EPISTEMEUS
ESSAYS

VOLUME 1 ; ISSUE 1 17.05.2026

From Entropy to Causation: Reconstructing Asymmetry in a Time-Symmetric World

Hosea Pratama Sinaga

ABSTRACT

A WORLD governed by time-symmetric physical laws appears, at first sight, hostile to any primitive direction of causation. If the fundamental equations do not privilege past over future, the familiar order in which causes precede their effects cannot simply be assumed as a metaphysical given. This paper argues that causal asymmetry is best understood not as a fundamental feature added to the physical structure of the world, but as an emergent pattern grounded in thermodynamic asymmetry. The central claim is that entropy supplies the background conditions under which causal direction becomes intelligible: records preserve traces of lower-entropy conditions, interventions operate within macroscopic gradients, and explanatory practices depend upon stable asymmetries between accessible pasts and open futures. On this view, causation is neither eliminated nor reduced to a mere psychological projection. It remains real at the macroscopic level, while losing its status as a primitive metaphysical relation. By reconstructing causal order from entropic structure, the paper offers a middle position between causal fundamentalism and eliminativist reduction. The arrow of causation does not stand apart from the thermodynamic arrow; is carved from the same physical asymmetry that makes temporal orientation, memory, and intervention possible.

Keywords:

causation, entropy, arrow of time, time-symmetry, thermodynamics, metaphysics of science, philosophy of physics.

Introduction

A world described by time-symmetric laws does not naturally offer a privileged direction of causation. If fundamental equations can represent physical evolution without building in a strict metaphysical distinction between past and future, the familiar order of cause before effect begins to lose its appearance of inevitability. Russell's classical challenge to the notion of cause in physics remains useful here: causal language may appear indispensable in ordinary explanation while failing to map neatly onto the formal structure of physical law (Russell, 1913). The pressure is not only historical. Contemporary philosophy of physics still treats the relation between causation and physical theory as an unresolved problem. One central issue concerns whether causal claims require truth-makers inside the physical structure of the world, or whether they function as higher-level patterns supervening on physical facts. This distinction matters because a metaphysics of causation that cannot be made compatible with accepted physics risks becoming detached from the very world it aims to describe (Reutlinger & Saatsi, "Causation in Physics," SEP). Causal reasoning also carries an interventionist grammar. To call one event a cause is often to say that changing it would make a difference to another event. Experimental practice depends on this structure: variables are manipulated, conditions are isolated, outcomes are recorded, and explanations are built from controlled dependencies. Interventionist accounts clarify why causation remains cognitively and scientifically powerful, while also exposing the difficulty of applying causal language directly to domains where intervention is not straightforward (Woodward, "Causation and Manipulability," SEP). Entropy enters this problem as more than a thermodynamic quantity. It supplies one of the most serious candidates for grounding temporal asymmetry without adding a primitive direction to fundamental law. The thermodynamic arrow raises a foundational question: whether the directionality observed in macroscopic processes can be explained through entropy, statistical mechanics, and boundary conditions rather than through a built-in metaphysical arrow of time (Uffink, "Thermodynamic Asymmetry in Time," SEP). The central thesis of this paper follows that path but applies it specifically to causation. Causal asymmetry need not be treated as an independent metaphysical primitive. It can be reconstructed from the thermodynamic asymmetry that structures records, interventions, memory, and macroscopic irreversibility. Rovelli's recent account is especially relevant here: oriented causation is described as a macroscopic thermodynamic phenomenon whose temporal direction is tied to the entropy gradient and to the traces left by interventions (Rovelli, 2023).

This reconstruction does not eliminate causation from scientific practice. Physics itself often uses causal reasoning, especially in contexts involving retarded and advanced solutions, radiation phenomena, dispersion theory, and explanatory constraints. Frisch's work challenges the idea that causal reasoning is merely an everyday or special-science convenience, arguing instead that time-asymmetric causal structures can belong to the representational toolkit of physics (Frisch, 2014/2017). The low-entropy past sharpens the issue. If the universe began in a highly special low-entropy condition, then the asymmetry between influencing the future and not influencing the past may be connected to the same physical facts that underwrite thermodynamic irreversibility. The debate remains live because this connection promises a reduction of causal asymmetry while also facing serious objections about whether entropy alone can explain influence, control, and intervention (Frisch, "Does a low-entropy constraint prevent us from influencing the past?", 2010). Quantum theory adds a further constraint on the argument. Any account of causation in fundamental physics must face cases where ordinary causal order becomes unstable, weakened, or formally reconfigured. Recent work on process matrices and quantum causal modelling argues that quantum foundations may contain a notion of causal order weaker than common- sense causation because it need not involve the familiar asymmetry of cause before effect (Adlam, 2022). The argument developed here occupies a middle position. Against causal fundamentalism, it denies that causal direction must be written into the basic furniture of the world. Against eliminativism, it refuses to treat causation as illusion or verbal convenience. Causation remains real at the macroscopic level because the physical patterns that sustain it are stable, explanatory, and intervention-supporting. Its reality does not require fundamentality. Its direction can be carved from the entropic structure of a world whose basic laws, taken alone, do not speak in the grammar of cause and effect.

