMB}} \approx s_\gamma V_{\mathrm{obs}} \approx 7.28 \times 10^{66}\ \mathrm{J\,K^{-1}}. \tag{50}$$

In dimensionless units,

$$\frac{S_{\mathrm{CMB}}}{k_{\mathrm{B}}} \approx 5.27 \times 10^{89}, \tag{51}$$

which is already enormous, yet still far below the entropy associated with the black-hole sector in realistic cosmic inventories [25]. The universe therefore evolves not toward the repetition of detailed historical form but toward increasingly entropic macrostates.

Penrose has emphasized that the puzzling feature of our universe is not that entropy increases now but that the early universe began in an extraordinarily special low-gravitational-entropy condition [?,8]. This is sometimes expressed through the Weyl curvature hypothesis, according to which the initial singularity was characterized by very low Weyl curvature compared with generic gravitational singularities. The thermodynamic arrow is therefore traced not simply to local physical law but to special cosmological boundary conditions [60, 61]. If so, an exact cycle would require those boundary conditions to recur with extremely high fidelity. The hypothesis of literal periodic evolution thus inherits a boundary problem: what mechanism enforces repeated low-entropy initial data?

A more local statement of irreversibility can be written in terms of free energy. For Helmholtz free energy,

$$F = U - TS, \tag{52}$$

one has at fixed temperature and volume

$$dF \le 0 \tag{53}$$

for spontaneous processes [13]. Work extraction relies on gradients of free energy, not merely on energy itself. The Earth receives low-entropy solar radiation and exports higher-entropy infrared radiation, thus maintaining local far-from-equilibrium structures while increasing the total entropy of the larger system [17]. Hence the existence of life, geology, meteorology, and civilization does not violate the Second Law. Rather, it depends upon it. A literal recurrence of history would require not only the same total energy but the same hierarchy of free-energy reservoirs, chemical disequilibria, atmospheric compositions, tectonic states, biomass histories, sediment distributions, and astronomical conditions. The number of constraints is so immense that the recurrence of a detailed historical trajectory becomes statistically negligible.

One may quantify the improbability of exact microstate return for a macroscopic system by the equilibrium fluctuation probability

$$P \propto \exp\left(-\frac{\Delta S}{k_{\mathrm{B}}}\right), \tag{54}$$

where $\Delta S$ is the entropy deficit relative to equilibrium [20,26]. If the required restoration of a past macrostate involved merely

$$\Delta S = 10^{20}\ \mathrm{J\,K^{-1}}, \tag{55}$$

then

$$\frac{\Delta S}{k_{\mathrm{B}}} \approx 7.24 \times 10^{42}, \tag{56}$$

so that

$$P \propto e^{-7.24\times 10^{42}}. \tag{57}$$

This is effectively zero for all practical and cosmological purposes. Such estimates are precisely why the spontaneous restoration of extinct species, replenishment of fossil fuel reserves, reversal of radioactive decay products, reconstruction of glaciers, and exact resetting of anthropogenic materials cannot be treated as ordinary statistical possibilities.

To appreciate the scale of ordinary terrestrial irreversibility, consider human primary energy consumption. A representative present-day global power use is approximately

$$P_{\mathrm{hum}} \approx 2.0 \times 10^{13}\ \mathrm{W}. \tag{58}$$

Over 5000 years the dissipated energy is

$$E_{\mathrm{hum},5000} = P_{\mathrm{hum}} \Delta t_{5000} \approx 3.16 \times 10^{24}\ \mathrm{J}. \tag{59}$$

At a sink temperature of about 300 K this corresponds to entropy production of order

$$\Delta S_{\mathrm{hum},5000} \sim \frac{E_{\mathrm{hum},5000}}{300} \approx 1.05 \times 10^{22}\ \mathrm{J\,K^{-1}}. \tag{60}$$

This is tiny compared with stellar and cosmological entropy budgets, but it is still enormous compared with any ordinary laboratory scale. Furthermore, industrial civilization also produces durable material traces whose removal would require additional low-entropy work. Thermodynamics therefore undercuts exact recurrence both through energy degradation and through the cumulative history embedded in matter distributions.

Radioactive decay supplies another simple illustration. If $N(t)$ nuclei remain undecayed at time $t$, then

$$N(t) = N_0 e^{-\lambda t}, \tag{61}$$

with half-life

$$t_{1/2} = \frac{\ln 2}{\lambda}. \tag{62}$$

For uranium-238,

$$t_{1/2} \approx 4.47 \times 10^9 \text{ yr}, \tag{63}$$

so over 5000 years the fraction decayed is small but nonzero:

$$f_{\text{dec}} = 1 - 2^{-5000/(4.47\times10^9)} \approx 7.75 \times 10^{-7}. \tag{64}$$

For sufficiently large samples this still represents an enormous number of irreversible nuclear events. Thus even if one ignored biology, geology, and gravitation, the exact restoration of the same material composition after every cycle would require the undoing of stochastic decay histories. Similar remarks apply to mutation accumulation, impact cratering, tectonic rearrangement, and chemical weathering.

The philosophical literature has often emphasized that the Second Law by itself does not explain temporal asymmetry unless combined with a low-entropy "Past Hypothesis" [20, 60, 61]. Let $\Gamma_{\text{PH}}$ denote the special low-entropy macroregion corresponding to the initial universe. Then one may state the Past Hypothesis schematically as

$$\Gamma(t_0) \in \Gamma_{\text{PH}}, \tag{65}$$

with

$$\mu(\Gamma_{\text{PH}}) \ll \mu(\Gamma_{\text{eq}}), \tag{66}$$

where $\mu$ is the relevant phase-space measure and $\Gamma_{\text{eq}}$ denotes equilibrium macroregions [16, 20]. Then the asymmetry of observed entropy growth arises because typical microstates compatible with (65) evolve toward larger macroregions:

$$\mu(\Gamma(t + \Delta t)) > \mu(\Gamma(t)) \tag{67}$$

for overwhelmingly many trajectories compatible with the initial constraint. If a cyclic universe is proposed, one must decide whether the Past Hypothesis recurs at every cycle boundary or whether it holds only once. If it recurs, a new law-like reset is required. If it does not recur, exact periodicity is lost. This dilemma is one of the deepest reasons why cyclic time remains difficult to reconcile with thermodynamics [**?**, 34, 61].

One might try to avoid the problem by proposing that the universe returns not to the same microstate but only to the same phenomenological sequence of conscious experience. That strategy will be explored later in the paper. For the present section the key conclusion is narrower and more rigorous. The quantitative structure of thermodynamics and statistical mechanics strongly disfavors any model in which the same physical world-state is recreated after a finite temporal period. Equations (6) through (67) jointly show that exact recurrence would have to overcome the cumulative entropy production associated with radiative transfer, mechanical dissipation, chemical irreversibility, nuclear transformation, gravitational structure formation, and the overwhelming phase-space dominance of higher-entropy macrostates. The problem is not a minor tension that can be ignored by appeal to intuition. It is a central theoretical obstacle. Any serious doctrine of cyclic time must therefore either deny the applicability of the Second Law at the cosmological level, posit a highly nontrivial entropy-resetting mechanism, or abandon the notion of literal cyclic evolution in favor of a more discontinuous and ontologically subtle model.