Time-Symmetric Laws and the Problem of Causal Direction

The puzzle begins with a structural mismatch. Time-reversal symmetry in physical theory concerns whether the laws permit a reversed description of a process under an appropriate transformation of temporal orientation and relevant physical quantities. Causal reasoning, by contrast, appears to privilege one direction: from preparation to outcome, from intervention to effect, from trace to source. The metaphysical pressure arises because these two vocabularies do not line up automatically. A law may be symmetric under time reversal while the explanatory practices built around it remain stubbornly asymmetric. Roberts frames the issue as a problem about the relation between time-reversal symmetry in physical theories and the arrow of time itself, rather than as a simple question about whether time "really flows" in ordinary experience (Roberts, 2022). The appeal to timesymmetric laws must be handled carefully. It is too quick to say that classical mechanics is simply time-reversal invariant in every relevant sense, as if the matter were settled by textbook slogans. Some classical systems fail to exhibit time-reversal invariance under plausible interpretations, while a broad class of familiar conservative systems still preserve it. The lesson is not that time symmetry disappears, but that it must be stated with technical discipline. A vague contrast between "reversible microphysics" and "irreversible macrophysics" risks hiding the very distinction the argument needs to explain (Dougherty, 2013). Electromagnetism makes the same point with sharper teeth. The debate over whether classical electromagnetic theory is time-reversal invariant turns partly on how the time-reversal operation treats magnetic fields. Malament argues that inverting magnetic fields is not an arbitrary trick but is supported by the geometry of the theory, and he offers a four-dimensional formulation that avoids treating the issue as a mere convention about field signs. The causal arrow cannot be extracted by casually inspecting equations. The formal structure of the theory decides what reversal means before any metaphysical conclusion about direction can be drawn (Malament, 2004). The older thermodynamic problem presses from the opposite side. Reichenbach saw the difficulty clearly: microscopic motions and collisions are often described by reversible laws, while macroscopic processes display irreversibility. The contrast is not cosmetic. It generates the central problem for any account that wants to derive temporal direction from physics without already smuggling direction into the derivation. A glass shattering, a gas spreading, or a footprint forming in sand belongs to a macroscopic world where reversed processes are not observed under ordinary conditions, even when the microscopic equations do not forbid reversed trajectories in the abstract (Reichenbach, 1956; SEP overview). Causal direction adds a second layer to that thermodynamic asymmetry. Reichenbach's Common Cause Principle connects causal structure with probabilistic correlations: when two events are correlated and neither causes the other, a common cause is expected to explain the correlation. The principle matters here because it turns causal ordering into a constraint on explanation rather than a decorative label placed after the physics is done. Causal inference depends on distinguishing common causes from common effects, and that distinction already carries a temporal orientation. The causal arrow enters through the architecture of explanation, correlation, and screening-off relations (Hitchcock & Rédei, 2020).

Price and Weslake sharpen the philosophical target: causes typically precede their effects, and the causal arrow is strongly aligned with the temporal arrow. Treating that alignment as obvious would beg the question. The alignment itself is what needs explaining. If the physical description at the fundamental level does not privilege one temporal orientation, then causal asymmetry cannot be justified by merely pointing to the order in which causes are ordinarily narrated. The task is to identify what in the physical world licenses that narration without making causation primitive by assumption (Price & Weslake, 2009). The Past Hypothesis offers one route into that problem. By positing a low-entropy boundary condition in the early universe, philosophers of statistical mechanics try to explain why thermodynamic behavior overwhelmingly points in one direction. Winsberg's critique is useful because it resists a lazy version of the move: conditioning on the Past Hypothesis may help with the universe's overall entropy increase, yet further work is needed to explain the behavior of smaller isolated systems without running into reversibility objections. The causal story cannot lean on "low entropy past" as a magic phrase. It has to show how that boundary condition supports records, interventions, and asymmetric control (Winsberg, 2004). Loschmidt's paradox keeps the pressure alive. If the microscopic dynamics are reversible, then any argument deriving irreversible entropy increase from those dynamics seems vulnerable to reversal: the same reasoning can be run backward to produce entropy decrease. The point is not that the Second Law is false in ordinary thermodynamic practice. The point is that irreversibility cannot be obtained from time-symmetric dynamics by formal derivation alone. Boundary conditions, probability measures, coarse-graining, and macroscopic constraints enter the story. Causal asymmetry inherits the same burden: it cannot be read straight off the equations without explaining why the world occupies the asymmetric conditions that make causal order usable (Popper, 1973). The section leaves us with a narrower problem than the one we began with. The question is not whether causes precede effects in ordinary life; they do, in the domains where causal reasoning is stable. The question is whether that direction belongs to the fundamental furniture of the world or emerges from the thermodynamic and statistical architecture of macroscopic reality. A satisfactory account must respect the time-symmetric character of large parts of physical theory while explaining why records point backward, interventions point forward, and causal explanation works only within that asymmetric arrangement.

Entropy and the Thermodynamic Arrow of Time

Entropy is the hinge on which the physical problem of temporal direction turns. Classical thermodynamics introduced entropy as a state function capable of tracking whether a process can occur spontaneously, especially in cases involving heat flow, work, and irreversible transformation. The Clausius form of the second law states that heat does not spontaneously pass from a colder body to a hotter body; in thermodynamic terms, spontaneous processes require a non-negative total entropy change. Written compactly, the condition is $\Delta Stotal \geq 0$. The inequality carries more philosophical weight than its simple notation suggests. It gives macroscopic physics a direction without placing that direction directly into Newtonian or Hamiltonian dynamics. A process can satisfy energy conservation while still being

$$S_B(M) = k_B \ln |\Gamma_M|,$$

$$S_G[\rho] = -k_B \int \rho(q,p) \ln \rho(q,p) \, dq \, dp.$$

$$\frac{\partial \rho}{\partial t} + \{\rho, H\} = 0,$$

with ρ, H denoting the Poisson bracket. Phase-space incompressibility blocks any simple story where microscopic dynamics directly compresses low entropy into high entropy. Fine- grained information is preserved under the dynamics. Macroscopic entropy growth enters only after the physical state is partitioned into macrostates, coarse-grained, or interpreted through typicality assumptions. The arrow of time cannot be pulled from the equations alone. It requires a disciplined account of how exact microdynamics gives rise to stable irreversible patterns. Boltzmann's answer depends on typicality rather than strict dynamical necessity. For a system initially located in a low-volume macroregion, the overwhelming majority of compatible

$$\Delta S = nR \ln\left(\frac{V_2}{V_1}\right).$$

where N is the number of particles. The formula has a direct statistical reading: doubling the accessible volume multiplies the spatial possibilities available to each molecule. A gas initially confined to the left half of a box naturally spreads into the full box because there are enormously more microstates corresponding to the spread-out macrostate. The reverse process is compatible with the microscopic equations, yet its phase-space weight is vanishingly small for macroscopic N. The same example becomes subtler once nonequilibrium macrostates are defined with finite resolution. In a one-dimensional gas model, a macrostate can be specified by counting particles in cells ΔxΔv of position-velocity space. The entropy SB (t) then depends on how those cells are chosen, especially on the velocity coarsegraining scale Δv. The time dependence of entropy is not a raw microscopic fact read directly from particle trajectories. It is a macroscopic description that becomes stable when large numbers, typical initial conditions, and an appropriate resolution scale work together. This matters for causation because interventions and records also live at finite resolution. A cause does not pick out a microstate with infinite precision; it picks out a macroscopic condition stable enough to support explanation. Coarse-graining is not a philosophical embarrassment to be hidden in the footnotes. It is part of the machinery that makes thermodynamic description physically usable. By ignoring microscopic correlations that cannot be controlled or observed at the relevant scale, coarse- grained entropy tracks the information unavailable to a macroscopic description. The increase of entropy then reflects the dispersal of information into correlations, environmental degrees of freedom, or microscopic details no agent can keep fixed. A broken cup, a dissipated heat pulse, or a recorded measurement all involve information being redistributed across degrees of freedom. The macroscopic world becomes irreversible because its accessible descriptions erase distinctions that the microscopic dynamics may still preserve in principle. Jaynes gives this point an epistemic discipline without turning entropy into mere subjectivity. Statistical mechanics can be treated as a problem of inference: given macroscopic constraints, choose the probability distribution that maximizes entropy while respecting those constraints. The maximum entropy principle does not say the world is made of ignorance. It gives a rule

$$C_{abcd} \approx 0$$

Reconstructing Causal Asymmetry

Causal asymmetry becomes sharper once causation is treated as a relation of intervention rather than a mysterious metaphysical glue. In structural causal models, a system can be represented through variables governed by structural equations, roughly:

$$P(Y \mid do(X = x_1)) \neq P(Y \mid do(X = x_0)).$$

$$I(E; R) = \sum_{e,r} p(e,r) \log\left(\frac{p(e,r)}{p(e)p(r)}\right).$$

$$P(E_{t_2} \mid do(C_{t_1} = c), B_{t_0}), \qquad t_0 < t_1 < t_2.$$

$$P(C_{t_1} \mid do(E_{t_2} = e), B_{t_0}),$$

$$\frac{dS_{\text{macro}}}{dt} > 0, \qquad I(E_{\text{past}}; R_{\text{present}}) > 0, \qquad P(E_{\text{future}} \mid do(C), B) \neq P(E_{\text{future}} \mid B).$$