# 3 Classical Cyclic Time Models and Thermodynamic Constraints

The hypothesis that time may be cyclic has appeared repeatedly in both philosophical and cosmological traditions. In modern theoretical physics, cyclic models are typically framed in terms of cosmological dynamics governed by general relativity or its extensions. However, as already quantified in Section 2, the Second Law of Thermodynamics imposes severe constraints on any model that proposes exact recurrence of physical states. The present section analyzes classical cyclic models in explicit quantitative terms and demonstrates why entropy accumulation generically obstructs exact periodicity.

A natural starting point is the Friedmann–Lemaître–Robertson–Walker (FLRW) metric,

$$ds^2 = -c^2dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right], \tag{68}$$

where $a(t)$ is the scale factor and $k \in \{-1, 0, +1\}$ denotes spatial curvature [27,28]. The evolution of $a(t)$ is governed by the Friedmann equations:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}, \tag{69}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}. \tag{70}$$

A classical cyclic universe is often constructed by choosing parameters such that $a(t)$ undergoes oscillations between a minimum and maximum value. For example, in a closed universe with $k = +1$ and negligible cosmological constant, one may obtain solutions in which the universe expands from a Big Bang, reaches a maximum radius, and then recontracts to a Big Crunch [29]. A simplified parametric solution is

$$a(\eta) = A(1 - \cos\eta), \quad t(\eta) = B(\eta - \sin\eta), \tag{71}$$

where $\eta$ is a conformal parameter. The period of a full cycle is approximately

$$T_{\text{cycle}} \sim \frac{\pi A}{c}. \tag{72}$$

However, Tolman showed that when entropy is included, successive cycles cannot be identical [29]. If the total entropy $S$ increases from cycle to cycle, then the maximum scale factor $a_{\max}$ must also increase. One may express this relation heuristically as

$$a_{\max}^{(n+1)} > a_{\max}^{(n)}, \tag{73}$$

with entropy growth

$$S_{n+1} > S_n. \tag{74}$$

Thus the universe exhibits a sequence of ever-larger cycles rather than exact periodic repetition.

The entropy of radiation in a comoving volume is given by

$$S_\gamma = \frac{4}{3}aT^3V, \tag{75}$$

consistent with equation (45). Since photon production and irreversible processes increase entropy, each cycle accumulates additional radiation entropy, modifying the dynamics.

To quantify entropy growth, consider a dissipative process during a cycle that produces entropy $\Delta S$. Using the Boltzmann relation (22), the ratio of accessible phase-space volumes between successive cycles is

$$\frac{W_{n+1}}{W_n} = \exp\left(\frac{\Delta S}{k_{\mathrm{B}}}\right). \tag{76}$$

Even a modest $\Delta S$ leads to an enormous expansion in accessible microstates, preventing recurrence of the original macrostate.

Another classical attempt is the oscillatory universe with a scalar field or modified gravity. The energy density may include contributions from matter, radiation, and scalar fields:

$$\rho = \rho_m + \rho_r + \rho_\phi. \tag{77}$$

The scalar field $\phi$ obeys

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0, \tag{78}$$

where $H = \dot{a}/a$. Although such models can produce bouncing behavior, entropy production during each bounce still leads to cumulative growth [30, 31].

The ekpyrotic and cyclic models inspired by string theory propose a sequence of brane collisions generating repeated Big Bang-like events [32]. In these models, entropy is diluted during expansion phases, but not eliminated. If the entropy per comoving volume is $s$, then after expansion by a factor $\alpha$,

$$s_{\mathrm{new}} = \frac{s_{\mathrm{old}}}{\alpha^3}, \tag{79}$$

yet total entropy increases due to new production mechanisms. Consequently, exact recurrence remains unattainable.

A further constraint arises from black hole entropy, given in Section 2 by equation (41). During each cycle, gravitational collapse produces black holes, whose entropy dominates the cosmic entropy budget. Since black hole entropy scales as

$$S_{\mathrm{BH}} \propto M^2, \tag{80}$$

even small increases in mass distribution produce large entropy increases. Without a mechanism to remove or reset this entropy, cyclic models diverge from periodicity.

One may attempt to impose exact periodicity by requiring

$$S(t+T) = S(t), \tag{81}$$

for some period $T$. However, combining this with the Second Law (9) implies

$$\frac{dS}{dt} = 0, \tag{82}$$

which can only hold for systems in thermodynamic equilibrium. A universe in equilibrium would lack structure, gradients, and dynamics, contradicting observed cosmology [**?**, 34].

The recurrence time argument from Section 2, equation (35), further reinforces this conclusion. For realistic cosmic entropy values, recurrence times vastly exceed any plausible cycle duration, rendering exact periodicity physically irrelevant.

Finally, quantum considerations introduce additional constraints. The von Neumann entropy of a density matrix $\rho$ is

$$S_{\mathrm{vN}} = -k_{\mathrm{B}}\mathrm{Tr}(\rho \ln \rho), \tag{83}$$

which increases under decoherence and coarse-graining [33]. Quantum irreversibility thus complements classical entropy growth.

In summary, classical cyclic models fail to produce exact recurrence because entropy increases monotonically across cycles. The accumulation of thermodynamic, gravitational, and quantum entropy ensures that each cycle differs from the previous one. Therefore, any viable theory of cyclic time must depart from the notion of literal repetition of physical states and instead consider alternative formulations that circumvent entropy constraints.

# 4 Presentism and Linear Temporal Evolution

Presentism is the metaphysical doctrine according to which only present events exist, while the past no longer exists and the future does not yet exist. In contrast to cyclic or eternalist views, presentism implies a dynamically evolving universe in which reality is continually updated along a preferred temporal direction. This notion aligns naturally with the thermodynamic arrow of time introduced in Section 2, particularly the monotonic entropy increase expressed in equation (9). The purpose of this section is to examine presentism in quantitative and physical terms, and to evaluate its compatibility with modern physics.

A central feature of presentism is the existence of a global time parameter $t$ that distinguishes present events from past and future. In Newtonian mechanics, such a parameter is absolute and universal. The evolution of a system is described by deterministic equations of motion,

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}, \quad \frac{d\mathbf{p}}{dt} = \mathbf{F}, \tag{84}$$

where $\mathbf{x}$ is position, $\mathbf{p}$ momentum, and $\mathbf{F}$ force. These equations define a trajectory in phase space,

$$\Gamma(t) = (\mathbf{x}(t), \mathbf{p}(t)), \tag{85}$$

which evolves continuously in time.

The entropy of a macroscopic system, given by the Boltzmann relation (22), evolves along this trajectory. Combining (22) with (9), one obtains

$$\frac{d}{dt}\left(k_{\mathrm{B}} \ln W(t)\right) \geq 0, \tag{86}$$

which implies

$$\frac{dW}{dt} \geq 0. \tag{87}$$

Thus, presentism is naturally aligned with a monotonic expansion of accessible microstates.

In relativistic physics, however, the notion of a universal present becomes problematic. The Minkowski spacetime interval is given by

$$ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2, \tag{88}$$

and Lorentz transformations mix time and space coordinates:

$$t' = \gamma \left( t - \frac{vx}{c^2} \right), \quad x' = \gamma(x - vt), \tag{89}$$

where

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}. \tag{90}$$

These relations imply that simultaneity is frame-dependent, undermining the idea of a globally defined present [41,42].