Metaphysical Interpretation: Real but Non-Fundamental Causation

The metaphysical question is no longer whether causal language is useful. Its usefulness is too deeply woven into scientific explanation, experimental design, and ordinary reasoning to require defense at that level. The sharper question concerns ontological status: what kind of thing is causation, if it is a thing at all? The traditional options are familiar. Causation may be treated as a primitive relation written into the structure of reality, as a reducible pattern of dependence, as a feature of counterfactual structure, or as a projection of agency and explanation onto a world that contains no causal joints of its own. The account defended here rejects the first and last options. Causation is neither a basic metaphysical ingredient nor a mere fiction. It is a physically grounded macroscopic structure sustained by entropy, records, and intervention-sensitive dependence (Schaffer, 2016; Paul & Hall, 2013; Hitchcock, 1996). A causal fundamentalist treats causation as part of the world's basic inventory. On this view, causal directedness does not need reconstruction from thermodynamics, agency, or records; it is already there, structuring the world from the ground up. The attraction is obvious: cause and effect appear objective, and many explanations seem incomplete without them. The cost is equally sharp. A primitive causal arrow sits uneasily beside physical theories whose fundamental equations often lack the same directed grammar. The metaphysical account then risks explaining causal asymmetry by stipulation: causes point forward because causation itself is directed. That move secures the arrow by placing it where the puzzle began (Tooley, 1987; Armstrong, 1997; Carroll, 1994). Counterfactual approaches offer a cleaner route by connecting causation to difference-making. The guiding idea is that C causes E when, roughly, E depends on C across relevant alternatives: had C not occurred, E would not have occurred, or would have occurred differently. Lewis's early theory gave this thought its canonical form, while later causal-model frameworks refined it through structural equations and interventionist tools (Lewis, 1973; Collins, Hall, & Paul, 2004; Pearl, 2009). The difficulty for the present paper lies in temporal orientation. Difference-making can describe a dependency, but the direction from cause to effect still needs a physical account. Without thermodynamic grounding, counterfactual dependence risks inheriting the temporal asymmetry it is supposed to explain.

$$P(E \mid do(C = c_1), B) \neq P(E \mid do(C = c_0), B).$$

Causal relations operate in this higher-level register. Their reality lies in stable functional organization, not in one privileged microphysical implementation. The reduction need not erase explanatory autonomy. In biology, philosophers of reduction have often argued that higher-level causal relations can remain explanatorily stronger than lower- level molecular descriptions when they are more robust under disturbance or intervention (Waters, 1990; Sarkar, 1998; Brigandt, 2006). A similar lesson applies here. The microphysical state of a laboratory contains too much detail to serve as a practical causal explanation. The causal explanation selects robust macroconditions: preparation, trigger, interaction, measurement, trace. A full microphysical description may contain every coordinate and field value, yet still fail to isolate the explanatory pattern that makes the outcome intelligible. The causal level earns its place by tracking stable dependencies under macroscopic control. Minimal-model explanations give another route to the same metaphysical conclusion. Batterman and Rice argue that some explanations succeed because details distinguishing systems are irrelevant to the large-scale behavior being explained (Batterman & Rice, 2014). Causal explanation often works in this way. The exact microstate of every air molecule is irrelevant to the claim that striking a dry match in oxygen causes ignition. The explanatory force comes from a macro-level pattern that holds across a broad class of systems. The entropic account treats causal asymmetry as one such large-scale pattern: it persists because many microscopic differences wash out under coarse-graining, while entropy gradients and record structures remain stable enough to support intervention and explanation. The position also sits between Humean and anti-Humean metaphysics of law. Humeans usually treat laws as descriptive summaries of the distribution of particular facts; non-Humeans treat laws as governing or constraining the physical possibilities (Lewis, 1986; Maudlin, 2007; Chen & Goldstein, 2021). The account developed here does not require a fully Humean metaphysics. One can accept that laws constrain physical possibilities while denying that those laws require a primitive direction of causal production. Chen and Goldstein's minimal primitivism is relevant: governance need not mean a dynamical push from earlier states into later states. Laws may constrain rather than produce. That model allows a nonHumean to accept a thermodynamic reconstruction of causal asymmetry without turning causation into an ultimate metaphysical engine. Lichtenstein makes the compatibility even sharper by arguing that anti-Humeans can embrace a thermodynamic reduction of time's causal arrow (Lichtenstein, 2021). The standard alignment is too quick: Humeans are often paired with reduction, while anti-Humeans are paired with primitive production. A more careful view permits reduction-plus-production: causal production may be robust within the space of physically possible histories while the direction of that production depends on thermodynamic asymmetry and the Past Hypothesis. The metaphysical payoff is attractive. One can preserve a serious notion of production at the macroscopic level without claiming that causal direction is fundamental in the same sense as a basic physical law or boundary condition. A perspectival element remains, but it is not arbitrary subjectivism. Causal agents are physical systems with sensors, actuators, learning mechanisms, and thermodynamic costs. Milburn, Shrapnel, and Evans argue that causal relations can be grounded in the internal physical states of autonomous irreversible systems capable of learning functional relations between sensor and actuator records (Milburn, Shrapnel, & Evans, 2020). The perspectival feature enters through