To formalize presentism in relativity, one may attempt to define a foliation of spacetime into spacelike hypersurfaces $\Sigma(t)$ such that each hypersurface represents the present moment. The spacetime metric can then be written in ADM form,

$$ds^2 = -N^2 dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt), \tag{91}$$

where $N$ is the lapse function and $N^i$ the shift vector [37]. The evolution of the spatial metric $h_{ij}$ is governed by Einstein's equations, which can be expressed as

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}. \tag{92}$$

However, the choice of foliation is not unique, and different observers may define different hypersurfaces of simultaneity. This leads to a tension between presentism and the relativistic structure of spacetime [44,45]. One may attempt to resolve this by selecting a preferred cosmological frame, such as the frame in which the cosmic microwave background is isotropic. In this frame, one may define a cosmic time parameter $t_{\text{cos}}$, which approximates a universal present.

The expansion of the universe provides a natural time parameter through the scale factor $a(t)$, governed by the Friedmann equation (69). The Hubble parameter is

$$H(t) = \frac{\dot{a}}{a}. \tag{93}$$

At the present epoch,

$$H_0 \approx 70 \text{ km s}^{-1}\,\text{Mpc}^{-1} \approx 2.27 \times 10^{-18} \text{ s}^{-1}. \tag{94}$$

The age of the universe is approximately

$$t_0 \approx \frac{1}{H_0} \approx 4.4 \times 10^{17} \text{ s}. \tag{95}$$

This provides a physically meaningful time parameter that can be associated with presentism.

Entropy evolution in an expanding universe can be expressed as

$$\frac{dS}{dt} = \int \sigma dV, \tag{96}$$

where $\sigma$ is the entropy production rate density. For irreversible processes,

$$\sigma \geq 0. \tag{97}$$

Combining this with (9), one obtains a global arrow of time consistent with presentism.

Quantum mechanics introduces additional structure. The Schrödinger equation,

$$i\hbar\frac{\partial\psi}{\partial t} = \hat{H}\psi, \tag{98}$$

is time-reversible, yet measurement processes introduce effective irreversibility. The von Neumann entropy (83) increases under decoherence, aligning quantum processes with the thermodynamic arrow [33].

A key difficulty for presentism is reconciling the apparent flow of time with the block structure implied by relativity. If only the present exists, then the past must be reconstructed from records and memory, while the future is open. One may formalize this by defining a state functional $\Psi(t)$ that encodes all information accessible at time $t$:

$$\Psi(t) = \mathcal{F}[\Gamma(t)], \tag{99}$$

where $\Gamma(t)$ is the phase-space state defined in (85). The evolution of $\Psi(t)$ is governed by both deterministic and stochastic processes, reflecting classical and quantum dynamics.

The growth of entropy implies that $\Psi(t)$ contains increasing information about past states. If $I(t)$ denotes the information content, one may write

$$I(t) \sim S(t), \tag{100}$$

indicating that information storage and entropy production are closely related [40]. This suggests that presentism is compatible with a cumulative record of the past encoded in physical systems.

Nevertheless, presentism faces a fundamental challenge: the laws of physics are largely time-symmetric, while presentism requires a preferred direction. This asymmetry is introduced through boundary conditions, as discussed in Section 2 via equation (65). Without such conditions, the distinction between past and future would not arise naturally.

In conclusion, presentism provides a coherent framework for linear temporal evolution consistent with the thermodynamic arrow of time. However, its compatibility with relativity and quantum mechanics requires additional structure, such as preferred foliations or boundary conditions. These challenges motivate the exploration of alternative frameworks, such as eternalism, which will be examined in the next section.

## 5 Eternalism and the Block Universe

The previous sections established two results that place severe pressure on any literal doctrine of cyclic temporal evolution. First, the thermodynamic asymmetry of the universe is quantitatively robust: entropy production in radiative, chemical, geological, biological, and gravitational processes accumulates over time and renders exact recurrence of a prior physical macrostate overwhelmingly implausible. Second, presentism, although aligned with everyday experience and with the intuitive picture of temporal becoming, faces substantial difficulties when confronted with relativity, especially the relativity of simultaneity and the absence of a unique observer-independent present hypersurface. The present section develops the alternative ontology of eternalism, also known as the block universe interpretation, and argues that it provides the natural conceptual setting for rethinking recurrence without demanding a thermodynamic reset of the universe.

The central claim is not that eternalism solves every problem, but that it converts the problem of cyclic time from one of impossible physical restoration into one of spacetime structure, worldline organization, and observer-location within a fixed four-dimensional manifold [44, 46, 48, 49].

In special relativity, events are represented as points in Minkowski spacetime, equipped with the invariant interval

$$ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2, \tag{101}$$

which remains unchanged under Lorentz transformations [41, 42]. A timelike worldline satisfies

$$ds^2 < 0, \tag{102}$$

and the proper time along that worldline is defined by

$$d\tau^2 = -\frac{ds^2}{c^2}. \tag{103}$$

For motion with ordinary speed $v$ relative to an inertial frame, one obtains

$$d\tau = dt\sqrt{1 - \frac{v^2}{c^2}}, \tag{104}$$

so that the elapsed proper time between two timelike-separated events is

$$\tau = \int_{t_1}^{t_2} \sqrt{1 - \frac{v^2(t)}{c^2}}\, dt. \tag{105}$$

Equation (105) shows immediately that time is not a single universal flowing parameter in relativity. Instead, distinct observers trace different proper-time histories through one and the same spacetime manifold. The ontological shift from presentism to eternalism is therefore not an arbitrary metaphysical flourish appended to physics from outside; it is strongly suggested by the formal structure of relativistic kinematics itself [46–48].

The relativity of simultaneity sharpens the point. For two inertial frames in standard configuration, the Lorentz transformation reads

$$t' = \gamma\left(t - \frac{vx}{c^2}\right), \tag{106}$$

$$x' = \gamma(x - vt), \tag{107}$$

where

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}. \tag{108}$$

Suppose two events are simultaneous in one frame, so that $\Delta t = 0$. Then from (106),

$$\Delta t' = -\gamma\frac{v\,\Delta x}{c^2}. \tag{109}$$

If $\Delta x \neq 0$ and $v \neq 0$, then $\Delta t' \neq 0$. Hence simultaneity is frame-dependent. A presentist who maintains that only the present exists must either privilege one foliation of spacetime over all others or accept that existence itself becomes frame-relative, which is metaphysically unstable and physically unattractive [45, 46, 49]. Eternalism avoids this problem by asserting that all spacetime events exist, while observer-dependent foliations merely describe different ways of coordinatizing the same ontological totality.

In general relativity, the block-universe picture becomes more geometrically sophisticated. Spacetime is represented by a differentiable manifold $\mathcal{M}$ with Lorentzian metric $g_{\mu\nu}$, and the metric is constrained by Einstein's field equations,

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}. \tag{110}$$

These equations do not describe a three-dimensional universe gradually being brought into existence by an external temporal process. Rather, they constrain the four-dimensional structure of spacetime as a whole. To formulate dynamics one often foliates spacetime into spacelike hypersurfaces, but the foliation is representational rather than ontologically fundamental. In ADM variables one writes

$$ds^2 = -N^2 dt^2 + h_{ij} \left(dx^i + N^i dt\right) \left(dx^j + N^j dt\right), \tag{111}$$

where $N$ is the lapse function, $N^i$ the shift vector, and $h_{ij}$ the induced spatial metric [37,43]. The same spacetime may admit many foliations, which is precisely why eternalists take the four-geometry to be primary and any particular "present slice" to be secondary.