$$\text{Causal Reality} \neq \text{Causal Fundamentality}$$

Objections and Replies

A first objection comes from the Russellian suspicion that causation has no serious place in fundamental physics. If physical theory works through equations, states, symmetries, and boundary conditions, causal language may look like a residue of ordinary speech rather than a structure in the world. Norton pushes this suspicion further by treating causation as a useful but limited folk framework rather than a universal principle of nature (Russell, 1913; Norton, 2003). The reply is not to force causation into the fundamental equations. The point is narrower. Causation becomes legitimate in the macroscopic regimes where intervention, record formation, and stable dependence are physically available. A second objection says that entropy explains temporal direction, not causal direction. Entropy increase may explain why gases spread, heat dissipates, and macroscopic processes become irreversible, but causation involves more than temporal order. That objection is right as far as it goes. The present account does not identify causation with entropy increase. It treats entropy as the asymmetric background within which causal modelling becomes physically meaningful. Structural causal models explain dependence through interventions, while thermodynamics explains why intervention itself has a direction inside macroscopic practice (Uffink, 2014; Pearl, 2009; Woodward, 2003). A third objection attacks interventionism. If causation is explained through intervention, then the explanation may already assume causal agency. That worry is serious only if intervention is treated as an unanalysed act of will. A physical intervention is not a metaphysical miracle. It is an operation performed by a thermodynamic system capable of preparation, manipulation, measurement, and memory. Woodward's interventionist framework clarifies the logic of causal dependence, while Landauer-style thermodynamics reminds us that information-bearing systems have physical costs (Woodward, 2003; Landauer, 1961; Bennett, 1982). A fourth objection claims that the account is too dependent on observers. Records, interventions, and memories may seem to introduce epistemology where metaphysics is needed. The answer is to naturalize the observer rather than remove it. Rovelli's account treats the knowing subject as a physical system whose orientation is itself rooted in the entropy gradient. Milburn, Shrapnel, and Evans develop a related perspectival view in which causal relations arise for autonomous systems embedded in irreversible physical processes (Rovelli, 2023; Milburn, Shrapnel, & Evans, 2020). The account is perspectival, but not arbitrary. A perspective can be physically constrained. A fifth objection targets the Past Hypothesis. If causal asymmetry depends on a low-entropy past, then the explanation may simply move the mystery backward. The objection has bite. A special early universe remains a deep cosmological problem. The account still gains explanatory power because the Past Hypothesis helps explain why present records constrain past macrohistories differently from future macrohistories. Recent work on present records sharpens this issue by showing how record asymmetry depends on the relation between present traces and low-entropy boundary conditions (Albert, 2000; Loewer, 2012; Robertson, 2024). A sixth objection comes from backward causation. If the underlying equations are time- symmetric, why not allow future events to cause past events under the right description? Price and Weslake press this challenge because the priority of cause over effect cannot be assumed without argument (Price & Weslake, 2009). The entropic reconstruction does not deny every formal retrocausal model. It explains why ordinary macroscopic causation is forward-directed. Agents can prepare systems, produce traces, and alter later outcomes. Altering an earlier macrocondition would require coordinated control over correlations already dispersed through the world's record structure (Frisch, 2010; Price & Weslake, 2009). Quantum theory gives a stronger challenge. Process-matrix frameworks allow correlations that do not fit inside a single definite causal order. Oreshkov, Costa, and Brukner show that quantum correlations can be described without assuming a pre-existing global causal structure, while Adlam argues that quantum causal order is weaker than ordinary causation because it need not involve the familiar asymmetry of cause before effect (Oreshkov, Costa, & Brukner, 2012; Adlam, 2023). This does not defeat the present account. It limits its domain. The reconstruction offered here concerns the macroscopic level where records, interventions, thermodynamic irreversibility, and agent-like systems already exist. A further objection says that emergence is too weak to carry the metaphysical burden. If causation is only emergent, perhaps it is less real than the underlying microphysics. That conclusion moves too quickly. Emergent structures can be dependent without being fictional. Temperature, pressure, phase transitions, and many biological functions are not fundamental in the strict microphysical sense, yet they remain indispensable in successful scientific explanation. The same pattern applies to causation. Its reality lies in robust macroscopic organization rather than primitive ontological status (O'Connor & Wong, 2023; Batterman & Rice, 2014). The strongest version of the objection says that causal explanation loses depth once it becomes level-relative. A causal claim about a match lighting, a detector firing, or a glass breaking does not specify the complete microstate of the system. It selects stable macrovariables that remain explanatorily useful under perturbation. That selectivity is not a defect. Minimal model explanations often work precisely because many lower-level details are irrelevant to the pattern being explained (Batterman & Rice, 2014; Lange, 2018). Causal explanation earns its autonomy by identifying dependencies that survive across many microphysical realizations. These objections narrow the thesis rather than dissolve it. The claim is not that entropy alone is causation. It is not that causation appears in the fundamental equations under another name. It is not that human psychology invents the causal arrow. The claim is more disciplined. Causal asymmetry becomes real and intelligible where entropy gradients, records, intervention- sensitive dependence, and macroscopic robustness converge. The causal arrow belongs to the architecture of irreversible macroscopic reality, not to a primitive metaphysical layer beneath physics (Rovelli, 2023; Woodward, 2003; Price & Weslake, 2009).