A useful way to formalize eternalism is to regard the universe as a four-dimensional set of events with local field values assigned throughout spacetime. Let $\Phi(x)$ denote the total field content at event $x \in \mathcal{M}$. Then the physical universe may be schematized as the pair

$$\mathcal{U} = (\mathcal{M}, \Phi). \tag{112}$$

The classical action is a functional of the full history,

$$\mathcal{S}[\Phi, g] = \int_{\mathcal{M}} \mathcal{L}(\Phi, \nabla\Phi, g) \sqrt{-g}\, d^4x, \tag{113}$$

and the field equations follow from

$$\delta\mathcal{S} = 0. \tag{114}$$

What is important for the present paper is the ontological lesson: the formalism is naturally written over the total four-dimensional domain, not over a sequence of three-dimensional presents being successively generated [44, 51, 59].

The relation between eternalism and the thermodynamic arrow of time is subtle. Eternalism does not deny that entropy increases toward what observers call the future. It denies that this increase requires an objective ontological coming-into-being of future events. Let $\Sigma_\lambda$ be a foliation of spacetime by spacelike hypersurfaces labeled by parameter $\lambda$, and let the matter-entropy functional on each hypersurface be

$$S_{\mathrm{m}}[\Sigma_\lambda] = \int_{\Sigma_\lambda} s(x)\, dV, \tag{115}$$

where $s(x)$ is the entropy density and $dV$ the induced volume element. The thermodynamic arrow can then be represented by the condition

$$\frac{d}{d\lambda} S_{\mathrm{m}}[\Sigma_\lambda] \geq 0 \tag{116}$$

for foliations adapted to the large-scale cosmological orientation and to ordinary irreversible processes. Eternalism interprets (116) not as proof that the future is unreal until it comes into existence, but as a structural gradient across the block universe. The asymmetry is in the spacetime distribution of entropy, not in the ontology of existence [12, 34, 52].

This can be made more explicit by introducing an entropy current $s^{\mu}$ and writing local entropy production as

$$\nabla_{\mu} s^{\mu} = \sigma, \tag{117}$$

with

$$\sigma \geq 0. \tag{118}$$

Equation (117) is a covariant local version of the Second Law. The sign condition (118) picks out a physically distinguished orientation in spacetime, but it does not force a presentist reading. In the eternalist picture, all events at which entropy is lower and all events at which entropy is higher coexist in the four-dimensional manifold. The relation between them is one of ordering, not one of ontological generation.

A simple numerical estimate clarifies why this matters for the problem of recurrence. Suppose a historical epoch of duration

$$\Delta t \approx 5000 \text{ yr} \approx 1.58 \times 10^{11} \text{ s} \tag{119}$$

contains an entropy increase of order

$$\Delta S \sim 10^{35} \text{ J K}^{-1}, \tag{120}$$

which is consistent with solar-radiative degradation estimates developed earlier in the paper. If one insists on literal cyclic evolution, then the universe must return from the final macrostate to the initial lower-entropy macrostate of the cycle. Using Boltzmann's relation, the corresponding multiplicity ratio is

$$\frac{W_{\text{final}}}{W_{\text{initial}}} = \exp\left(\frac{\Delta S}{k_{\text{B}}}\right). \tag{121}$$

Since

$$\frac{\Delta S}{k_{\text{B}}} \sim \frac{10^{35}}{1.380649 \times 10^{-23}} \approx 7.24 \times 10^{57}, \tag{122}$$

one obtains

$$\frac{W_{\text{final}}}{W_{\text{initial}}} \approx e^{7.24 \times 10^{57}}. \tag{123}$$

The exact physical restoration of the earlier low-entropy macrostate is therefore not merely difficult but fantastically disfavored. Eternalism avoids this impossible demand because it does not require any lower-entropy past slice to be recreated after the higher-entropy future slice. Both slices are simply different regions of the already-existing block.

The block-universe interpretation is also favored by the treatment of worldlines. Let a material observer have spacetime path

$$x^{\mu} = x^{\mu}(\tau), \tag{124}$$

with tangent four-velocity

$$u^{\mu} = \frac{dx^{\mu}}{d\tau}, \tag{125}$$

satisfying the normalization

$$g_{\mu\nu} u^{\mu} u^{\nu} = -c^2. \tag{126}$$

What an observer experiences as temporal succession is the ordered sequence of events on this worldline. Thus one may represent the experiential history of a conscious subject as the ordered set

$$\mathcal{E}_\gamma = \{x^\mu(\tau) \mid \tau_1 \leq \tau \leq \tau_2\}\,. \tag{127}$$

The block-universe thesis is that the entire set (127) exists as part of spacetime, whether or not the subject is currently located at a given value of $\tau$. Passage is then reinterpreted as perspectival movement of awareness along an already-laid-out worldline, not as the coming-into-being of one event after another.

One might object that such a view freezes the universe and cannot accommodate becoming. Yet physics itself already distinguishes between coordinate descriptions and invariant content. For instance, along a congruence of timelike geodesics with tangent field $u^\mu$, the expansion scalar is

$$\theta = \nabla_\mu u^\mu, \tag{128}$$

and the Raychaudhuri equation gives

$$\frac{d\theta}{d\tau} = -\frac{1}{3}\theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}u^\mu u^\nu, \tag{129}$$

where $\sigma_{\mu\nu}$ is the shear tensor and $\omega_{\mu\nu}$ the vorticity tensor [43]. Equation (129) describes focusing and defocusing properties of worldline congruences entirely within the block-universe setting. There is no need to appeal to an external global flow of time in order to recover dynamical structure. The geometry itself contains the relevant asymmetries and correlations.

In cosmology, eternalism fits naturally with the full FLRW spacetime. If the metric is written as

$$ds^2 = -c^2 dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right], \tag{130}$$

then a presentist reads $a(t)$ as the actual size of the universe changing with time, whereas an eternalist reads $a(t)$ as part of the four-dimensional metric field over spacetime. The Hubble parameter,

$$H(t) = \frac{\dot{a}(t)}{a(t)}, \tag{131}$$

is then a geometric feature of the block rather than evidence that only one instantaneous cosmic slice exists at a time. For present observational values,

$$H_0 \approx 2.27 \times 10^{-18}\ \mathrm{s}^{-1}, \tag{132}$$

and the corresponding Hubble time is

$$t_H = H_0^{-1} \approx 4.41 \times 10^{17}\ \mathrm{s} \approx 14.0\ \mathrm{Gyr}. \tag{133}$$

These numbers describe large-scale relations within spacetime; they do not require that only the hypersurface at cosmic time $t = t_0$ be ontologically privileged.

The role of gravitational entropy further supports the block perspective. For a Schwarzschild black hole of mass $M$, the Bekenstein–Hawking entropy is

$$S_{\mathrm{BH}} = \frac{4\pi k_{\mathrm{B}} G M^2}{\hbar c}, \tag{134}$$

and therefore scales quadratically with mass. For a solar-mass black hole with

$$M_\odot \approx 1.989 \times 10^{30}\ \mathrm{kg}, \tag{135}$$

one obtains

$$\frac{S_{\mathrm{BH}}}{k_{\mathrm{B}}} \approx 1.05 \times 10^{77}. \tag{136}$$

Because gravitational entropy grows so enormously in the later universe, any literal cyclic restoration of an earlier low-entropy state becomes nearly inconceivable. In a block universe, however, early low-entropy and late high-entropy regions simply coexist as different portions of the four-geometry [34, 53–55].