Conclusion

The central problem began with a mismatch. Fundamental physical descriptions often allow time-reversed representation, while causal explanation speaks in a directed grammar. Causes precede effects, interventions aim forward, and records point backward. Treating that asymmetry as primitive would solve the problem too quickly. It would place into metaphysics the very direction that physics asks us to explain. The better route is reconstructive. Causation becomes directional only inside a world already structured by thermodynamic asymmetry (Russell, 1913; Price & Weslake, 2009; Rovelli, 2023).

$$P(E \mid do(C = c_1), B) \neq P(E \mid do(C = c_0), B).$$

The first condition gives an entropy gradient, the second gives record asymmetry, and the third gives intervention-sensitive dependence. None is sufficient alone. Together they describe the physical setting in which causal direction becomes available (Pearl, 2009; Woodward, 2003; Robertson, 2024). This view rejects causal fundamentalism without collapsing into eliminativism. Causation is real because the macroscopic structures that support it are real. It is non-fundamental because its direction depends on entropy gradients, low-entropy boundary conditions, records, and physical systems capable of intervention. Scientific realism does not require every legitimate explanatory structure to be fundamental. Structural realism and emergence both show how higher-level patterns can remain legitimate even when they depend on deeper physical bases (Worrall, 1989; Ladyman, 1998; O'Connor & Wong, 2023). The result is a modest but sharp metaphysical position. A time-symmetric world can contain causal direction, provided that causal direction is not demanded from the fundamental equations alone. The arrow of causation is neither a brute feature of nature nor a fiction imposed by human thought. It is a physically grounded macroscopic pattern made possible by entropy, information, and irreversible record formation. The world does not need causation at its deepest level in order for causal explanation to be real at the level where agents act, experiments operate, and records survive (Frisch, 2010; Rovelli, 2023; Adlam, 2023).

Bibliography

1. Adlam, E. (2023). Is there causation in fundamental physics? New insights from process matrices and quantum causal modelling. Synthese, 201(5), Article 154. `https://doi.org/10.1007/s11229-023-04160z`

2. Albert, D. Z. (2000). Time and chance. Harvard University Press.

3. Armstrong, D. M. (1997). A world of states of affairs. Cambridge University Press.

4. Batterman, R. W. (2002). The devil in the details: Asymptotic reasoning in explanation, reduction, and emergence. Oxford University Press.

5. Batterman, R. W., & Rice, C. C. (2014). Minimal model explanations. Philosophy of Science, 81(3), 349–376. `https://doi.org/10.1086/676677`

6. Bennett, C. H. (1982). The thermodynamics of computation, a review. International Journal of Theoretical Physics, 21, 905–940. `https://doi.org/10.1007/BF02084158`

7. Britannica, The Editors of Encyclopaedia. (n.d.). Entropy. Encyclopaedia Britannica. Retrieved May 15, 2026, from `https://www.britannica.com/science/thermodynamics/Entropy`

8. Carroll, J. W. (1994). Laws of nature. Cambridge University Press.

9. Chakraborti, S., Dhar, A.,

10. Goldstein, S., Kundu, A., & Lebowitz, J. L. (2021). Entropy growth during free expansion of an ideal gas. arXiv. `https://arxiv.org/abs/2109.07742`

11. Chen, E. K., &

12. Goldstein, S. (2021). Governing without a fundamental direction of time: Minimal primitivism about laws of nature. arXiv. `https://arxiv.org/abs/2109.09226`