The strongest relevance of eternalism to the present paper lies in its ability to support a non-restorative account of recurrence. Let the ordinary history of an observer correspond to worldline segment

$$\gamma_1 : \tau \in [\tau_a, \tau_b] \mapsto x^\mu(\tau). \tag{137}$$

A classical cyclic-evolution model would demand that after $\tau_b$ the physical universe be driven back to a state isomorphic to that at $\tau_a$. By contrast, a block-universe reinterpretation can instead imagine that what recurs is not the physical construction of a second identical cosmos but the reassociation of experiential sequence with an already-existing earlier region of spacetime. Formally, one may represent a discontinuous reassignment map

$$\mathcal{R} : \gamma_1(\tau_b) \mapsto \gamma_0(\tau_a), \tag{138}$$

where $\gamma_0$ is an earlier worldline segment embedded elsewhere in the same spacetime manifold. Since the manifold already contains both regions, no entropy-decreasing reconstruction is required. The thermodynamic obstacle is thereby transformed into a problem of ontology and transition rather than a problem of macroscopic reversal.

This does not mean that general relativity straightforwardly licenses such reassignment. It does not. But GR does contain solutions with nontrivial global causal structure, including closed timelike curves and wormhole geometries, that show how local forward evolution and global temporal nontriviality can coexist in principle [58, 63, 64]. A static spherically symmetric traversable wormhole metric may be written as

$$ds^2 = -e^{2\Phi(l)}c^2dt^2 + dl^2 + r^2(l)\left(d\theta^2 + \sin^2\theta\, d\phi^2\right), \tag{139}$$

where $\Phi(l)$ is the redshift function and $r(l)$ the shape function. At the throat,

$$\left.\frac{dr}{dl}\right|_{l=0} = 0, \tag{140}$$

and the flare-out condition requires

$$\left.\frac{d^2r}{dl^2}\right|_{l=0} > 0. \tag{141}$$

Such wormholes typically violate classical energy conditions. For a null vector $k^\mu$, the null energy condition reads

$$T_{\mu\nu}k^\mu k^\nu \geq 0, \tag{142}$$

whereas traversable wormholes generally require

$$T_{\mu\nu}k^\mu k^\nu < 0 \tag{143}$$

in some region [63,64]. These solutions remain speculative, but they serve the conceptual purpose needed here: they display how spacetime can, at least mathematically, connect distant temporal regions without requiring the universe to thermodynamically rewind.

It is therefore possible to state the core advantage of eternalism in exact terms. Let $M_L$ denote a low-entropy macroregion of spacetime and $M_H$ a later high-entropy macroregion, with

$$S(M_H) - S(M_L) = \Delta S > 0. \tag{144}$$

A cyclic-evolution model demands a physical process

$$M_H \to M_L \tag{145}$$

that effectively reverses the entropy gradient. An eternalist reinterpretation instead requires only that some observer-relevant ordering relation $\prec_{\text{exp}}$ be re-established so that experiential succession re-enters $M_L$:

$$M_H \prec_{\text{exp}} M_L. \tag{146}$$

The second relation is conceptually strange, but it is not thermodynamically contradictory in the way the first one is. This is precisely why eternalism is the indispensable bridge to the later proposal of cyclic experience.

The cost, however, should not be understated. Eternalism weakens the intuitive metaphysics of becoming, raises questions about the status of temporal passage, and risks making subjective experience appear epiphenomenal. Moreover, the move from static block ontology to discontinuous experiential reassignment is not supplied by standard relativity alone. Additional metaphysical or psychophysical structure is required. Still, from the standpoint of strict consistency with thermodynamics, eternalism is vastly superior to any naive doctrine of exact physical recurrence. It preserves the irreversibility measured by entropy gradients while leaving open the possibility that what recurs is not cosmic manufacture but conscious traversal.

For the purposes of the present paper, the conclusion is therefore clear. Eternalism and the block universe provide the first ontology encountered so far that is both compatible with relativity and capable of absorbing the full force of the entropy objections developed earlier. Low-entropy early epochs, high-entropy late epochs, stellar evolution, extinction, geological change, and civilizational traces all remain where they are in the block and do not need to be recreated or erased. The problem of recurrence is thereby redefined. It ceases to be the problem of how the universe could physically return to a pristine earlier state and becomes the problem of whether observer-history can, in some coherent sense, be redirected toward already-existing earlier spacetime structure. That reformulation will be the basis of the next section.

## 6 From Cyclic Evolution to Cyclic Experience

The preceding sections have established three constraints that any viable theory of cyclic time must satisfy. First, the Second Law of Thermodynamics, expressed in equation (9), enforces monotonic entropy increase along physical processes. Second, classical cyclic cosmologies fail because they require entropy reduction across cycles, contradicting equations such as (74). Third, eternalism provides a consistent ontological framework in which all spacetime events coexist, allowing temporal ordering without ontological becoming.

The purpose of this section is to construct a mathematically explicit framework in which cyclicity is transferred from *physical evolution* to *observer-dependent experiential ordering*. This move replaces an impossible global dynamical requirement with a local structural property of observer trajectories in spacetime.

## 6.1 Observer Trajectories and State Functionals

Let spacetime be a Lorentzian manifold $(\mathcal{M}, g_{\mu\nu})$ satisfying the Einstein equations (110). An observer is represented by a timelike worldline

$$\gamma : \tau \mapsto x^\mu(\tau), \tag{147}$$

with proper time defined by (103).

Define the total physical state along the worldline as a restriction of the global field configuration $\Phi$:

$$\Phi_\gamma(\tau) = \Phi(x^\mu(\tau)). \tag{148}$$

We now introduce a *conscious state functional*

$$\mathcal{C}(\tau) = \mathcal{F}[\Phi_\gamma(\tau)], \tag{149}$$

which maps physical states to experiential states. The functional $\mathcal{F}$ is not specified in detail, but it is assumed to be local or quasi-local in spacetime.

## 6.2 Entropy Along Worldlines

Let entropy along the worldline be defined via coarse-grained macrostates:

$$S(\tau) = k_\mathrm{B} \ln W(\tau), \tag{150}$$

in agreement with equation (22). The Second Law implies

$$\frac{dS}{d\tau} \geq 0. \tag{151}$$

Let two events along the worldline satisfy

$$\tau_a < \tau_b, \quad S(\tau_a) < S(\tau_b). \tag{152}$$

Any attempt to impose cyclic evolution would require a physical process reversing this inequality, which contradicts (151).

## 6.3 Reassignment Operator and Cyclic Experience

We now define the central object of this section: a *reassignment operator*

$$\mathcal{R} : \mathcal{E}_\gamma \to \mathcal{E}_\gamma, \tag{153}$$

acting on the ordered set of experiential states

$$\mathcal{E}_\gamma = \{\mathcal{C}(\tau)\}. \tag{154}$$

The operator $\mathcal{R}$ induces a mapping

$$\mathcal{R} : \mathcal{C}(\tau_b) \mapsto \mathcal{C}(\tau_a), \tag{155}$$

with $\tau_a < \tau_b$.

This mapping defines a new ordering relation $\prec_{\text{exp}}$ such that

$$\mathcal{C}(\tau_b) \prec_{\text{exp}} \mathcal{C}(\tau_a), \tag{156}$$

while leaving the physical ordering unchanged.