13. Collins, J., Hall, N., &

14. Paul, L. A. (Eds.). (2004). Causation and counterfactuals. MIT Press.

15. Costa, F., & Shrapnel, S. (2016). Quantum causal modelling. New Journal of Physics, 18, Article 063032. `https://doi.org/10.1088/13672630/18/6/063032`

16. Dougherty, J. (2013). When we do and do not have a classical arrow of time. Philosophy of Science, 80(5), 1112–1124. `https://doi.org/10.1086/674001`

17. Dowe, P. (2000). Physical causation. Cambridge University Press.

18. Fodor, J. A. (1974). Special sciences, or the disunity of science as a working hypothesis. Synthese, 28(2), 97–115. `https://doi.org/10.1007/BF00485230`

19. Frisch, M. (2010). Does a low-entropy constraint prevent us from influencing the past? In G. Ernst & A. Hüttemann (Eds.), Time, chance, and reduction: Philosophical aspects of statistical mechanics. Cambridge University Press.

20. Frisch, M. (2014). Causal reasoning in physics. Cambridge University Press.

21. Goldstein, S., & Lebowitz, J. L. (2004). On the Boltzmann entropy of nonequilibrium systems. Physica D: Nonlinear Phenomena, 193(1–4), 53–66. `https://doi.org/10.1016/j.physd.2004.01.007`

22. Halpern, J. Y. (2000). Axiomatizing causal reasoning. Journal of Artificial Intelligence Research, 12, 317–337. `https://doi.org/10.1613/jair.648`

23. Hitchcock, C., & Rédei, M. (2020). common cause principle. Reichenbach's In E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy Fall 2020 Edition. `https://plato.stanford.edu/archives/fall2020/entries/physics-Rpcc/`

24. Jaynes, E. T. (1957). tical mechanics. Information theory and statisPhysical Review, 106(4), 620–630. `https://doi.org/10.1103/PhysRev.106.620`

25. Kiefer, C. (2021). On a quantum Weyl curvature hypothesis. arXiv. `https://arxiv.org/abs/2111.02137`

26. Kim, J. (1992). Multiple realization and the metaphysics of reduction. Philosophy and Phenomenological Research, 52(1), 1–26. `https://doi.org/10.2307/2107741`

27. Ladyman, J. (1998). What is structural realism? Studies in History and Philosophy of Science Part A, 29(3), 409–424. `https://doi.org/10.1016/S0039-3681(98)80129-5`

28. Ladyman, J., & Ross, D. (2007). Every thing must go: Metaphysics naturalized. Oxford University Press.

29. Landauer, R. (1961). Irreversibility and heat generation in the computing process. IBM Journal of Research and Development, 5(3), 183–191. `https://doi.org/10.1147/rd.53.0183`

30. Lange, M. (2016). Because without cause: Non-causal explanations in science and mathematics. Oxford University Press.

31. Leifer, M. S., & Spekkens, R. W. (2013). Towards a formulation of quantum theory as a causally neutral theory of Bayesian inference. Physical Review A, 88(5), Article 052130. `https://doi.org/10.1103/PhysRevA.88.052130`

32. Lewis, D. (1973). Causation. The Journal of Philosophy, 70(17), 556–567. `https://doi.org/10.2307/2025310`

33. Lewis, D. (1986). Philosophical papers, Volume II. Oxford University Press.

34. Lichtenstein, E. I. (2021). How anti-Humeans can embrace a thermodynamic reduction of time's causal arrow. Philosophy of Science. `https://philsci-archive.pitt.edu/`

35. Loewer, B. (2007). Counterfactuals and the second law. In H. Price & R. Corry (Eds.), Causation, physics, and the constitution of reality: Russell's republic revisited (pp. 293–326). Oxford University Press.

36. Loewer, B. (2012). The emergence of time's arrows and special science laws from physics. Interface Focus, 2(1), 13–19. `https://doi.org/10.1098/rsfs.2011.0072`

37. Malament, D. B. (2004). On the time reversal invariance of classical electromagnetic theory. Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 35(2), 295–315. `https://doi.org/10.1016/j.shpsb.2003.09.006`

38. Maroney, O. J. E. (2020). thermodynamic entropy. Information processing and In E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy Fall 2020 Edition. `https://plato.stanford.edu/archives/fall2020/entries/informationentropy/`

39. Milburn, G. J., Shrapnel, S., & Evans, P. W. (2023). Physical grounds for causal perspectivalism. Entropy, 25(8), Article 1190. `https://doi.org/10.3390/e25081190`

40. Norton, J. D. (2003). Causation as folk science. Philosophers' Imprint, 3(4), 1–22. https://hdl.handle.net/2027/spo.3521354.0003.004