## 6.4 Consistency with Thermodynamics

We now state a consistency result.

**Proposition.** The reassignment operator $\mathcal{R}$ does not violate the Second Law if it acts only on experiential ordering and not on physical state evolution.

**Proof.** Physical entropy is defined along spacetime trajectories via (151). The reassignment operator does not alter $\Phi(x)$ or the spacetime manifold $\mathcal{M}$. Therefore,

$$\frac{dS}{d\tau} \geq 0 \tag{157}$$

remains valid for all physical processes. Since $\mathcal{R}$ modifies only the ordering of $\mathcal{C}$ and not the underlying trajectory $\gamma$, no entropy-decreasing process is introduced. Hence the Second Law is preserved. □

## 6.5 Hilbert Space Formulation

Let the global quantum state be described by a density matrix $\rho$ on Hilbert space $\mathcal{H}$. The von Neumann entropy is

$$S_{\text{vN}} = -k_{\text{B}} \text{Tr}(\rho \ln \rho), \tag{158}$$

consistent with equation (83).

Define a sequence of reduced states along the worldline:

$$\rho(\tau) = \text{Tr}_{\mathcal{H}_{\text{env}}} \rho_{\text{global}}. \tag{159}$$

Decoherence implies

$$\frac{dS_{\text{vN}}}{d\tau} \geq 0, \tag{160}$$

in agreement with thermodynamic entropy growth [33, 62].

The reassignment operator acts not on $\rho(\tau)$ but on the indexing of conscious states:

$$\mathcal{R} : \rho(\tau_b) \mapsto \rho(\tau_a) \tag{161}$$

at the level of experiential identification, without requiring physical evolution $\rho(\tau_b) \to \rho(\tau_a)$.

### 6.6 Graph-Theoretic Representation

Define a directed graph $\mathcal{G} = (V, E)$ with

$$V = \{x^\mu(\tau)\}, \quad E = \{(\tau_i, \tau_j)\}. \tag{162}$$

Standard evolution corresponds to edges

$$(\tau, \tau + d\tau) \in E. \tag{163}$$

Cyclic experience introduces nonlocal edges

$$(\tau_b, \tau_a) \in E, \tag{164}$$

forming closed loops in experiential ordering while preserving acyclicity in physical spacetime.

### 6.7 Numerical Considerations

Let entropy increase over an interval be

$$\Delta S \sim 10^{35} \ \mathrm{J\,K^{-1}}, \tag{165}$$

as estimated earlier. Then

$$\frac{\Delta S}{k_\mathrm{B}} \sim 10^{58}, \tag{166}$$

implying recurrence probability

$$P \sim e^{-10^{58}}, \tag{167}$$

which is effectively zero. The reassignment framework avoids this suppression entirely.

### 6.8 Interpretational Consequences

The framework developed here implies that cyclicity is not a property of spacetime evolution but of experiential structure. The universe does not return to earlier states; instead, observer trajectories may be nontrivially organized within a fixed spacetime manifold.

This preserves:

$$\text{Thermodynamics} + \text{Relativity} + \text{Cosmology} \tag{168}$$

while allowing

$$\text{Cyclic Experience.} \tag{169}$$

## 7 Wormholes, Discontinuity, and Continuity Paradoxes

The preceding section introduced the concept of cyclic experience through a reassignment operator acting on observer-dependent experiential orderings. While this construction preserves thermodynamic consistency, it raises a fundamental objection: whether discontinuous reassignment of experiential states is compatible with physical continuity, causal structure, and identity over time. The present section addresses this objection by analyzing the role of spacetime topology, wormhole geometries, and continuity conditions within general relativity and quantum theory.

## 7.1 Continuity in Classical Worldlines

In standard relativistic physics, an observer is represented by a smooth timelike worldline $\gamma(\tau)$ satisfying

$$g_{\mu\nu}\frac{dx^\mu}{d\tau}\frac{dx^\nu}{d\tau} = -c^2, \tag{170}$$

as already established in equation (126). Continuity requires that $\gamma(\tau)$ be at least $C^1$, implying

$$\lim_{\epsilon\to 0} x^\mu(\tau+\epsilon) = x^\mu(\tau). \tag{171}$$

Under this condition, causal propagation is local, and no discontinuous jumps in spacetime position are permitted. However, the reassignment operator introduced in equation (153) does not modify $\gamma(\tau)$ itself, but rather the ordering of experiential states. Thus, physical continuity is preserved even if experiential continuity is altered.

## 7.2 Wormhole Geometries as Geometric Analogues

To understand how discontinuous experiential transitions might be embedded within spacetime, it is instructive to examine wormhole solutions of Einstein's equations. A static, spherically symmetric wormhole metric can be written as

$$ds^2 = -e^{2\Phi(l)}c^2dt^2 + dl^2 + r^2(l)\left(d\theta^2 + \sin^2\theta d\phi^2\right), \tag{172}$$

where $\Phi(l)$ is the redshift function and $r(l)$ the shape function [63, 64].

The throat of the wormhole occurs at

$$r(l_0) = r_{\min}, \tag{173}$$

with the flare-out condition

$$\left.\frac{d^2r}{dl^2}\right|_{l=l_0} > 0. \tag{174}$$

Traversability requires the absence of horizons, implying

$$\Phi(l) < \infty. \tag{175}$$

These geometries permit paths connecting distant spacetime regions without violating local continuity. However, they typically require violation of the null energy condition,

$$T_{\mu\nu}k^\mu k^\nu \geq 0, \tag{176}$$

which must instead satisfy

$$T_{\mu\nu}k^\mu k^\nu < 0, \tag{177}$$

as discussed in [63, 64].

The relevance to cyclic experience is conceptual rather than literal. Wormholes demonstrate that spacetime geometry can connect regions that are distant in coordinate time without requiring global reversal of entropy or dynamics.

## 7.3 Continuity Paradox

The central paradox may be formulated as follows. Let $\mathcal{C}(\tau)$ denote the sequence of conscious states along a worldline. Standard continuity implies

$$\lim_{\epsilon \to 0} \mathcal{C}(\tau + \epsilon) = \mathcal{C}(\tau). \tag{178}$$

Cyclic experience, however, introduces a mapping

$$\mathcal{R} : \mathcal{C}(\tau_b) \mapsto \mathcal{C}(\tau_a), \tag{179}$$

with $\tau_a < \tau_b$, which appears to violate continuity.

The resolution lies in distinguishing between two notions of continuity:

$$\text{Physical continuity: } x^\mu(\tau) \tag{180}$$

$$\text{Experiential continuity: } \mathcal{C}(\tau) \tag{181}$$

The reassignment operator preserves (180) while modifying (181). Thus, the paradox dissolves once these two levels are separated.

## 7.4 Causal Structure and Discontinuity

Causality in spacetime is governed by light cones. For events $x$ and $y$,

$$(x - y)^2 \leq 0 \tag{182}$$

ensures causal connection.

The reassignment operator does not introduce new spacetime trajectories, and therefore does not violate

$$\frac{ds^2}{d\tau^2} < 0. \tag{183}$$

Instead, it modifies the ordering relation on experiential states. Therefore, causal paradoxes such as grandfather paradoxes do not arise, since no physical backward-in-time influence is introduced.

## 7.5 Quantum Discontinuity and Decoherence

Quantum theory provides additional insight. The evolution of a closed system is unitary:

$$\rho(t) = U(t)\rho(0)U^\dagger(t), \tag{184}$$

but effective evolution is non-unitary under decoherence:

$$\rho \to \sum_i p_i \rho_i. \tag{185}$$

The von Neumann entropy defined in equation (158) increases under such processes. Importantly, quantum state reduction already introduces a form of discontinuity in state description, even though underlying dynamics remain continuous [33, 62].

This suggests that discontinuity at the level of description does not necessarily imply discontinuity at the level of physical law.

## 7.6 Identity Over Discontinuous Sequences

A deeper issue concerns personal identity. Let identity be defined over a sequence of states:

$$\mathcal{I} = \{\mathcal{C}(\tau)\}. \tag{186}$$

Under reassignment, identity becomes

$$\mathcal{I}' = \{\mathcal{C}(\tau_1), \dots, \mathcal{C}(\tau_b), \mathcal{C}(\tau_a), \dots\}. \tag{187}$$

Continuity of identity requires that successive states maintain sufficient correlation. One may define a correlation function

$$\mathcal{K}(\tau_i, \tau_j) = \langle \mathcal{C}(\tau_i) | \mathcal{C}(\tau_j) \rangle, \tag{188}$$

and require

$$\mathcal{K}(\tau_b, \tau_a) \approx 1 \tag{189}$$

for continuity of identity.

## 7.7 Numerical Considerations

Let entropy difference between two regions be

$$\Delta S \sim 10^{35} \ \mathrm{J\,K^{-1}}, \tag{190}$$

as previously estimated. The probability of spontaneous recurrence is

$$P \sim \exp\left(-\frac{\Delta S}{k_{\mathrm{B}}}\right), \tag{191}$$

which is effectively zero.

The reassignment framework avoids this constraint entirely, since it does not rely on dynamical recurrence.

## 7.8 Conclusion

The continuity paradox arises only if one assumes that experiential continuity must mirror physical continuity. By separating these notions, and by recognizing that spacetime geometry permits nontrivial global structures, one can construct a consistent framework in which cyclic experience is possible without violating thermodynamics, causality, or relativity.

# 8 Conclusion and Implications

The analysis developed throughout this paper has addressed a central tension in the philosophy and physics of time: the apparent incompatibility between cyclic conceptions of time and the thermodynamic arrow imposed by the Second Law. By combining quantitative estimates of entropy growth with the structural features of relativistic spacetime, we have shown that any doctrine of exact cyclic evolution—understood as the literal recurrence of physical states—is overwhelmingly implausible.

The core difficulty arises from the exponential growth of accessible phase space as entropy increases. As expressed by Boltzmann's relation,

$$S = k_{\mathrm{B}} \ln W, \tag{192}$$

even modest entropy increments lead to enormous increases in the number of compatible microstates. Consequently, the probability of spontaneous return to a prior macrostate,

$$P \sim \exp\left(-\frac{\Delta S}{k_{\mathrm{B}}}\right), \tag{193}$$

is effectively zero for any realistic system. This conclusion is reinforced by considerations of gravitational entropy, radiative processes, and quantum decoherence, all of which contribute irreversibly to the entropy budget of the universe.

Classical cyclic cosmologies, including oscillatory and bouncing models, therefore fail not because of dynamical inconsistency alone, but because they implicitly require a global entropy reset. As previously discussed, if $S_n$ denotes the entropy of successive cycles, then

$$S_{n+1} > S_n, \tag{194}$$

which precludes exact periodicity. The thermodynamic arrow is thus not a superficial feature but a fundamental constraint on any viable model of temporal structure.

The key conceptual advance of this work lies in identifying and relaxing an implicit assumption shared by these models, namely that cyclicity must be realized through the dynamical evolution of the universe itself. By abandoning this assumption, we have proposed an alternative framework in which cyclicity is instead attributed to the structure of observer-dependent experience within a fixed spacetime manifold.

Within the eternalist interpretation of spacetime, all events coexist in a four-dimensional structure governed by the Einstein field equations. Observers are represented by timelike worldlines,

$$\gamma : \tau \mapsto x^{\mu}(\tau), \tag{195}$$

along which physical states evolve monotonically in accordance with thermodynamic laws. However, the ordering of experiential states along these worldlines need not be globally constrained by the same monotonic parameter. By introducing a reassignment operator acting on sequences of conscious states, it becomes possible to construct cyclic experiential orderings without requiring any reversal of physical processes.

This distinction between physical evolution and experiential ordering is crucial. Physical continuity and causality are preserved, as no modification of the underlying spacetime manifold or field dynamics is required. At the same time, the framework allows for a form of recurrence that is not subject to the exponential suppression associated with entropy-driven phase-space expansion. In this sense, cyclic experience is not a violation of thermodynamics but a reinterpretation of temporal structure within its constraints.

The introduction of discontinuous experiential mappings raises important questions concerning continuity, identity, and causality. As analyzed in the preceding section, these issues can be addressed by distinguishing between physical continuity of worldlines and experiential continuity of conscious states. The use of wormhole geometries as conceptual analogues illustrates how nontrivial spacetime structures can connect distant regions without requiring local violations of causality. Similarly, quantum theory provides examples in which effective discontinuities arise at the level of description without contradicting underlying dynamical laws.

Despite its internal consistency, the framework proposed here is not without limitations. Most notably, it relies on a mapping between physical states and conscious experience that is not yet fully understood within current physical theory. The functional relation between neural or physical configurations and subjective states remains an open problem in both neuroscience and philosophy of mind. Furthermore, the reassignment operator introduced in Section 6 is presently a formal construct rather than a mechanism derived from known physical laws.

These limitations point toward several directions for future research. One avenue involves the development of a more detailed theory of the physical basis of consciousness, potentially drawing on quantum information theory or emergentist models. Another concerns the exploration of spacetime topologies and boundary conditions that might naturally support nontrivial experiential orderings. Finally, the conceptual implications of cyclic experience for questions of identity, memory, and personal continuity merit further philosophical investigation.

In conclusion, the principal result of this paper is a reframing of the problem of cyclic time. Rather than attempting to reconcile cyclic cosmological evolution with the Second Law—a task that appears fundamentally untenable—we have proposed that cyclicity may instead reside in the structure of experience within a block universe. This shift preserves the empirical success of thermodynamics and relativity while opening a new conceptual pathway for understanding recurrence. Whether this framework can be further developed into a predictive or testable theory remains an open question, but it provides a coherent foundation for future work at the intersection of physics, philosophy, and the study of time.

# References

[1] H. B. Callen, *Thermodynamics and an Introduction to Thermostatistics*, Wiley, 1985.

[2] R. Penrose, *The Emperor's New Mind*, Oxford University Press, 1989.

[3] H. Price, *Time's Arrow and Archimedes' Point*, Oxford University Press, 1996.

[4] T. Maudlin, *Philosophy of Physics: Space and Time*, Princeton University Press, 2012.

[5] S. Carroll, *From Eternity to Here*, Dutton, 2010.

[6] H. Reichenbach, *The Direction of Time*, University of California Press, Berkeley, 1956.

[7] A. Grünbaum, Time and entropy, *American Scientist* **43** (1955), 403–412.

[8] R. Penrose, Singularities and time-asymmetry, in *General Relativity: An Einstein Centenary Survey*, edited by S. W. Hawking and W. Israel, Cambridge University Press, Cambridge, 1979, pp. 581–638.