41. O'Connor, T., & Wong, H. Y. (2023). Emergent properties. In E. N. Zalta & U. Nodelman (Eds.), The Stanford Encyclopedia of Philosophy Fall 2023 Edition. https://plato.stanford.edu/archives/fall2023/entries/propertiesemergent/

42. Oreshkov, O.,

43. Costa, F., & Brukner, Č. (2012). Quantum correlations with no causal order. Nature Communications, 3, Article 1092. https://doi.org/10.1038/ncomms2076

44. Parrondo, J. M. R., Horowitz, J. M., & Sagawa, T. (2015). Thermodynamics of information. Nature Physics, 11, 131–139. https://doi.org/10.1038/nphys3230

45. Paul, L. A., & Hall, N. (2013). Causation: A user's guide. Oxford University Press.

46. Pearl, J. (2009). Causality: Models, reasoning, and inference 2nd ed. Cambridge University Press.

47. Popper, K. R. (1973). Alternative statement of the second law of thermodynamics. https://doi.org/10.1038/242456a0 Nature, 242, 456–457.

48. Price, H. (1996). Time's arrow and Archimedes' point: New directions for the physics of time. Oxford University Press.

49. Price, H., & Weslake, B. (2009). The time-asymmetry of causation. In H. Beebee, C.

50. Hitchcock, & P. Menzies (Eds.), The Oxford handbook of causation (pp. 414–443). Oxford University Press.

51. Putnam, H. (1967). Psychological predicates. In W. H. Capitan & D. D. Merrill (Eds.), Art, mind, and religion (pp. 37–48). University of Pittsburgh Press.

52. Reeb, D., &Wolf, M. M. (2014). An improved Landauer principle with finite-size corrections. New Journal of Physics, 16, Article 103011. https://doi.org/10.1088/1367-2630/16/10/103011

53. Reichenbach, H. (1956). The direction of time. University of California Press.

54. Reutlinger, A., & Saatsi, J. (2020). Causation in physics. In E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy Fall 2020 Edition. `https://plato.stanford.edu/archives/fall2020/entries/causationphysics/`

55. Roberts, B. W. (2022). Reversing the arrow of time. Cambridge University Press. `https://arxiv.org/abs/2212.03489`

56. Robertson, K. (2024). Present records of the Past Hypothesis. Synthese, 203, Article 214. `https://doi.org/10.1007/s11229-024-04643-7`

57. Rovelli, C. (2023). How oriented causation is rooted into thermodynamics. Philosophy of Physics, 1(1), Article 4. `https://doi.org/10.31389/pop.46`

58. Russell, B. (1913). On the notion of cause. Proceedings of the Aristotelian Society, 13(1), 1–26. `https://doi.org/10.1093/aristotelian/13.1.1`

59. Salmon, W. C. (1984). Scientific explanation and the causal structure of the world. Princeton University Press.

60. Schaffer, J. (2016). The metaphysics of causation. In E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy. `https://plato.stanford.edu/entries/causation-metaphysics/`

61. Spirtes, P., Glymour, C., & Scheines, R. (2000). Causation, prediction, and search 2nd ed. MIT Press.

62. Thompson, J., Garner, A. J. P., Mahoney, J. R., Crutchfield, J. P., Vedral, V., & Gu, M. (2018). Causal asymmetry in a quantum world. Physical Review X, 8(3), Article 031013. `https://doi.org/10.1103/PhysRevX.8.031013`

63. Tooley, M. (1987). Causation: A realist approach. Oxford University Press.

64. Uffink, J. (2014). Thermodynamic asymmetry in time. In E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy Spring 2014 Edition. `https://plato.stanford.edu/archives/spr2014/entries/time-thermo/`

65. Uffink, J. (2024). Boltzmann's work in statistical physics. In E. N. Zalta & U. Nodelman (Eds.), The Stanford Encyclopedia of Philosophy. `https://plato.stanford.edu/entries/statphys-Boltzmann/`

66. Wallace, D. (2012). The emergent multiverse: Quantum theory according to the Everett interpretation. Oxford University Press.

67. Williams, P. (2022). Entanglement, complexity, and causal asymmetry in quantum theories. Foundations of Physics, 52(2), Article 38. `https://doi.org/10.1007/s10701-022-00562-0`

68. Winsberg, E. (2004). Can conditioning on the "Past Hypothesis" militate against the reversibility objections? Philosophy of Science, 71(4), 489–504. `https://doi.org/10.1086/423749`

69. Woodward, J. (2003). Making things happen: A theory of causal explanation. Oxford University Press.

70. Woodward, J. (2022). Causation and manipulability. In E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy Spring 2022 Edition. `https://plato.stanford.edu/archives/spr2022/entries/causation-mani/`

71. Worrall, J. (1989). Structural realism: The best of both worlds? Dialectica, 43(1–2), 99–124. `https://doi.org/10.1111/j.17468361.1989.tb00933.x`