[9] C. Callender, Thermodynamic asymmetry in time, *Stanford Encyclopedia of Philosophy*, 2001 and later revisions, `https://plato.stanford.edu/entries/time-thermo/`.

[10] H. Price, *Time's Arrow and Archimedes' Point*, Oxford University Press, Oxford, 1996.

[11] D. Wallace, Gravity, entropy, and cosmology: In search of clarity, *The British Journal for the Philosophy of Science* **61** (2010), 513–540.

[12] J. Gołosz, Entropy and the direction of time, *Entropy* **23** (2021), 388.

[13] H. B. Callen, *Thermodynamics and an Introduction to Thermostatistics*, 2nd ed., Wiley, New York, 1985.

[14] M. Planck, *Treatise on Thermodynamics*, Dover, New York, 1945.

[15] J. L. Lebowitz, Boltzmann's entropy and time's arrow, *Physics Today* **46**(9) (1993), 32–38.

[16] S. Goldstein, Boltzmann's approach to statistical mechanics, in *Chance in Physics: Foundations and Perspectives*, edited by J. Bricmont et al., Springer, Berlin, 2001, pp. 39–54.

[17] E. D. Schneider and D. Sagan, *Into the Cool: Energy Flow, Thermodynamics, and Life*, University of Chicago Press, Chicago, 2005.

[18] A. Annila, Philosophy of thermodynamics, *Philosophical Transactions of the Royal Society A* **381** (2023), 20220281.

[19] G. E. Uhlenbeck, *Lectures in Statistical Mechanics*, American Mathematical Society, Providence, 2004.

[20] D. Z. Albert, *Time and Chance*, Harvard University Press, Cambridge, MA, 2000.

[21] L. Boltzmann, *Lectures on Gas Theory*, English translation, University of California Press, Berkeley, 1964. Original German edition 1896–1898.

[22] L. Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics*, Cambridge University Press, Cambridge, 1993.

[23] P. Bocchieri and A. Loinger, Quantum recurrence theorem, *Physical Review* **107** (1957), 337–338.

[24] J. Earman, *A Primer on Determinism*, Reidel, Dordrecht, 1986.

[25] C. A. Egan and C. H. Lineweaver, A larger estimate of the entropy of the universe, *The Astrophysical Journal* **710** (2010), 1825–1834.

[26] L. D. Landau and E. M. Lifshitz, *Statistical Physics, Part 1*, 3rd ed., Pergamon, Oxford, 1980.

[27] S. Weinberg, *Cosmology*, Oxford University Press, 2008.

[28] B. Ryden, *Introduction to Cosmology*, Cambridge University Press, 2017.

[29] R. C. Tolman, *Relativity, Thermodynamics and Cosmology*, Oxford University Press, 1934.

[30] A. Ijjas and P. J. Steinhardt, Bouncing cosmology made simple, *Classical and Quantum Gravity* **35** (2018), 135004.

[31] R. Brandenberger and P. Peter, Bouncing cosmologies: progress and problems, *Foundations of Physics* **47** (2017), 797–850.

[32] P. J. Steinhardt and N. Turok, A cyclic model of the universe, *Science* **296** (2002), 1436–1439.

[33] W. H. Zurek, Decoherence and the transition from quantum to classical, *Reviews of Modern Physics* **75** (2003), 715–775.

[34] D. Wallace, Gravity, entropy, and cosmology, *British Journal for the Philosophy of Science* **61** (2010), 513–540.

[35] A. Einstein, On the electrodynamics of moving bodies, *Annalen der Physik* **17** (1905), 891–921.

[36] W. Rindler, *Relativity: Special, General, and Cosmological*, Oxford University Press, 2006.

[37] R. Arnowitt, S. Deser, and C. W. Misner, The dynamics of general relativity, *General Relativity and Gravitation* **40** (2008), 1997–2027.

[38] T. Maudlin, *Philosophy of Physics: Space and Time*, Princeton University Press, 2012.

[39] S. Savitt, Presentism and relativity, in *The Ontology of Spacetime*, Elsevier, 2006.

[40] R. Landauer, Irreversibility and heat generation in the computing process, *IBM Journal of Research and Development* **5** (1961), 183–191.

[41] A. Einstein, Zur Elektrodynamik bewegter Körper, *Annalen der Physik* **17** (1905), 891–921.

[42] W. Rindler, *Relativity: Special, General, and Cosmological*, 2nd ed., Oxford University Press, Oxford, 2006.

[43] R. M. Wald, *General Relativity*, University of Chicago Press, Chicago, 1984.

[44] T. Maudlin, *Philosophy of Physics: Space and Time*, Princeton University Press, Princeton, 2012.

[45] S. Savitt, Presentism and relativity, in *The Ontology of Spacetime*, edited by D. Dieks, Elsevier, Amsterdam, 2006, pp. 111–132.

[46] D. Peterson and M. Silberstein, Relativity of simultaneity and eternalism: In defense of the block universe, in *Space, Time, and Spacetime: Physical and Philosophical Implications of Minkowski's Unification*, edited by V. Petkov, Springer, Berlin, 2010, pp. 209–238.

[47] S. E. Power, *Philosophy of Time: A Contemporary Introduction*, Routledge, London, 2021.

[48] B. Dainton, *Time and Space*, 2nd ed., Routledge, London, 2016.

[49] P. Thyssen, *The Block Universe: A Philosophical Investigation in Four Dimensions*, PhD thesis, Université de Genève, 2020.

[50] S. Carroll, *Something Deeply Hidden*, Dutton, New York, 2019.

[51] M. H. S. Ahmed, *The Metaphysics of Time Within Physics*, PhD dissertation, The American University in Cairo, 2024.

[52] M. Khorwat, Pulse ontology and the arrow of time: Reconciling block universe with quantum becoming, PhilArchive, 2025.

[53] J. D. Bekenstein, Black holes and entropy, *Physical Review D* **7** (1973), 2333–2346.

[54] S. W. Hawking, Particle creation by black holes, *Communications in Mathematical Physics* **43** (1975), 199–220.

[55] G. E. Romero, Black hole philosophy, *Crítica* **53**(159) (2021), 73–95.

[56] M. S. Morris and K. S. Thorne, Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity, *American Journal of Physics* **56** (1988), 395–412.

[57] M. Visser, *Lorentzian Wormholes: From Einstein to Hawking*, AIP Press, New York, 1995.

[58] R. Rupasinghe, *The Philosophy and Physics of Time Travel: The Possibility of Time Travel*, Honors thesis, University of Minnesota Morris, 2017.

T. Maudlin, *Philosophy of Physics: Space and Time*, Princeton University Press, 2012.

[59] S. Carroll, *Something Deeply Hidden*, Dutton, 2019.

[60] H. Price, *Time's Arrow and Archimedes' Point*, Oxford University Press, 1996.

[61] C. Callender, Thermodynamic asymmetry in time, *Stanford Encyclopedia of Philosophy.*

[62] M. Schlosshauer, *Decoherence and the Quantum-To-Classical Transition*, Springer, 2007.

[63] M. S. Morris and K. S. Thorne, Wormholes in spacetime, *American Journal of Physics* **56** (1988), 395–412.

[64] M. Visser, *Lorentzian Wormholes*, AIP Press, 1995.

[65] T. Maudlin, *Philosophy of Physics: Space and Time*, Princeton University Press, 2012.